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Wet Waste Hydrothermal Liquefaction and Biocrude Upgrading to Hydrocarbon Fuels: 2021 State of Technology

April 2022

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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 2021 State of Technology (2021 SOT). In addition, costs for the current and previous SOTs as well as the 2022 projection have been updated using new system boundary assumptions reflecting ownership and operating of the HTL plant by a separate industrial entity from the water resource recovery facility (WRRF). Figure S.1 shows the modeled minimum fuel selling price (MFSP) for the 2021 SOT, along with the previous years SOTs (Snowden-Swan et al. 2020, 2021) and the 2022 projected goal case set forth in the original design report (Snowden-Swan et al. 2017). 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 are in 2016 dollars. Corresponding cost breakdowns and technical parameters for each case are given in Appendix B. Options with and without ammonia (NH_3) stripping treatment of the HTL aqueous phase recycle stream are included in the analysis to account for municipalities where direct recycle of untreated HTL aqueous phase (AP) back to the wastewater treatment plant is feasible.

With the updates from the FY21 technical progress and new system boundary assumptions, the modeled fuel blendstock MFSP for the 2021 SOT is estimated at $2.85 per gasoline-gallon equivalent (GGE) and $2.83/GGE for cases including and excluding NH_3 stripping of the AP, respectively. This represents a reduction of $0.64/GGE and $0.54/GGE, or 18% and 16%, relative to the 2020 SOT cases including and excluding AP NH_3 removal, respectively. It is important to note that the sludge feedstock cost has been updated from a zero cost for the old system boundary assumptions to -$44/wet ton (2019$) for the new system boundaries to reflect a tipping fee (feedstock credit for the HTL plant) paid by the WRRF to the HTL owner/operator. This fee is representative of the current average price that WRRFs pay to dispose of their waste solids. Research progress on the HTL process includes an increase of feed solids content from 20% to 25% (dry basis) along with an increase in biocrude yield from 43.5% to 44.5% (dry, ash-free basis), resulting in a 23-cent reduction in modeled MFSP (for the case including AP NH_3 removal). Over 2000 hours of time-on-stream was demonstrated for the biocrude hydrotreating guard bed and main bed catalysts showing stable catalyst performance. With this progress, a main bed catalyst lifetime of 1 year and guard bed catalyst lifetime of 2000 hours is assumed for the 2021 SOT. The increase in hydrotreater guard bed and main bed catalyst lifetimes relative to the 2020 SOT (552 hours for both) result in reductions of $0.28/GGE and $0.16/GGE, respectively (for the case with NH_3 removal).

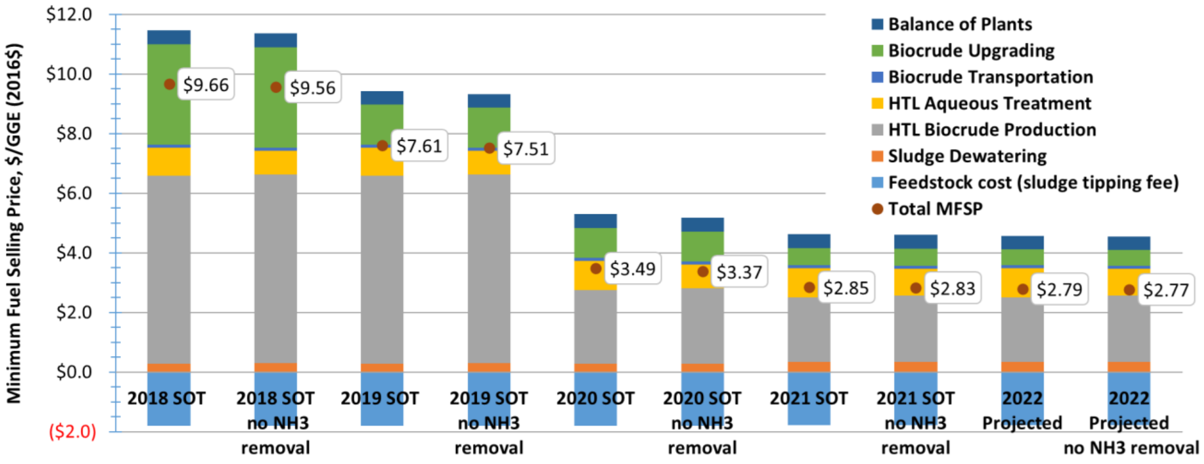

Figure S.1. Wet waste HTL and upgrading pathway cost allocations with updated HTL system boundary.

Wet waste feedstocks tested in this year's HTL and biocrude hydrotreating research include:

- Three sources of food waste, including:
  - Kitchen/cafeteria waste from a correctional facility (tested in bench scale system)
  - Kitchen/cafeteria waste from an army base (tested in bench scale system)
  - Food waste engineered bioslurry (EBS®) from Waste Management for anerobic digestion (AD) (tested in bench scale system)
- Blend of wastewater sludge, food waste, and fats/oils/greases (FOG) in a 50/40/10 blend (dry weight), approximately representative of the blend generated in Detroit and the surrounding region (tested in bench scale system)
- Primary/secondary sludge mixture from wastewater treatment at Great Lakes Water Authority (GLWA) in Detroit, MI [tested in the engineering scale system, the Modular Hydrothermal Liquefaction System (MHTLS)]

This year's feedstock testing has demonstrated that HTL can process several sources of food waste and to date, all four of the major high-volume wet wastes available as feedstocks (wastewater solids, manures, FOG and food waste) have now been characterized and successfully tested in PNNL's continuous systems.

Testing of catalytic conversion of HTL AP to alkenes over ZnZr catalyst was also conducted in FY21 and the results were used to update the preliminary AP treatment TEA sensitivity case conducted for the 2020 SOT (Snowden-Swan et al. 2021). Testing was scaled up 10-fold and generated a data set that provided an improved mass balance for this year's modeling. When used in conjunction with ammonia stripping, the testing and analysis indicate the process could provide a measured 92% removal of chemical oxygen demand (COD), a measured 78% carbon reduction, and an estimated 92% removal of ammonia nitrogen, with recovery of a salable ammonia by-product. Organic nitrogen removal efficiency is a data gap and modeled as 91% to satisfy the measured COD and carbon reductions and overall elemental balance. Additional data is needed on the fate of organic nitrogen species. The updated TEA results for the ZnZr method indicate that the SOT MFSP can be reduced by 28 cents per GGE biocrude ($0.30/GGE for fuel blendstock) relative to the 2021 SOT for the case including AP NH_3 removal.

As a sensitivity case, TEA was also performed for a regional waste collection and blending scenario for a 3,800-TPD integrated HTL and upgrading plant processing a sludge/food/FOG waste blend representative of that generated in the Detroit and surrounding area. The plant is assumed to be co-located with the Detroit WRRF (Great Lakes Water Authority). The analysis is based on PNNL's actual testing data for an industrial waste blend proportionally equivalent to that generated in the Detroit area (50/40/10 sludge/food/FOG waste by dry weight). Using median wet waste feedstock prices from Badgett et al. (2019) and a feedstock transportation cost of $50/tonne, the minimum production cost for fuel blendstocks from the regional waste-to-fuel plant is estimated at $2.17/GGE, as compared to $2.85/GGE for the baseline scale SOT case.

Future work is needed to further advance the pathway's technology readiness and reduce costs in the following areas:

- HTL: The research progress on continuous HTL has effectively reduced the modeled MFSP by $4.0/GGE since the initial pathway SOT was published. While much progress has been made on the process performance of sludge HTL, several areas of potential improvement remain including efficient feed deashing methods for high-ash feedstocks such as certain sludges, biosolids, and manures, advanced solids removal methods that minimize biocrude losses and reduce equipment wear-and-tear compared to the current blowdown method, catalytic HTL to improve yields from certain waste feedstocks, and the use of inserts in heat exchangers for enhanced heat transfer rates. All of these strategies may further improve the economic and environmental performance of the HTL process.

- Biocrude Catalytic Upgrading: Research progress on hydrotreating performance has reduced the modeled MFSP by $2.8/GGE since the initial pathway SOT was published. Operating costs associated with the main bed catalyst have been reduced to 1 cent per GGE with the current assumed lifetime of 1 year. At the current assumed lifetime of 2000 hours, the guard bed catalyst contributes 10 cents per GGE to the current SOT. A slurry bed configuration was tested this year and showed promising results. Translation of these results into the necessary capital and operating costs is necessary in future analysis to elucidate the potential cost savings for this type of configuration. In addition, testing of low-cost catalysts in the slurry bed is needed. Lastly, research and analysis is needed to understand the potential of HTL to produce sustainable aviation fuel (SAF) and marine fuel in the future.
- AP Treatment Methods: Testing results and TEA indicate that the ACU process may be a promising method in terms of cost, carbon and nitrogen removal efficiency, and feasibility to recover a clean ammonia coproduct from the AP. More testing and analysis work is needed to verify the fate of the AP organic nitrogen and the full environmental benefits of the ACU process. Several additional strategies for product, energy, and/or nutrient recovery from the AP are currently under investigation by PNNL and others and will need to be evaluated via TEA and life cycle analysis to estimate cost and environmental impacts on the SOT. Testing of ammonia stripping of raw AP as well as effluent AP from the ACU and other methods in development will be needed to validate separation efficiency and ammonia nutrient recovery rates assumed in the model.

Acronyms and Abbreviations

ACU	aqueous phase catalytic upgrading
AFDW	ash-free dry weight
AP	aqueous phase
BETO	Bioenergy Technologies Office
CCCSD	Central Contra Costa Sanitary District
CHG	catalytic hydrothermal gasification
COD	chemical oxygen demand
CSTR	continuous stirred-tank reactor
DAF	dry, ash-free
EBS	engineered bioslurry
EPA	Environmental Protection Agency
FOG	fats, oils, and grease
FY	fiscal year
GGE	gasoline-gallon equivalent
GHG	greenhouse gas
GLWA	Great Lakes Water Authority
HTL	hydrothermal liquefaction
HPLC	high-performance liquid chromatography
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
RFS	Renewable Fuel Standard
SAF	sustainable aviation fuel
SCREW	steam phase-catalytic reduction of wastewater
SOT	state of technology
TEA	techno-economic analysis
TOC	total organic carbon
TOS	time-on-stream
TPD	U.S. ton/day
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). This report summarizes the R&D progress and associated techno-economic analysis (TEA) for the pathway 2021 SOT. Methods and economic assumptions for the nth 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 (2016) 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, which includes conversion of sludge from a water resource recovery facility (WRRF) via HTL and biocrude upgrading. The modeled process scales for the HTL plant and the centralized biocrude upgrading plant are 110 dry ton/day sludge and 38 million gal/yr biocrude feed, respectively, consistent with the design case and SOTs (Snowden-Swan et al. 2017, 2020, 2021). The centralized biocrude upgrading plant processes 10 times the amount of biocrude generated from one 110 dry ton/day HTL plant.

The overall technical process configuration remains the same as the 2020 SOT case, however an adjustment in analysis system boundaries has been made to better represent the most likely scenario for project ownership. In previous years' analyses, we assumed the HTL plant project would be taken on by the WRRF, as illustrated in Figure 1A. As such, the avoided cost of sludge disposal, the majority of dewatering costs, and disposal costs for the HTL solids and AP were assumed to be absorbed by the WRRF and therefore were excluded from the HTL plant costs. After years of working with our industry partners, it has become evident that it is most likely that the HTL plant would be owned and operated by a separate private entity (while still located near the WRRF), as illustrated in Figure 1B. As a representative example of this type of business relationship, Detroit's WRRF, which is managed by the Great Lakes Water Authority (GLWA), currently contracts with NEFCO to take 75% of their sludge waste (NEFCO 2022). The GLWA pumps thickened sludge to NEFCO's facility across the street where it is dried and then sold as a fertilizer product. Modeled after a similar scenario to this, we have adjusted several assumptions such that the SOT analysis system boundaries are clearly defined between the WRRF and the HTL plant owner/operator.

With the new system boundaries that assume separate HTL plant ownership (Figure 1B), 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 (see Section 3.2 for basis). 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 AP to the municipal sewer system. A national average tipping fee is used for the cost of solids landfilling and typical industrial surcharge rates for chemical oxygen demand (COD) and ammonia (NH_3) are used for the cost of discharging of the AP (see Section 4.2 for details). The updated system boundaries and associated costs are more realistic and also better facilitate systematic analysis of the economic and environmental tradeoffs for AP and solids treatment alternatives being investigated by the team at Pacific Northwest National Laboratory (PNNL) and others. 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.

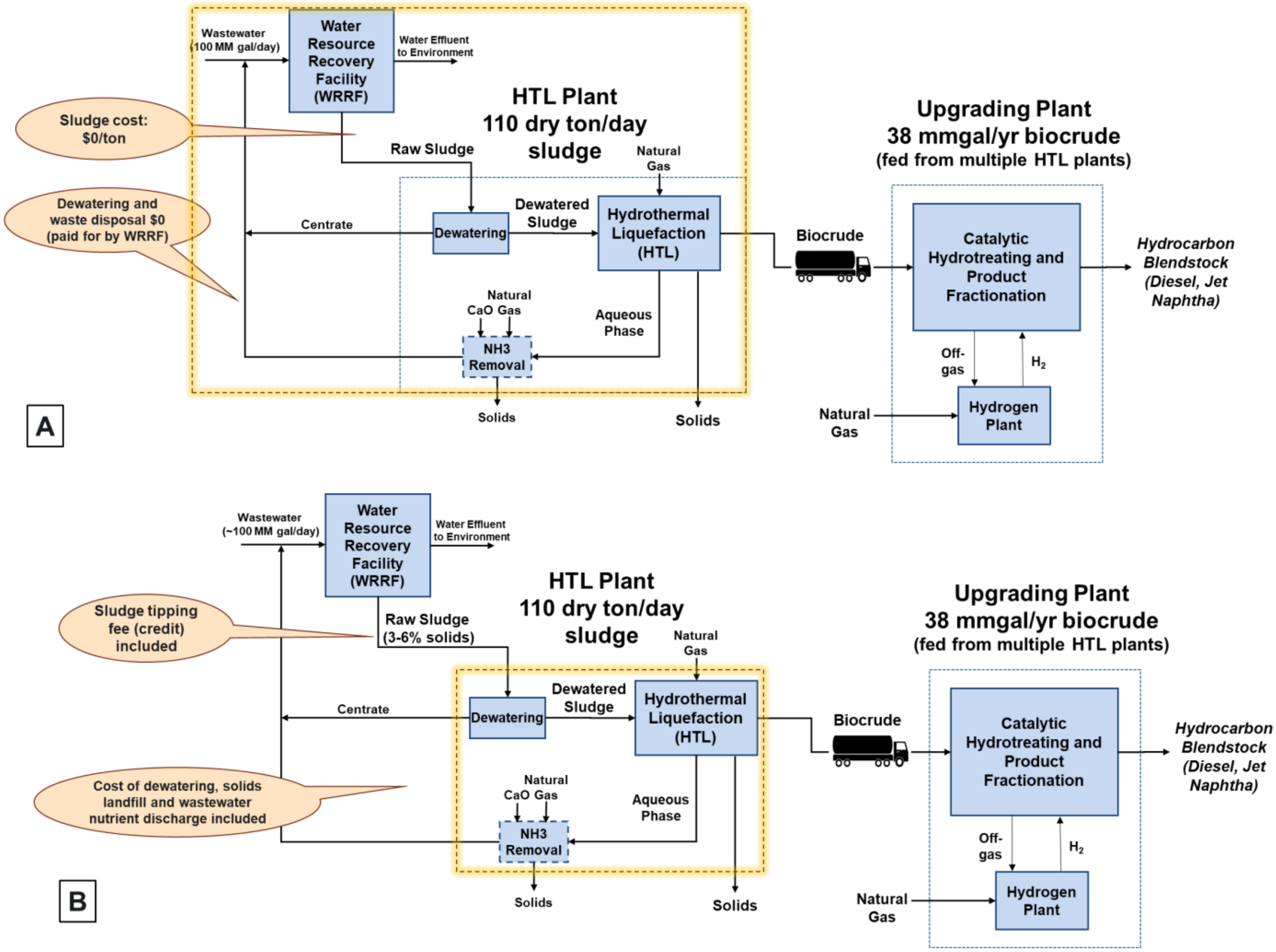

Figure 1. Process flowsheet for 2021 SOT showing updated HTL plant ownership (yellow dashed boxes) from the WRRF for previous SOTs (A) to a separate owner/operator for the 2021 SOT (B).

A sensitivity case is presented that considers a a larger scale regional HTL plant for collection, blending, and processing of additional food and fats, oils, and grease (FOG) wastes, as illustrated in Figure 2. Other municipal solid wastes such as yard waste, paper waste, and landfilled municipal solid waste could also be considered for blending but are not included in the present analysis. Geospatial siting analysis was conducted to determine estimates of plant scale, waste blending ratio, transportation distance, and transportation cost for an urban area regional case study. Section 4.4 gives the details of the analysis and the TEA results for this case. Note that with the larger HTL scale for the regional case (3800 dry TPD) compared to the 110 dry TPD base case, it is assumed that the upgrader would be integrated with the HTL plant, precluding the need for biocrude transportation.

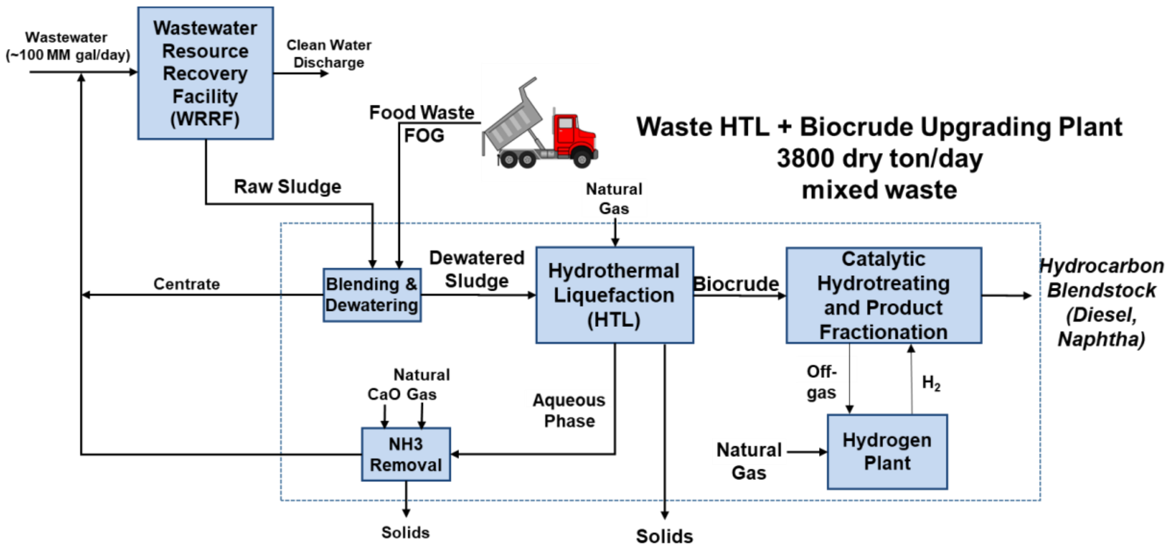

Figure 2. Sludge HTL and biocrude upgrading block diagram for regional waste blending scenario.

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 FY21 R&D include 1) wet waste compositional analysis; 2) wet waste HTL processing; 3) aqueous phase (AP) treatment testing; and, 4) hydrotreating of wet waste HTL biocrudes. The following sections present the experimental data and a discussion of how it was used in the analysis. The basis for feedstock costs/credits used in the analysis for sludge, food and FOG wastes is also presented. 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 effectively advances the pathway.

3.1 Wet Waste Feedstock Composition

Wet waste feedstocks tested in FY21 include the following:

- Three sources of food waste, including:
  - Kitchen/cafeteria waste from a correctional facility (tested in bench scale)
  - Kitchen/cafeteria waste from an army base (tested in bench scale)
  - Food waste engineered bioslurry (EBS®) from Waste Management for AD (tested in bench scale)
- Blend of wastewater sludge, food waste, and fats/oils/greases (FOG) in a 50/40/10 blend (dry weight), approximately representative of the blend generated in Detroit and the surrounding region (tested in bench scale)
- Primary/secondary sludge mixture from wastewater treatment at Great Lakes Water Authority (GLWA) in Detroit, MI (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. Four sources of food waste were tested in FY21. The first (WW20) contained kitchen scraps and cafeteria food waste from Coyote Ridge Corrections Central facility in Eastern Washington State. The second (WW21) is food waste collected from several restaurants located on Joint Base Lewis McChord (JBLM), an army/air base in Western Washington State. These cafeteria/kitchen wastes have very similar compositional makeup, both with respect to elemental and carbohydrate, fat and protein contents, which generally is to be expected. The third source of food waste (WW23) is engineered bioslurry (EBS®) from a food waste recycling program run by Waste Management. The EBS® consists of pre- and post-consumer food waste that has been processed to remove non-degradable contaminants and blended into a feed that can be co-fed, with sludge, to anaerobic digestion. The EBS® waste is notably lower in carbohydrate and higher in fat content compared to the restaurant wastes tested. It is also of note that all of the food wastes are much lower in ash (5-7% dry weight) than other feedstocks previously tested such as sludges and manures.

A blend of wastewater treatment primary/secondary sludge, food waste, and FOG was tested (WW22) to represent the approximate ratio of urban wet wastes generated in the Detroit and surrounding area. The ratio of feedstocks was determined from waste resource geospatial analysis of an extensive database developed earlier (Skaggs et al. 2018; Seiple 2021; Snowden-Swan et al. 2021). The data from the blend test provides the basis for the regional waste collection scenario analyzed as a sensitivity case for the SOT (see Section 4.4). The sludge was sourced from GLWA (same as feedstock for MHTLS 15), the FOG was a scum sample decanted from primary sludge at the Contra Costa Central Sanitary District (CCCSD) WRRF, and the food waste was the kitchen/cafeteria food waste from Coyote Ridge (same as feedstock for WW20). Note that manure was omitted from the blend testing and associated hot spot analysis due to the high contaminant (dirt, grit, straw) content and more significant processing challenges and uncertainty associated with HTL of manure compared with other feedstocks.

Lastly, a primary /secondary sludge mixture from GLWA (MHTLS 15) was tested this year in the engineering scale system. This sample was collected directly from GLWA's treatment train and is estimated to consist of approximately 43:57 (dry wt) primary/secondary sludges. This differs slightly from the original WW06 run with GLWA sludge (see Table A.1), where pure primary and pure secondary sludges were collected separately by GLWA and then blended at PNNL to a 50/50 ratio for testing. Ultimate analysis of the two GLWA sludge feedstocks (WW06 and MHTLS 15) are very similar, however proximate analysis show significantly different fat and carbohydrate contents for the two samples. It should be noted that early in our testing, samples for proximate analysis were not dried and therefore analysis for WW06 could be less reliable.

To date, all of the identified major wet waste feedstock categories that could be available as energy feedstock (DOE 2017) (wastewater solids, manure, food waste, and fats/oils/grease [FOG]) have successfully been processed in PNNL's bench scale and/or engineering scale systems using real-world samples from existing industrial waste generators. A comprehensive list of all wet waste feedstocks tested to date in support of the development of this pathway is given in Appendix A.

The modeled 2021 SOT feedstock composition remains unchanged in order to maintain consistency with the design case and to show the impact of HTL, hydrotreating, and AP treatment research progress on advancement of the technology. The only change in the feedstock for the baseline case is an increase of feed solids to the HTL reactor from 20% to 25%, which was demonstrated through this year's testing (see Section 3.3). As previously introduced in the 2020 SOT report, it is conceivable and desirable that in a sustainable and circular economy of the future, wastes could be efficiently collected in areas of the country where generation is concentrated, thereby improving economies of scale for the HTL conversion plant. To investigate the feasibility and impact of such a regional scenario, a sensitivity case is included in the TEA, using the composition and testing data for the sludge/food/FOG blend (WW22).

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

	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 43/57 Sludge GLWA (Dry)	MHTLS 15 43/57 Sludge GLWA (DAF)	2021 SOT and 2022 Models (Dry)	2021 SOT and 2022 Models (DAF)
C	49.3	52.3	51.5	54.1	48.2	55.4	50.8	54.8	40.8	51.7	46.8	52.1
H	7.3	7.7	7.6	8.0	7.3	8.4	6.6	7.1	5.5	7.0	6.5	7.2
O	35.5	37.7	34.3	36.0	29.1	33.4	32.2	34.7	26.4	33.5	29.7	33.1
N	3.5	3.7	3.3	3.5	4.7	5.4	3.2	3.5	5.3	6.7	5.7	6.3
S	0.0	0.0	0.2	0.2	0.6	0.7	0.2	0.2	0.9	1.1	1.2	1.3
Ash	6.5	n/a	4.1	n/a	13.5	n/a	8.6	n/a	21.1	n/a	15.0	n/a
P	1.0	n/a	0.4	n/a	1.4	n/a	0.4	n/a	2.3	n/a	1.9	n/a
Carb	53.6	56.9	53.1	55.8	31.3	36.0	41.4	44.7	26.8	33.7	Not modeled	
Fat	18.6	19.7	20.0	21.0	23.3	26.8	27.7	29.9	14.2	17.8	Not modeled	
Protein	21.6	22.9	20.7	21.7	30.2	34.7	22.8	24.6	38.5	48.5	Not modeled	
FAME	5.4	5.7	16.0	16.8	16.4	18.9	21.4	23.1	9.2	11.6	Not modeled	
Ash	5.8	n/a	4.9	n/a	13.0	n/a	7.3	n/a	20.6	n/a	Not modeled	

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

3.2 Wet Waste Feedstock Cost Basis

As discussed previously, for the 2018-2020 SOTs and original design case, the HTL plant was assumed to be owned and operated by the WRRF, with the sludge available at no cost. While this assumption was perhaps more reasonable when considering an HTL plant owned by a WRRF, it is unreasonable when considering a plant owned and operated by separate entity, as sludge is a liability on which WRRFs spend a significant portion of their annual budget. Therefore, it is fair to assume that a WRRF generator would pay an HTL plant to take their sludge at a price, or “tipping fee”, that is mutually beneficial to both the municipality and the HTL plant owner/operator. Continual feedback from our industrial partners as well as documentation on current costs for WRRFs also supports inclusion of a tipping fee of sorts in the analysis. In reality, a municipality and potential owner/operator would arrive at a negotiated contract price that is mutually beneficial to both parties.

There is a lack of systematic data on the price or disposal cost of wet waste in the literature. Moreover, costs presented are highly variable widely depending on location, disposal method, transportation costs, and other factors. Badgett et al. (2019) is one of the only studies to estimate prices of wet wastes on a national (U.S.) level using a systematic method. Sludge price from this study was defined as the sum of the dewatering cost (positive value) plus the disposal fee (negative value). Based on data extracted from sludge price curves presented in Badgett et al. (2019), a weight averaged price of -$39.7/wet tonne (-$36.0/wet ton) was estimated, as shown in Table 2. This value was then adjusted by subtracting out the average dewatering cost from the study (personal communication with A. Badgett, August 6, 2021) since we include separate dewatering costs in the HTL plant economics. The adjusted feedstock cost assumed is -$44/wet ton (-$49/wet tonne) in 2019 dollars (-$187/dry ton in 2019$; -$171/dry ton in 2016$). This price also falls in line with the average solids disposal costs from state surveys of dozens of WRRFs in the northern and southern California regions (BACWA 2021, SCAP 2016). For example, Figure 3 shows the annual sludge production and sludge management cost for each disposal alternative based on the BACWA 2021 biosolids survey (Bay Area Clean Water Agencies, 2021). The BACWA survey collected sludge management information from 31 agencies and reports a cost range of $14-139/wet ton with an average of $52/wet ton for the Bay Area. A similar survey of the southern California region agencies gave a range of $7 to $86 per wet ton with an average of $50/wet ton (SCAP 2016). The management costs from these surveys include the “rate at the gate” and transportation cost, which averaged 129 miles one-way for SCAP and 56 miles one-way for BACWA.

Table 2. Data extracted from Badgett et al. (2019) for sludge feedstock cost (tipping fee) estimate.

Cumulative Percent	Wet Sludge Supply, millions of tonnes	Sludge Price, $/wet tonnes
0.0%	0.0	-152.9
2.8%	2.3	-123.5
8.8%	7.1	-120.6
15.5%	12.5	-113.2
21.8%	17.6	-102.9
24.4%	19.7	-69.1
28.1%	22.6	-58.8
33.0%	26.6	-51.5
38.2%	30.7	-48.5
42.8%	34.5	-39.7
47.2%	38.1	-42.6
53.5%	43.1	-29.4
59.3%	47.8	-22.1
66.7%	53.7	-5.9
74.0%	59.7	0.0
81.3%	65.5	2.9
88.5%	71.3	2.9
95.0%	76.6	7.4
100.0%	80.6	8.8
Weighted Averaged Cost, $/wet tonne		**-39.7**(a)

(a) Badgett et al. 2019 includes dewatering costs. Because we use separate dewatering costs for the analysis, the average dewatering cost (-$9/wet tonne, Badgett via personal communication, August 6, 2021) was subtracted from this value to give -$49/wet tonne (-$44/wet ton).

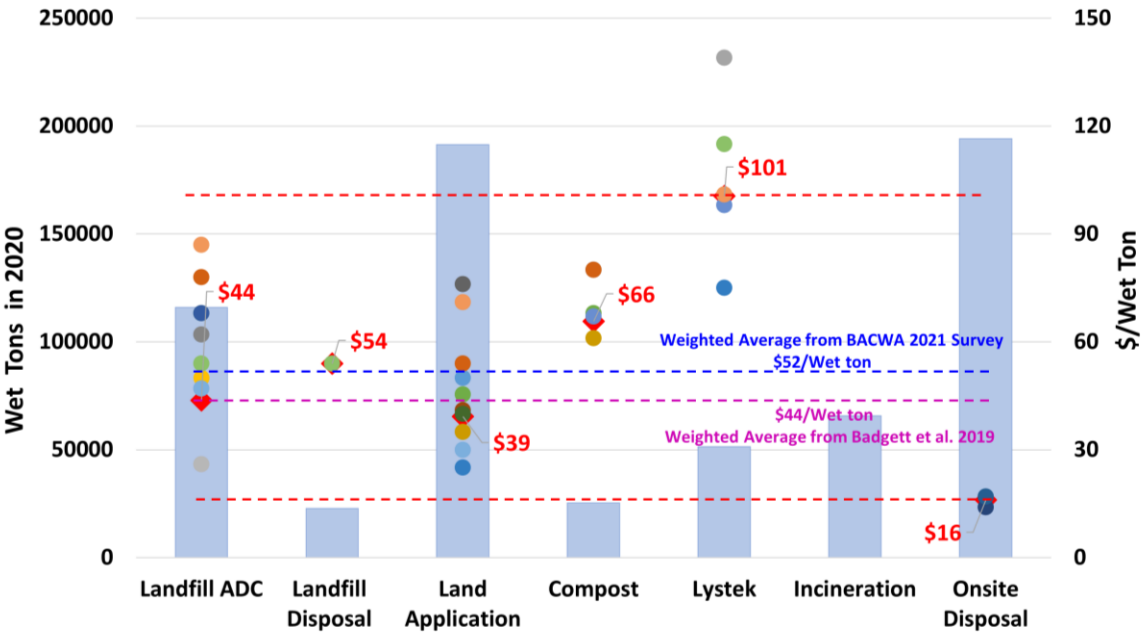

Figure 3. The annual sludge production and sludge management cost for each disposal alternative collected from 31 WRRFs in the BACWA 2021 Survey. (The dots represent sludge cost data from different agencies; the blue bars represent the total wet tons of sludge per disposal method; the red numbers are the weighted average cost for each disposal method.)

3.3 Wet Waste Hydrothermal Liquefaction Data

Testing of HTL at PNNL is performed in bench-scale and engineering-scale systems. The capacities of the 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. 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 previous SOT report (Snowden-Swan et al. 2021). Testing with the three food wastes and the sludge/food/FOG blend (WW20-23) were run in the bench scale unit. Testing of the GLWA primary/secondary sludge (MHTLS 15) was run in a pure plug flow configuration in the engineering scale system.

Experimental HTL testing conditions and results are given in Table 3, along with the parameters used for the modeled SOT and projected cases. Product yields are given on a percent dry, ash-free (DAF) mass basis (lb DAF product/lb DAF feed multiplied by 100). The cafeteria and restaurant food wastes were run at feed solids concentrations of 22% (WW20) and 26% (WW21) and produced biocrude yields of 37% and 42%, respectively. With the compositional makeup being relatively equal between these two feedstocks, the general trend of increased biocrude yield with increasing feed solids content is to be expected. The EBS® feed (WW23) was run at 19% solids content and produced a biocrude yield of 46%, significantly higher than with the other food wastes. Possible reasons for this are that the EBS® has a higher fat content than the other food wastes and is a more consistent/homogeneous feedstock compared to what we can produce in the lab from our raw food wastes for WW20 and WW21. Also of note is the low moisture content and heating value of the EBS®-derived biocrude relative to other feedstocks.

The waste blend consisting of 50:40:10 (dry wt) wastewater treatment sludge, food waste, and fats/oils/greases (FOG) waste (WW22) was tested at 19% and 25% feed solids. The biocrude yield increased a modest 1% from 44% to 45% with the higher solids run.

Note that two of the tested feedstocks were successfully processed at the 2022 target of 25% feed solids content. Although processing 25% sewage sludge feedstock was not directly demonstrated in the lab, 25% solids is adopted for the 2021 SOT as this is expected to be well within the capabilities of commercial-scale slurry pumps (Berglin et al. 2012). We have also recently reached out to a prominent slurry pump manufacturer and confirmed this fact. In addition, the biocrude yield for the SOT is increased from 44% to 45%, based on the relative yield increase shown between the 19% and 20% runs for the sludge/food waste/FOG blend (WW22 A and B). The regional blending sensitivity case presented in Section 4.4 is based on the WW22B data (run at 25% solids feed).

Table 3. Wet waste HTL testing results and model assumptions.

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	2021 SOT Model	2022 Projected Model
Temperature, °F (°C)	653 (345)	642 (339)	639 (337)	639 (337)	639 (337)	655 (346)	656 (347)	656 (347)
Pressure, psia (MPa)	2855 (19.7)	2915 (20.1)	2765 (19.1)	2765 (19.1)	2840 (19.6)	2765 (19.1)	2979 (20.5)	2979 (20.5)
Feed solids, wt%								
Ash included	22.3%	25.7%	19.4%	24.6%	18.7%	15.4%	25%	25%
Ash-free basis	20.9%	24.6%	16.8%	21.3%	17.1%	12.0%	21%	21%
Liquid hourly space velocity, vol./h per vol. reactor	3.6	6.0	10.3	10.0	5.5	4.0	4.0	6
Equivalent residence time, min.	17	10	6	6	11	15	15	10
Product yields(a) (dry, ash-free sludge), wt%								
Oil (biocrude)	37%	42%	44%	45%	46%	42%	45%	48%
Aqueous	43%	36%	29%	31%	34%	36%	28%	25%
Gas	13%	20%	19%	18%	18%	17%	16%	16%
Solids	7%	2%	8%	6%	2%	5%	12%	11%
Carbon yields								
Oil (biocrude)	58%	64%	58%	61%	62%	52%	67%	72%
Aqueous	22%	22%	24%	23%	27%	33%	23%	18%
Gas	8%	11%	9%	9%	9%	9%	10%	10%
Solids	13%	3%	9%	7%	3%	7%	1%	1%
HTL dry biocrude analysis, wt%	75.9%	74.1%	75.0%	74.7%	76.4%	77.8%	78.3%	78.3%
C	11.3%	11.1%	11.3%	11.6%	9.6%	12.4%	10.8%	10.8%
H	8.4%	10.6%	8.1%	8.0%	9.4%	3.6%	4.8%	4.8%
O	4.0%	4.0%	4.8%	4.9%	4.0%	5.3%	4.9%	4.9%
N	0.0%	0.0%	0.7%	0.7%	0.0%	0.9%	1.2%	1.2%
S	0.09%	0.00%	0.0%	0.00%	0.00%	0%	Not modeled(b)	Not modeled(b)
P	0.10%	0.11%	0.17%	0.14%	0.03%	0.03%		
Ash							0.0%	0.0%
HTL dry biocrude H:C ratio (mol)	1.8	1.8	1.8	1.9	1.7	1.9	1.6	1.6
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)	17,100 (39.7)	17,100 (39.7)
HTL biocrude moisture, wt%	2.6%	4.8%	3.7%	4.6%	1.7%	9.8%	4.0%	4.0%
HTL biocrude wet density @ 77°F (25°C) (g/ml)	1.00	1.01	0.96	0.96	0.98	0.97	0.98	0.98
AP chemical oxygen demand (mg/L)	90,500	111,550	81,500	100,100	74,333	81,600	94,022	61,100

(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).

3.4 Aqueous Phase (AP) Treatment Data

The AP from the HTL process contains significant loads of COD and nitrogen which may be costly and potentially problematic for a WRRF to process and therefore should be treated to destroy or recover these nutrients prior to discharge. PNNL and others are investigating possible strategies for treating and/or valorizing the carbon, nitrogen and phosphorus in this stream. The design case and SOTs to date assume that a minimum of NH_3 stripping would be used to reduce levels of NH_3 nitrogen in the AP, however, data is needed to validate this assumption. Moreover, this is not the optimal choice as removed NH_3 is not pure enough to recover as a fertilizer by-product due to the presence of organics that are stripped along with the NH_3. Better options are needed for recovering nutrients, energy and/or chemical co-products from the HTL AP.

Compositional analysis of the AP from PNNL's HTL testing to date (Table 3 and Table A.3) shows concentrations of total organic carbon (TOC) of up to 3.4% and total nitrogen levels of up to 1% in the HTL AP, depending on the range of feedstock types and feed solids concentrations tested. It is anticipated that, at least in some circumstances, treatment will be necessary to reduce the nutrient load and perhaps remove specific problematic components before the AP can be recycled back to the WRRF. Collaborative work with industrial partners has indicated that there may be impacts on the WRRF's UV absorption process and nitrogen discharge limits, depending on the specific WRRF's treatment train capabilities. Further research is needed to elucidate the precise nature of the impacts of HTL AP on the WRRF's operations, to identify specific mitigation strategies, and to develop appropriate treatment processes. A summary of AP composition including total nitrogen, ammonia nitrogen (NH_3-N), total carbon, total organic carbon, and organics identified from high-performance liquid chromatography (HPLC) from historical HTL wet waste testing at PNNL is given in Figure 4A. Figure 4B shows normalized concentrations for 25% feed solids (adjusting for water content) which is leveraged for the current SOT model. From these TOC and HPLC analyses, it is estimated that approximately 19-45% of organic carbon contained in the AP is identified through HPLC. Note that the HPLC has not been calibrated to detect nitrogen-containing organics in the AP.

In FY20, three thermochemical methods were evaluated for treating the HTL AP before it is sent to the NH_3 stripping unit and then recycled to the WRRF, including catalytic hydrothermal gasification (CHG), steam phase-catalytic reduction of wastewater (SCREW) and AP catalytic upgrading (ACU) (Snowden-Swan et al. 2021). The focus was to reduce potential risk from HTL components recycled to the WRRF and to recover high-purity NH_3 to produce $(NH_4)_2SO_4$ as by-product for better economic performance. High-level TEA was conducted to compare the different methods based on limited experimental data. The results of this initial TEA indicated that among these three thermochemical methods, the ACU method using a two-stage catalyst bed (ZnZr followed by ZSM-5) at a relatively low pressure provides the lowest modeled minimum biocrude selling price (MBSP). Therefore, work in FY21 focused on the further development of the ACU method, including testing with improved performance measures and updating the TEA with the new system boundary accordingly.

The conceptual process flowsheet of the ACU unit at a commercial scale is shown in Figure 5. Here, the HTL AP product is first sent to a hydrocyclone to remove solids, preheated, and then sent to the reactors to convert most of the organic compounds into CO_2, CH_4 and light alkenes. A guard bed packed with low-cost carbon is used to protect the ZnZr and ZSM-5 catalyst beds in the main reactor from impurities in the AP feed. The assumptions for catalyst and carbon price and lifetime are given in Section 4.3 (Table 13). The treated water from the ACU unit, with considerable NH_3, is first sent to the NH_3 stripping unit to recover high purity NH_3 for $(NH_4)_2SO_4$ production, and then discharged to the WRRF via the municipal sewer system for final treatment. The gas-phase product from the reactor, mainly CO_2, CH_4, and light alkenes, is sent to the hot oil system fired heater used to heat the sludge up to reactor temperature and supply heat for $(NH_4)_2SO_4$ crystallization. The heat provided by the fuel gas is enough to reduce natural gas usage by 50% relative to the SOT base case. Note that the configuration shown in Figure 5 does not exactly match the laboratory-scale experimental setup. For example, in the laboratory system, solids in the untreated AP from HTL are separated by settling in a large source container and heat is not recovered, as would be standard in a commercial-scale plant.

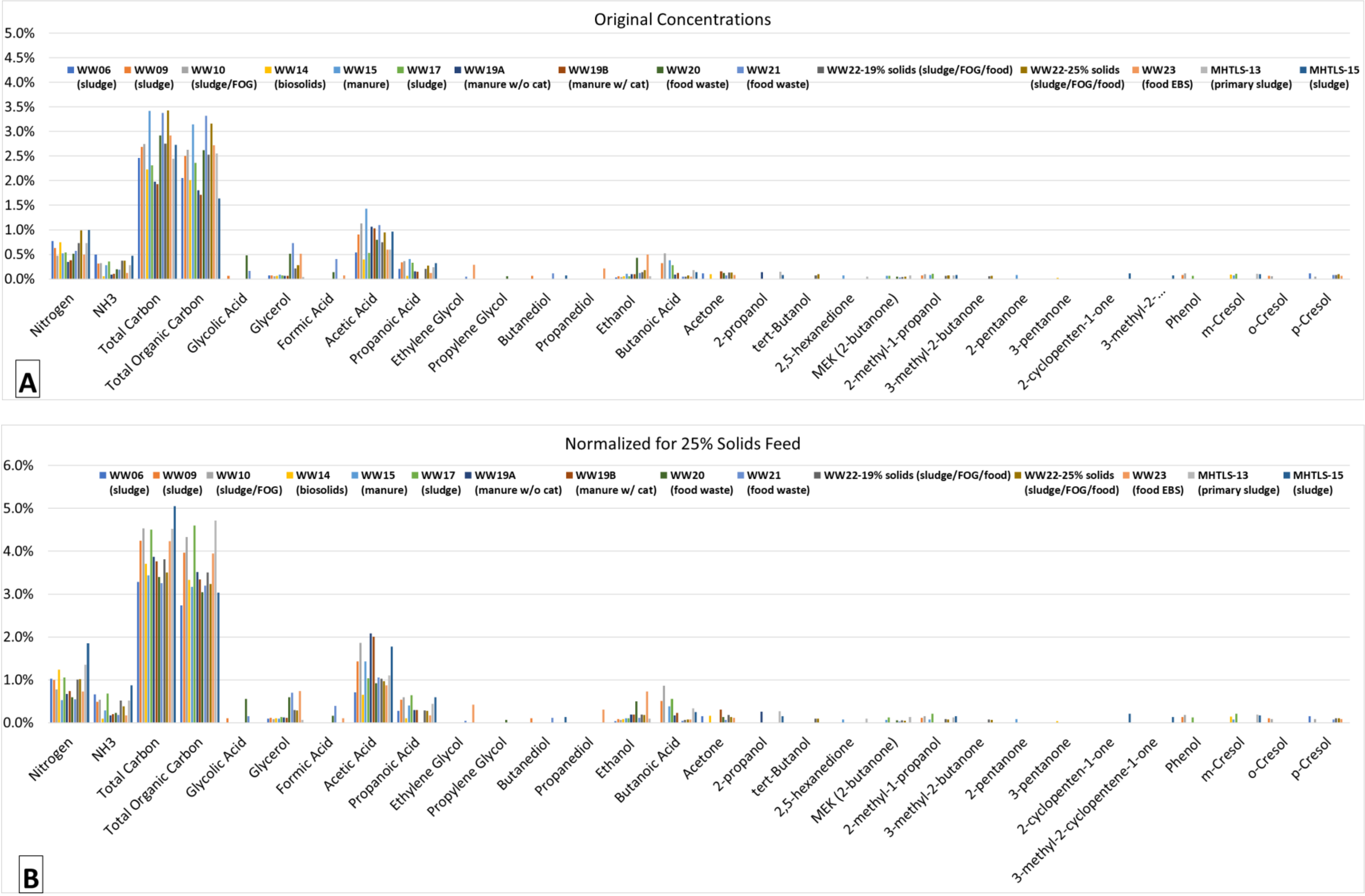

Figure 4. AP compositional data from historical HTL runs at PNNL. (A) original data and (B) normalized for 25% feed solids.

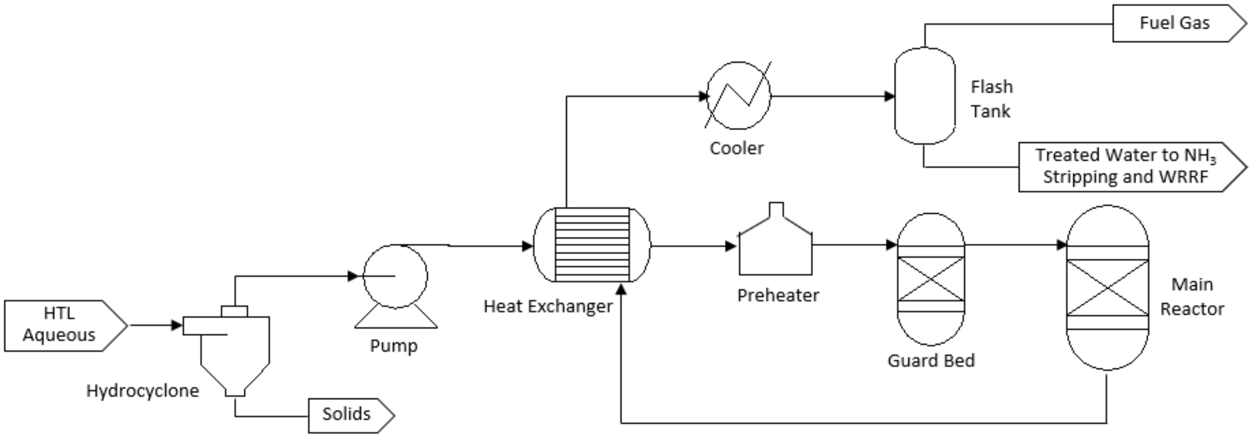

Figure 5. Modeled process design of the ACU method for HTL AP upgrading.

In FY20, the ACU technology with a two-stage catalyst bed (ZnZr followed by ZSM-5) was developed to upgrade AP products from HTL into alkenes. The purpose of the zeolite is to reduce the ketones (formed with the ZnZr catalyst) into alkenes. However, at that point, we were not able to close the mass balance with the early-stage development reactor (2g catalyst). In FY21, the ACU system was scaled up to a 20g catalyst bed to improve the mass balance. HTL AP produced from a mixed wet waste feed (WW22, see Table 1 and Table 3) was fed to the reactor with a two-stage ZnZr/ZSM-5 catalyst bed for a total of 471 hours of operation with no shutdowns. The on-stream time of 471 hour (20 days) is twice the FY20 assumption of guard bed life, which will lead to a lower variable cost in the economic evaluation. Table 4 summarizes the performance of the ACU method at different operational conditions tested in FY21. The results indicate that levels of carbon and COD removal increase with operating temperature but decrease with weight hourly space velocity (WHSV). For the ACU method, the operating conditions of Run 1 (temperature = 400 °C, WHSV of 0.1 hr^{-1}) give the highest carbon and COD reductions of 78% and 92%, respectively, as well as a better mass balance. Given that COD reduction is a primary goal for the AP treatment step, the experimental data and operating conditions presented in Run 1 were selected as the baseline for the process design and economic analysis update.

Table 4. Experimental results of the ACU method at different operating conditions.

	2020 early-stage*	2021 Run 1	2021 Run 2	2021 Run 3
Operating condition				
Temperature (°C)	400	400	375	375
WHSV (hr^{-1})	0.2	0.1	0.1	0.2
Pressure (bar)	1.1	8.6	8.6	8.6
Carbon yield (%)				
CO_2	31	39	19	16
CH_4	20	6	2	3
Ethylene		3.2	1.4	2.9
Propylene		9.7	3.7	4.3
Butene	26	1.1	0.5	1.3
Pentene		0.0	0.4	0.5
Acetone	8			
Other gases		17	6	8
Total gases	85	76	33	36
AP product quality				
Carbon reduction (%)	85	78	60	50
COD reduction (%)	Not measured	92	65	51

[*] In the 2020 early-stage test, the mass balance was not fully closed. Data listed here were preliminary assumptions for the high-level screening TEA.

3.5 Biocrude Catalytic Hydrotreating Data

In FY21, PNNL completed a hydrotreater run lasting over 2000 hours with biocrude derived from wet waste feedstocks, with no process perturbations shown during the first 1500 hours of steady state operation. Over the steady-state period, no deactivation was observed. The oxygen content of the upgraded product was stable between 0.15 and 0.25 wt%. This run upgraded feedstocks from four wet waste HTL biocrudes, including two from sewage sludge and two from food waste. The biocrude was hydrotreated in the fixed-bed bench-scale system described previously (Snowden-Swan et al. 2020). The process consists of an initial step whereby the feed is first flowed over a fixed guard bed (CoMo catalyst) to remove the majority of inorganics (through hydrodemetalization) and then a second packed bed (NiMo catalyst) where most of the deoxygenation and denitrogenation of the biocrude occurs. The reactor is packed with catalyst extrudates to ensure identical pore diffusion limitations will be observed at both lab and commercial scales. Inert SiC fines are co-packed with the catalyst to ensure the catalyst is fully wetted and has ideal plug flow (these will only be issues at the lab scale because as the higher superficial velocity at a commercial scale will eliminate these issues with catalyst wetting and plug flow). Table 5 gives the reactor conditions and product results from biocrude derived from both sludges (MHTLS13 and MHTLS15), and food wastes (WW20 and WW21), in addition to a sludge, food and FOG blend (50:40:10) (WW22) and the 2020 SOT and the 2022 goal case models for comparison. Because the goal was to understand catalyst deactivation at industrially-relevant time on streams (>1000 hours) and this was the first attempt at an extended hydrotreater campaign, the reactor was operated at a WHSV of 0.5hr^{-1} for both the guard bed and main hydrotreater bed (versus the SOT of 0.72 hr^{-1} and 1.03 hr^{-1} for the guard bed and main bed). The deactivation rate was minimal, as shown by the density curve in Figure 6.

Table 5. Wet waste biocrude hydrotreating experimental results and model assumptions.

Component	WW22	MHTLS13	WW20	WW21	MHTLS15	2021 SOT Model	2022 Projected Model
Temperature, °F (°C)	752 (400)	752 (400)	752 (400)	752 (400)	752 (400)	752 (400)	752 (400)
Pressure, psia	1560	1560	1560	1560	1560	1540	1515
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	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	CoMo/alumina Purchased presulfided
Guard bed WHSV, wt./hr per wt. catalyst	0.5	0.5	0.5	0.5	0.5	0.72	1.3
Main bed WHSV, wt./hr per wt. catalyst	0.5	0.5	0.5	0.5	0.5	1.03	0.75
HTL biocrude feed rate, ml/h	2.52	2.52	2.52	2.52	2.52	Commercial scale	Commercial scale
Time-on-stream (catalyst life)	>135	284	284 to 591	591 to 1075	1075 to 2165	2000 hours (guard) 1 year (main)	2 years (guard and main)
Chemical H_2 consumption, wt/wt HTL biocrude (wet)	0.047	0.035	0.050	0.053	0.034	0.046	0.044
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)	0.84 (0.97)
Aqueous phase	0.09	0.15	0.12	0.12	0.12	0.12	0.13 (0.19)
Gas	0.07	0.05	0.06	0.05	0.06	0.10	0.07
Product oil, wt%							
C	86.0	85.1	85.2	85.1	84.7	85.3	85.3
H[b]	13.4	13.7	13.4	13.5	14.1	14.1	14.1
O	0.1	0.2	0.2	0.2	0.2	0.6	0.6
N	0.5	<1	1.1	1.1	<1	0.04	0.04
S	Below detection	0.0	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	2.0
Aqueous carbon, wt%	Not measured	Not measured	Not measured	Not measured	Not measured	0.6	0.2
Gas analysis, volume%							
CO_2, CO	0	0	0	0	0	0	0
CH_4	20	32	39	42	37	39	33
C_2+	80	68	61	58	63	35	38
NH_3	Not measured	Not measured	Not measured	Not measured	Not measured	23	26
NH_4HS	Not measured	Not measured	Not measured	Not measured	Not measured	3	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	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)	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.

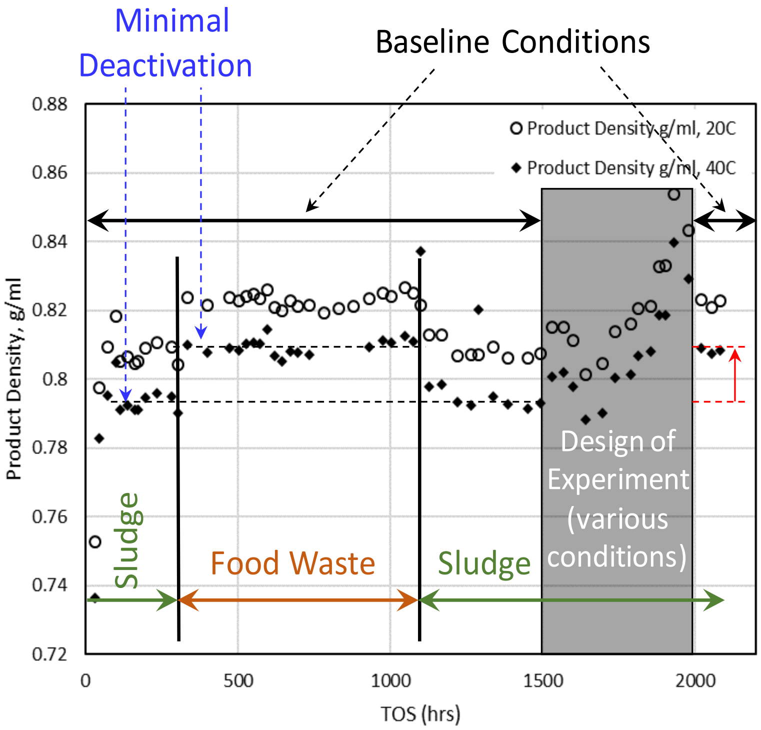

Figure 6. Density of upgraded biocrude from GLWA sludge (MHTLS13, MHTLS15) and food wastes (WW20, WW21) generated in PNNL's HTL bench-scale unit as a function of time-on-stream (TOS). (Reprinted with permission from S. Subramaniam, D. Santosa, C. Brady, M. Swita, K. Ramasamy, and M. Thorson. "Extended Catalyst Lifetime Testing for HTL Biocrude Hydrotreating to Produce Fuel Blendstocks from Wet Wastes." 2021. *ACS Sustainable Chem. Eng.* American Chemical Society.)

Figure 7 shows the GCMS of the upgraded product for the four feedstocks tested. The product composition is similar between the food wastes and sewage sludges, with the main peaks corresponding to the n-alkanes in the upgraded fuels. Specifically, the highest concentration species in the produced fuel are C18, C16, C17, and C15 n-alkanes. Figure 8 shows the simulated distillations for the fuels produced from HTL biocrude derived from sewage sludge and food waste. The boiling point distributions match quite well due to the similar fuel makeup (as seen in the GCMS).

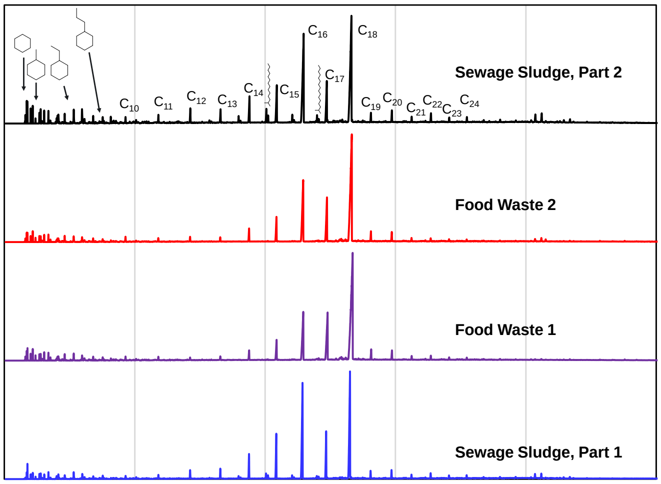

Figure 7. GCMS traces of the upgraded undistilled product from the various HTL biocrudes used in the extended hydrotreater run.

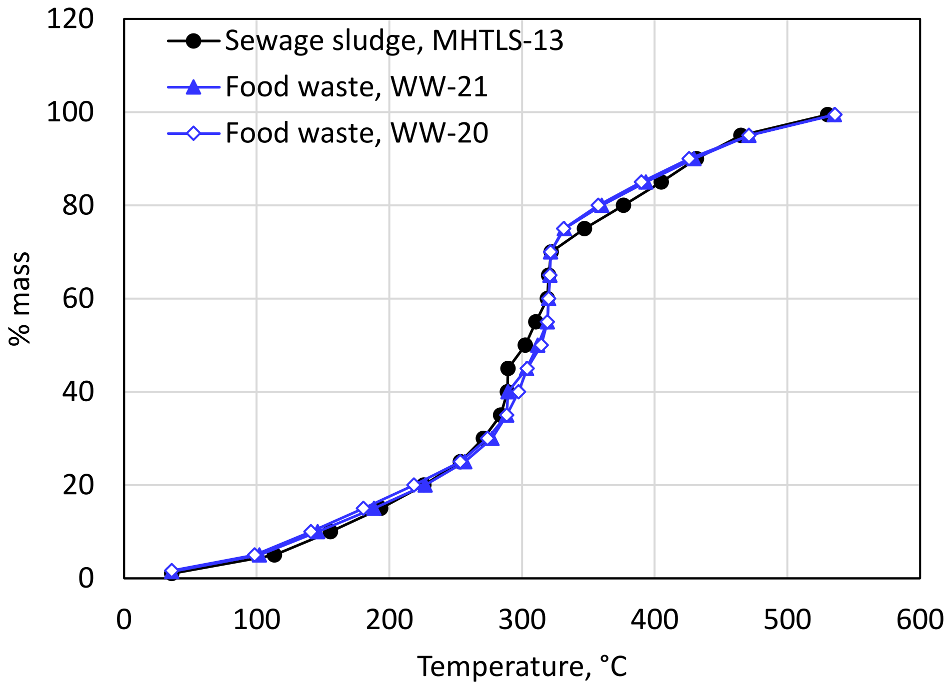

Figure 8. Boiling point distribution (ASTM D2887) of upgraded product for sewage sludge (MHTLS13) and food wastes (WW20, WW21).

As an alternative configuration to the fixed-bed guard bed, we evaluated a slurry reactor to reduce the metal content in the biocrude through hydrodemetallization to prevent plugging of a fixed bed reactor. Given the considerable level of metals content in the biocrude, this type of configuration is likely the most appropriate choice over a fixed bed. Reaction data was collected from the stirred reactor configuration to predict performance of a scaled-up slurry reactor. In a slurry configuration, the stirred reactor was operated at 400°C (in-place of the 325 or 350°C fixed bed guard bed) and at a WHSV of 4 to reduce the metal content. The hydrogen consumption was 0.0056g H_2/g biocrude with 98% of the biocrude mass going to the liquid hydrotreated product. Table 6 summarizes the results from the slurry guard bed test.

Table 6. Results of hydrotreater run using sludge-derived biocrude (MHTLS13) and a slurry reactor for the guard bed.

Data Component	Guard Bed	Main Bed
HTL Feedstock / HTL and HT Run Numbers		
Temperature, °F (°C)	400	400
Pressure, psia	1000	1500
catalyst	CoMo	NiMo
WHSV, wt./hr per wt. catalyst	4	0.5
HTL biocrude feed rate, ml/h	20	2.52
Time-on-stream (catalyst life)	46	163
Chemical H_2 consumption, wt/wt HTL biocrude (wet)	0.0056	0.04
WHSV, wt./hr per wt. catalyst	4	0.5
Product yields[(a)], lb/lb dry biocrude (vol/vol wet biocrude)		
Hydrotreated oil	0.98	0.84
Aqueous phase	0	0.13
Gas	0.02	0.03
Product oil, wt%		
C	No Data	85.8
H	13	16.9
O	Not measured	0.2
N	3.83	<1.0
S	2426 ppm	11.5 ppm
Gas analysis, volume%		
CO_2, CO	14	0
CH_4	41	33
C_2+	56	67
NH_3	Not measured	Not measured
NH_4HS	Not measured	Not measured

4.0 2021 SOT Modeled Performance and Costs

This section presents the economic and performance results for the SOT. All costs are in 2016 dollars. Both the results with the original system boundaries and with the updated system boundaries described in Section 2.0 are presented to provide transparent tracking and consistency with the previous SOT. Section 4.1 presents results for the old system boundaries and Section 4.2 presents results with the new system boundaries, the latter of which will serve as the official 2021 SOT. Section 4.3 presents a sensitivity case that includes enhanced AP treatment with ACU for COD removal (Section 3.4) prior to NH_3 removal. Section 4.4 presents a case where regional sludge, food and FOG waste is collected, blended, and processed into fuel blendstocks at a larger scale than the SOT base case. It is important to note that the TEA conducted herein does not include the potential value of Renewable Fuel Standard (RFS) credits or other incentives. Under the current RFS, no avenue currently exists for biointermediates that are produced by one entity and upgraded by another. However, the EPA has proposed a rule which will enable this structure if promulgated (EPA 2021).

4.1 Base Case with Old System Boundaries (owned/operated by WRRF)

Table 7 lists the major economic results for the HTL plant for the 2021 SOT using the original system boundaries (see Figure 1A) consistent with previous analyses (Snowden-Swan et al., 2017, 2020, 2021). Costs for the 2018-2020 SOTs and the 2022 projected (goal) case are also given for comparison. The HTL plant processes 110 dry ton/day of sludge feed and produces 10,578 gal/day of biocrude. The results included in Table 7 are for cases including NH_3 stripping treatment of the AP. Appendix B gives the HTL cost breakdown for cases excluding AP NH_3 stripping to represent plants not requiring treatment of the AP before recycling back to the WRRF.

The main technical updates for the HTL plant for the 2021 SOT relative to the 2020 SOT are an increase in feed solids content from 20% to 25% (dry basis) and an increase in the biocrude yield from 43.5% to 44.6% (DAF basis) as described in Section 3.3. As illustrated in Figure 9, increasing feed solids content from 20% to 25% results in a 17% lower equipment capacity and corresponding reductions in capital and operating costs for the plant. The increased solids content and yield values are based on the experimental research which has demonstrated successful processing of 25% solids feeds for several feedstocks and has shown an increase in yield of about 1% when comparing 19% solids feed and 25% solids feed (see Table 3, WW-22A and B). The higher solids content for the 2021 SOT compared to the 2020 SOT reduced the capital and operating costs for the HTL and AP NH_3 stripping areas, thereby lowering the MBSP for the HTL plant by 37 cents/GGE (40 cents/GGE fuel blendstock). The improved biocrude yield resulted in a 5 cent reduction in the MBSP ($0.05/GGE fuel blendstock).

Table 7. Economic results for 110 dry ton/day sludge HTL plant (with AP NH_3 stripping) using original HTL system boundary.

	2018 and 2019 SOT	2020 SOT	2021 SOT	2022 Projected
Capital Costs, $ million				
Installed costs				
Sludge feedstock dewatering	1.3	1.3	1.3	1.3
HTL biocrude production	19.5	16.9	14.4	12.3
HTL aqueous phase recycle treatment	2.8	2.8	2.1	2.3
Balance of plant	0.6	0.6	0.6	0.6
Total installed capital cost	24.2	21.6	18.4	16.5
Fixed capital investment	45.7	40.8	34.8	31.3
Total capital investment (TCI)	48.1	42.9	36.6	32.9
Operating Costs, $/GGE biocrude ($ million/yr)				
Variable operating cost				
Avoided sludge disposal cost	0	0	0	0
Natural gas	0.11 (0.4)	0.07 (0.3)	0.04 (0.2)	0.09 (0.4)
Chemicals	0.20 (0.7)	0.20 (0.7)	0.14 (0.5)	0.18 (0.7)
Electricity	0.17 (0.6)	0.17 (0.6)	0.16 (0.6)	0.11 (0.4)
Fixed costs	0.88 (3.2)	0.83 (3.1)	0.76 (2.9)	0.67 (2.7)
Capital depreciation	0.41 (1.5)	0.38 (1.4)	0.32 (1.2)	0.25 (1.0)
Average income tax	0.12 (0.5)	0.11 (0.4)	0.09 (0.3)	0.08 (0.3)
Average return on investment	1.15 (4.3)	1.02 (3.8)	0.86 (3.2)	0.74 (3.0)
MBSP, $/gal biocrude	3.27	3.00	2.55	2.27
MBSP, $/GGE biocrude	3.04	2.79	2.37	2.11

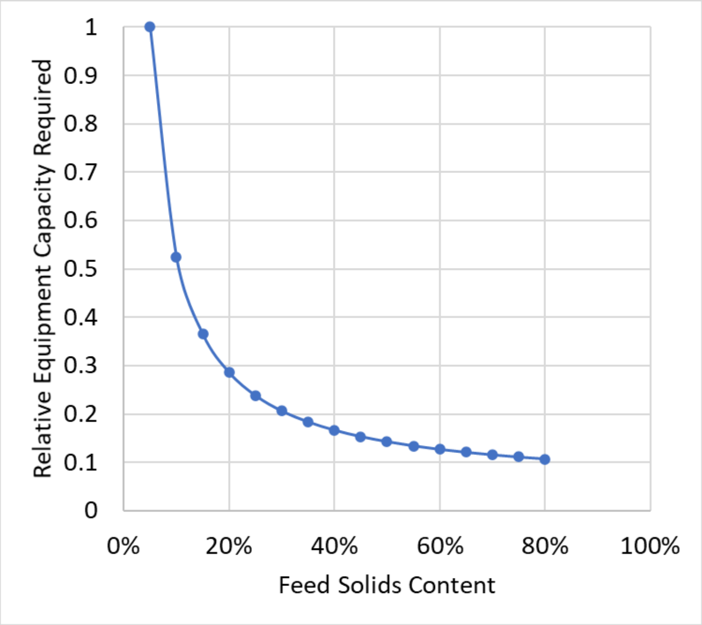

Figure 9. Relationship between feed solids content and equipment capacity (relative to 5% solids feed).

Table 8 lists the primary economic results for the biocrude upgrading plant for the corresponding HTL cases listed in Table 7. The centralized upgrading plant is envisioned to receive 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 (27,888 gal/day naphtha and 81,360 gal/day diesel). 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. The main technical updates to the modeled upgrading plant are extended lifetimes for the hydrotreater guard bed and main reactor catalysts as demonstrated by the experimental research (see Section 3.5). Based on catalyst performance during the 2000-hour hydrotreating run this year, the team is predicting that a catalyst life of 1 year for the main bed catalyst is reasonable and therefore is assumed for the 2021 SOT. A more conservative value of 2000 hours (0.23 years) is used for the guard bed as it serves primarily to filter/absorb inorganic contaminants (e.g., Fe, Si) from the biocrude prior to the main hydrotreating catalyst bed and therefore will inherently have a more limited life than the main bed material. A slurry bed may be the most feasible configuration for the guard bed at commercial scale to allow efficient and continuous regeneration of catalyst to prevent plugging. Further analysis is needed to estimate the impact of the slurry bed configuration using the testing data (Section 3.5).

The increased catalyst lifetimes for the guard and main beds resulted in conversion cost reductions of $0.28/GGE and $0.16/GGE, respectively, relative to the 2020 SOT with the old system boundaries. Reactor WHSV is maintained at 0.72 hr-1 for the guard bed and 1.02 hr-1 for the main hydrotreating bed. Note that economic results are given in Table 7 and Table 8 are dependent on plant scale, which is set at 110 ton/day sludge feed for the HTL plant and 38 mmgal/yr biocrude feed for the upgrading plant, commensurate with the original design case (Snowden-Swan et al. 2017). Note also that the 2022 projected costs differ slightly from the costs presented in the original design case due to updates made in the modeled year and income tax rate (see Appendix D).

Table 8. Economics for biocrude upgrading plant processing ~115,000 gal/day using original HTL system boundaries.

	2018 SOT	2019 SOT	2020 SOT	2021 SOT	2022 Projected
Capital Costs, $ million					
Installed costs					
Hydrotreating	46.7	41.9	37.9	37.9	31.6
Hydrocracking	6.1	6.1	6.1	6.1	6.2
Hydrogen plant	26.3	26.3	26.3	26.3	25.6
Steam cycle	1.7	1.7	1.7	1.7	1.5
Balance of plant	6.2	6.2	6.2	6.2	6.1
Total installed capital cost	87.0	82.2	78.2	78.2	71.0
Indirect costs	60.9	57.5	54.7	54.7	49.6
Fixed capital investment	162.5	153.4	145.8	145.8	132.3
Total capital investment (TCI)	173.7	164.0	155.9	155.9	141.5
Operating Costs, $/GGE ($ million/yr)					
Biocrude feedstock[a], including transport	3.37 (127.6)	3.37 (127.6)	3.10 (125.8)	2.65 (100.3)	2.32 (89.6)
Natural gas	0.04 (1.4)	0.04 (1.4)	0.04 (1.4)	0.04 (1.4)	0.05 (1.7)
Catalyst	2.80 (105.9)	0.84 (31.9)	0.54 (20.5)	0.12 (4.4)	0.01 (0.5)
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	0.02 (0.9)	0.02 (0.9)	0.02 (0.9)	0.02 (0.9)	0.02 (0.9)
Fixed costs	0.27 (10.2)	0.26 (9.9)	0.25 (9.6)	0.25 (9.6)	0.24 (9.1)
Capital depreciation	0.143 (5.4)	0.14 (5.1)	0.13 (4.9)	0.13 (4.9)	0.002 (4.4)
Average income Tax	0.05 (1.9)	0.04 (1.6)	0.04 (1.5)	0.014 (1.5	0.04 (1.4)
Average return on investment	0.47 (17.7)	0.40 (15.0)	0.37 (14.0)	0.36 (13.6)	0.43 (16.7)
MFSP, $/GGE fuel blendstock[a]	7.16	5.11	4.50	3.61	3.11
MFSP, $/GGE (conversion cost only)	3.79	1.74	1.40	0.96	0.79
MFSP, $/gal diesel[a]	7.67	5.48	4.82	3.87	3.33
MFSP, $/gal naphtha[a]	7.07	5.05	4.44	3.56	3.06

a Cost is for biocrude production from HTL process for case including ammonia stripping of AP plus transportation cost.

Figure 10 illustrates the annual modeled MFSP from the SOTs and the projected 2022 goal case for the combined wet waste HTL and biocrude upgrading process pathway with the old HTL system boundaries. The complete list of combined HTL and upgrading processing area costs and key technical parameters and targets for the SOT and projected cases with the old HTL system boundary are given in Appendix B. Results for the separate HTL plant are also given in Appendix B.

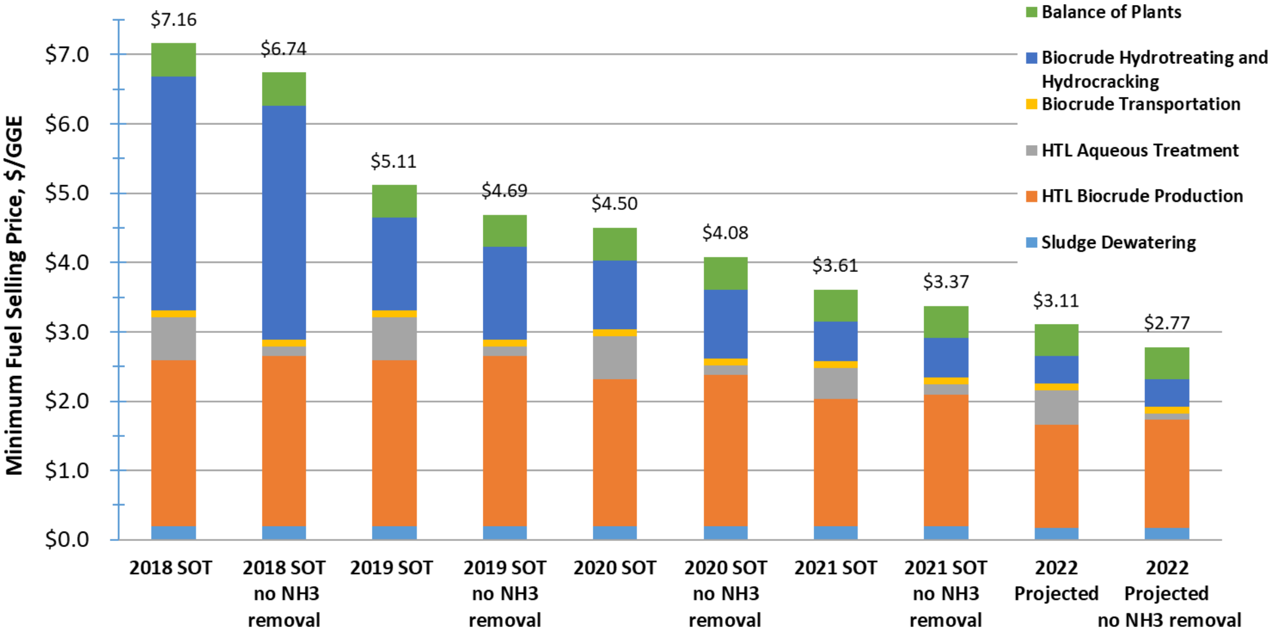

Figure 10. Combined HTL and biocrude upgrading process cost allocations for original system boundaries.

4.2 Base Case with New System Boundaries (separate HTL plant owner/operator)

As discussed in Section 2.0, the analysis system boundaries and several associated assumptions were updated this year to reflect ownership of the HTL plant by a separate industrial owner/operator rather than by a WRRF. The resulting adjusted systems boundaries and costs presented in this section will be adapted for SOT analyses moving forward. Table 9 summarizes the changes in the system boundary related assumptions compared to the original design case and earlier SOTs.

Table 9. Summary of changes in HTL system boundary and assumptions for SOTs.

Assumption	Old	New	Justification and Source
Ownership of HTL Plant	Owned by the WRRF/municipality	Owned by a separate owner/operator	It is most likely that a separate owner/operator would take on the HTL project (similar to GLWA relationship with NEFCO).
Sludge Feedstock Cost (Avoided Disposal Cost / Tipping Fee)	$0/dry ton	-$187/dry ton (-$44/wet ton) (2019$)	WRRFs pay to treat and dispose of their solids and will continue to do so via the least expensive option. See Section 3.2 for basis.
Sludge Dewatering and Grinding Cost	Partially included (low)	Power and polymer costs included at $24/dry ton (2020$)	Data and industry feedback provided by GLWA.
Solids Disposal Cost	Not included	Included at $55/ton (2019$) for disposal of HTL solids and lime sludge (for NH_3 stripping)	This is appropriate with the new owner/operator configuration. Costs are from Environmental Research & Education Foundation (2019).
Wastewater (HTL Aqueous Phase) Surcharge Fee	Not directly included; indirect power use at WRRF included for processing of COD (0.4 kWh/lb COD)	Included surcharge rate of $0.13/lb COD in excess of 500 mg/L and $0.56/lb NH_3 in excess of 25 mg/L (2020$) based on industrial discharger rate information	Appropriate with the new owner/operator configuration. Costs from Durham (2014) and MCES 2021.

The cost results for the HTL plant with the new system boundary assumptions (Table 9) are presented in Table 10. Note that the previous year's SOTs were also adjusted (back-casted) with the new boundary assumptions to provide consistency in illustrating the year-to-year R&D progress. In addition, the heat transfer coefficient used for the original heat exchanger configuration assumed in the 2018 and 2019 SOTs was updated to a more realistic value of 13 Btu/hr/ft^2/°F for the 2018 and 2019 SOTs. For those cases we originally assumed a coefficient value of 50 Btu/hr/ft^2/°F which was based on our lab scale system data. We have since learned through our rheology work that this value was overly optimistic for the exchangers at commercial scale. Note also that the 2022 Projected case was adjusted with the new system boundaries as well as with several major technical learnings (Table 10) including the new heating and pumping configuration adapted for the 2020 SOT (Snowden-Swan et al. 2021; Thorson et al. 2022) and more realistic HTL and upgrading performance targets aligned with the testing progress to date and current SOT.

Table 10. Economic results for 110 dry ton/day sludge HTL plant (with AP NH_3 stripping) with new system boundary.

	2018 and 2019 SOT	2020 SOT	2021 SOT	2022 Projected
Capital Costs, $ million				
Installed costs				
Sludge feedstock dewatering	1.5	1.5	1.5	1.5
HTL biocrude production	58.2	16.9	14.4	14.4
HTL aqueous phase recycle treatment	2.8	2.8	2.1	2.1
Balance of plant	0.6	0.6	0.6	0.6
Total installed capital cost	63.1	21.8	18.6	18.6
Fixed capital investment	119.3	41.1	35.2	35.2
Total capital investment (TCI)	125.6	43.3	37.1	37.1
Operating Costs, $/GGE biocrude ($ million/yr)				
Variable operating cost				
Avoided sludge disposal cost	-1.68 (-6.2)	-1.68 (-6.2)	-1.65 (-6.2)	-1.65 (-6.2)
Natural gas	0.05 (0.2)	0.07 (0.3)	0.04 (0.1)	0.04 (0.1)
Chemicals	0.27 (1.0)	0.27 (1.0)	0.25 (0.9)	0.25 (0.9)
Electricity	0.05 (0.2)	0.06 (0.2)	0.05 (0.2)	0.05 (0.2)
Waste disposal	0.76 (2.8)	0.76 (2.8)	0.91 (3.4)	0.91 (3.4)
Fixed costs	1.58 (5.8)	0.83 (3.1)	0.76 (2.9)	0.76 (2.9)
Capital depreciation	1.08 (4.0)	0.38 (1.4)	0.32 (1.2)	0.32 (1.2)
Average income tax	0.32 (1.2)	0.11 (0.4)	0.09 (0.4)	0.09 (0.4)
Average return on investment	2.92 (10.8)	1.04 (3.8)	0.88 (3.3)	0.88 (3.3)
MBSP, $/gal biocrude	5.77	1.99	1.78	1.78
MBSP, $/GGE biocrude	5.36	1.85	1.66	1.66

As shown in Table 10, the negative cost for the sludge (tipping fee) assumed with the new system boundaries greatly reduces the MBSP by $1.65/GGE compared with the original system boundaries (see Table 7). Conversely, inclusion of costs for solid waste disposal, AP wastewater discharge and higher polymer consumption costs add $0.91/GGE of operating cost relative to the 2020 SOT. Note that electricity costs are reduced compared to the old system boundaries because the WRRF power cost to process AP COD content was removed from the analysis in lieu of the wastewater COD and NH_3 surcharge rates that are now included (see Table 9). Several improved methods over the baseline waste management methods (landfilling of HTL solids and AP NH_3 stripping) such as the ACU process that are currently under investigation by the PNNL team and others can facilitate recovery of nutrient, chemical, and/or energy co-products from these waste streams. Section 4.3 illustrates the potential cost benefit of the ACU process. Future analyses will include TEA of other methods as data are available.

Table 11. Summary of additional updates for the 2022 projected case based on R&D learnings to date.

Parameter	Old Assumption	New Assumption (consistent with 2021 SOT)	Justification
Biocrude Yield (lb biocrude/lb sludge, DAF)	48%	44.5%	Maximum yield to date from sludge
HX Design and Costing	1 stage heating with high pressure on both tube and shell	2 stage heating with low pressure on shell (hot oil)	Lower cost design
Hydrotreater Catalyst Life	2 year	1 year	Data show stability over the 2000+ hour run
Hydrotreater Guard Bed	Not included	Included	Necessary as demonstrated in lab
Hydrotreater Guard Bed Life	Not accounted for	0.5 yr	2 times the longest time-on-stream demonstrated
Hydrotreater WHSV	0.8 hr^{-1}	1.0 hr^{-1}	Demonstrated in lab
Guard Bed WHSV	N/A	0.7 hr^{-1}	Demonstrated in lab

Table 12 lists the economics for the upgrading plant using the updated HTL biocrude price based on the new system boundaries (Table 9). Note that the only difference between the values listed in this table and Table 8 is the updated price of biocrude and other adjustments made to the HTL model described earlier in this section. The conversion cost (excluding the cost of the biocrude feedstock) is unchanged.

Table 12. Economics for biocrude upgrading plant processing ~115,000 gal/day using new HTL system boundary.

	2018 SOT	2019 SOT	2020 SOT	2021 SOT	2022 Projected
Capital Costs, $ million					
Installed costs					
Hydrotreating	46.7	41.9	37.9	37.9	37.9
Hydrocracking	6.1	6.1	6.1	6.1	6.1
Hydrogen plant	26.3	26.3	26.3	26.3	26.3
Steam cycle	1.7	1.7	1.7	1.7	1.7
Balance of plant	6.2	6.2	6.2	6.2	6.2
Total installed capital cost	87.0	82.2	78.2	78.2	78.2
Indirect costs	60.9	57.5	54.7	54.7	54.7
Fixed capital investment	162.5	153.4	145.8	145.8	145.8
Total capital investment (TCI)	173.7	164.0	155.9	**155.9**	155.9
Operating Costs, $/GGE ($ million/yr)					
Biocrude feedstock[a], including transport	5.87 (222.2)	5.87 (222.2)	2.09 (79.1)	1.88 (71.3)	1.88 (71.3)
Natural gas	0.04 (1.4)	0.04 (1.4)	0.04 (1.4)	0.04 (1.4)	0.04 (1.4)
Catalyst	2.80 (105.9)	0.84 (31.9)	0.54 (20.5)	0.12 (4.4)	0.06 (2.5)
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	0.02 (0.9)	0.02 (0.9)	0.02 (0.9)	0.02 (0.9)	0.02 (0.9)
Fixed costs	0.27 (10.2)	0.26 (9.9)	0.25 (9.6)	0.25 (9.6)	0.25 (9.6)
Capital depreciation	0.14 (5.4)	0.14 (5.1)	0.13 (4.9)	0.13 (4.9)	0.13 (4.9)
Average income tax	0.05 (1.9)	0.04 (1.6)	0.04 (1.5)	0.04 (1.5	0.04 (1.5)
Average return on investment	0.47 (17.7)	0.40 (15.0)	0.37 (14.0)	0.36 (13.6)	0.36 (13.6)
MFSP, $/GGE fuel blendstock[a]	9.66	7.61	3.49	2.85	2.79
MFSP, $/GGE (conversion cost only)	3.79	1.74	1.40	0.96	0.91
MFSP, $/gal diesel[a]	10.35	8.16	3.74	3.05	2.99
MFSP, $/gal naphtha[a]	9.54	7.52	3.44	2.81	2.76

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

Figure 11 illustrates the modeled MFSP breakdown for the 2021 SOTs, prior SOTs and 2022 projection with the new HTL process boundary assumptions and other updates described above. As shown, the R&D progress made in FY21 resulted in a \$0.64/GGE reduction in MFSP for the case including NH_3 removal (\$0.54/GGE reduction for the case without NH_3 removal). Running at a higher solids content of 25% lowered the modeled HTL conversion cost by \$0.23/GGE and improved catalyst lifetimes for the hydrotreater catalyst and guard bed lowered conversion cost by \$0.44/GGE relative to the 2020 SOT (for the case including NH_3 removal). Note that the difference in the 2020 and 2021 SOT MFSPs shown in Figure 11 adds to \$0.64/GGE due to a 3 cent/GGE lower (less negative) feedstock credit resulting from the slightly higher biocrude yield for the 2021 SOT. An interesting result with the new system boundary assumptions is that there is now an insignificant difference between the 2021 SOT cases with and without NH_3 stripping. This is because the analysis now includes the cost to discharge the AP COD and NH_3 nutrient loads to the sewer system. In the case with NH_3 stripping we are paying to remove NH3 at the HTL plant, whereas in the case without NH_3 stripping we are paying the WRRF to treat the raw AP.

The complete list of processing area costs and key technical parameters and targets for the SOT and projected cases with the new HTL system boundary are given in Appendix B. Appendix C gives the life cycle inventory of inputs and outputs for the HTL and upgrading plants that is used for the pathway the Supply Chain Sustainability Analysis to be published in a separate report (Cai et al. 2022). Carbon and energy efficiencies for the pathway are also presented in Appendix C. Moving forward, the costs presented in Figure 11 using the new system boundary assumptions will be the basis of the 2021 SOT and future analyses.

Regarding remaining improvements for the HTL process, biocrude yields have largely been optimized for processing of sludge from the continuous system testing carried out for the 2018-2021 SOTs. While there are feedstocks that result in higher yields (e.g., higher lipid feedstocks) limited improvement to the performance of raw sludge feedstock is expected relative to the current SOT (45%, DAF basis). Efficient feedstock deashing has the potential to further reduce costs, increase yields, and reduce equipment plugging risks for the HTL plant for all feedstocks, in particular high-ash materials like manures, certain high-ash sludges, and biosolids from anaerobic digestion. Additionally, advanced methods for recovering nutrients, energy, and other co-products from the HTL aqueous and solid phase waste streams are needed to optimize costs and minimize environmental impacts. Advanced solids removal methods are needed beyond the current blowdown approach, which inherently leads to biocrude losses and is disruptive in nature and therefore limits equipment life. Catalytic HTL could improve process yields for certain feedstocks and should also be considered.

Regarding process improvements for the upgrading plant, costs related to the main hydrotreating catalyst performance have been minimized (to 1 cent/GGE) with the current 1-year lifetime. The guard bed catalyst, for which the lifetime is 2000 hours (0.23 year), currently contributes \$0.10/GGE to the MFSP. Based on testing to date, it is expected that the guard bed catalyst can be optimized at approximately twice the current lifetime (approximately 0.5 year), which would reduce costs by \$0.05/GGE to the MFSP of \$2.79/GGE and is assumed for the new 2022 Projected case. Further research is needed to validate the 2022 projection for the fixed bed configuration and analysis is needed to assess the impacts of a slurry bed configuration based on the experimental data (Section 3.5). Investigation of the feasibility of sustainable aviation fuel (SAF) and marine fuel from the wet waste HTL pathway is also underway and will be included in future assessments.

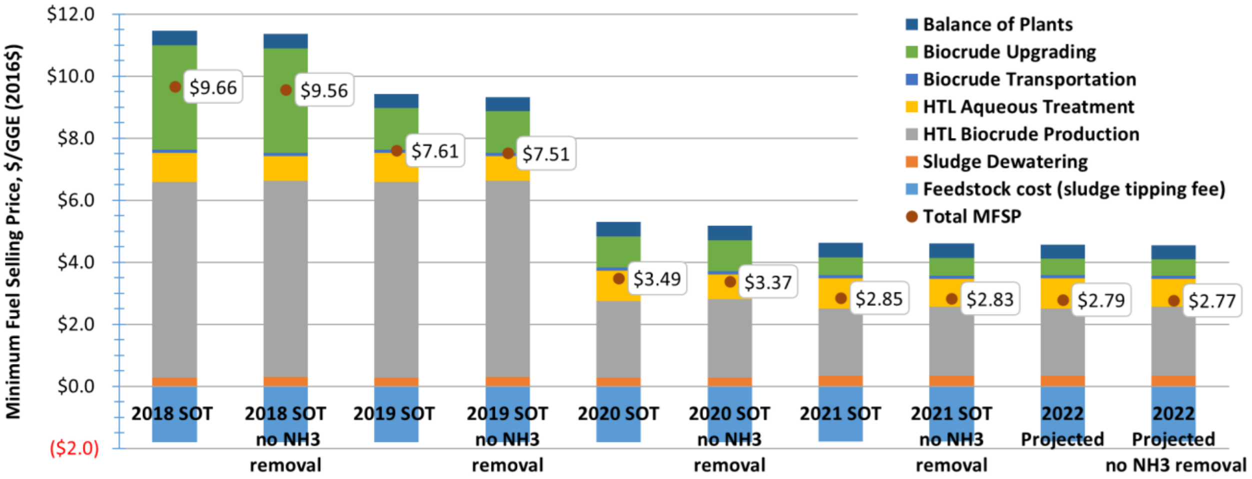

Figure 11. Combined HTL and biocrude upgrading pathway cost allocations for new system boundaries.

Sensitivity of the 2021 SOT MFSP to the variability in process and economic parameters is shown in Figure 12. As shown, the MFSP is highly sensitive to feedstock cost depending on regional factors and ultimately the negotiated price that a WRRF is willing to pay the HTL facility to take their waste. The range of feedstock cost investigated is based on the range of average disposal cost ($16-101/wet ton in 2019$ or $15-92/wet ton in 2016$) and average solids content (23.7%) from the BACWA survey (see Figure 3 and BACWA 2021). The HTL plant scale is also very influential on MFSP and highly variable depending on the scale of the individual WRRF. The range shown roughly represents 50% of the sludge produced nationally (i.e., about half of all sludge is generated at WRRFs processing over 30 million gallon/day of wastewater). Note that the scaling sensitivity is conducted by simply applying typical engineering rules of thumb scale exponents to original individual equipment costs and therefore does not take into account the impact if certain equipment can be numbered up rather than scaled up, as would be the case with modular application. In addition to equipment scales of economy, there are typically increased efficiencies associated with larger scale plants (to a certain degree). While it follows that smaller plants would be less economical based on standard scaling factors, modularilization may be particularly relevant and beneficial at smaller community scales. These impacts are outside the scope of this analysis but should be considered in the future. Figure 13 further illustrates the strong dependence of MBSP on sludge tipping fee (feedstock cost) and scale, showing cost curves at several HTL scales (i.e., approximate WRRF scales). Note that Figure 13 depicts the cost of producing the intermediate biocrude at the HTL plant. The cost of final fuel blendstock is calculated by adding the biocrude cost in Figure 13 to the cost to transport the biocrude ($0.092/biocrude), multiplying by the yield of upgraded fuel blendstock (1.076 GGE fuel blendstock/GGE biocrude) and adding this to the cost of upgrading ($0.97/GGE).

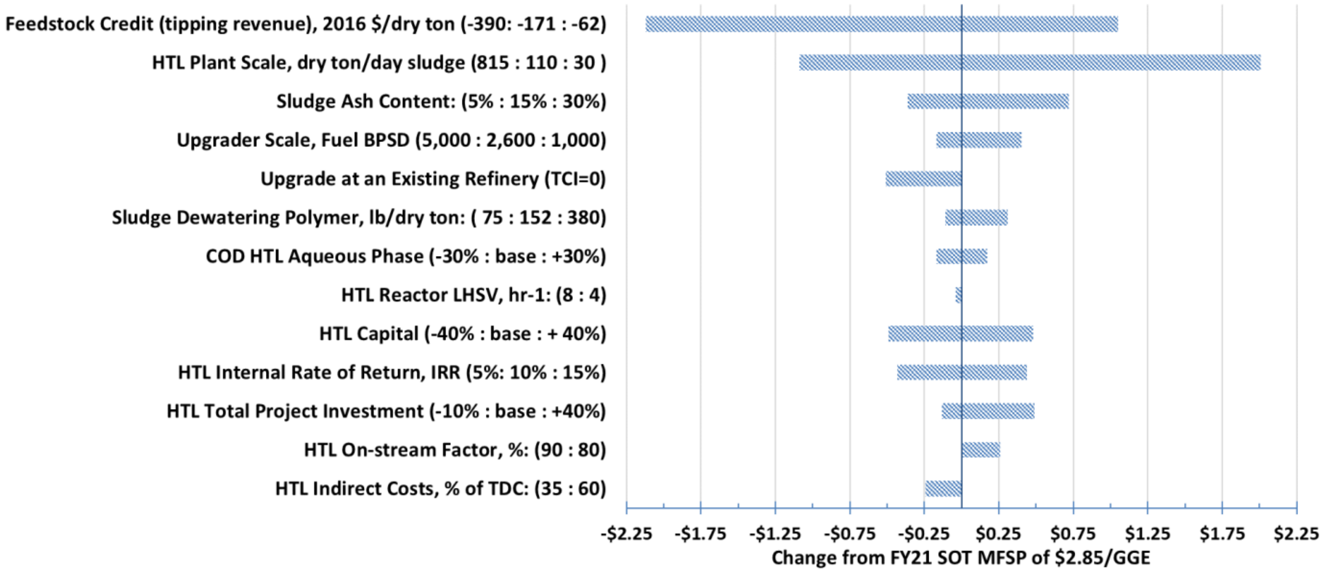

Figure 12. Sensitivity of SOT MFSP to various process parameters and economic assumptions.

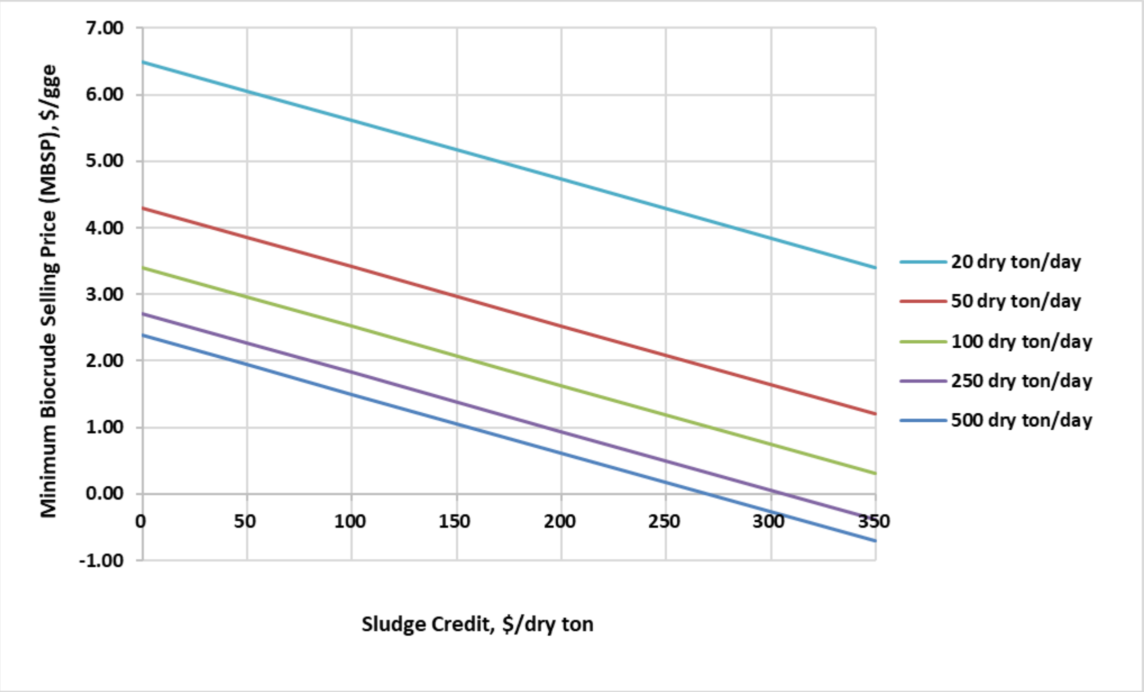

Figure 13. Biocrude production 2021 SOT cost dependency on sludge tipping fee (feedstock cost) and scale of the HTL plant.

4.3 Sensitivity Case with Aqueous Phase (AP) Catalytic Upgrading

A sensitivity case study was conducted to evaluate the potential impact of the ACU method (described in Section 3.4) for AP treatment on the MBSP of the wet waste HTL process and compare it with the 2021 SOT baseline. The modeled COD reduction and carbon removal are 92%, and 78%, respectively, which match with the experimental measures shown in Table 4. The organic nitrogen removal was assumed to be 91% to satisfy the elemental balance given the light gases yield, COD reduction, and carbon removal. Further experimental data quantifying remaining organic nitrogen species after ACU treatment is needed to fill this data gap and improve the model accuracy. The modeled NH_3 recovery rate from the combined ACU/NH_3 stripping process is about 92%. The conversion rate of NH_3 to $(NH_4)_2SO_4$ is near 100% with a NH_3:H_2SO_4 molar ratio of 1:0.54. Table 13 provides the additional assumptions for process modeling and TEA. Work is needed to validate the performance of NH_3 stripping and recovery rate of NH_3 co-product from ACU-treated AP.

Table 13. Key modeling and economic assumption for the ACU method for AP treatment.

	Value
Catalyst price (\$/kg)$^{(a)}$	2.2
Catalyst life (year)	1
Guard bed carbon price (\$/kg)$^{(b)}$	1.3
Guard bed carbon replacing frequency (day)	20
Solid waste disposal cost (\$/kg)	0.3
Number of guard beds in parallel	2
WHSV of guard bed (hr^{-1})	0.7

(a) PEP Yearbook, 2007
(b) PEP Yearbook, 2014

Figure 14 illustrates the modeled MBSP of 2021 SOT with new system boundary and the 2021 SOT with ACU for AP treatment. As shown, adding ACU into the HTL process for AP treatment will decrease the MBSP by \$0.28/GGE biocrude (MFSP by \$0.30/GGE fuel blendstock). There is a \$0.32/GGE credit to the MBSP due to the sale of recovered $(NH_4)_2SO_4$ (labeled “by-product credits” in Figure 14). Without the stripping process, it is not possible to recover a pure enough NH_3 stream and therefore the case without NH_3 stripping is not considered here. Note that for the preliminary analysis performed for the 2020 SOT with the initial experimental data (Snowden-Swan et al. 2021), the addition of the ACU process to the SOT resulted in a higher MBSP, while for the present (2021) SOT, the ACU process reduces MBSP. The difference is mainly due to the change in system boundaries for the present case (Section 4.2). As discussed in Sections 2.0, 4.1, and 4.2, the cost of dewatering, solids landfill and wastewater discharge was not included in the 2020 SOT, but are included in the 2021 SOT with new system boundary. Figure 11 suggests that the impact of HTL AP treatment/recovery can be significant if the wastewater disposal cost is considered and the AP stream is directly discharged to the municipal sewer system without onsite COD reduction. The ACU unit can significantly reduce the COD content of AP stream discharged to municipal sewer system and therefore reduce the associate disposal cost leading to lower MBSP and MFSP. Other changes in MBSP due to the installation of the ACU unit is similar to that of 2020 analysis. Because of the relatively low WHSV and requirement of guard bed for protection of the ACU catalyst, the variable cost related to catalyst replacement and disposal adds \$0.20/GGE to the MBSP relative to the SOT. The installed equipment cost of the ACU unit is about 3.21 MM\$, which adds \$0.05/GGE to the modeled MBSP. Additionally, because the NH_3 recovered from ACU treated AP is available at high purity, it can be converted into $(NH_4)_2SO_4$ as by-products to offset part of the variable and capital costs of the ACU unit.

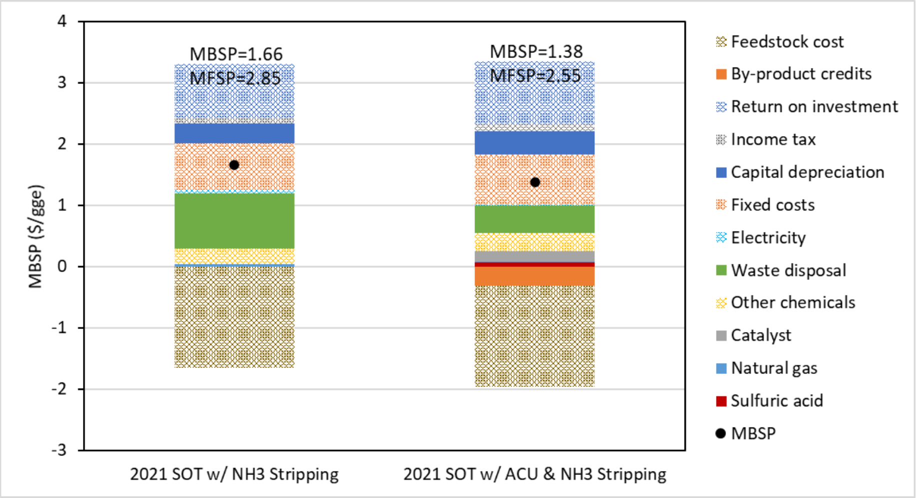

Figure 14. MBSP and cost allocation of the HTL plant with the ACU and ammonia stripping process relative to the 2021 SOT with new system boundary.

4.4 Sensitivity Case for Regional Waste Blending

While wet waste represents a large feedstock resource that is currently available for renewable fuel production, it is spatially distributed which may make it challenging to achieve economic scales comparable to typical biorefinery scales (e.g., 2000 TPD). To investigate the potential feasibility of a waste-to-fuel plant where additional sludge, food waste and FOG waste is collected at a large WRRF in a concentrated waste generation area (or “hot spot”), a sensitivity case was conducted for comparison with the SOT base case. The Detroit area was selected for modeling because it is representative of urban feedstock mixes, which are dominated by municipal sludge and food waste. PNNL also has an existing partnership with GLWA to acquire sludge samples for testing.

Geospatial analysis was conducted to estimate total annual feedstock mass that could be delivered at or below a weight-averaged transport cost limit of USD $50 per dry metric tonne ($55 per US ton). Feedstock availability was based on the previously compiled National Wet Waste Inventory of ~55,000 georeferenced waste sites in the U.S. (Seiple & Milbrandt, 2020). Non-domestic wastes and a minor amount of domestic manure occurring in the Detroit region were excluded from the analysis to focus the scenario on typical U.S. urban waste-to-energy conversion performance, otherwise it was assumed that 100% of regional wastes were available for import.

Feedstock aggregation was simulated assuming pre-formatted wastes were transported in a rented 30m^3 container truck at a cost of USD $85 per hour, typical for hauling biosolids, from the point-of-generation to a hypothetical HTL conversion and upgrading facility integrated with the Detroit WRRF. Transport distances were calculated using ESRI’s ArcGIS Point Distance function, after projecting waste point data to NAD83 Equadistant Conic (meters) for the the contiguous US (EPSG: 102005). Waste sites were ordered by travel distance (ascending), then sequentially aggregated to calculate the weight-averaged delivery price and determine the maximum amount of feedstock that could be accumulated while meeting the delivery price target. Imported waste had an assumed average moisture content of 80%, typical of landfilled biosolids, which means each truck hauled the equivalent of 6.25 tonnes of dry solids per trip. Total transport costs included round-trip driving and wait times (i.e., loading and unloading). Waste generated onsite by GLWA was assigned a transport cost of $0, because the conversion plant is assumed to be co-located with the WRRF (see Figure 2).

Figure 15 shows all the available feedstock spots at or below transportation cost of $50 per dry metric tonne in the Detroit area while Figure 16 illustrates the potential cumulative feedstock mass in the Detroit dear by the weight-averaged transportation cost from $0-$50/ dry tonne. As shown, there is tradeoff between larger scale feedstock resource and feedstock delivery cost. Note that the regional case is collocated at the GLWA WRRF and thus the delivery cost is zero for the sludge from GLWA (~570 dry tonne/day). Points of sludge generation other than the GLWA site on the map represent smaller publicly owned treatment works (most under 1 million gallon/day wastewater inflow) within the collection radius studied. The results of the geospatial waste aggregation model indicated a total of 1.14 dry Tg/y (1.25 million dry US ton/y) of cost-effective feedstock occurs in proximity to GLWA, including 581, 440, and 114 Gg/y of sludge, food, and FOG waste, respectively resulting in an approximate dry weight sludge/food/FOG blend ratio of 50/40/10. At the 90.4% plant on-stream factor assumed for the analysis, this equates to plant scale of approximately 3400 tonne/day (~3,800 dry US ton/day), which is the assumed plant throughout for the sensitivity case. Undigested sludge generated onsite at GLWA (~570 dry tonne/day) accounted for 18% (dry weight basis) of delivered feedstock.The cost-effective feedstock had a maximum travel distance of 175 kilometers (109 miles) and a weight-averaged transportation distance of 78 km (48 miles). For comparison, the round-trip distances reported for transporting sludge to final disposal/use by the CA Bay Area ranged from 0 to 480 miles (BACWA 2021 survey report). The average 1-way distance for the 2016 SCAF survey respondents was 129 miles (SCAF 2016 survey report).

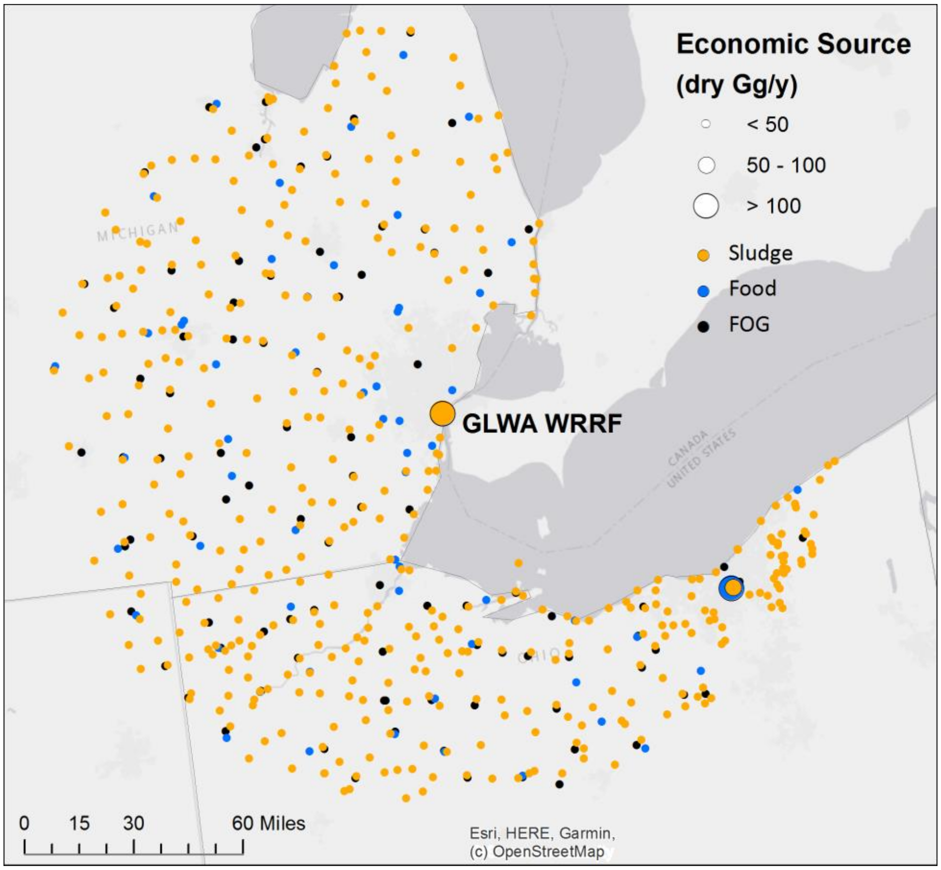

Figure 15. Detroit-area feedstock with a weight-averaged cost ≤ USD $50 per dry tonne.

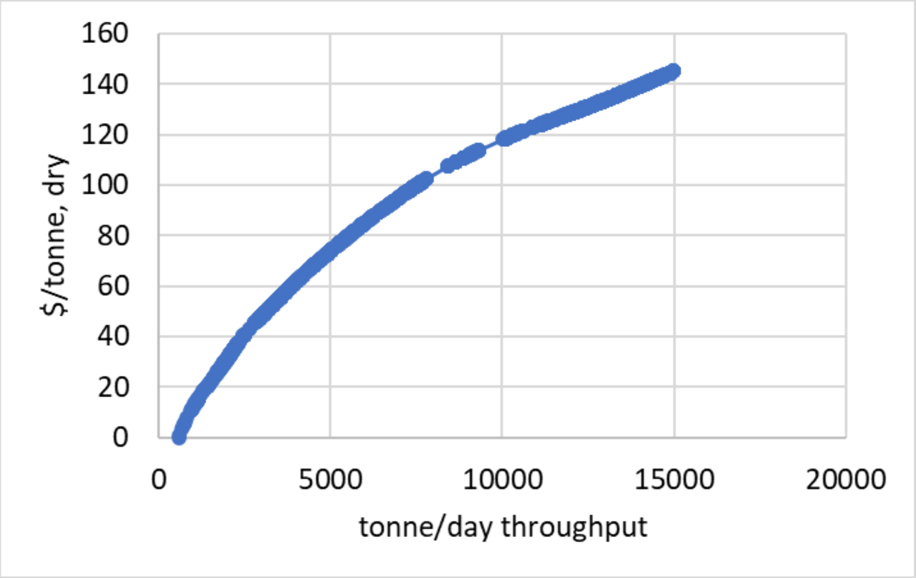

Figure 16. Detroit-area cumulative feedstock mass by weight-averaged delivered cost.

An average feedstock (mixed wet waste) cost of $-101/dry ton ($-111/dry tonne, or $-27/wet tonne) in 2019 $ was estimated from value ranges given in Badgett et al. 2019, Badgett et al. 2021, and EPA 2021. Specifically a weight-averaged sludge cost was calculated based on the nationwide sludge price profile from Badgett et al. (2019) as detailed in Section 3.2. The food waste cost was based on the tipping fee range ($18-32/wet ton) collected by food waste aerobic digestion (AD) facilities in EPA's recent survey. Also, Badgett et al. (2021) indicated that food waste AD facilities typically charge 65% of the landfilling fee as the tipping fee, which is about $36/wet ton based on the national average landfilling fee at of $55/wet ton. FOG was commoditized and thus the price is determined by the demand market and FOG type. In this work, a weighted FOG price was estimated based on the FOG price range in Badgett et al. (2019) and FOG availability in DOE 2017. Details of this calculation are presented in Table 14. In addition, the average solid content in the sludge, food waste and FOG are 24%, 21% and 90%, respectively, based on historical data from the BACWA survey, PNNL's food waste test data, and FOG moisture data in the literature. Note that the cost of sludge dewatering was not included in the raw feedstock calculation, as capital and operating costs for sludge dewatering are included in the HTL plant costs.

Table 14. Feedstock cost estimation for 50/40/10 (dry wt) regional blend of sludge, food, and FOG wastes.

		$/ Wet Tonne			Average Dry Solids Content	$/ Dry Tonne		
		Min	Max	Avg		Min	Max	Avg
Sewage Sludge (w/ dewatering)(a)		-153	9	-40	24%(g)	-647	37	-168
Sludge dewatering(a)						31	58	38
Sewage Sludge (w/o dewatering)						-678	-20	-206
Food Waste		-40	-28	-33(h)	21%(c)	-186	-129	-157
FOG	% in FOG national mix(b)							
Inedible Tallow	26%	650	650	650	99%(d)	660	660	660
Poultry Fat	9%	550	550	550	98%(d)	561	561	561
Choice White Grease	10%	550	550	550	99%(d)	556	556	556
Yellow Grease	21%	510	510	510	99%(e)	515	515	515
Brown Grease	33%	350	350	350	73%(f)	483	483	483
FOG (Weighted Average)				502	90%			551
50%Sludge/40%Food/10%FOG (Dry Weight Average)								-111
52%Sludge/46%Food/3%FOG (Wet Weight Average)								-27

(a) Badgett et al 2019 & Personal communication with A. Badgett
(b) DOE 2017
(c) Based on as-received food wastes (WW20, WW21)
(d) NRA 2008
(e) Tao et al 2017; Borgese and Privitera 2011
(f) Kolet et al. 2020
(g) Historical data of the annual sludge production data in the BACWA survey
(h) Average value based on the tipping fees in EPA 2021 and Badgett et al 2020

Table 15 shows the plant economics for the regional waste blending scenario while Figure 17 illustrates the modeled MFSP and cost allocation for the regional waste blending scenario, along with the 2021 SOT (with NH_3 removal case) for comparison. Assuming the scale and average feedstock cost derived for this analysis, the MFSP is estimated at $2.17/GGE, a 24% reduction relative to the 2021 SOT cost of $2.85/GGE. A large scale regional waste blending plant can reduce the fuel cost due to economies of scale with the tradeoff of acquisition and transportation of higher cost feedstocks such as FOG and food waste. In the regional case, the average feedstock price is -$111/dry tonne ($-27/wet tonne) in 2019$ with an average delivery cost of $50/dry tonne. The sludge price without dewatering cost in the SOT case is -$206/dry tonne (-$49/wet tonne) with zero delivery cost. Overall, the feedstock avoided disposal fee in the regional waste blending case (-$0.88/GGE) is about 50% of the feedstock credit in the SOT case due to high FOG price and lower credits of food waste in the regional waste blending scenario. In addition, while there is a cost of $0.40/GGE in the MFSP associated with transporting feedstock in the regional waste blending case (other than the sludge already generated at the WRRF/HTL facility in the SOT case), there is a 9 cent savings from not having to transport biocrude. The cost reduction of $0.68/GGE for the regional waste blending case relative to the SOT is mainly due to cost savings from larger HTL scale (HTL biocrude cost of $1.11/GGE at 3800 TPD versus $2.18/GGE at 110 TPD for the SOT). Note that for the large scale plant, equipment was limited to reasonable capacities and multiple trains are used. For example, heat exchanger effective areas are limited to under 5000 ft^2 (Couper et al. 2012) with 4 trains and multiple exchangers in series (38 for HX-100, 25 for HX-101 and 6 for HX-102).

Table 15. Economics for a 3,800 TPD regional waste-to-fuel plant corresponding to availability in the Detroit, MI area.

Capital Costs, $ million	
Installed costs	
Feedstock dewatering	8.3
HTL biocrude production	313.2
HTL aqueous phase treatment	37.9
Hydrotreating	96.2
Hydrocracking	26.0
Hydrogen Plant	61.1
Steam Cycle	3.8
Balance of plant	8.9
Total installed capital cost	555
Fixed capital investment	1,047
Total capital investment (TCI)	1,122
Operating Costs, $/GGE ($ million/yr)	
Variable operating cost	
Feedstock cost (avoided disposal+transport)	-0.49 (-63.2)
Natural gas	0.11 (14.5)
Catalysts and chemicals	0.27 (35.1)
Waste Disposal	0.75 (98.0)
Electricity	0.07 (9.5)
Fixed costs	0.34 (44.9)
Capital depreciation	0.27 (34.9)
Average income tax	0.08 (10.9)
Average return on investment	0.75 (98.4)
MFSP, $/GGE	2.17
MFSP w/o feedstock credits, $GGE	2.66

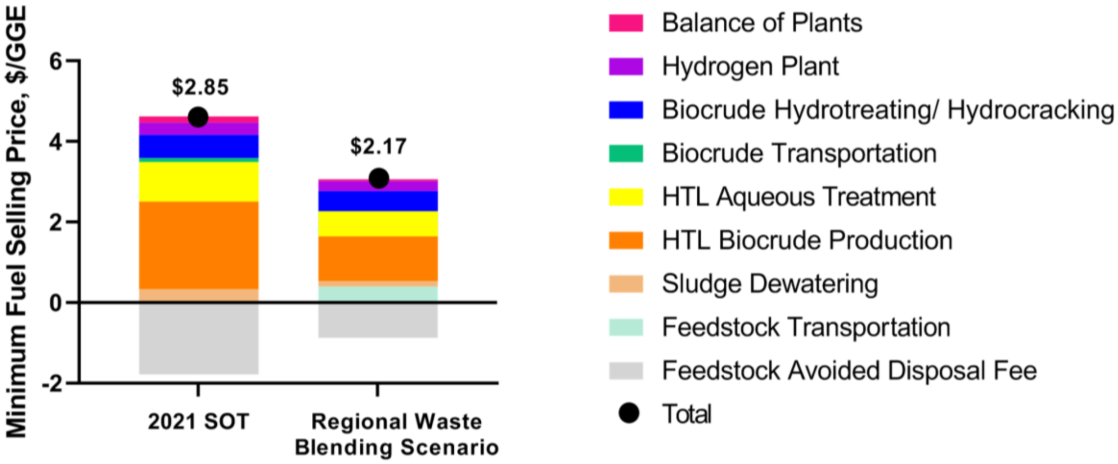

Figure 17. MFSP and cost allocation of regional waste blending case compared to the 2021 SOT.

5.0 Conclusions and Future Work

Important progress was made in FY21 to demonstrate continuous processing of 25% solids feed for HTL of several wet waste feedstocks and a 1% increase in biocrude yield at 25% solids compared to the 20% concentration assumed for the previous SOT. With this progress, the 2021 SOT was updated to a system feed solids content of 25% and biocrude yield performance of 45% (DAF) for the modeled conceptual HTL plant. Pumping of 25% solids feed to the operating pressure of the initial heat exchanger (~1000 psia) is expected to be well within the capabilities of industrial slurry pumps and has been verified by several vendors, further corroborating this process assumption for scaled-up operations. The hydrotreating team demonstrated over 2000 hours time-on-stream with stable catalyst performance. With this accomplishment, the SOT catalyst lifetimes for the guard bed and main hydrotreater bed have been updated to 2000 hours and 1 year, respectively. The research advancements in the HTL and biocrude hydrotreating areas in FY21 have effectively reduced the modeled conversion MFSP by $0.64/GGE of fuel blendstock relative to the 2020 SOT.

Additional testing of the ACU process for AP treatment via conversion of the organics was performed at a scale 10-fold larger than the initial 2020 work, verifying process performance and showing a two-fold increase in guard bed catalyst lifetime. Using the updated data from this year's research, the process modeling and TEA sensitivity analysis indicates that the ACU process with subsequent NH_3 stripping (as modeled) could provide 78%, 92%, and 91% of carbon, COD, and nitrogen removal from the AP, respectively, and reduces the modeled HTL plant MBSP by $0.28/GGE ($0.30/GGE MFSP) due to reduced AP discharge fees and the ability to recover a pure NH_3 fertilizer co-product.

Several wet waste feedstocks including food waste from two industrial cafeteria/kitchen operations and EBS® were tested this year, resulting in biocrude yields of 37 to 46% (DAF). All of the major high-volume wet waste feedstocks viable for waste-to-energy conversion including wastewater solids, food waste, manures, and FOG have now been tested in PNNL's lab and engineering scale systems using actual industry-generated wet waste samples. In addition, a sludge/food waste/FOG blend that is proportionally representative community waste generated in a metropolitan area (Detroit, MI area) was successfully processed and yielded 45% biocrude (DAF basis).

The regional waste blending sensitivity case using the data from the sludge/food/FOG testing indicates that for a 3,800 TPD scale regional waste collection and processing plant, MFSP is reduced from $2.85/GGE to $2.17/GGE relative to the 110 TPD sludge base case for the SOT. The primary benefits of the regional blending scenario result from economies of scale and omitting the need for biocrude transportation with the integrated HTL/upgrading configuration. Whereas this scenario potentially provides a way to valorize more of the distributed resource in an economically feasible way, there is also much uncertainty associated with the analysis, especially with regard to feedstock cost, land requirements for this large of a plant, and logistics of waste collection in urban areas. Future work is needed to provide in-depth geospatial collection/transportation and specific siting analysis for waste hub scenarios around the nation to address these uncertainties and better understand the potential for wet waste collection applications.

Future technical research is needed to advance the technology readiness and further improve production cost, GHGs and other environmental aspects of the pathway, focusing on the following areas:

HTL: Much progress has been made to improve performance and reduce cost of the HTL process since the initial 2018 SOT, effectively reducing the modeled MFSP by $4.0/GGE. This includes design of a less costly heating and pumping configuration for the HTL plant, and processing demonstrations of increased feed solids concentrations, reactor LHSV, and biocrude yields. Process conditions (temperature, pressure, feed solids) have been optimized and a wealth of knowledge gained from PNNL's wet waste testing has been applied to several pilot plant project opportunities currently in development with industrial partners. That said, there are several remaining areas of potential improvement. Efficient deashing methods are needed for high-ash sludges and other wet wastes could help further reduce capital and operating costs, optimize biocrude yields, and reduce the risks associated with equipment plugging. The use of inserts in the feed heat exchangers could enhance tube fluid velocity and associated heat transfer rates thereby reducing areas and costs. Testing of core inserts for the three main heat exchanger services (heating cold sludge feed at 1000 psi; heating warm sludge at 3000 psi; and cooling hot HTL reactor liquid effluent) at a vendor testing facility and/or in PNNL's engineering-scale system is planned in FY22. Advanced solids removal methods are needed to reduce equipment wear-and-tear and minimize biocrude losses. Catalytic HTL could improve process yields for certain feedstocks and should also be considered.

Biocrude Catalytic Upgrading: Research progress on hydrotreating performance, including demonstration of industrially relevant catalyst time-on-stream, increased WHSV, and a lower cost catalyst, has reduced the modeled pathway MFSP by $2.8/GGE. With the 1-year catalyst lifetime adopted for the current SOT, the hydrotreating catalyst contributes only 1 cent per GGE to the MFSP and thus there are diminishing returns for demonstrating prolonged life beyond 1 year. Operating cost associated with the guard bed material contributes 10 cents per GGE to the 2021 SOT MFSP, leaving potential for further reduced guard-bed costs. Testing of a slurry bed configuration for the guard bed has showed promising results. Translation of these results into the necessary capital and operating costs for this type of configuration is necessary to elucidate the potential cost savings. The use of a lower-cost guard bed catalyst relative to the current SOT (CoMo) could also reduce operating costs. Testing is needed to identify the feasibility of low-cost catalysts and their performance in a slurry bed configuration. Investigation of the feasibility of sustainable aviation fuel (SAF) and marine fuel from the wet waste HTL pathway is also underway and will be included in future SOT assessments.

Recovery of Co-Product, Nutrient, and/or Energy from the AP and HTL Solids: Nitrogen and COD removal from the AP may be necessary to mitigate negative impact to a WRRF's treatment train and are potentially more economically and environmentally preferable to discharging them to the WRRF. Several methods for removal of nitrogen and COD from AP have been tested to date including catalytic hydrothermal gasification, steam phase catalytic reduction of wastewater, anaerobic digestion, and the ACU process (Snowden-Swan et al. 2021). Initial experimental results and TEA indicate that the ACU process has promise in terms of cost, levels of carbon and nitrogen removal, and feasibility to recover a clean NH_3 coproduct from the AP. More work is needed to verify the fate of AP organic nitrogen in the ACU process. Additionally, testing is needed on the subsequent NH_3 stripping step that is included in the modeled design to validate the modeled separation efficiency and NH_3 nutrient recovery rates. The 2021 SOT assessment for the algae HTL pathway (Zhu et al. 2022) showed struvite generation and recovery from the HTL solids and AP has the potential to reduce the modeled MFSP by over $3/GGE and provide GHG benefits through generation of green fertilizer co-product. Testing and TEA is needed on struvite generation, purification, and recovery from sludge HTL to elucidate the potential impacts on this pathway.

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Appendix A – Comprehensive List of Waste Feedstocks Testing Data

Table A.1. List of feedstocks tested to date in support of the HTL SOT and pathway development.

	WW06 50/50 Sludge GLWA (Dry)	WW06 50/50 SludgeGLWA (DAF)	WW09 50/50 Sludge CCCSD (Dry)	WW09 50/50 Sludge CCCSD (DAF)	WW10 CCCSD Sludge/FOG (80/20) (Dry)	WW10 CCCSD Sludge/FOG (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. List 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)	2021 SOT and 2022 Models (Dry)	2021 SOT and 2022 Models (DAF)
C	49.3	52.3	51.5	54.1	48.2	55.4	50.8	54.8	40.8	51.7	46.8	52.1
H	7.3	7.7	7.6	8.0	7.3	8.4	6.6	7.1	5.5	7.0	6.5	7.2
O	35.5	37.7	34.3	36.0	29.1	33.4	32.2	34.7	26.4	33.5	29.7	33.1
N	3.5	3.7	3.3	3.5	4.7	5.4	3.2	3.5	5.3	6.7	5.7	6.3
S	0.0	0.0	0.2	0.2	0.6	0.7	0.2	0.2	0.9	1.1	1.2	1.3
Ash	6.5	n/a	4.1	n/a	13.5	n/a	8.6	n/a	21.1	n/a	15.0	n/a
P	1.0	n/a	0.4	n/a	1.4	n/a	0.4	n/a	2.3	n/a	1.9	n/a
Carb	53.6	56.9	53.1	55.8	31.3	36.0	41.4	44.7	26.8	33.7	Not modeled	
Fat	18.6	19.7	20.0	21.0	23.3	26.8	27.7	29.9	14.2	17.8	Not modeled	
Protein	21.6	22.9	20.7	21.7	30.2	34.7	22.8	24.6	38.5	48.5	Not modeled	
FAME	5.4	5.7	16.0	16.8	16.4	18.9	21.4	23.1	9.2	11.6	Not modeled	
Ash	5.8	n/a	4.9	n/a	13.0	n/a	7.3	n/a	20.6	n/a	Not modeled	

(a) WW22 consisted of a 50/40/10 (dry wt basis) blend of sludge/food waste/FOG(scum)

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/FoodWaste/FOG (25% feed solids) WW22B	Food waste (From EBS®) WW23	Sludge primary/ secondary (from GLWA) MHTLS 15	2021 SOT Model	2022 Projected Model
Temperature, °F (°C)	653 (345)	642 (339)	639 (337)	639 (337)	639 (337)	655 (346)	656 (347)	656 (347)
Pressure, psia (MPa)	2855 (19.7)	2915 (20.1)	2765 (19.1)	2765 (19.1)	2840 (19.6)	2765 (19.1)	2979 (20.5)	2979 (20.5)
Feed solids, wt%								
Ash included	22.3%	25.7%	19.4%	24.6%	18.7%	15.4%	25%	25%
Ash-free basis	20.9%	24.6%	16.8%	21.3%	17.1%	12.0%	21%	21%
Liquid hourly space velocity, vol./h per vol. reactor	3.6	6.0	10.3	10.0	5.5	4.0	4.0	6
Equivalent residence time, min.	17	10	6	6	11	15	15	10
Product yields[a] (dry, ash-free sludge), wt%								
Oil (biocrude)	37%	42%	44%	45%	46%	42%	45%	48%
Aqueous	43%	36%	29%	31%	34%	36%	28%	25%
Gas	13%	20%	19%	18%	18%	17%	16%	16%
Solids	7%	2%	8%	6%	2%	5%	12%	11%
Carbon yields								
Oil (biocrude)	58%	64%	58%	61%	62%	52%	67%	72%
Aqueous	22%	22%	24%	23%	27%	33%	23%	18%
Gas	8%	11%	9%	9%	9%	9%	10%	10%
Solids	13%	3%	9%	7%	3%	7%	1%	1%
HTL dry biocrude analysis, wt%								
C	75.9%	74.1%	75.0%	74.7%	76.4%	77.8%	78.3%	78.3%
H	11.3%	11.1%	11.3%	11.6%	9.6%	12.4%	10.8%	10.8%
O	8.4%	10.6%	8.1%	8.0%	9.4%	3.6%	4.8%	4.8%
N	4.0%	4.0%	4.8%	4.9%	4.0%	5.3%	4.9%	4.9%
S	0.0%	0.0%	0.7%	0.7%	0.0%	0.9%	1.2%	1.2%
P	0.09%	0.00%	0.0%	0.00%	0.00%	0%	Not modeled[b]	Not modeled[b]
Ash	0.10%	0.11%	0.17%	0.14%	0.03%	0.03%	0.0%	0.0%
HTL dry biocrude H:C ratio (mol)	1.8	1.8	1.8	1.9	1.7	1.9	1.6	1.6
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)	17,100 (39.7)	17,100 (39.7)
HTL biocrude moisture, wt%	2.6%	4.8%	3.7%	4.6%	1.7%	9.8%	4.0%	4.0%
HTL biocrude wet density @ 77°F (25°C) (g/ml)	1.00	1.01	0.96	0.96	0.98	0.97	0.98	0.98
AP chemical oxygen demand (mg/L)	90,500	111,550	81,500	100,100	74,333	81,600	94,022	61,100

(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	2020 SOT Model	2022 Projected Model
Temperature, °F (°C)	752 (400)	752 (400)	752 (400)	752 (400)	752 (400)	752 (400)	752 (400)
Pressure, psia	1540	1535	1535	1515	1562	1540	1515
Guard bed catalyst sulfided?	CoMo/alumina Yes	CoMo/alumina Yes		CoMo/alumina Yes	CoMo/alumina Yes	CoMo/alumina Yes	CoMo/alumina Purchased presulfided
Main bed catalyst sulfided?	CoMo/alumina Yes	NiMo/alumina Yes		NiMo/alumina Yes	NiMo/alumina Yes	NiMo/alumina Yes	CoMo/alumina Purchased presulfided
Guard bed WHSV, wt./hr per wt. catalyst	0.46	0.68	0.65	0.42	0.72	0.72	1.3
Main bed WHSV, wt./hr per wt. catalyst	0.29	0.39	0.38	0.42	1.03	1.03	0.75
HTL biocrude feed rate, ml/h	5.6	7.3		2.16		130 (main bed)	Commercial scale
Time-on-stream (catalyst life)	302 hours	552 hours		133 hours		112 hours	2 years
Chemical H_2 consumption, wt/wt HTL biocrude (wet)	0.046	0.058	0.051	0.043	0.050	0.046	0.044
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	0.82 (0.97)	0.84 (0.97)
Aqueous phase	0.14 (0.13)	0.13	0.17	0.13	0.16	0.14	0.13 (0.19)
Gas	0.08	0.08	0.06	0.06	0.04	0.10	0.07
Product oil, wt%							
C	85.6	85.0	84.8	85.7	84.7	85.3	85.3
H	14.6	14.3	15.1	12.9	14.3	14.1	14.1
O	1.0	<0.5	<0.5	<0.5	0.22	0.6	0.6
N	<0.05	0.73	0.07	1.60	0.84	0.04	0.04
S	7-10 ppm	0.03	0.14	<0.03	<0.3	0.0	0.0
Aqueous carbon, wt%	0.10	Not measured	Not measured	Not measured	Not measured	0.6	0.2
Gas analysis, volume%							
CO_2, CO	0	5	4	0	3	0	0
CH_4	51	9	33	45	19	39	33
C_2+	49	86	63	55	78	35	38
NH_3	Not measured	Not measured	Not measured	0	Not measured	23	26
NH_4HS	Not measured	Not measured	Not measured	0	Not measured	3	3
Total acid number, feed (product)	59 (<0.01)	Not measured	Not measured	Not calculated	Not calculated	Not calculated	Not calculated
Viscosity@40°C, cSt, feed (product)	400 (2.7)	Not measured	166 (3.7)	1040 (5.6)	165 (3.7)	Not calculated	Not calculated
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)	0.98 (0.79)	0.98 (0.79)

(a) Yield after phase separation.

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

Component	WW22	MHTLS 13	WW20	WW21	MHTLS 15	2021 SOT Model	2022 Projected Model
Temperature, °F (°C)	752 (400)	752 (400)	752 (400)	752 (400)	752 (400)	752 (400)	752 (400)
Pressure, psia	1560	1560	1560	1560	1560	1540	1515
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	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	CoMo/alumina Purchased presulfided
Guard bed WHSV, wt./hr per wt. catalyst	0.5	0.5	0.5	0.5	0.5	0.72	1.3
Main bed WHSV, wt./hr per wt. catalyst	0.5	0.5	0.5	0.5	0.5	1.03	0.75
HTL biocrude feed rate, ml/h	2.52	2.52	2.52	2.52	2.52	Commercial scale	Commercial scale
Time-on-stream (catalyst life)	>135	284	284 to 591	591 to 1075	1075 to 2165	2000 hours (guard) 1 year (main)	2 years (guard and main)
Chemical H_2 consumption, wt/wt HTL biocrude (wet)	0.047	0.035	0.050	0.053	0.034	0.046	0.044
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)	0.84 (0.97)
Aqueous phase	0.09	0.15	0.12	0.12	0.12	0.12	0.13 (0.19)
Gas	0.07	0.05	0.06	0.05	0.06	0.10	0.07
Product oil, wt%							
C	86.0	85.1	85.2	85.1	84.7	85.3	85.3
H(b)	13.4	13.7	13.4	13.5	14.1	14.1	14.1
O	0.1	0.2	0.2	0.2	0.2	0.6	0.6
N	0.5	<1	1.1	1.1	<1	0.04	0.04
S	Below detection	0.0	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	2.0
Aqueous carbon, wt%	Not measured	Not measured	Not measured	Not measured	Not measured	0.6	0.2
Gas analysis, volume%							
CO_2, CO	0	0	0	0	0	0	0
CH_4	20	32	39	42	37	39	33
C_2+	80	68	61	58	63	35	38
NH_3	Not measured	Not measured	Not measured	Not measured	Not measured	23	26
NH_4HS	Not measured	Not measured	Not measured	Not measured	Not measured	3	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	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)	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 and projected cases for the combined wet waste HTL and upgrading pathway (**using old system boundary** – see Section 4.1).

Processing Area Cost Contributions & Key Technical Parameters	Metric	2018 SOT with NH_3 removal	2018 SOT no NH_3 removal	2019 SOT with NH_3 removal	2019 SOT no NH_3 removal	2020 SOT with NH_3 removal	2020 SOT no NH_3 removal	2021 SOT with NH_3 removal	2021 SOT no NH_3 removal	2022 Projected with NH_3 removal	2022 Projected no NH_3 removal
Fuel selling price	$/GGE	$7.16	$6.74	$5.11	$4.69	$4.50	$4.08	$3.61	$3.37	$3.11	$2.77
Conversion Contribution	$/GGE	$7.06	$6.64	$5.01	$4.59	$4.4	$3.98	$3.51	$3.28	$3.01	$2.67
Perfomance Goal	$/GGE									$3	$3
Production Diesel	mm gallons/yr	27	27	27	27	27	27	27	27	28	28
Production Naphtha	mm gallons/yr	9	9	9	9	9	9	9	9	9	9
Diesel Yield (AFDW sludge basis)	gal/US ton sludge	79	79	79	79	79	79	80	80	89	89
Naphtha Yield (AFDW sludge basis)	gal/us ton sludge	27	27	27	27	27	27	28	28	30	30
Natural Gas Usage (AFDW sludge basis)	scf/US ton sludge	4,951	3,898	4,951	3,898	3,717	2,664	2,588	2,377	4,914	3,861
Feedstock											
Total Cost Contribution	$/GGE fuel	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Feedstock Cost (dry sludge basis)	$/US ton sludge	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Sludge Dewatering											
Total Cost Contribution	$/GGE fuel	$0.20	$0.20	$0.20	$0.20	$0.20	$0.20	$0.19	$0.19	$0.18	$0.18
Capital Cost Contribution	$/GGE fuel	$0.10	$0.10	$0.10	$0.10	$0.10	$0.10	$0.10	$0.10	$0.09	$0.09
Operating Cost Contribution	$/GGE fuel	$0.10	$0.10	$0.10	$0.10	$0.10	$0.10	$0.10	$0.10	$0.09	$0.09
Sludge HTL											
Total Cost Contribution	$/GGE fuel	$2.40	$2.45	$2.40	$2.45	$2.12	$2.18	$1.83	$1.89	$1.49	$1.55
Capital Cost Contribution	$/GGE fuel	$1.46	$1.46	$1.46	$1.46	$1.27	$1.27	$1.07	$1.07	$0.83	$0.83
Operating Cost Contribution	$/GGE fuel	$0.94	$0.99	$0.94	$0.99	$0.84	$0.91	$0.76	$0.82	$0.66	$0.72
HTL Biocrude Yield (dry)	lb/lb sludge	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.48	0.48
Liquid Hourly Space Velocity (LHSV)	vol/h/vol	3.6	3.6	3.6	3.6	4.0	4.0	4.0	4.0	6.0	6.0
Preheaters Capital Cost (installed)	$MM	12	12	12	12	9	9	8	8	6	6
HTL Water Recycle Treatment											
Total Cost Contribution	$/GGE fuel	$0.61	$0.13	$0.61	$0.13	$0.62	$0.13	$0.45	$0.15	$0.49	$0.09
Capital Cost Contribution	$/GGE fuel	$0.21	$0.00	$0.21	$0.00	$0.21	$0.00	$0.16	$0.00	$0.16	$0.00
Operating Cost Contribution	$/GGE fuel	$0.40	$0.13	$0.40	$0.13	$0.41	$0.13	$0.30	$0.15	$0.33	$0.09
Balance of Plant - HTL											
Total Cost Contribution	$/GGE fuel	$0.06	$0.07	$0.06	$0.07	$0.07	$0.07	$0.07	$0.07	$0.07	$0.07
Capital Cost Contribution	$/GGE fuel	$0.04	$0.04	$0.04	$0.04	$0.05	$0.05	$0.04	$0.04	$0.04	$0.04
Operating Cost Contribution	$/GGE fuel	$0.02	$0.02	$0.02	$0.02	$0.02	$0.02	$0.02	$0.03	$0.03	$0.03
Biocrude Transport	$/gge fuel	$0.10	$0.10	$0.10	$0.10	$0.10	$0.10	$0.10	$0.10	$0.10	$0.10

Processing Area Cost Contributions & Key Technical Parameters	Metric	2018 SOT with NH_3 removal	2018 SOT no NH_3 removal	2019 SOT with NH_3 removal	2019 SOT no NH_3 removal	2020 SOT with NH_3 removal	2020 SOT no NH_3 removal	2021 SOT with NH_3 removal	2021 SOT no NH_3 removal	2022 Projected with NH_3 removal	2022 Projected no NH_3 removal
Biocrude Upgrading to Finished Fuels											
Total Cost Contribution	$/GGE fuel	$3.38	$3.38	$1.34	$1.34	$1.00	$1.00	$0.57	$0.57	$0.40	$0.40
Capital Cost Contribution	$/GGE fuel	$0.40	$0.40	$0.34	$0.34	$0.30	$0.30	$0.30	$0.30	$0.25	$0.25
Operating Cost Contribution	$/GGE fuel	$2.97	$2.97	$1.01	$1.01	$0.70	$0.70	$0.27	$0.27	$0.15	$0.15
Hydrotreating Mass Yield on dry Biocrude	lb/lb biocrude	0.82	0.82	0.82	0.82	0.82	0.82	0.82	0.82	0.84	0.84
Guard Bed Weight Hourly Space Velocity (WHSV)	wt/h/wt	0.46	0.46	0.67	0.67	0.72	0.72	0.72	0.72	1.30	1.30
Guard Bed Catalyst Lifetime	years	0.03	0.03	0.06	0.06	0.06	0.06	0.23	0.23	1	1
Hydrotreater Weight Hourly Space Velocity (WHSV)	wt/h/wt	0.29	0.29	0.39	0.39	1.02	1.02	1.02	1.02	0.75	0.75
Hydrotreater Catalyst Lifetime	years	0.03	0.03	0.06	0.06	0.06	0.06	1.00	1.00	2	2
Balance of Plant - Upgrading											
Total Cost Contribution	$/GGE fuel	$0.42	$0.42	$0.40	$0.40	$0.40	$0.40	$0.39	$0.39	$0.39	$0.39
Capital Cost Contribution	$/GGE fuel	$0.26	$0.26	$0.24	$0.24	$0.24	$0.24	$0.23	$0.23	$0.22	$0.22
Operating Cost Contribution	$/GGE fuel	$0.16	$0.16	$0.16	$0.16	$0.16	$0.16	$0.16	$0.16	$0.17	$0.17
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.bkp		Sludge HTL 2021 SOT final.bkp; Sludge HTL Biocrude Upgrading 2021 SOT.bkp		Sludge HTL Goal Case 8-17-2017 FINAL 110 TPD 1.bkp;WW-06 Bio-Oil Upgrading 10X 110 TPD.bkp	

Table B.2. Processing area cost contributions and key technical parameters for the SOT and projected cases for the separate wet waste HTL plant (**using old system boundary** – see Section 4.1).

Processing Area Cost Contributions & Key Technical Parameters	Metric	2018 SOT with NH_3 removal	2018 SOT no NH_3 removal	2019 SOT with NH_3 removal	2019 SOT no NH_3 removal	2020 SOT with NH_3 removal	2020 SOT no NH_3 removal	2021 SOT with NH_3 removal	2021 SOT no NH_3 removal	2022 Projected with NH_3 removal	2022 Projected no NH_3 removal
HTL Biocrude selling price	$/GGE	$3.04	$2.65	$3.04	$2.65	$2.79	$2.40	$2.37	$2.15	$2.11	$1.79
Conversion Contribution, Biocrude	$/GGE	$3.04	$2.65	$3.04	$2.65	$2.79	$2.40	$2.37	$2.15	$2.11	$1.79
Production Biocrude	mm GGE/yr	4	4	4	4	4	4	4	4	4	4
Production Biocrude	mm gallons/yr	3	3	3	3	3	3	3	3	4	4
Biocrude Yield (AFDW sludge basis)	gal/US ton sludge	111	111	111	111	111	111	113	113	123	123
Natural Gas Usage (AFDW sludge basis)	scf/US ton sludge	3,760	2,707	3,760	2,707	2,527	1,474	1,378	1,167	3,303	2,250
Feedstock											
Total Cost Contribution	$/GGE fuel	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Feedstock Cost (AFDW sludge basis)	$/US ton sludge	$0	$0	$0	$0	$0	$0	$0	$0	$0	$0
Sludge Dewatering											
Total Cost Contribution	$/GGE biocrude	$0.18	$0.18	$0.18	$0.18	$0.18	$0.18	$0.18	$0.18	$0.17	$0.17
Capital Cost Contribution	$/GGE biocrude	$0.09	$0.09	$0.09	$0.09	$0.09	$0.09	$0.09	$0.09	$0.08	$0.08
Operating Cost Contribution	$/GGE biocrude	$0.09	$0.09	$0.09	$0.09	$0.09	$0.09	$0.09	$0.09	$0.08	$0.08
Sludge HTL											
Total Cost Contribution	$/GGE biocrude	$2.23	$2.28	$2.23	$2.28	$1.97	$2.03	$1.70	$1.76	$1.41	$1.47
Capital Cost Contribution	$/GGE biocrude	$1.36	$1.36	$1.36	$1.36	$1.18	$1.18	$0.99	$1.00	$0.79	$0.79
Operating Cost Contribution	$/GGE biocrude	$0.87	$0.92	$0.87	$0.92	$0.78	$0.84	$0.71	$0.76	$0.62	$0.68
HTL Biocrude Yield (dry)	lb /lb sludge	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.44	0.48	0.48
Liquid Hourly Space Velocity (LHSV)	vol/h/vol	3.6	3.6	3.6	3.6	4.0	4.0	4.0	4.0	6.0	6.0
Preheaters Capital Cost (installed)	$MM	12	12	12	12	9	9	8	8	6	6
HTL Water Recycle Treatment											
Total Cost Contribution	$/GGE biocrude	$0.57	$0.12	$0.57	$0.12	$0.58	$0.12	$0.42	$0.14	$0.46	$0.08
Capital Cost Contribution	$/gge biocrude	$0.19	$0.00	$0.19	$0.00	$0.20	$0.00	$0.15	$0.00	$0.15	$0.00
Operating Cost Contribution	$/GGE biocrude	$0.37	$0.12	$0.37	$0.12	$0.38	$0.12	$0.28	$0.14	$0.32	$0.08
Balance of Plant											
Total Cost Contribution	$/GGE biocrude	$0.06	$0.06	$0.06	$0.06	$0.06	$0.06	$0.06	$0.07	$0.06	$0.07
Capital Cost Contribution	$/GGE biocrude	$0.04	$0.04	$0.04	$0.04	$0.04	$0.04	$0.04	$0.04	$0.04	$0.04
Operating Cost Contribution	$/GGE biocrude	$0.02	$0.02	$0.02	$0.02	$0.02	$0.02	$0.02	$0.02	$0.02	$0.03
Models: Case References		Sludge HTL 2018 SOT final 2016$.bkp				Sludge HTL 2020 SOT final-base-split-hotoil_v2.bkp		Sludge HTL 2021 SOT.bkp		Sludge HTL Goal Case 8-17-2017 FINAL 110 TPD 1.bkp	

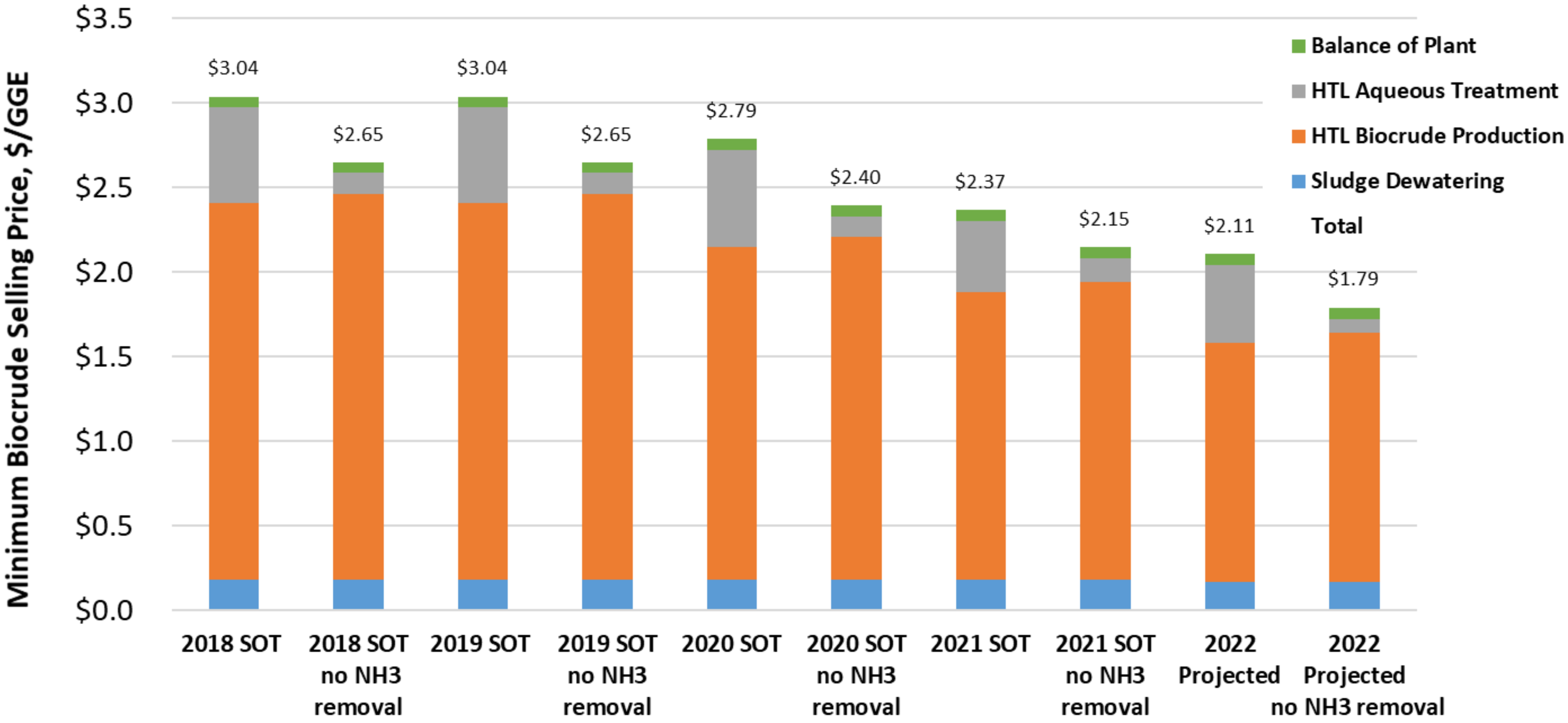

Figure B.1. Hydrothermal liquefaction biocrude cost allocations (using old system boundary – see Section 4.1).

Table B.3. Processing area cost contributions and key technical parameters for the SOT and projected cases for the combined wet waste HTL and upgrading pathway (**using new system boundary** – see Section 4.2).

Processing Area Cost Contributions & Key Technical Parameters	Metric	2018 SOT with NH_3 removal	2018 SOT no NH_3 removal	2019 SOT with NH_3 removal	2019 SOT no NH_3 removal	2020 SOT with NH_3 removal	2020 SOT no NH_3 removal	2021 SOT with NH_3 removal	2021 SOT no NH_3 removal	2022 Projected with NH_3 removal	2022 Projected no NH_3 removal
Fuel selling price	$/GGE	$9.66	$9.56	$7.61	$7.51	$3.49	$3.37	$2.85	$2.83	$2.79	$2.77
Conversion Contribution	$/GGE	$11.37	$11.27	$9.32	$9.22	$5.19	$5.08	$4.52	$4.50	$4.47	$4.45
Perfomance Goal	$/GGE										
Production Diesel	mm gallons/yr	27	27	27	27	27	27	27	27	27	27
Production Naphtha	mm gallons/yr	9	9	9	9	9	9	9	9	9	9
Diesel Yield (AFDW sludge basis)	gal/US ton sludge	79	79	79	79	79	79	80	80	80	80
Naphtha Yield (AFDW sludge basis)	gal/us ton sludge	27	27	27	27	27	27	28	28	28	28
Natural Gas Usage (AFDW sludge basis)	scf/US ton sludge	3,055	2,003	3,055	2,003	3,717	2,664	2,588	2,377	2,588	2,377
Feedstock											
Total Cost Contribution	$/GGE fuel	-$1.81	-$1.81	-$1.81	-$1.81	-$1.81	-$1.81	-$1.78	-$1.78	-$1.78	-$1.78
Feedstock Cost (dry sludge basis)	$/US ton sludge	($171)	($171)	($171)	($171)	($171)	($171)	($171)	($171)	($171)	($171)
Sludge Dewatering											
Total Cost Contribution	$/GGE fuel	$0.28	$0.29	$0.28	$0.29	$0.28	$0.28	$0.33	$0.33	$0.33	$0.33
Capital Cost Contribution	$/GGE fuel	$0.11	$0.11	$0.11	$0.11	$0.11	$0.11	$0.11	$0.11	$0.11	$0.11
Operating Cost Contribution	$/GGE fuel	$0.17	$0.18	$0.17	$0.18	$0.17	$0.17	$0.22	$0.22	$0.22	$0.22
Sludge HTL											
Total Cost Contribution	$/GGE fuel	$6.30	$6.33	$6.30	$6.33	$2.46	$2.53	$2.18	$2.24	$2.18	$2.24
Capital Cost Contribution	$/GGE fuel	$4.29	$4.29	$4.29	$4.29	$1.28	$1.28	$1.08	$1.08	$1.08	$1.08
Operating Cost Contribution	$/GGE fuel	$2.01	$2.03	$2.01	$2.03	$1.18	$1.24	$1.09	$1.15	$1.09	$1.15
HTL Biocrude Yield (dry)	lb/lb sludge	0.44	0.44	0.44	0.44	0.44	0.44	0.45	0.45	0.45	0.45
Liquid Hourly Space Velocity (LHSV)	vol/h/vol	3.6	3.6	3.6	3.6	4.0	4.0	4.0	4.0	4.0	4.0
Preheaters Capital Cost (installed)	$MM	51	51	51	51	9	9	8	8	8	8
HTL Water Recycle Treatment											
Total Cost Contribution	$/GGE fuel	$0.94	$0.80	$0.94	$0.80	$0.99	$0.80	$0.98	$0.90	$0.98	$0.90
Capital Cost Contribution	$/GGE fuel	$0.21	$0.00	$0.21	$0.00	$0.21	$0.00	$0.16	$0.00	$0.16	$0.00
Operating Cost Contribution	$/GGE fuel	$0.73	$0.80	$0.73	$0.80	$0.78	$0.80	$0.83	$0.90	$0.83	$0.90
Balance of Plant - HTL											
Total Cost Contribution	$/GGE fuel	$0.06	$0.06	$0.06	$0.06	$0.07	$0.07	$0.07	$0.07	$0.07	$0.07
Capital Cost Contribution	$/GGE fuel	$0.04	$0.04	$0.04	$0.04	$0.05	$0.05	$0.05	$0.05	$0.05	$0.05
Operating Cost Contribution	$/GGE fuel	$0.01	$0.01	$0.01	$0.01	$0.02	$0.02	$0.02	$0.03	$0.02	$0.03
Biocrude Transport	$/gge fuel	$0.10	$0.10	$0.10	$0.10	$0.10	$0.10	$0.10	$0.10	$0.10	$0.10
Biocrude Upgrading to Finished Fuels											
Total Cost Contribution	$/GGE fuel	$3.38	$3.38	$1.34	$1.34	$1.00	$1.00	$0.57	$0.57	$0.52	$0.52
Capital Cost Contribution	$/GGE fuel	$0.40	$0.40	$0.34	$0.34	$0.30	$0.30	$0.30	$0.30	$0.30	$0.30
Operating Cost Contribution	$/GGE fuel	$2.97	$2.97	$1.01	$1.01	$0.70	$0.70	$0.27	$0.27	$0.22	$0.22

Processing Area Cost Contributions & Key Technical Parameters	Metric	2018 SOT with NH_3 removal	2018 SOT no NH_3 removal	2019 SOT with NH_3 removal	2019 SOT no NH_3 removal	2020 SOT with NH_3 removal	2020 SOT no NH_3 removal	2021 SOT with NH_3 removal	2021 SOT no NH_3 removal	2022 Projected with NH_3 removal	2022 Projected no NH_3 removal
Hydrotreating Mass Yield on dry Biocrude	lb/lb biocrude	0.82	0.82	0.82	0.82	0.82	0.82	0.82	0.82	0.82	0.82
Guard Bed Weight Hourly Space Velocity (WHSV)	wt/h/wt	0.46	0.46	0.67	0.67	0.72	0.72	0.72	0.72	0.72	0.72
Guard Bed Catalyst Lifetime	years	0.03	0.03	0.06	0.06	0.06	0.06	0.23	0.23	0	0
Hydrotreater Weight Hourly Space Velocity (WHSV)	wt/h/wt	0.29	0.29	0.39	0.39	1.02	1.02	1.02	1.02	1.02	1.02
Hydrotreater Catalyst Lifetime	years	0.03	0.03	0.06	0.06	0.06	0.06	1.00	1.00	1	1
Balance of Plant - Upgrading											
Total Cost Contribution	$/GGE fuel	$0.42	$0.42	$0.40	$0.40	$0.40	$0.40	$0.39	$0.39	$0.39	$0.39
Capital Cost Contribution	$/GGE fuel	$0.26	$0.26	$0.24	$0.24	$0.24	$0.24	$0.23	$0.23	$0.23	$0.23
Operating Cost Contribution	$/GGE fuel	$0.16	$0.16	$0.16	$0.16	$0.16	$0.16	$0.16	$0.16	$0.16	$0.16
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.bkp		Sludge HTL 2021 SOT final.bkp; Sludge HTL Biocrude Upgrading 2021 SOT.bkp		Sludge HTL Goal Case 8-17-2017 FINAL 110 TPD 1.bkp;WW-06 Bio-Oil Upgrading 10X 110 TPD.bkp	

Table B.4. Processing area cost contributions and key technical parameters for the SOT and projected cases for the separate wet waste HTL plant (**using new system boundary** – see Section 4.2).

Processing Area Cost Contributions & Key Technical Parameters	Metric	2018 SOT with NH_3 removal	2018 SOT no NH_3 removal	2019 SOT with NH_3 removal	2019 SOT no NH_3 removal	2020 SOT with NH_3 removal	2020 SOT no NH_3 removal	2021 SOT with NH_3 removal	2021 SOT no NH_3 removal	2022 Projected with NH_3 removal	2022 Projected no NH_3 removal
HTL Biocrude selling price	$/GGE	$5.36	$5.27	$5.36	$5.27	$1.85	$1.74	$1.66	$1.64	$1.66	$1.64
Conversion Contribution, Biocrude	$/GGE	$7.17	$7.08	$7.17	$7.08	$3.65	$3.55	$3.31	$3.29	$3.31	$3.29
Production Biocrude	mm GGE/yr	4	4	4	4	4	4	4	4	4	4
Production Biocrude	mm gallons/yr	3	3	3	3	3	3	3	3	3	3
Biocrude Yield (AFDW sludge basis)	gal/US ton sludge	111	111	111	111	111	111	113	113	113	113
Natural Gas Usage (AFDW sludge basis)	scf/US ton sludge	1,865	812	1,865	812	2,527	1,474	1,378	1,167	1,378	1,167
Feedstock											
Total Cost Contribution	$/GGE fuel	-$2	-$2	-$2	-$2	-$2	-$2	-$2	-$2	-$2	-$2
Feedstock Cost (AFDW sludge basis)	$/US ton sludge	($171)	($171)	($171)	($171)	($171)	($171)	($171)	($171)	($171)	($171)
Sludge Dewatering											
Total Cost Contribution	$/GGE biocrude	$0.26	$0.27	$0.26	$0.27	$0.26	$0.26	$0.31	$0.31	$0.31	$0.31
Capital Cost Contribution	$/GGE biocrude	$0.10	$0.10	$0.10	$0.10	$0.11	$0.11	$0.10	$0.10	$0.10	$0.10
Operating Cost Contribution	$/GGE biocrude	$0.16	$0.17	$0.16	$0.17	$0.16	$0.16	$0.20	$0.20	$0.20	$0.20
Sludge HTL											
Total Cost Contribution	$/GGE biocrude	$5.86	$5.88	$5.86	$5.88	$2.28	$2.35	$2.02	$2.08	$2.02	$2.08
Capital Cost Contribution	$/GGE biocrude	$3.99	$3.99	$3.99	$3.99	$1.19	$1.19	$1.00	$1.01	$1.00	$1.01
Operating Cost Contribution	$/GGE biocrude	$1.87	$1.89	$1.87	$1.89	$1.10	$1.16	$1.02	$1.07	$1.02	$1.07
HTL Biocrude Yield (dry)	lb /lb sludge	0.44	0.44	0.44	0.44	0.44	0.44	0.45	0.45	0.45	0.45
Liquid Hourly Space Velocity (LHSV)	vol/h/vol	3.6	3.6	3.6	3.6	4.0	4.0	4.0	4.0	4.0	4.0
Preheaters Capital Cost (installed)	$MM	51	51	51	51	9	9	8	8	8	8
HTL Water Recycle Treatment											
Total Cost Contribution	$/GGE biocrude	$0.87	$0.75	$0.87	$0.75	$0.92	$0.75	$0.91	$0.84	$0.91	$0.84
Capital Cost Contribution	$/gge biocrude	$0.19	$0.00	$0.19	$0.00	$0.20	$0.00	$0.15	$0.00	$0.15	$0.00
Operating Cost Contribution	$/GGE biocrude	$0.68	$0.75	$0.68	$0.75	$0.72	$0.75	$0.77	$0.84	$0.77	$0.84
Balance of Plant											
Total Cost Contribution	$/GGE biocrude	$0.05	$0.05	$0.05	$0.05	$0.06	$0.06	$0.06	$0.07	$0.06	$0.07
Capital Cost Contribution	$/GGE biocrude	$0.04	$0.04	$0.04	$0.04	$0.04	$0.04	$0.04	$0.04	$0.04	$0.04
Operating Cost Contribution	$/GGE biocrude	$0.01	$0.01	$0.01	$0.01	$0.02	$0.02	$0.02	$0.02	$0.02	$0.02
Models: Case References		Sludge HTL 2018 SOT final 2016$.bkp				Sludge HTL 2020 SOT final-base-split-hotoil_v2.bkp	Sludge HTL 2021 SOT.bkp	Sludge HTL Goal Case 8-17-2017 FINAL 110 TPD 1.bkp		Sludge HTL 2018 SOT final 2016$.bkp	

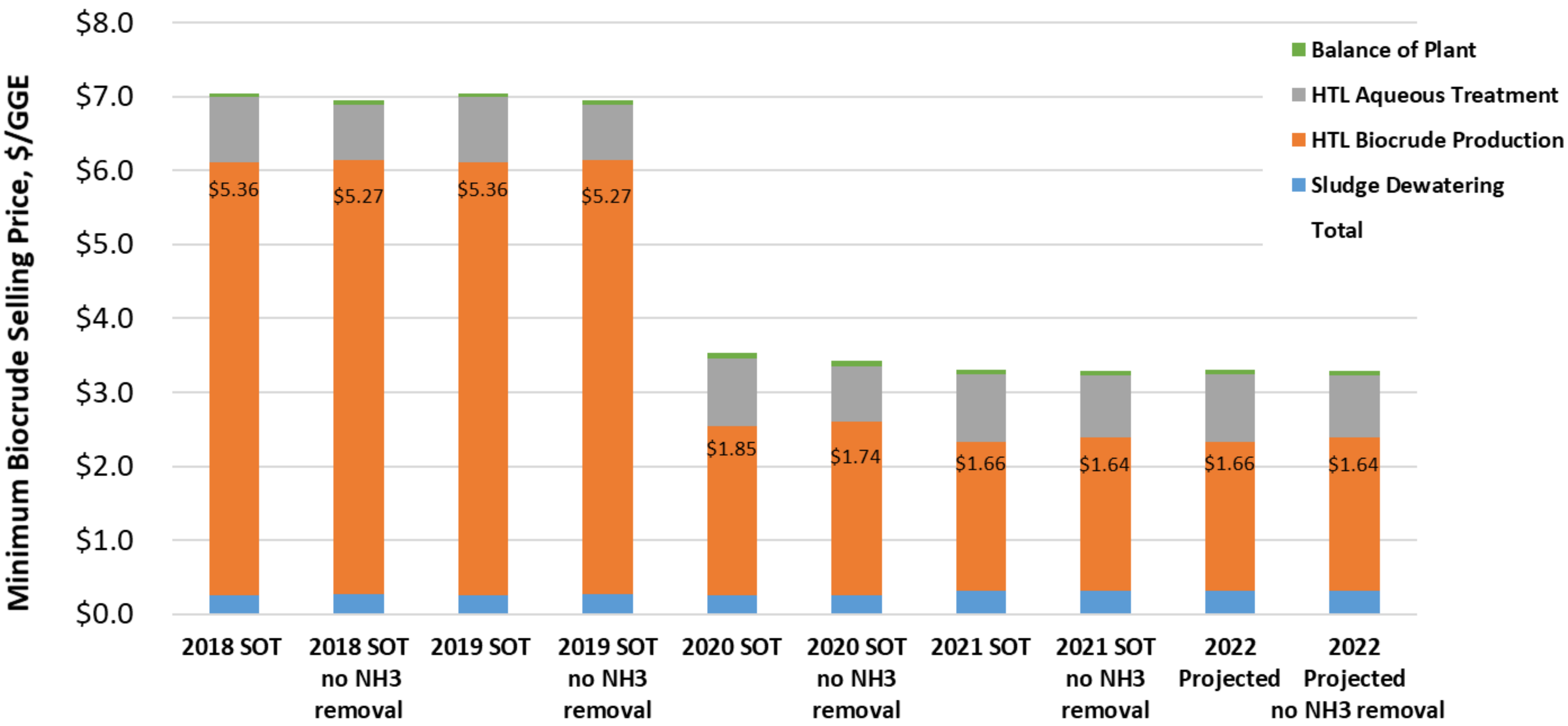

Figure B.2. Hydrothermal liquefaction biocrude cost allocations (**using new system boundary** – see Section 4.1).

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 Projected with NH_3 Removal	2022 Projected 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% and 60% moisture for SOT and projected case, respectively.
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 (w/ adjustments to 2022 projection – see Section 4.2).

Upgrading Plant	2018 SOT	2019 SOT	2020 SOT	2021 SOT	2022 Projected
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	124,423
Naphtha density, lb/gal	6.13	6.13	6.13	6.13	6.13
Naphtha lower heating value, Btu/gal	114,650	114,650	114,652	114,562	114,562
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	2,182
Electricity, kW	1,673	1,673	1,673	1,673	1,673
Cooling tower chemical, lb/hr	0.4	0.4	0.4	0.4	0.4
Boiler chemical, lb/hr	0.3	0.3	0.3	0.3	0.3
Hydrotreating catalyst, lb/hr	811	317	184	19.7	19.7
Hydrocracking catalyst, lb/hr	0.3	0.3	0.3	0.3	0.3
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	25,050
Boiler feedwater makeup, lb/hr	11,022	11,022	11,022	11,021	11,021
Outputs					
Diesel, lb/hr	22,577	22,577	22,583	22,583	22,583
Naphtha, lb/hr	7,124	7,124	7,119	7,119	7,119
Wastewater, lb/hr	22,773	22,773	22,460	22,460	22,460
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

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