PNNL-25464 Rev.1

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Hydrothermal Liquefaction and Upgrading of Municipal Wastewater Treatment Plant Sludge: A Preliminary Techno-Economic Analysis

September 2016

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

PACIFIC NORTHWEST NATIONAL LABORATORY
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UNITED STATES DEPARTMENT OF ENERGY
under Contract DE-AC05-76RL01830

Printed in the United States of America

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RECORD OF REVISION		
Revision	**Description of Changes**	**Comments**
0	Initial issue	
1	Added Appendix B containing methods and results of preliminary fuel greenhouse gas emissions analysis. Also added list of abbreviations.	No changes were made to the existing text.

Summary

A preliminary process model and techno-economic analysis (TEA) was completed for fuel produced from hydrothermal liquefaction (HTL) of sludge waste from a municipal wastewater treatment plant (WWTP) and subsequent biocrude upgrading. The model is adapted from previous work by Jones *et al.* (2014) for algae HTL, using experimental data generated in fiscal year 2015 (FY15) bench-scale HTL testing of sludge waste streams. Testing was performed on sludge samples received from Metro Vancouver's Annacis Island WWTP (Vancouver, B.C.) as part of a collaborative project with the Water Environment and Reuse Foundation (WERF). The full set of sludge HTL testing data from this effort will be documented in a separate report to be issued by WERF. This analysis is based on limited testing data and therefore should be considered preliminary. In addition, the testing was conducted with the goal of successful operation, and therefore does not represent an optimized process. Future refinements are necessary to improve the robustness of the model, including a cross-check of modeled biocrude components with the experimental GCMS data and investigation of equipment costs most appropriate at the relatively small scales used here. Environmental sustainability metrics analysis is also needed to understand the broader impact of this technology pathway.

The base case scenario for the analysis consists of 10 HTL plants, each processing 100 dry U.S. ton/day (92.4 ton/day on a dry, ash-free basis) of sludge waste and producing 234 barrel per stream day (BPSD) biocrude, feeding into a centralized biocrude upgrading facility that produces 2,020 barrel per standard day of final fuel. This scale was chosen based upon initial wastewater treatment plant data collected by PNNL's resource assessment team from the EPA's Clean Watersheds Needs Survey database (EPA 2015a) and a rough estimate of what the potential sludge availability might be within a 100-mile radius. In addition, we received valuable feedback from the wastewater treatment industry as part of the WERF collaboration that helped form the basis for the selected HTL and upgrading plant scales and feedstock credit (current cost of disposal). It is assumed that the sludge is currently disposed of at $16.20/wet ton ($46/dry ton at 35% solids; $50/ton dry, ash-free basis) and this is included as a feedstock credit in the operating costs. The base case assumptions result in a minimum biocrude selling price of $3.8/gge and a minimum final upgraded fuel selling price of $4.9/gge.

Several areas of process improvement and refinements to the analysis have the potential to significantly improve economics relative to the base case:

- Optimization of HTL sludge feed solids content
- Optimization of HTL biocrude yield
- Optimization of HTL reactor liquid hourly space velocity (LHSV)
- Optimization of fuel yield from hydrotreating
- Combined large and small HTL scales specific to regions (e.g., metropolitan and suburban plants)

Combined improvements believed to be achievable in these areas can potentially reduce the minimum selling price of biocrude and final upgraded fuel by about 50%. Further improvements may be possible through recovery of higher value components from the HTL aqueous phase, as being investigated under separate PNNL projects. Upgrading the biocrude at an existing petroleum refinery could also reduce the

MFSP, although this option requires further testing to ensure compatibility and mitigation of risks to a refinery. And finally, recycling the HTL aqueous phase product stream back to the headworks of the WWTP (with no catalytic hydrothermal gasification treatment) can significantly reduce cost. This option is uniquely appropriate for application at a water treatment facility but also requires further investigation to determine any technical and economic challenges related to the extra chemical oxygen demand (COD) associated with the recycled water.

Acknowledgments

The authors gratefully acknowledge the support for this research provided by the U.S. Department of Energy through the Bioenergy Technologies Office (BETO). Pacific Northwest National Laboratory is operated for the U.S. Department of Energy by Battelle under Contract DE-AC06-76RL01830. The authors would like to thank the PNNL resource assessment team, Rick Skaggs, Andre Coleman and Tim Seiple, for developing estimates of sludge production that helped form the initial scale basis of this analysis. We would also like to thank Jeff Moeller of the Water Environment and Reuse Foundation and the entire LIFT6W16 Project team and steering committee for their helpful guidance and feedback on the refinement of key assumptions regarding scale, sludge disposal cost and other aspects of process configuration at a wastewater treatment plant.

Abbreviations

AD	Anaerobic Digestion
AFDW	Ash-Free Dry Weight
BETO	Bioenergy Technologies Office
BPSD	Barrels Per Stream Day
CHG	Catalytic Hydrothermal Gasification
COD	Chemical Oxygen Demand
CSTR	Continuous Stirred Tank Reactor
CWNS	Clean Watershed Needs Survey
EPA	Environmental Protection Agency
GCMS	Gas Chromatography Mass Spectrometry
gge	gasoline gallon equivalent
HHV	Higher Heating Value
HTL	Hydrothermal Liquefaction
LHSV	Liquid Hourly Space Velocity
MFSP	Minimum Fuel Selling Price
PFR	Plug Flow Reactor
PNNL	Pacific Northwest National Laboratory
TAN	Total Acid Number
TCI	Total Capital Investment
TEA	Techno-Economic Analysis
WERF	Water Environment and Reuse Foundation
WHSV	Weight Hourly Space Velocity
WWTP	Waste Water Treatment Plant

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Introduction

Every year in the U.S., approximately 11 trillion gallons of municipal wastewater are treated, generating about 7 million dry U.S. tons of sewage sludge (Mateo-Sagasta *et al.* 2015). Sludge management and disposal accounts for 45-65% of the total wastewater treatment plant (WWTP) operating expenses (Nowak 2006; Applied CleanTech 2014; Gray 2010). Sludge management costs from the literature vary widely, for example, California pays in the range of $5.40-$89.50/wet ton, with an average of $52.29/wet ton (SCAP 2013). Wastewater treatment produces sludge (wet solids) as a residual of the primary and secondary treatment processes. According to the EPA's Clean Watershed Needs Survey (CWNS), approximately 84% of municipal wastewater treatment facilities have both primary and secondary treatment included in their process (EPA 2016). The most common methods that WWTPs use to manage their sludge include stabilization/treatment with anaerobic digestion (AD), landfill disposal, and incineration. The AD process produces biogas, which is used for onsite heat, and biosolids, which can be used as fertilizer on agricultural land. The type of crop to which biosolids may be applied depends on their classification as either Class A or B biosolids, which is determined according to the temperature and residence time of the digestion process. Land application of biosolids provides a beneficial use for this waste stream, but in some areas, faces the challenge of public concern over health risks (SCAP 2013). Whatever the option, sludge management is costly and some options, such as landfilling, provide no added benefit. Production of fuel via hydrothermal liquefaction (HTL) could provide an economically favorable alternative to AD and other existing sludge management practices. The purpose of this study is to provide a preliminary techno-economic analysis for this strategy, including sensitivity analyses around key technical and economic assumptions for the conversion plant.

1.0 Techno-Economic Analysis Approach

The approach to developing conversion process techno-economics is similar to that employed in previous reports produced for the Bioenergy Technologies Office (BETO) [Dutta *et al.* 2011, Humbird *et al.* 2011, Jones *et al.* 2013, Jones *et al.* 2014]. Process flow diagrams and models are based on experimental results from completed and ongoing research, as well as information from commercial vendors for mature and similar technologies. To assure consistency across all biomass conversion pathways, BETO developed a set of economic assumptions that are used for all technoeconomic analyses (see Appendix) and are documented in BETO's Multi-Year Program Plan (DOE 2016). An important aspect of these assumptions is that they reflect an "n^{th} plant" design. The n^{th} plant design assumes that several plants have already been built and operated and therefore does not account for additional first-of-a-kind plant costs. All costs presented are in 2011 dollars.

2.0 Process Design and Assumptions

2.1 Process Overview

The design and cost basis is largely based on previous work for algae HTL and biocrude upgrading (Jones *et al* 2014). A simplified block diagram of the overall HTL and biocrude upgrading process configuration is shown in Figure 1. The HTL facility is co-located with the WWTP and produces biocrude and an aqueous stream containing about 1.25% carbon. Catalytic hydrothermal gasification (CHG) is used to treat the aqueous phase and recover energy from this stream prior to discharge. The biocrude is transported by tanker truck at a cost of $0.10/gge (Sheppard 2011) to a centralized upgrading plant where it is converted to final fuels. Natural gas is used at the HTL and upgrading facilities for process heat and hydrogen, respectively. All capital equipment costs for the HTL plant and the upgrading facility are scaled on values used in the algae HTL design case (Jones *et al.* 2014). The HTL and CHG equipment costs are scaled on costs originally obtained for a much larger plant scale of 2,200 dry ton/day (Knorr 2013). Future work will include revisiting these estimates and updating with costs more appropriate at this comparatively small scale.

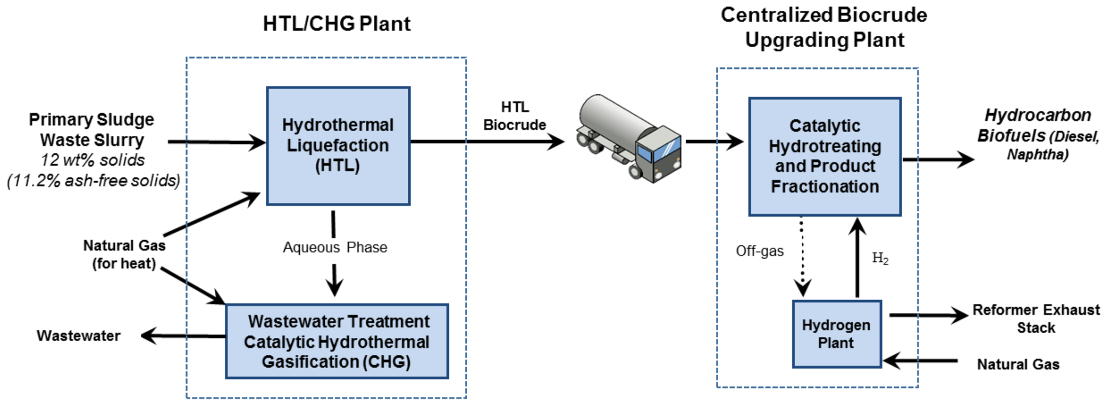

Figure 1. Simplified block diagram for the HTL/CHG plant and centralized biocrude upgrading plant.

2.2 Feedstock and Plant Scale

In FY15, PNNL conducted experimental testing of HTL on municipal WWTP sludge waste, CHG of the HTL aqueous phase, and upgrading of the HTL biocrude. The sludge was provided by the Annacis Island WWTP operated by MetroVancouver in Vancouver, B.C. The Annacis Island water treatment process is shown in Figure 2. The process produces primary and secondary sludge solids that are then processed in thermophilic anaerobic digesters, resulting in Class A biosolids. Class A biosolids is the designation for sewage solids that meet U.S. EPA guidelines for land application with no restrictions (EPA 2015b). Experimental testing of HTL and biocrude upgrading included primary sludge, secondary sludge, and biosolids resulting from tertiary treatment. Data for primary sludge was used in the process modeling for this analysis. The primary sludge resulted in the highest biocrude yields as compared to the secondary and biosolid samples. The comprehensive data set, analysis, and validation from the experimental work for all sludge streams tested will be published separately in a report to be issued by the WERF.

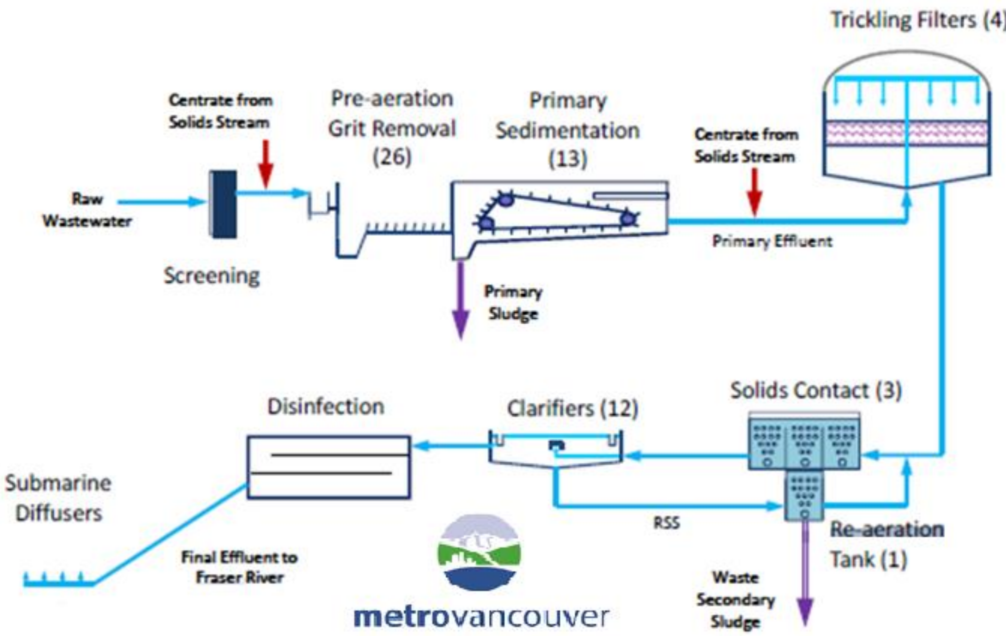

Figure 2. Simplified flow diagram of Annacis Island WWTP (Metro Vancouver 2015) showing primary and secondary sludge generation that is then treated with thermophilic anaerobic digestion.

The modeled HTL plant processes 100 dry ton/day (92.4 ton/day dry, ash-free basis) of sludge in a slurry (water + solids) containing 12% total solids (11.2% ash-free solids). For perspective, a WWTP producing 100 dry ton/day of primary and secondary sludge mixture would treat roughly 133 million gal/day of wastewater (Shammas and Wang 2008) and would serve an approximate population of 1.7 million (EPA 2015a). A feedstock credit of $-16.20/wet ton ($-46/dry ton at 35% solids; $-50/ton dry, ash-free basis) is included in the analysis to account for the fact that WWTPs currently pay to have their sludge disposed. Biocrude product is transported at a cost of $0.10/gge (Sheppard 2011) to a centralized upgrading plant up to 100 miles from the HTL plant. The upgrading plant receives biocrude from 10 HTL plants and produces 2,020 BPSD of final fuel. The chosen plant scales are based upon initial estimates of sludge generation from EPA CWNS data (EPA 2015a) and a rough estimate of what the potential sludge availability might be within a 100-mile radius. In addition, we received valuable feedback from the wastewater treatment industry as part of the WERF collaboration that helped form the basis for the selected plant scales, as well as the assumed feedstock credit (current sludge disposal cost). For comparison, the upgrading plant scale is about 40% of other BETO design cases of ~5,000 BPSD (Jones *et al.* 2014, Jones *et al.* 2013) and only 4% of the average scale for gasoline and diesel production at U.S. refineries of about 50,000 BPSD (EIA 2015). Sensitivity analysis is conducted to investigate the effect of both scale and sludge credit on the minimum fuel selling price (MFSP) of biocrude and final fuel.

Table 1 lists the primary sludge composition data used in the AspenPlus model. The original sample received from the WWTP required dilution with water to 88% moisture content. This level of solids was chosen to guarantee problem-free pumping for these initial tests and was not optimized for economical performance. It is assumed that the sludge is dewatered at the WWTP to the level needed for the HTL process. Costs for dewatering are not included in the analysis, and should be considered in future refinements of the model.

Table 1. Primary sludge elemental composition and ash content.

Primary Sludge Characteristics	Experimental Data Used for Model Basis (Primary Sludge, WERF 02)	
Component	Wt%	Wt% ash free
C	47.8	51.9
H	6.5	7.1
O	33.6	36.5
N	3.6	4.0
S	0.5	0.5
ash	7.5	
P	0.7	
HHV BTU/lb [(a)]		9,589
H:C Ratio (mole)	1.62	

(a) Calculated by the Boie Equation: HHV (Btu/lb) = (151.2 C + 499.77 H +45.0 S -47.7 O + 27 N) *100 - 189.0

2.3 Hydrothermal Liquefaction

The HTL section of the plant is shown in Figure 1. As described previously for the algae HTL process (Jones *et al.* 2014), the slurry feed (sludge + water) is pumped and preheated to the reactor conditions of 2926 psia and 622°F (339°C). The reactor effluent is composed of an organic biocrude phase, a separate aqueous phase, and small amounts of solids and gases. Solids are filtered and the biocrude, aqueous and gas phases are cooled and then separated. The biocrude is then shipped to the upgrading facility, while the aqueous phase is treated by catalytic hydrothermal gasification (CHG) and the off-gas used for process heat. Additional natural gas is needed to provide enough heat for the HTL and CHG processes. The remaining heat is used to produce steam for a steam driver. It is assumed that the solids are disposed of in a landfill, however, it may be possible to sell them for beneficial reuse (e.g., fertilizer). Table 2 gives the HTL reactor conditions and product results from the experimental data and from the model.

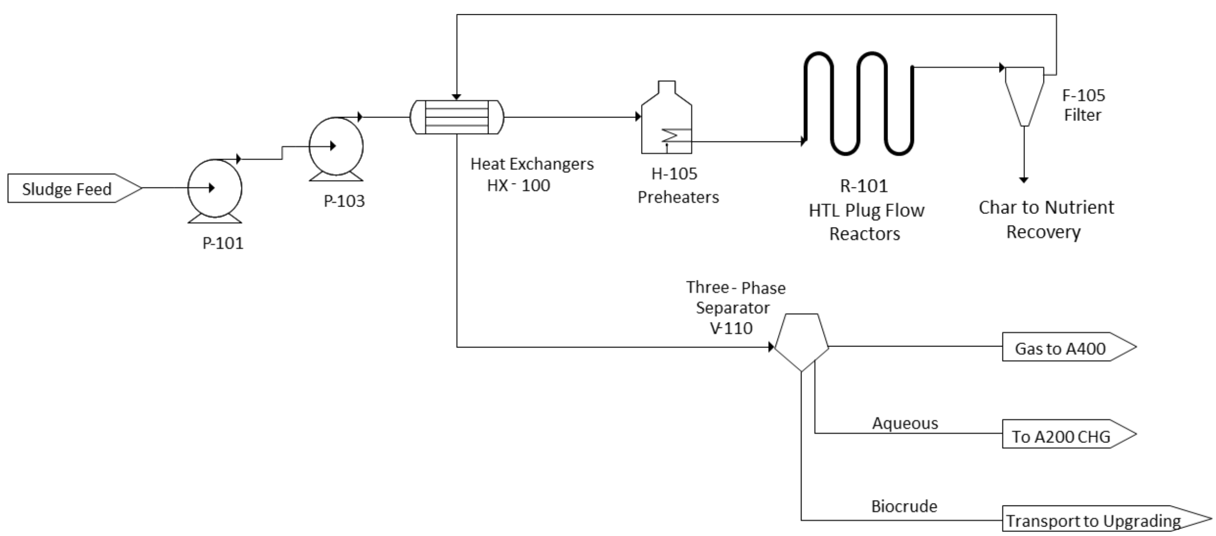

Figure 3. HTL process diagram.

An important note regarding this preliminary analysis is that the biocrude chemical constituents chosen for inclusion in the sludge model are identical to those used in the algae model. Only the amounts of each compound were modified to match the mass balance data from the sludge experimental testing. It is recommended that any future work should include a more thorough analysis of the sludge biocrude GCMS data and incorporation of any needed changes to the modeled biocrude chemical component list.

Table 2. Primary sludge HTL experimental results and model assumptions.

Operating Conditions and Results	Experimental Results (WERF 02 1240)	Aspen Model
Temperature, °F (°C)	642 (339)	642 (339)
Pressure, psia	2926	2926
Feed solids, wt%		
Ash included	11.9%	12.0%
Ash free basis	11.0%	11.2%
LHSV, vol./h per vol. reactor	2.1 Hybrid PFR-CSTR	2 PFR
Equivalent residence time, minutes	29	30
Product yields (dry, ash free sludge), wt%		
Oil	40.2%	40.6%[a]
Aqueous	34.6%	34.2%
Gas	21.6%	22.0%
Solids	3.6%	3.2%
HTL dry oil analysis, wt%		
C	75.7%	76.0%
H	10.2%	10.3%
O	8.9%	8.9%
N	4.2%	4.1%
S	0.6%	0.6%
P	0.0	Not modeled[b]
Ash	0.29%	0.0%
HTL dry oil H:C Ratio	1.61	1.61
HTL oil moisture, wt%	10.2 wt%	10.2 wt%
HTL oil wet density	1.00	1.0
HTL oil dry HHV, Btu/lb (MJ/kg)	16,165 (37.6)	16,251 (37.8)
Aqueous phase COD (mg/L)	41,200	40,300
Aqueous phase density (g/ml)	1.0	0.995 Aspen est.

(a) Biocrude yield after separations is 39.8%.
(b) Phosphorus partitioning is not directly modeled in Aspen because of the small quantity, most of which reports to the solid phase.

2.4 HTL Aqueous Phase Treatment by Catalytic Hydrothermal Gasification (CHG)

As shown in Figure 4, the aqueous phase from HTL is treated with CHG to recover energy from the dissolved organics and to reduce the chemical oxygen demand (COD) of the water for subsequent disposal or reuse. The COD in the water is 99.9% converted in the CHG process and the produced gas is used for heat in the HTL and CHG areas. It is assumed that the treated CHG water is returned to the headwaters of the wastewater treatment plant. Table 3 lists the reactor conditions and product results from the CHG experimental data and from the model.

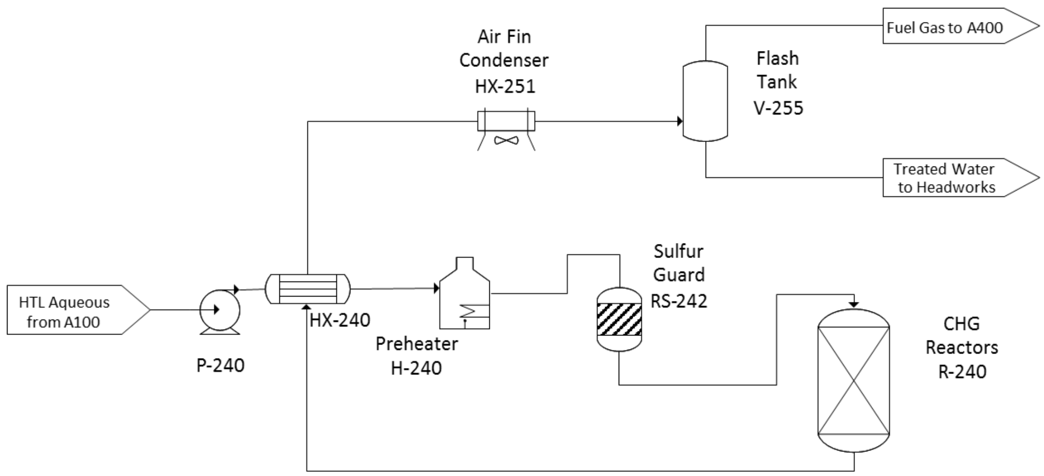

Figure 4. CHG process diagram.

Table 3. Primary sludge HTL aqueous phase CHG experimental results and model assumptions.

Component	Experimental (WERF 02)	Model
Guard Bed	Raney nickel	Raney nickel
Temperature, °F (°C)	653 (345)	662 (350)
Pressure, psia	3010±30	3079
Catalyst	7.8 wt% Ru/C	7.8% Ru/C
LHSV, vol./hour per vol. catalyst	2.0	2.0
WHSV, wt./hr per wt. catalyst	3.7	3.7
% COD conversion	99.9%	99.9%
% Carbon to gas [(a)]	64%	64%
Gas analysis, volume %		
CO_2	22.3%	20.9%
H_2	1.2%	1.5%
CH_4	73.8%	71.7%
C_{2+}	0.5%	1.1%
N_2+O_2	2.0%	--
Water	--	4.8%
COD of CHG treated water (mg/L)	12	Low, discharge to WWTP headworks

(a) Note that the remaining converted carbon is dissolved bicarbonate

2.5 Sludge HTL Oil Upgrading

The HTL biocrude is transported from the WWTP to a centralized upgrading facility and is supplied to the plant at 26 psia and 110°F. The upgrading process is shown in Figure 5. It is then pumped to 1540 psia, mixed with compressed hydrogen, and preheated to the hydrotreater reactor temperature of 752°F (400°C). Hydrogen is produced onsite via steam reforming of the upgrading offgas and purchased natural gas. During the hydrotreating process, biocrude oxygen is converted to CO_2 and water, nitrogen is converted to ammonia, and sulfur is converted to hydrogen sulfide. The reactor effluent is cooled to condense the produced water and hydrocarbons, the latter of which is then fractionated into lights, naphtha, diesel and heavy oil. The hydrotreater reactor conditions and product results from the experimental data and the model are listed in Table 4.

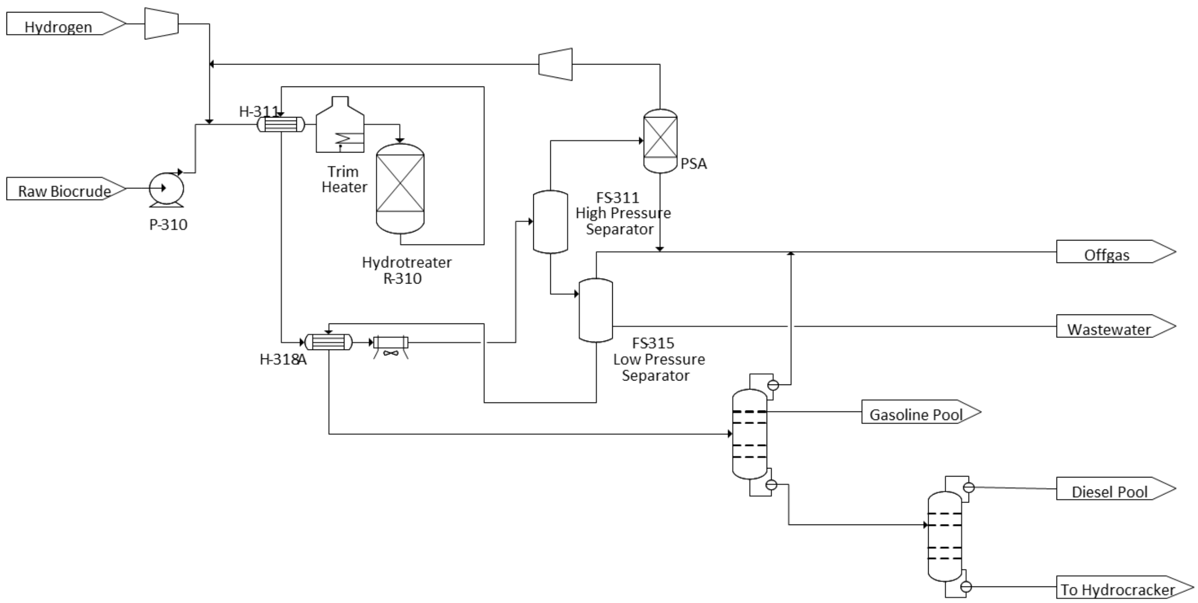

Figure 5. HTL biocrude hydrotreating process diagram.

Table 4. Primary sludge biocrude hydrotreating experimental results and model assumptions.

Component	Experimental (WERF 02-19)	Model
Temperature, °F (°C)	752 (400)	752 (400)
Pressure, psia	1540	1515
Catalyst	CoMo/alumina-F	CoMo/alumina
Sulfided?	Yes	Purchased presulfided
LHSV, vol./hour per vol. catalyst	0.21	0.25
WHSV, wt./hr per wt. catalyst	0.37	0.30
HTL oil feed rate, lb/h (g/h)	0.009 (4.01)	Commercial scale
Total continuous run time, hours	31 (total run) (19-31 hr sample)	Not applicable
Chemical H_2 consumption, wt/wt raw HTL biocrude (wet)	0.044	0.045
Product yields, lb/lb dry biocrude (vol/vol wet biocrude)		
Hydrotreated oil	0.767 (0.841)	0.786 (0.857)[a]
Aqueous phase	0.182 (0.158)	0.159 (0.161)
Gas	0.064	0.100
Product oil, wt%		
C	84.6%	85.8%
H	14.2%	13.9%
O	1.2%	<0.25%
N	0.04%	0.04%
S	Not reported	0.0%
Aqueous carbon, wt%	Not reported	0.02%
Gas analysis, volume%		
CO_2, CO	0%	0%
CH_4	31%	44%
C_2+	69%	50%
NH_3	Not measured	6%
TAN, feed (product)	65 (<0.01)	Not calculated
Viscosity@40 °C, cSt, feed (product)	571 (2.2)	Not calculated

Component	Experimental (WERF 02-19)	Model
Density@40 °C, g/ml, feed (product)	1 (0.794)	Aspen: (0.79)

(a) Oil yield after separations is 0.76 lb/lb dry biocrude.

Again, it should be noted that the chemical compounds used in the sludge biocrude upgrading model are identical to those used in the algae biocrude upgrading model. Only the amounts of each compound were adjusted to match the experimental mass balance and simulated distillation data for the hydrotreated product from the sludge biocrude. Figure 6 shows the boiling point curves from simulated distillation (D2887) for the hydrotreated biocrude product from experimental testing and the modelled hydrotreated product. As illustrated by the similarity between distillation curves for sludge and algae products, the assumption to use the same compounds in the sludge model as the algae model appears to be reasonable.

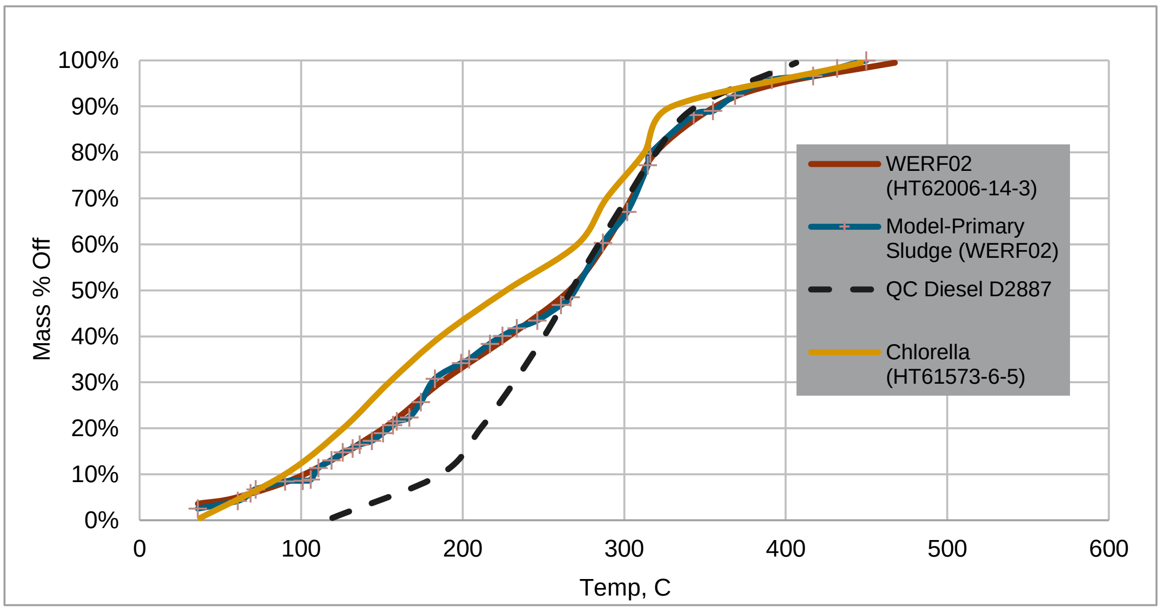

Figure 6. Boiling point curve (ASTM D2887) for product from sludge HTL biocrude hydrotreating.

The heavy oil from hydrotreating is assumed to be hydrocracked into additional gasoline and diesel range fuel. No experimental data are yet available for hydrocracking of hydrotreated HTL biocrude, so it is assumed that the heavy fraction is processed similar to petroleum operations. The hydrocracking assumptions for the model are given in Table 5.

Table 5. Hydrocracking model assumptions.

Process	Basis	Assumptions
Hydrocracking heavier than diesel portion of hydrotreated HTL oil	No experimental data, assumed to be similar to conventional hydrocrackers Temperature: 734 °F (390 °C) Pressure: 1010 psia	H_2 chemical consumption: 0.004 wt/wt heavy oil Product breakdown: Gas (excluding excess H_2); 3 wt% Liquid fuels: 96 wt% Aqueous: 1 wt%

3.0 Process Economics and Sensitivity Analysis

The MFSP for the sludge HTL biocrude production plant and the centralized biocrude upgrading plant is determined using a discounted cash flow rate of return analysis. The summary economics and performance for the HTL plant and the upgrading plant are presented in the following sections. Sensitivity analysis around key technical and economic assumptions is also presented.

3.1 Sludge HTL Plant

Table 6 gives the overall process economics for the base case sludge HTL plant. The plant processes 92.4 ton/day dry, ash-free basis primary sludge and produces 3 million gal/yr (234 BPSD) of biocrude at a MFSP of $3.8/gge ($3.7/gal). The total capital investment for the plant is $58 million, with the HTL and CHG sections contributing 64% and 29%, respectively.

Figure 7 shows the results of sensitivity analysis around the primary economic and technical modeling assumptions. A wide range of plant scale of 20 to 950 dry ton/day (19 to 462 dry, ash-free ton/day) is selected to include the largest plants in the U.S.. This range represents about 56% of the total primary and secondary sludge production estimated from the CWNS data. The HTL biocrude yield sensitivity range was chosen based on that achieved in experimental testing of primary, secondary and biosolids sludge, as well as what the researchers feel is attainable with future research advancements. The ash-free dry weight (AFDW) yields attained in the laboratory are 32-40% for primary sludge, 25% for secondary sludge, and 31-35% for biosolids. A 10% improvement in yield is thought to be achievable for the HTL of primary sludge. Therefore, a range of 25-45% is chosen for the sensitivity analysis. The base case sludge feedstock credit of $-50/ton AFDW ($-16.20/wet ton) is an initial approximation of what WWTPs currently pay for sludge/biosolids disposal or land application. A brief literature review indicates that municipalities pay as much as $125/dry ton for disposal of sludge wastes (EPA 1995) and feedback from the WERF project participants indicate costs can be much higher in certain areas of the country. For slurry solids content, a maximum of 20% total solids is thought to be possible while still enabling effective pumping. Given that the HTL plant is co-located with the WWTP, a sensitivity case is included where the HTL water is recycled directly to the headworks, mitigating the need for CHG. Note that the price for this case assumes no additional incurred cost associated with sending this water back to the WWTP headworks. This assumption will be revisited in future refinements of the analysis.

As shown in Figure 7, several technical parameters have a significant impact on the biocrude MFSP, including plant scale, yield, slurry solids content, whether or not CHG is used, and sludge credit price. Increased feed solids loading reduces the total mass flow to the plant (for constant dry ton/day sludge fed) and effectly shrinks all equipment and associated capital costs, as well as operating costs. Higher solids loadings have also been shown to increase the amount of carbon reporting to the biocrude phase during HTL, resulting in additional cost benefit. Increasing LHSV only reduces the capital cost of the HTL reactor and therefore is less impactful than solids loading, but still important for optimizing plant economics. The economic assumptions that most significantly affect MFSP are internal rate of return, total project investment and HTL section capital cost estimates.

Table 6. Base case summary economics and performance for sludge HTL/CHG plant.

Biocrude from Sludge Hydrothermal Liquefaction and Catalytic Hydrothermal Gasification

Primary Wastewater Treatment Sludge (12 wt% total solids)

Sludge Credit/Cost: -$50 $/U.S. ton sludge (dry, ash free basis)

Minimum Selling Price - Gasoline Gallon Equivalent	**$3.8**	**$/gge**
Minimum Selling Price	$3.7	$/gallon
Bio-oil	3	million gge/yr
	369,265	million Btu/yr
	104.3	gge/US ton AFDW sludge
	12	million Btu/US ton AFDW sludge
Internal Rate of Return (After-Tax)	10%	
Equity Percent of Total Investment	40%	
Cost Year	2011	

CAPITAL COSTS

HTL Oil Production	$20,000,000	64%
CHG Water Treatment	$9,100,000	29%
Steam Cycle	$600,000	2%
Balance of Plant	$1,400,000	5%
Total Installed Capital Cost	$31,100,000	100%
Building, site development, add'l piping	$4,400,000	
Indirect Costs	$19,600,000	
Working Capital	$2,800,000	
Land (plant located at WWTP)	$0	
Total Capital Investment (TCI)	$57,900,000	
Installed Capital per Annual GGE Bio-oil	$10	
TCI per Annual GGE Bio-oil	$18	
Loan Rate	8.0%	
Term (years)	10	
Capital Charge Factor (computed)	0.136	

MANUFACTURING COSTS

Plant Hours per year 7920

Feed rate, dry ash-free sludge 92.4 ton/day

	$/gge	$/year
Sludge feedstock cost, dry ash-fre	-0.48	-$1,500,000
Natural Gas	0.28	$900,000
Catalysts & Chemicals	0.30	$900,000
Waste Disposal	0.04	$100,000
Electricity and other utilities	0.07	$200,000
Fixed Costs	1.07	$3,400,000
Capital Depreciation	0.57	$1,800,000
Average Income Tax	0.33	$1,000,000
Average Return on Investment	1.61	$5,100,000
	3.8	

PERFORMANCE

Total Electricity Usage (KW)	371
Electricity Produced Onsite (KW)	469
Electricity Purchased from Grid (KW)	99
Electricity Sold to Grid (KW)	0
Net Electricity Use (KWh/gge product)	0.9
Input Energy (NG+Power) / Product Energy	44%
Overall Carbon Efficiency to Biocrude	
On sludge + natural gas	50%
On sludge	58%

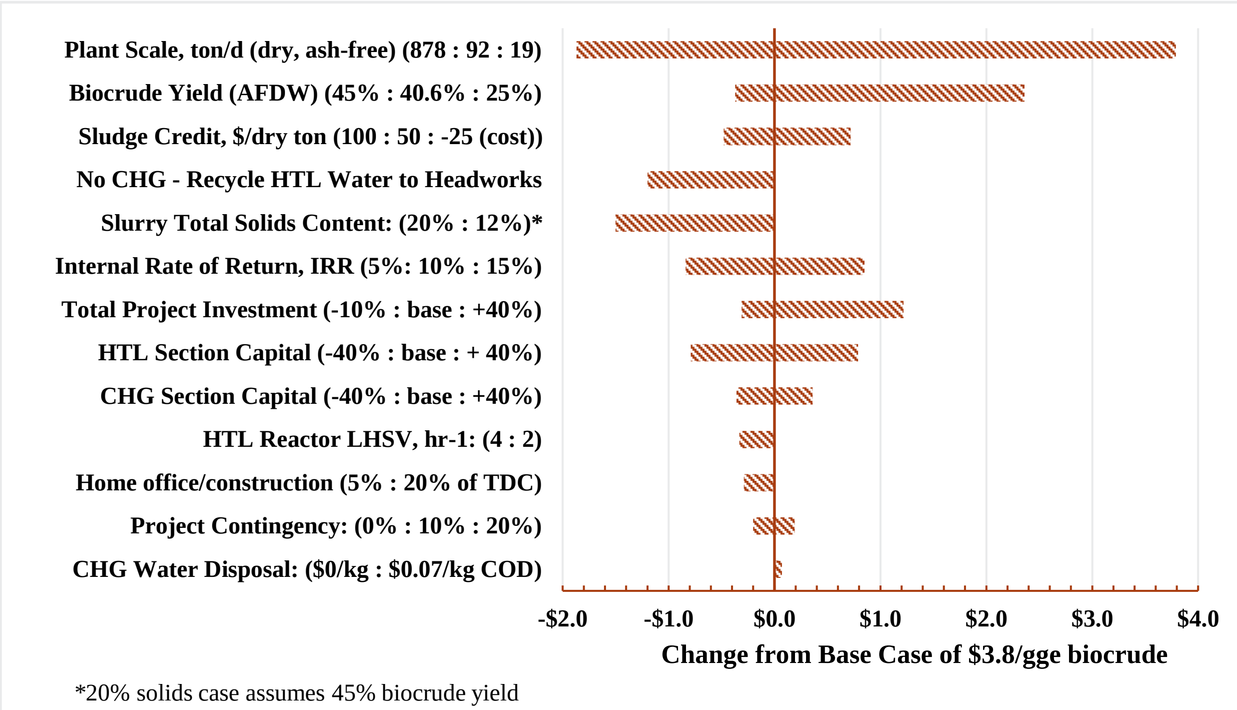

Figure 7. Sensitivity analysis for HTL plant processing waste sludge.

Given that plant scale and sludge disposal costs are highly variable and uncertain at this time, Figure 8 shows more detail on the impact of these factors on biocrude price. Using the base case assumptions, plant scales below about 92 ton/day dry, ash-free sludge (100 dry ton/day total solids) capacity do not appear economically feasible, even with a large sludge credit. However, smaller scales may be feasible when yields, solids loadings and other process parameters are optimized. In addition, upgraders combining biocrude from plants of varying size (e.g., a large metropolitan plant and several smaller ones in the suburbs) is more likely and could help improve economics. For example, the weight-averaged biocrude price for an upgrading plant that processes biocrude from two 230-ton/day, three 92-ton/day, and four 46-ton/day HTL plants is about 25 cents less than the base case ($3.5/gge), as shown in Table 7.

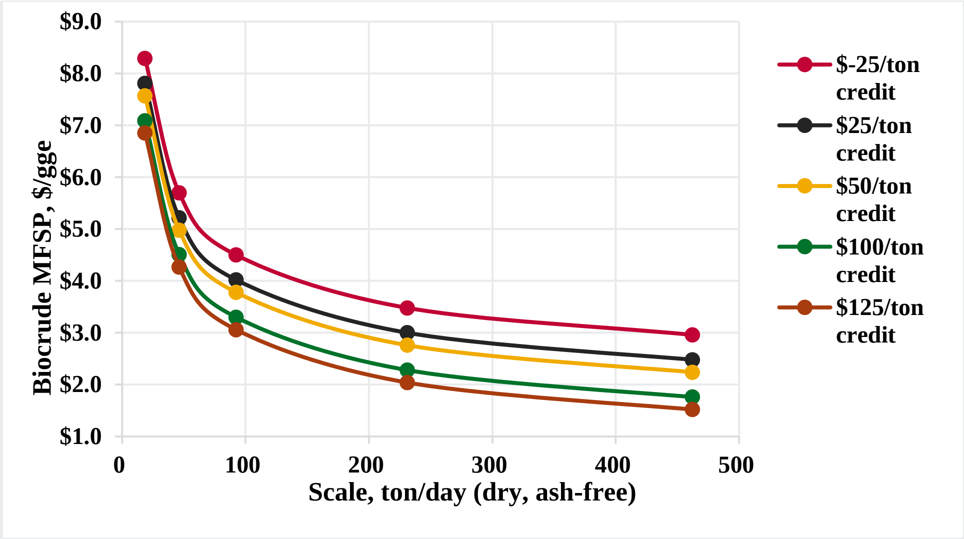

Figure 8. Effect of plant scale and sludge credit on biocrude MFSP.

Table 7. Overall biocrude price for an upgrader using feed from variable HTL plant sizes.

Ton/day (dry, ash-free)	Number of Plants	Biocrude Price ($/gge)
230	2	2.79
92	3	3.78
46	4	4.95
Weight Averaged Price:		3.52 (3.62 w/ shipping)

The base case price of $3.8/gge biocrude is based on initial proof-of-concept testing of sludge and as such, does not represent an optimized system. Optimization of key technical parameters identified in the sensitivity analysis can help reduce MFSP relative to the base case. For example, improvements thought to be achievable in biocrude yield, feed solids content, and HTL reactor LHSV, along with combined scale advantages, could potentially reduce the biocrude price by about half, as illustrated in Figure 9. Further bench scale and pilot scale testing is needed to demonstrate the feasibility of these advancements.

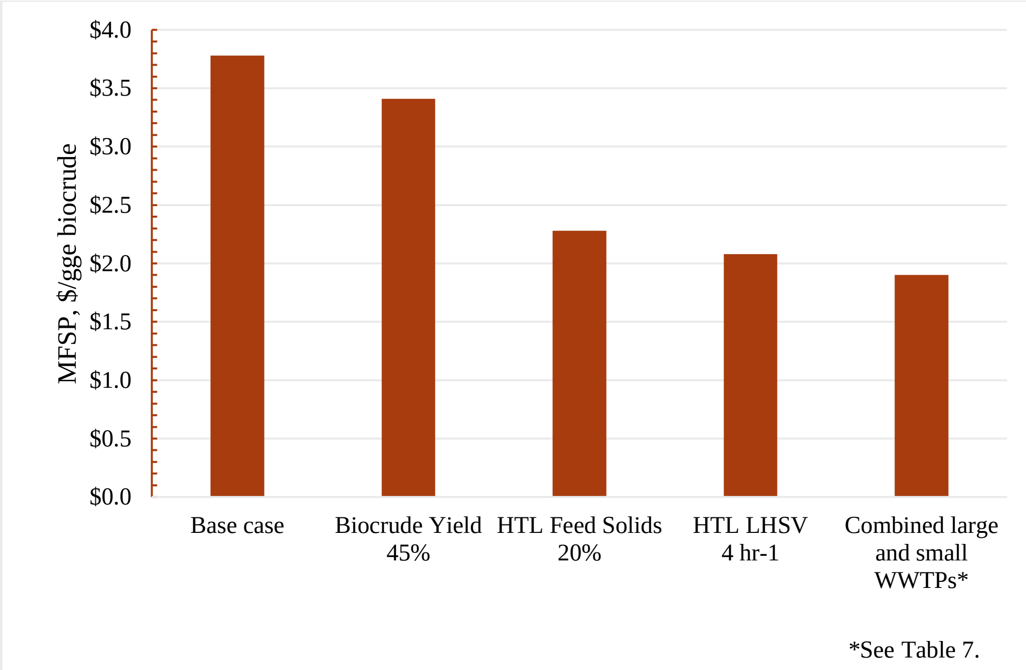

Figure 9. Potential overall reduction in biocrude price with combined process improvements.

3.2 Sludge Biocrude Upgrading Plant

Table 8 gives the summary economics for the base case HTL sludge biocrude upgrading plant. The plant produces 2,020 BPSD of naphtha and diesel fuel at a MFSP of $4.9/gge and a total capital investment of $79 million. Figure 10 shows the sensitivity of final upgraded fuel MFSP to several economic and technical parameters for the biocrude upgrading plant model. Biocrude feedstock price was varied widely according to the price range resulting from the HTL plant sensitivity analysis. The range for hydrotreating oil yield is based on that achieved in the experimental testing. A maximum upgraded oil yield of 0.93 lb dry oil/lb dry biocrude was achieved for biocrude from HTL of biosolids (0.90 lb/lb was chosen) and a minimum of 0.70 lb dry oil/lb dry biocrude was chosen as a conservative lower bound. Plant scale was varied from 1,000 to 5,000 BPSD final fuel. For plant scales above the base case, it is likely that a biocrude supply draw radius larger than the base case of 100 miles would be necessary. A sensitivity case where the biocrude is upgraded at an existing petroleum refinery (TCI=0) is also considered. As shown in Figure 10, the most impactful sensitivity parameters affecting the final fuel MFSP are the price of the biocrude, hydrotreated oil yield, plant scale and upgrading at an existing refinery. When potential process optimizations in the HTL process are combined with optimization of the fuel yield from hydrotreating (0.90 lb/lb dry biocrude), the overall final fuel MFSP can be reduced by about 50% relative to the base case, as illustrated in Figure 11.

Table 8. Base case summary economics for sludge HTL biocrude upgrading.

Liquid Fuels from Sludge HTL Biocrude Upgrading

Biocrude Feedstock Cost:	**$3.9**	**$/gge** (includes $0.10/gge transport cost)	
Minimum Fuel Selling Price (MFSP)	**$4.9**	**$/gge**	
Diesel Fuel Selling Price	$5.3	$/gal	
Naphtha Fuel Selling Price	$4.9	$/gal	

Naphtha	Diesel	Total		wt% in total fuel
573	1446	**2,000**	BPSD	**26.8%**
0.9	2.5	3	trillion Btu/yr, LHV basis	**73.2%**
		29	million gge/yr	
0.25	0.68	0.93	gge fuel/gge bio-oil	

Internal Rate of Return (After-Tax)	10%
Equity Percent of Total Investment	40%
Cost Year	2011

CAPITAL COSTS

Hydrotreating	$20,000,000	47%
Hydrogen Plant	$17,500,000	41%
Steam cycle	$900,000	2%
Balance of Plant	$4,400,000	10%
Total Installed Capital Cost	$42,800,000	100%
Building, site development, add'l piping	$5,200,000	
Indirect Costs	$26,300,000	
Working Capital	$3,700,000	
Land (included in feedstock cost)	$1,500,000	
Total Capital Investment (TCI)	$79,400,000	
Installed Capital per Annual GGE Fuel	$1.452	
TCI per Annual GGE Fuel	$2.694	
Loan Rate	8.0%	
Term (years)	10	
Capital Charge Factor (computed)	2.733	

MANUFACTURING COSTS

Plant Hours per year	7920	
Biocrude feed rate	32	mmgal/y

	$/gge	$/year
Biocrude	4.19	$123,400,000
Natural Gas	0.05	$1,600,000
Catalysts & Chemicals	0.04	$1,300,000
Waste Disposal	0.00	$100,000
Electricity and other utilities	0.03	$800,000
Fixed Costs	0.24	$6,900,000
Capital Depreciation	0.00	$2,500,000
Average Income Tax	0.05	$29,000,000
Average Return on Investment	0.32	$185,500,000
	4.9	

PERFORMANCE

Total Electricity Usage (KW)	1,448
Electricity Produced Onsite (KW)	1,491
Electricity Purchased from Grid (KW)	43
Net Electricity Use (KWh/gal product)	0.4
Overall Carbon Efficiency (Naphtha + Diesel)	
On biocrude + natural gas	82%
On biocrude	86%

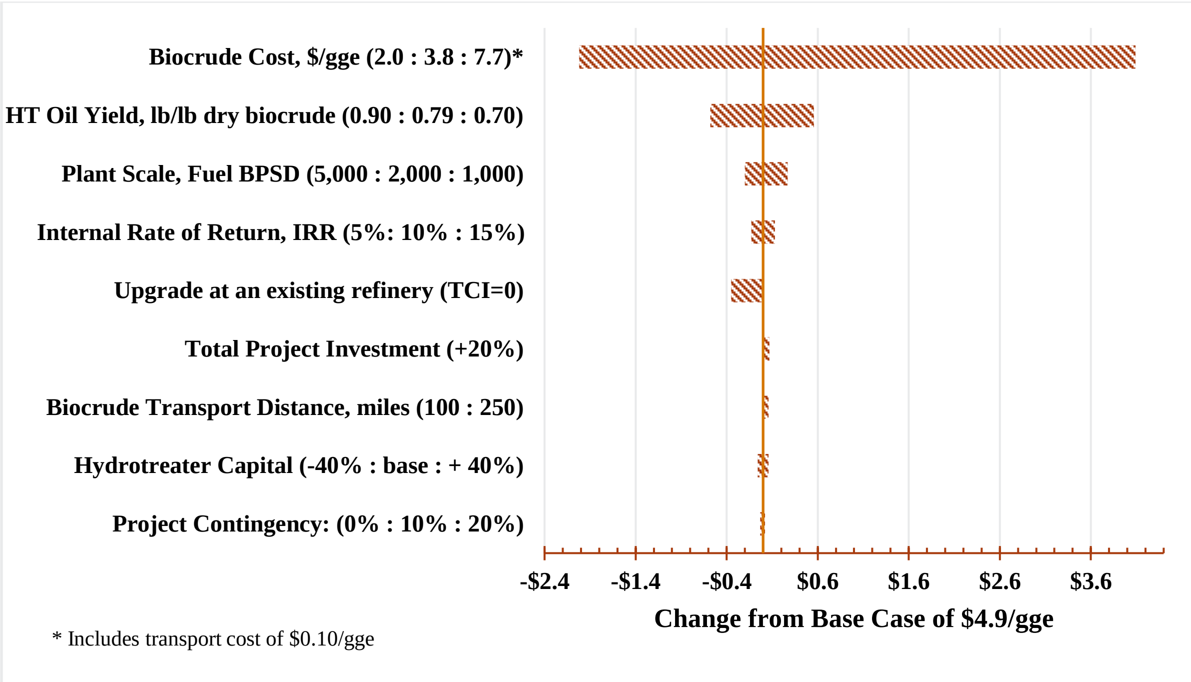

Figure 10. Sensitivity analysis for sludge HTL biocrude upgrading plant.

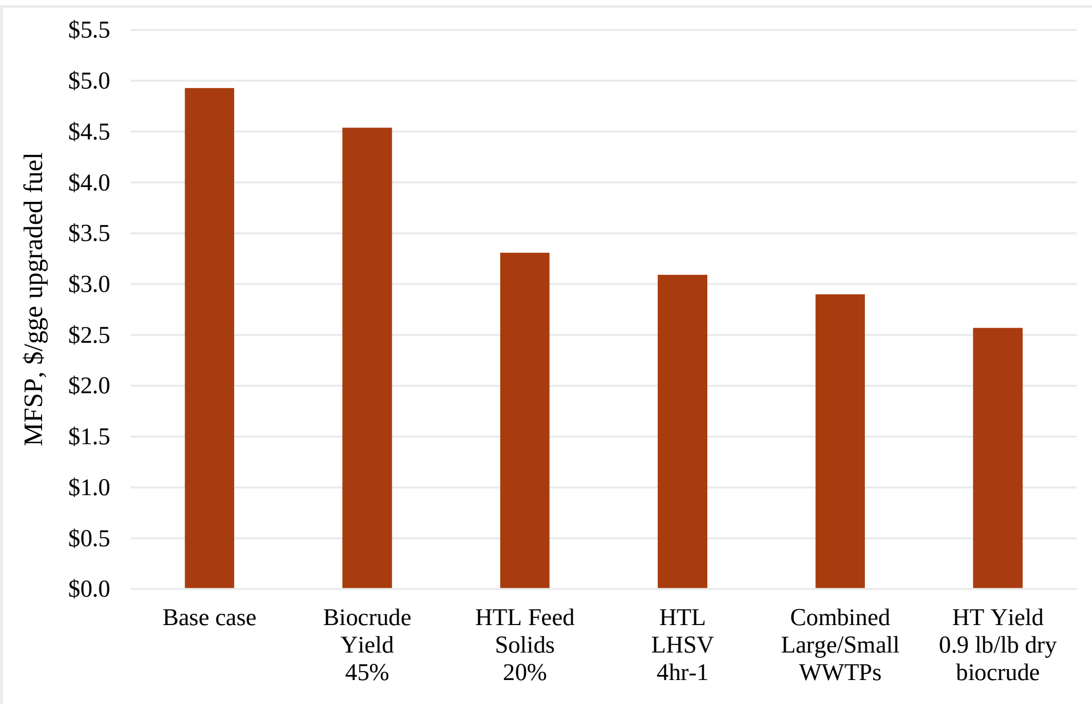

Figure 11. Potential overall reduction in upgraded fuel price with combined improvements.

4.0 Conclusions and Recommendations

Sludge HTL and biocrude upgrading is a viable alternative to AD and other sludge management methods that has the added benefits of producing salable fuel substitute for petroleum diesel and naphtha and reducing overall costs for a municipal WWTP. This analysis provides an initial estimate of the economics of the process and serves as a starting point from which advancements in the technology and refinements to the analysis may be identified and planned. The base case assumptions for a 100-dry ton/day (92.4 dry ton/day ash-free basis) HTL plant and upgrading plant producing 2,020 BPSD final fuel result in MFSPs of $3.8/gge biocrude and $4.9/gge final fuel, respectively. This analysis is based on limited testing, and as such, does not represent an optimized configuration of the process technology. Several areas of potential improvement have been identified:

- Biocrude yield is one of the most important factors driving economics of the HTL plant. A maximum yield of 45% is thought to be achievable, which alone would reduce the base case biocrude price by $0.37/gge. Further testing for optimization of biocrude yield is needed. In addition, as most wastewater treatment plants produce both primary and secondary sludge waste in approximately equal amounts, testing of appropriate ratios of these feeds will help to more realistically model the production plant.
- Increasing feed solids content improves economics through decreased capital costs (smaller equipment size) and increased energy efficiency (less water to heat and pump). Increased feed solids has also been shown to increase the amount of carbon reporting to the biocrude phase during HTL. A maximum 20% solids content with 45% biocrude yield is thought to be possible while still allowing effective pumping through the HTL system, which would reduce the base case biocrude MFSP by $1.50/gge. Further testing is needed to validate HTL performance at this level of solids and to ensure that dewatering and/or mixing of primary and secondary sludges to achieve 20% solids is feasible.
- The base case HTL reactor LHSV is assumed to be 2 hr^{-1} corresponding to the experimental testing conditions. Increasing LHSV from 2 hr^{-1} to 4 hr^{-1} reduces the biocrude MFSP by $0.33/gge from the base case. It is likely that a LHSV of 4 hr^{-1} can be achieved with future research, as similar levels have been accomplished for algae HTL.
- Sensitivity analysis indicates significant economic benefit for a plant where, in lieu of CHG, the HTL aqueous phase is recycled back to the headworks of the WWTP. This case is particularly well-suited for application at a WWTP and results in a $1.20/gge reduction in biocrude price relative to the base case. Further investigation into the technical feasibility and any additional water treatment costs needed for this option is needed to confirm the viability of this option.
- The base case assumes an upgraded biocrude yield of 0.79 lb/lb dry biocrude (based on testing of primary waste), however, yields as high as 0.93 lb/lb dry biocrude were achieved in the testing of biocrude from biosolids sample. An increase in yield to 0.90 lb/lb biocrude reduces the base case final fuel MFSP by $0.58/gge. Further testing is needed on biocrudes from primary, secondary, and biosolids wastes, and combinations thereof, to demonstrate optimized hydrotreated oil yields.
- The base case assumes that the biocrude is transported by tanker truck 100 miles to the upgrading plant at a cost of $0.10/gge biocrude, however, sensitivity analysis shows that larger draw radii that allow for larger upgrading plant scales could benefit economics. In addition, scenarios combining large and small scale WWTPs could result in significantly reduced MFSP. Further work with the resource analysis team is needed to develop regional scenarios in the U.S. that could be beneficial.

- When combined potential improvements are considered in the analysis, fuel price can be reduced by about half relative to the base case. In addition, separate BETO projects are investigating alternative HTL aqueous phase treatment methods that may yield higher-value products compared to methane, which could further improve plant economics. Configurations where the aqueous phase is recycled back to the WWTP headworks directly (without CHG) and/or where upgrading is conducted at an existing petroleum or fats/oils refinery could also provide advantages. Further investigation is needed into the technical feasibility of these options.

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Appendix A

Economic Assumptions

Table A.1. Nth-Plant Assumptions

Assumption Description	Assumed Value
Internal rate of return	10%
Plant financing debt/equity	60% / 40% of total capital investment (TCI)
Plant life	30 years
Income tax rate	35%
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 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% (7,884 operating hours per year)

Table A.2. Cost Factors for Direct and Indirect Costs

Item	% of Total Installed Cost (TIC)
Buildings	1.0%
Site development	9.0%
Additional piping	4.5%
Total Direct Costs (TDC)	15%
Indirect Costs	% of TDC
Prorated expenses	10%
Home office & construction fees	20%
Field expenses	10%
Project contingency	10%
Startup and permits	5%
Total Indirect Costs	55%
Working Capital	5% of FCI (Direct+Indirect Costs)

Appendix B

Preliminary Greenhouse Gas Emissions Analysis

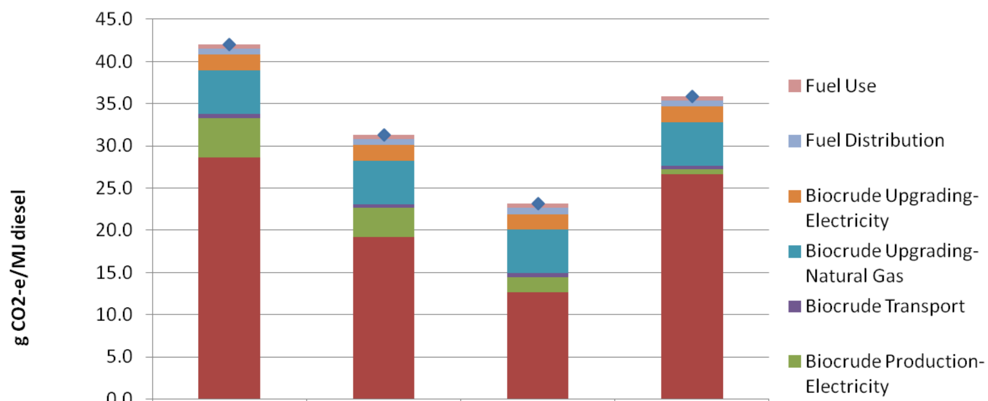
A preliminary life cycle greenhouse gas (GHG) emissions analysis was conducted for fuels from sludge HTL and biocrude upgrading in order to assess the potential for Renewable Fuel Standard (RFS) qualification. Sludge is treated as a waste product that has no feedstock-related GHG emissions. The scope of the analysis includes all stages of the fuel life cycle, including the HTL/CHG process, transport of biocrude to the upgrading plant, the biocrude upgrading process, distribution of the finished fuel, and combustion of fuel in a vehicle. Emissions from biogenic carbon contained in sludge that are emitted during fuel production and combustion are assumed to be balanced by CO_2 absorbed from the atmosphere during plant growth (other than a small amount of biogenic methane emissions from the fuel combustion stage). Any sequestration of carbon that may occur as a result of char production in HTL is not considered here. Any additional dewatering or grinding energy that is necessary for pretreatment of sludge prior to HTL is excluded in this phase of the analysis. Additional energy that may be required for the no-CHG case, such as extra aeration for secondary treatment, is also excluded. Testing is needed to validate and determine the impact and any needed mitigation strategies for the no-CHG option.

Key material and energy flows for biocrude production and upgrading stages of the fuel life cycle come from the Aspen model described in Section 2 and are listed in Table B.1. The produced biocrude is assumed to be transported 100 miles (200 mile roundtrip) to a centralized upgrading facility at 5.9 miles/gal. This mileage value was derived from Sheppard and Nichols (2011) and is equivalent to 4.8 gal/thousand ton-miles (with tanker capacity of 8400 gal), which is consistent with the range given in Davis *et al*. (2016). Emission factors for natural gas and electricity used in conversion, and diesel used for biocrude transport, were adapted from the GREET model (3.27 kg CO_2-e/kg natural gas; 169.987 kg CO_2-e/mmBtu electricity; 3.94 kg CO_2-e/kg diesel). Emissions associated with fuel distribution to the end user, including fuel transportation and operation of storage tanks and fueling stations, are modeled using an EcoInvent (2010) database process ("petrol, unleaded, at regional storage/ RER WITH US ELECTRICITY U"). Emissions of biogenic methane and N_2O from combustion of diesel in a motor vehicle (i.e., the "Fuel Use" stage) are also adapted from GREET (2014). For estimates of GHG reduction relative to petroleum, the results are compared to EPA's 2005 baseline diesel value of 91.94 g CO_2-e/MJ (EPA 2010), which includes the complete life cycle from extraction of crude oil to final combustion in a vehicle engine.

Table B.1. Key material and energy flows for conversion stages

Biocrude Production		Biocrude Upgrading	
Dry sludge feed, ton/hr	100	Biocrude feed, lb/hr	34,130
Natural gas, lb/hr	880	Natural gas, lb/hr	1,585
Electricity, kW	370.9	Electricity, kW	1,448
Biocrude product, lb/hr (mmBtu/hr, LHV)	3,413 (46.6)	Naphtha product, lb/hr (mmBtu/hr, LHV)	6,226 (116)
		Diesel product, lb/hr (mmBtu/hr, LHV)	16,960 (316)

Figure B.1 shows the estimated GHGs emissions associated with finished diesel from HTL of primary sludge and biocrude upgrading. Emissions results are shown for the base case and three cases that assume process improvements are achieved: an increased feed solids case of 15% with the base case biocrude yield of 40%; an increased feed solids case of 20% with increased yield of 45%; and the no-CHG option (with base case solids and yield assumptions). Natural gas used for process heat is the largest contributor of GHGs for the biocrude production stage. Relative to the base case, the increased solids cases result in significantly lower volumetric flowrates and therefore significantly reduced consumption of natural gas and electricity consumed for heating and pumping, respectively. The no-CHG case also results in lower GHGs than the base case, as the natural gas required for CHG process heating is no longer needed. Transportation related emissions are relatively insignificant due to the high energy density of biocrude and relatively short transport distance assumed. Natural gas consumed for the production of hydrogen (via steam reforming) used for hydrotreating and hydrocracking is the primary contributor of GHGs for the upgrading stage. Reductions in GHGs relative to petroleum diesel (91.94 g CO_2-e/MJ, from EPA 2010) are all greater than 50%, indicating fuel produced via this pathway may qualify for advanced or cellulosic biofuel under the RFS. While these estimates serve as an indication of fuel qualification, final determination is made by the Environmental Protection Agency through the formal RFS review process. The analysis will be updated as data comes available regarding potential process advancements, necessary feedstock pretreatment steps, and the impact of the no-CHG configuration at a wastewater treatment plant.



	12% Solids 40%yield (Base Case)	15% Solids 40% yield	20% Solids 45% yield	no CHG (12% solids 40% yield)
Fuel Use	0.5	0.5	0.5	0.5
Fuel Distribution	0.7	0.7	0.7	0.7
Biocrude Upgrading-Electricity	1.8	1.8	1.8	1.8
Biocrude Upgrading-Natural Gas	5.2	5.2	5.2	5.2
Biocrude Transport	0.5	0.5	0.5	0.5
Biocrude Production-Electricity	4.7	3.5	1.8	0.5
Biocrude Production-Natural Gas	28.6	19.2	12.6	26.7
Total	42	31	23	36
GHG Reduction From Petroleum:	54%	66%	75%	61%

Figure B.1. Life cycle GHGs for diesel fuel from HTL of primary sludge and biocrude upgrading.

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