

Supporting Information

# Techno-Economic and Life Cycle Assessment of Wet Waste Hydrothermal Liquefaction with Different Biocrude Upgrading Strategies

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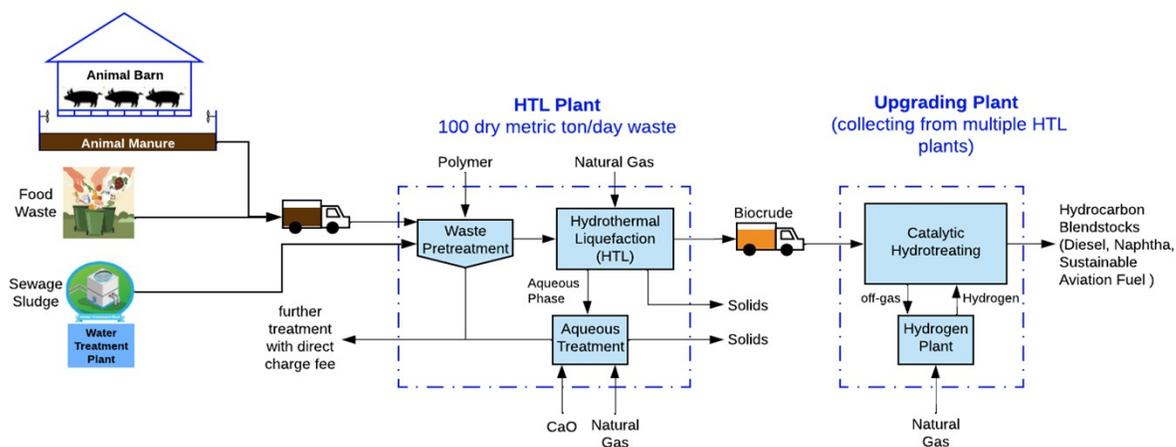
## **S1. Process Flow Diagram and Process Description of Wet Waste Hydrothermal Liquefaction**

As shown in Figure S1, the process begins with wet wastes, including high-moisture-content swine manure collected from a pig farm, food waste from local dining facilities, and sewage sludge from wastewater treatment plants. Prior to processing, the wet waste is dewatered to 25 wt% solids to minimize the capital and operating cost of the hydrothermal liquefaction (HTL) plant. The HTL plant processes 110 dry short tons of wet waste per day and is briefly described below.

The HTL reactor is operated at subcritical water status at high solubility with organic compounds. Before being sent to the reactor, the pretreated wet waste feedstock is pumped to 20 MPa and heated to 350 °C with a heat exchanger and trim heater. The HTL reactor has a shell-and-tube design with slurry in the tube side and hot heating oil in the shell side to maintain isothermal conditions. The organic matter in the feed is converted into biocrude, an aqueous phase with dissolved organic compounds, and some solids and gases. A filter is used to separate the solid product from liquid and gas, and the filtered effluents are cooled for aqueous-biocrude-gas phase separation. The gaseous product combined with natural gas is sent to a burner to generate process heat. The separated aqueous phase is sent to a series of treatment units before recycling back to the wastewater treatment plant. First, it is treated with quicklime to raise the pH to ~11 and then stripped with air to remove ammonia and volatile organic compounds. The removed ammonia and volatile organic compounds are destroyed in a thermal oxidizer with the help of natural gas and a catalyst. Biocrude is cooled for storage and then transported to a centralized upgrading plant.

A transportation cost of \$0.09 per gasoline gallon equivalent biocrude is assumed<sup>1</sup>. The main process steps of the upgrader include hydrotreating and hydrocracking. First, the biocrude feed is pumped to 10.5 MPa, mixed with compressed hydrogen, and preheated to the hydrotreater reactor temperature of 400 °C. The hydrotreating process can convert oxygen, nitrogen, and sulfur in the biocrude to carbon dioxide and water, ammonia, and hydrogen sulfide, respectively. The hydrotreater effluent is cooled to 25 °C to separate the gas and water. The hydrotreated biocrude may be sent to different downstream upgrading units, depending on the target finished fuel types. All the hydrotreated oil can be used as marine fuel without further fractionation. For diesel and sustainable aviation fuel, the hydrotreated oil needs to be further fractionated into lights, naphtha, diesel, and heavy oil. Heavy oil combined with hydrogen is then hydrocracked at 400 °C and 7

MPa to produce additional naphtha, diesel, and sustainable aviation fuel blendstocks. An additional deep hydrodenitrogenation phase is required to completely remove nitrogen in sustainable aviation fuel distillate. Hydrogen is produced on-site via steam reforming of the off-gases and purchased natural gas.



**Figure S1.** Wet waste hydrothermal liquefaction and biocrude upgrading process flow diagram.

## S2. HTL Model Components

We start to develop rigorous process models in Aspen Plus by leveraging our in-house large-scale sludge HTL models and the available PNNL's continuous HTL run data. Identifying chemicals in the derived biocrude and aqueous phase is very critical to the model accuracy and TEA results. Thus, we identified over 500 identified chemicals in biocrude via GCMS and compiled them into several groups such as hydrocarbon, N-, S-, O-containing organics, amide and acid, and then selected the high-content chemicals for each group as the model chemicals implemented in our process model. Note that GCMS can only identify about 67% C, 80% H, 74% O and 15% N in the biocrude and the unknown heavy compounds are represented by two heavy molecules in the model, which are  $C_{19}H_{16}N_4$  and  $C_{24}H_{30}O_4$  in our model. Similarly, the model chemicals in aqueous phase were identified and corrected in the Aspen model with the help of GCMS, HPLC, elemental composition as well as the property data such as total carbon, total nitrogen, COD and  $NH_3$  content. Table S1 shows the selected potential model chemicals based on the GCMS results for HTL biocrude as well as aqueous phase.

**Table S1.** Model component used for HTL Biocrude

	Chemical Name	Formula	
HTL Biocrude			
S-organic:	N-methylthiopyrrolidone	C5H9NS	
CxHy:	Toluene	C6H6	
	Indole	C8H7	
	Ethylbenzene	C8H10	
	Naphthalene, 1,2,3,4-tetrahydro- 1,1,6-trimethyl-	C13H18	
	1-Pentadecene	C15H30	
	Heneicosane	C21H44	
	N-organic:	1H-Pyrrole, 3-ethyl-2,4,5-trimethyl-	C9H15N
		Indolizine	C8H7N
Pyridine, 2-methyl-		C6H7N	
Pyrazine, methyl-		C5H6N2	
Benzonitrile, 2,4,6-trimethyl-		C10H11N	
O-organic:	Phenol	C6H6O	
	Cyclopentanone	C5H8O	
Amide:	Hexadecanamide	C16H33NO	
	9-Octadecenamide, (Z)-	C18H35NO	
	Pyrrolidine, 1-(1-oxo-9-octadecenyl)-, (Z)-	C23H43NO	
Acid:	n-Hexadecanoic acid	C16H32O2	
	Octadecanoic acid	C18H32O2	
Heavy Residue	Triphenylformazan	C19H16N4	
	Dibenzyl-sebacate	C24H30O4	
HTL Aqueous:			
	Methanol	CH4O	
	Ethanol	C2H6O	
	Acetone	C3H6O	
	Acetic Acid	C2H4O2	
	Propanoic Acid	C3H6O2	

Ammonia	NH4OH
Ethylamine	C2H7N
Triphenylformazan	C19H16N4
N-methylthiopyrrolidone	C5H9NS

### S3. Capital Cost Estimate Assumptions

Hydrothermal liquefaction pathway capital costs for each plant area are based on data from wet waste hydrothermal liquefaction design reports and publications from Pacific Northwest National Laboratory <sup>1</sup>. The assumptions for total direct cost, fixed capital investment, and total capital investment estimates are listed in Table S2.

**Table S2.** 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 cost (TDC)	18.5%
Indirect Costs	
Item	% of TDC
Prorated expenses	10%
Home office and construction fees	20%
Field expenses	10%
Project contingency	10%
Start-up and permits	10%
Total indirect costs	60%
Working capital	5% of Fixed Capital Investment (FCI)
Land	Hydrothermal liquefaction (HTL): 6 acres at \$15,000/acre Upgrading: 6% of total purchased equipment cost

### S4. Operating Costs

Table S3 lists the raw material, waste disposal, and utility costs assumed for estimating variable operating costs for the hydrothermal liquefaction (HTL) plant.

**Table S3.** Variable operating costs for the hydrothermal liquefaction pathways.

Variable Operating Costs	Value	Reference
<b>Raw Materials</b>		
Polymer, \$/lb (2020\$)	0.2	2
Quicklime, \$/ton (2014\$)	118.0	3
Hydrotreating guard bed catalyst, \$/lb (2014\$)	16.6	4
Hydrotreating main bed catalyst, \$/lb (2014\$)	10.5	4
Hydrocracking catalyst, \$/lb (2014\$)	16.6	4
Hydrodenitrogenation catalyst, \$/lb (2014\$)	10.5	4
Hydrogen plant catalyst, \$/Mscf H <sub>2</sub> (2014\$)	20.5	5
Cooling tower chemical, \$/lb (2007\$)	1.4	6
Boiler chemical, \$/lb (2007\$)	2.3	6
Natural Gas, \$/1000 scf (2016\$)	3.5	7
Electricity, ¢/kWh (2016\$)	6.8	8
Solid waste disposal fee, \$/U.S. ton (2019\$)	55.4	9
Wastewater POTW fee, \$/tonne (2001\$)	0.5	10
<b>Feedstock Tipping Fee</b>		
Sludge, \$/wet tonne (2019\$)	40	11
Food waste, \$/wet ton (2020\$)	36	12
Swine manure, \$/wet tonne (2019\$)	53	11

Sewage sludge management cost accounts for 40%–50% of a wastewater treatment (WWT) plant’s total annual operating cost, which includes dewatering/drying costs and tipping fees paid to final use/disposal facilities. A wet waste resources analysis conducted by the National Renewable Energy Laboratory showed that 64% of sludge in the United States has a negative price and that the average sludge price is –\$36 per wet ton (not including the dewatering cost)<sup>13</sup>, as shown in Table S4. The *2021 Biosolids Trends Survey Report* published by the Bay Area Clean Water Agencies indicated a sludge cost in the range of \$14–\$139 per wet ton, with an average of \$52 per wet ton for 31 WWT plants in the Bay Area<sup>14</sup>. A similar cost range of \$21–\$102 per wet ton was reported based on data collected by the Tohopekaliga Water Authority (FL), City of Calgary, City of Orlando, Metro Vancouver, and Santa Rosa Water<sup>15</sup>. In this work, \$40 per wet metric ton (not including dewatering cost) is a realistic average value that is representative of what WWTs currently would pay for the offtake of their waste solids. In addition, capital and operating costs associated with polymer and electricity consumption for sludge dewatering are included in the HTL plant costs.

**Table S4.** Data from <sup>11</sup> used for estimates of sludge feedstock costs (avoided disposal fee).

Cumulative Percent	Wet Sludge Supply, Millions of Tonne	Sludge Price, \$/Wet Tonne
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 Average Cost, \$/Wet Tonne	-40
	Weighted Average Cost, \$/Wet Ton	-36

Manure management cost includes on-farm nutrient management costs, off-farm transport costs, land treatment costs, manure and wastewater handling storage costs, and recordkeeping costs. A wet waste resources analysis conducted at the National Renewable Energy Laboratory <sup>11</sup> showed that 27% of animal manure in the United States has a negative price and that the average price is -\$48 per wet ton (-\$125 per dry ton), as shown in Table S5. A wide range of \$5-\$150 per dry ton is reported as the swine manure avoided disposal cost based on the U.S. Department of Agriculture method for estimating comprehensive nutrient management plan cost <sup>16</sup>.

**Table S5.** Data from <sup>11</sup> used for estimating manure feedstock cost (avoided disposal fee).

Cumulative Percent	Wet Manure Supply, Millions of Tonnes	Manure Price, \$/Wet Tonne
0%	9.5	-310.7
3%	12.4	-276.7
4%	14.9	-256.6
5%	15.6	-216.4
5%	16.0	-173.6
7%	17.9	-123.3
10%	21.9	-119.5
11%	22.7	-100.6
13%	25.3	-90.6
15%	28.0	-88.1
17%	30.9	-73.0
20%	35.3	-73.0
23%	39.4	-67.9
27%	43.6	-65.4
30%	48.1	-64.2
33%	51.7	-57.9
36%	55.3	-52.8
39%	59.8	-49.1
43%	64.6	-47.8
46%	69.4	-44.0
50%	74.0	-40.3
54%	78.7	-35.2
58%	83.9	-32.7
62%	89.5	-28.9
66%	94.4	-28.9
69%	98.9	-27.7
73%	104.0	-22.6
76%	108.0	-18.9
80%	112.5	-18.9
83%	116.5	-15.1
86%	121.0	-15.1
89%	125.2	-13.8
93%	129.7	-12.6
96%	134.2	-3.8
98%	137.0	6.3
100%	139.1	7.5
Weighted Average Cost, \$/Wet Tonne		-53
Weighted Average Cost, \$/Wet Ton		-48

However, the results of a swine manure resources assessment <sup>16</sup> demonstrated that the recoverable swine manure production rate per farm ranges widely, from <0.5 dry tons per day per farm to 250 dry tons per day per farm. Of the farms in the United States, 75% have a manure production rate of <1.0 dry tons per day. To reach the 110 dry tons per day scale, a similar transportation model to that described by <sup>16</sup> was used to estimate the potential delivery cost. Table S6 provides a breakdown of transportation costs based on the use of facility-owned tandem trucks with a capacity of 40 m<sup>3</sup>. The fixed transportation cost is a function of the number of trips per year, which varies according to the total volume of transported swine manure as well as according to truck utilization parameters such as loading/unloading time. A high yearly trip number can greatly reduce the unit fixed cost (\$/mile). Variable cost mainly includes tire costs and the costs associated with fuel, labor, and maintenance; thus, the unit variable cost is the same across different HTL plant scales. The unit total cost is the sum of the fixed operating costs. The calculation of trip cost can be based on the assumed collection radius and the estimated unit transportation cost. As shown, the transportation cost is approximately \$52 per dry ton for the 110 dry ton per day HTL plant scale.

**Table S6.** Transportation cost estimates for different plant scales (25 wt% solid, 100 miles/one-way trip).

HTL plant scale, dry tons/day	Collection radius, miles	Number of trips per year	Fixed cost	Variable cost	Total cost	Trip cost, \$	Dry solid cost, tons/trip	Unit cost \$/dry ton swine manure	Average unit cost \$/dry ton swine manure
			\$/mile wet swine manure						
110	100	948	0.61	1.92	2.53	253.1	11.55	21.92	51.54

HTL = hydrothermal liquefaction.

The food waste cost is based on the range for the tipping fee (\$18–\$32 per wet ton) collected by food waste aerobic digestion facilities reported in the U.S. Environmental Protection Agency’s recent survey <sup>17</sup>. Additionally, <sup>12</sup> indicated that food waste aerobic digestion facilities typically charge 65% of the landfilling fee as the tipping fee, which is approximately \$36 per wet ton based on the national average landfilling fee at of \$55 per wet ton.

## S5. Techno-Economic Analysis Key Assumptions

Table S7 summarizes the primary economic assumptions for the “n<sup>th</sup> plant” assumption adopted in this study. This approach does not account for special financing, equipment redundancies, large contingencies, or long start-up times because it assumes that several plants have already been built and are in operation.

**Table S7.** Key assumptions for the techno-economic analysis.

Assumption Description	Assumed Value
Cost year	2016\$
Internal rate of return	10%
Plant financing debt/equity	60%/40% of total capital investment
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 schedule <sup>a</sup>
Construction period	3 years (8% 1 <sup>st</sup> yr, 60% 2 <sup>nd</sup> yr, 32% 3 <sup>rd</sup> 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% (7920 operating hours per year)

<sup>a</sup> Modified accelerated cost recovery system

## S6. Life Cycle Emissions and Water Consumption from Business-as-Usual Management of Wet Wastes

**Table S8.** Business-as-usual emissions and water consumption for wet wastes.

	Wastewater Sludge	Swine Manure	Food Waste
GHG (kg CO <sub>2</sub> e/dry ton)	219	1257	1341
NO <sub>x</sub> (g/dry ton)	192	0	249
PM <sub>2.5</sub> (g/dry ton)	24	0	35
SO <sub>x</sub> (g/dry ton)	39	0	-75 <sup>a</sup>
Water consumption (gal/dry ton)	87	0	-141 <sup>a</sup>

<sup>a</sup> The negative values are attributable to the credits from excess electricity for displacing the U.S. average grid mix.

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