Electronic Supplementary Information

Hydrothermal liquefaction integrated with wastewater treatment plants – Life cycle assessment and technoeconomic analysis of process system options

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Part 1: Inventories for Concept 1 and Concept 2

Inventories for Concept 1, Scenarios 1a, 1b and 1c

Table A1 Life Cycle Inventory of HTL plant for Scenarios 1a, 1b and 1c

	Scenario 1a		**Scenario 1b**		**Scenario 1c**		
Output							
Name	***Amount***	***Unit***				***Unit***	***Related process***
Biocrude	1767	Kg/hr	1767	Kg/hr	1767	Kg/hr	HTL biocrude production
HTL Solids	2504	kg/hr	2504	kg/hr	2504	kg/hr	HTL biocrude production
Lime sludge	948	kg/hr	-	-	-	-	From HTL Aqueous treatment
Exhaust	26815	Kg/hr	-	-	-	-	From HTL Aqueous treatment
AD gas	-	-	-	-	416	kg/hr	From HTL AP treatment (AD unit)
Exhaust	5145	kg/hr	5145	kg/hr	5145	kg/hr	From Combustion
Water recycle to headworks	9588	kg/hr	-	-	2242	kg/hr	From HTL AP treatment
Aqueous phase from HTL recycled to headworks		kg/hr	11803	kg/hr	11803	kg/hr	From HTL Aqueous treatment
AD residue	-	-	-	-	36	kg/hr	From HTL AP treatment (AD unit)
Input							
Name	***Amount***	***Unit***					***Related process***
Dewatered Sludge (25% solids)	16631	kg/hr	16631	kg/hr	16631	kg/hr	HTL biocrude production
Natural Gas	170	kg/hr	170	kg/hr	0	kg/hr	Combustor
Air	4418	kg/hr	4418	kg/hr	4418	kg/hr	Combustor
Lime	596	kg/hr	-	-	0	kg/hr	HTL Aqueous treatment
Natural Gas	79	kg/hr	-	-	-	-	HTL Aqueous treatment
Air	26834	kg/hr	-	-	-	-	HTL Aqueous treatment

Power Consumption and Production (the same for Scenarios 1a, 1b & 1c)

Power consumption	Unit	Related process
122.4	kW	HTL biocrude production

38.0	kW	Combustor
56.0	kW	HTL Aqueous treatment

Table A2 Life Cycle Inventory of central Upgrading Plant

Output	Scenario 1a & 1b		Scenario 1c		
Name	***Amount***	***Unit***		***Unit***	***Related process***
Gasoline	3238	kg/hr	Gasoline	3238	Hydrotreatment
Diesel	10526	kg/hr	Diesel	10526	Hydrotreatment
Condensate to WWT	167	kg/hr	Condensate to WWT	167	From Hydrogen
Wastewater	2345	kg/hr	Wastewater	2345	from Hydrotreatment
Flue gas	33082	kg/hr	Flue gas	33082 (6530 biogenic and 1840 fossil CO2)	Steam Reforming
Wastewater to WWTP	7242	Kg/hr	Wastewater to WWTP	7242	Ammonia scrubber
Input					
Name	***Amount***	***Unit***			***Related process***
Biocrude from HTL	17672	kg/hr	17672	kg/hr	from HTL x10
Air	26404	kg/hr	26404	kg/hr	Hydrogen production
Natural Gas	12507	kg/hr	256	kg/hr	Hydrogen production
Water	6945	kg/hr	6945	kg/hr	Scrubber
Cooling Tower Water Makeup	10 652	kg/hr	10 652	kg/hr	Steam System

Power Consumption and production (the same for Scenarios 1a, 1b & 1c)

Power consumption	**Unit**	**Related process**
1632.6	kW	Hydrotreatment
69.3	kW	Hydrocracking
1190.4	kW	Hydrogen plant
Power production	**Unit**	**Related process**
1906.1	kW	Steam System

The net power consumption is refers to the needs of hydrogen plant. A priority of using the produced electricity on site is given to hydrotreatment and hydrocracking and the remaining electricity need is provided by the electricity network.

Scenarios 2, 3 and 4

Table A3 Life Cycle Inventory of HTL plant

Output	Scenario 2 & 3	Scenario 4		
Name	***Amount***		***Unit***	***Related process***
Biocrude	1767	1767	Kg/hr	HTL biocrude production
HTL Solids	2504	2504	kg/hr	HTL biocrude production
Exhaust	5145	-	kg/hr	From Combustion
Aqueous phase from HTL	11803	11803	kg/hr	From HTL biocrude production
Input				
Name				***Related process***
Dewatered	16631	16631	kg/hr	HTL biocrude

Sludge (25% solids)				production
Natural Gas	170	-	kg/hr	Combustor
Air	4418	-	kg/hr	Combustor

Power Consumption

Power consumption (Scenario 2 and 3)	**Power consumption (Scenario 4)**	**Unit**	**Related process**
122.4	1703	kW	HTL biocrude production
38.0	-	kW	Combustor

Table A4 Life Cycle Inventory of central Upgrading Plant for Scenarios 2,3 and 4

Output			
Name	***Amount***	***Unit***	***Related process***
Gasoline	3238	kg/hr	Hydrotreatment
Diesel	10526	kg/hr	Hydrotreatment
Wastewater	2345	kg/hr	from Hydrotreatment
Wastewater to WWTP	7242	Kg/hr	Ammonia scrubber
Input			
Name	***Amount***	***Unit***	***Related process***
Biocrude from HTL	17672	kg/hr	from HTL x10
Cooling Tower Water Makeup	10 652	kg/hr	Steam System
Hydrogen	958	Kg/hr	Electrolysis unit
Water	6945	kg/hr	Scrubber

Power Consumption

Power consumption	**Unit**	**Related process**
1632.6	kW	Hydrotreatment
69.3	kW	Hydrocracking
21,292	kW	Hydrogen plant (electrolysis plant)
Power production	**Unit**	**Related process**
10,057~40%*27MW	kW	Steam System (from the combustion of offgas)

Concept 2

Table A5 Life Cycle Inventory of HTL plant

Output			
Name	***Amount***	***Unit***	***Related process***
Biocrude	1767	Kg/hr	HTL biocrude production
HTL Solids	2504	kg/hr	HTL biocrude production
Exhaust	5145	kg/hr	From Combustion
Aqueous phase from HTL	11803	kg/hr	From HTL biocrude production
Input			
Name			***Related process***

Dewatered Sludge (25% solids)	16631	kg/hr	HTL biocrude production
Natural Gas	170	kg/hr	Combustor
Air	4418	kg/hr	Combustor

Power Consumption

Power consumption	Unit	Related process
122.4	kW	HTL biocrude production
38.0	kW	Combustor

Table A6 Upgrading HDO decentralized plant

Output			
Name	***Amount***	***Unit***	***Related process***
Hydrotreated biocrude	1237	kg/hr	Hydrotreatment (70% conversion of biocrude)
Wastewater	234.5	kg/hr	from Hydrotreatment
Wastewater to WWTP	724.2	Kg/hr	Ammonia scrubber
Input			
Name	***Amount***	***Unit***	***Related process***
Biocrude from HTL	1767,2	kg/hr	from one HTL plant
Hydrogen	61.8	Kg/hr	Electrolysis unit (35gr/kg hydrotreated biocrude)

Power Consumption

Power consumption	**Unit**	**Related process**
163.2	kw	Hydrotreatment
1374	kW	Hydrogen plant (Energy needs 61.8kg x 22kWh/kg H2)
Power production	**Unit**	**Related process**
1090	kW	Steam System (from the combustion of offgas)

Part 2: Cost data for Concepts 1 and 2

Table A7 Summarized cost data for Scenarios of Concept 1 for HTL production and upgrading level

	Scenario 1a	Scenario 1b	Scenario 1c	Scenario 2	Scenario 3	Scenario 4
GWP metric (kg CO2-eq/kg biocrude)/GWP metric (kg CO2-eq/MJ biocrude)/	**1.42/ 0.04**	**0.75/0.020**	**0.073/0.002**	**0.75/0.020**	**0.74/0.020**	**0.31/0.01**
CAPEX-TIC (Eur/kW-bio crude)	910.3	755.3	816.9	755.3	755.3	No detailed data
CAPEX-TCI (Eur/kW-biocrude)	1,811.69	1,551.19	1,654.72	1,551.19	1,551.19	1914
Variable OPEX (Eur/MWh-bio crude)	9.63	8.40	4.31	8.40	8.40	11.30
Total OPEX (Eur/MWh-biocrude)	24.54	20.41	16.61	20.41	20.41	23.3
Total Production costs (TPC) (Eur/MWh-biocrude)	54.61	46.16	44.08	46.16	46.16	55.04
GWP metric (kg CO2-eq/kg fuel blend)	**2.51/0.06**	**1.64/0.04**	**0.27/0.01**	**1.57/0.04**	**1.46/0.030**	**0.91/0.02**
CAPEX-TIC (Eur/kW-fuel blend)	1,313.64	1,155.49	1,218.34	1,194.48	1,194.48	No detailed data
CAPEX-TCI (Eur/kW-fuel blend)	2615.03	2349.35	2454.93	2440.25	2440.25	2,810
Variable OPEX (Eur/MWh-fuel blend)	2.39	2.39	1.00	4.55	4.55	4.55
Total OPEX (Eur/MWh-fuel blend)	32.23	28.06	21.96	29.54	29.54	32.42
Total Production costs (TPC) (Eur/MWh-fuel blend)	75.64	67.06	62.72	70.05	70.05	79.08

Table A8 CAPEX values for HTL biocrude production for scenarios 1a, 1b and 1c (for Scenario 2 and 3 capital costs are the same of Scenario 1b)

Plant Hours per year	7920				
Feed rate, dry sludge	110	ton/day			

Feed rate, dry ash-free sludge	93.5	ton/day			
HTL biocrude production	497.33	million MJ/yr			
	0.497	GJ/yr			
	13994.64	tonnes/year			
		Scenario 1a	**Scenario 1b**	**Scenario 1c**	**Scenario 4**
CAPITAL COSTS	**US dollars(2014)**	**Euro 2018**	**Euro 2018**	**Euro 2018**	**Euro 2018**
Sludge Dewatering	1,400,000	1,103,607	1,103,607	1,103,607	TCI was calculated based on a representative plant of ~2095kW and of a TCI of 3,700,000, that was scaled up linearly in the total capacity of 15 MW*
HTL Oil Production	13,100,000	10,326,609	10,326,609	10,326,609	
HTL Water Recycle Treatment	3,100,000	2,443,701	-	€ 971,148	
Balance of Plant	600,000	472,974	472,974	472,974	
Total Installed Capital Cost (TIC)	**18,200,000**	**14,346,892**	**11,903,190**	**12,874,338**	
Building, site development, add'l piping (18.5% TIC)	3,300,000	2,601,359	2,601,359	2,601,359	
Total Direct Costs (TDC)	21,500,000	16,948,251	14,504,550	15,475,698	
Indirect Costs (60% TDC)	12,900,000	10,168,951	8,702,730	9,285,419	
Fixed Capital Investment (FCI=TDC+Indirect Cost)	34,400,000	27,117,200	23,207,280	24,761,116	
Working Capital (5%FCI)	1,700,000	1,355,860	1,160,364	1,238,056	
Land (plant located at WWTP)	100,000	78,829	78,829	78,829	
Total Capital Investment (TCI)	**36,200,000**	**28,551,891**	**24,446,473**	**26,078,001**	**~30,766,000**
Installed Capital per Annual MJ Biocrude (Euro/MJ)		0.03			
TCI per Annual MJ Biocrude (Euro/MJ)		0.06			
Loan Rate		8.00%			
Term (years)		10			
Capital Charge Factor		0.141			

* Personal communication with https://circlianordic.com/

Table A9 Operating costs for HTL for Scenarios 1a, 1b, 1c and 4 (Scenario 2 and 3 have same operating with Scenario 1b)

Variable	**Value**	**Total Cost (2014), million USD/year**	**Million Euro (2014)/year**	**Million Euro (2018)/year**	**Million Euro (2018)/year**	**Million Euro (2018) /year**	**Million Euro (2018)/year**
				Scenario 1a	**Scenario 1b**	**Scenario 1c**	**Scenario 4**
Sludge Dewatering							
Polymer, $/lb (2013$)	1.73	0.33	0.24	0.25	0.25	0.25	0.25
HTL Processing							
Natural Gas, $/1000 scf (2014$)	5.62	0.39	0.29	0.29	0.29	-	
Electricity, ¢/kWh (2014$)	7.09	0.1	0.07	0.07	0.07	0.07	0.75

HTL Aqueous Phase Treatment							
Quicklime, $/ton (2014$)	107	0.42	0.31	0.31		-	
Natural gas (for THROX unit), $/1000 scf (2014$)	5.62	0.18	0.13	0.13		0.01	
					0.28*		0.28*
Extra Aeration at WWTP							
Electricity, kWh/lb COD removed (assuming100% COD removal)	0.4	0.36	0.26	0.27	0.27	0.27	0.27
Total		**1.78**	**1.30**	**1.33**	**1.16**	**0.60**	**1.55**
Fixed operating costs		0.81	0.59	0.60	0.60	0.60	0.60
Overhead & maintenance	90% of labor & supervisio n	0.73	0.53	0.54	0.54	0.54	0.54
Maintenance capital	3% of TIC	0.98	0.72	0.73	0.36	0.39	0.36
Insurance and taxes	0.7% of FCI	0.24	0.18	0.18	0.16	0.17	0.16
Total Fixed Operating Costs		**2.76**	**2.02**	**2.06**	**1.66**	**1.70**	**1.66****

*Average cost of treatment in a WWTP is considered, assuming 0.030Euro/kg of waste (Rerat et al., 2013) **assumed the same to Scenario 1b as presentative case due to lack of detailed data for Scenario 4

Table A10 CAPEX values for biocrude upgrading unit for all scenarios (Scenarios 1a, 1b and 1c have the same capital costs for the upgrading part)

Naphtha (million MJ/yr)	**Diesel (million MJ/yr)**	**Total (million MJ/yr)**		
1103.83	3590.48	4730.7		
25645	tonnes /year	Gasoline		
83366	tonnes /year	Diesel		
		Scenarios 1a, 1b and 1c	Scenario 2 and 3	Comments
CAPITAL COSTS	**US dollars (2014)**	**Euro (2018)**	**Euro (2018)**	
Hydrotreating	$33,600,000	26,486,569	26,486,569	
Hydrocracking	$6,600,000	5,202,719	5,202,719	

Hydrogen Plant	**$27,200,000**	**21,441,508**	**23,183,600**	**In scenarios 2 & 3 steam reforming unit is replaced by electrolysis. An average value of 1000 Euro/KW is given. Hydrogen produced is ~13MW**
Steam cycle	**$1,600,000**	**1,261,265**	**5,543,463**	**The initial unit is scaled up from 1800kw to 10MW**
Balance of Plant	$6,500,000	5,123,890	5,123,890	
Total Installed Capital Cost (TIC)	**$75,500,000**	**59,515,951**	**65,540,241**	
Building, site development, add'l piping (18.5% TIC)	$12,400,000	9,774,805	12,124,945	
Total Direct Costs (TDC)	**$87,900,000**	**69,290,756**	**77,665,185**	
Indirect Costs (60% TDC)	**$52,800,000**	**41,621,752**	**46,599,111**	
Fixed Capital Investment (FCI=TDC+Indirect Cost)	**$140,700,000**	**110,912,508**	**124,264,296**	
Working Capital (5%FCI)	$7,000,000	5,518,035	6,213,215	
Land (included in feedstock cost)	$2,700,000	2,128,385	2,128,385	
Total Capital Investment (TCI)	**$150,400,000**	**118,558,929**	**132,605,896**	
Loan Rate	8.00%			
Term (years)	10			
Capital Charge Factor (computed)	0.168			

Table A11 Operating costs for biocrude upgrading plant for all scenarios (Scenarios 1a, 1b and 1c have the same capital costs for the upgrading part)

Variable	**Value**	**Total Cost (2014), million USD/year**	**Million Euro 2014 /year**	**Million Euro 2018/year**				**Comments**
				Scenario 1a	**Scenario 1b**	**Scenario 1c**	**Scenarios 2, 3&4**	
Hydrotreating catalyst, $/lb (2014$) (2 year life)	16.6	0.4	0.29	0.3	0.3	0.3	0.3	Assumed to be the same
Hydrocracking catalyst, $/lb (2014$) (5 year life)	16.6	0.03	0.02	0.02	0.02	0.02	0.02	Assumed to be the same
Hydrogen plant catalyst, $/1000scf H2 (2014$) (5 year life)	0.0205	0.06	0.04	0.04	0.04	0.04	-	No need of natural gas

Natural gas, $/1000scf (2014$)	5.62	2.79	2.04	2.08	2.08	0.45	-	No need of natural gas
Cooling tower chemical, $/lb (2007$)	1.36	0.01	0.01	0.01	0.01	0.01	0.01	Assumed to be the same
Boiler chemical, $/lb (2007$)	2.27	0.01	0.01	0.01	0.01	0.01	0.01	Assumed to be the same
Electricity, ¢/kWh (2014$)	7.09	0.92	0.67	0.69	0.69	0.44	5.73	Electricity need is re-calculated
Water makeup, $/ton (2001$)	0.2	0.05	0.04	0.04	0.04	0.04	0.04	Assumed to be the same
Wastewater fee, $/ton (2001$)	0.48	0.07	0.05	0.05	0.05	0.05	0.05	Assumed to be the same
Total		**4.34**	**3.17**	**3.24**	**3.24**	**1.36**	**6.16**	
Fixed operating costs		2.19	1.6	1.63	1.63	1.63	1.63	Assumed to be the same
Overhead & maintenance	90% of labor & supervi sion	1.97	1.44	1.47	1.47	1.47	1.47	Assumed to be the same
Maintenance capital	3% of TIC	4.05	2.96	3.02	0.36	1.79	1.97	Assumed to be the same
Insurance and taxes	0.7% of FCI	0.99	0.72	0.74	0.16	0.78	0.87	Assumed to be the same
Total Fixed Operating Costs		**9.18**	**6.71**	**6.84**	**3.62**	**5.66**	**5.94**	**Assumed to be the same**

Cost data for Concept 2

Table A12 Summarized cost data for Scenario 4 of Concept 2 for HTL production and upgrading level

	Concept 2
GWP metric (kg CO2-eq/kg biocrude)/GWP metric (kg CO2-eq/MJ biocrude)/	**0.75/0.020**
CAPEX-TIC (Eur/kW-bio crude)	755.3
CAPEX-TCI (Eur/kW-biocrude)	1,551.2
Variable OPEX (Eur/MWh-bio crude)	8.4
Total OPEX (Eur/MWh-biocrude)	20.4
Total Production costs (TPC) (Eur/MWh-biocrude)	46.2
GWP metric (kg CO2-eq/kg fuel blend)	**1.33/0.03**

CAPEX-TIC (Eur/kW-fuel blend)	1,226.01
CAPEX-TCI (Eur/kW-fuel blend)	2,634.52
Variable OPEX (Eur/MWh-fuel blend)	1.88
Total OPEX (Eur/MWh-fuel blend)	27.83
Total Production costs (TPC) (Eur/MWh-fuel blend)	71.57

Table A13 CAPEX values for biocrude upgrading unit for Concept 2

	Concept 1		**Concept 2**	**Comments**
CAPITAL COSTS	**US dollars (2014)**	**Euro (2018)**	**Euro (2018)**	
Hydrotreating	$33,600,000	26,486,569	3,735,884	Scaled-down based on the reference report Snowden 2019
Hydrocracking	$6,600,000	5,202,719	-	It is not used in this concept
Hydrogen Plant	**$27,200,000**	**21,441,508**	**1,496,818**	**Steam reforming unit is replaced by electrolysis. An average value of 1000 Euro/Kw is given. Hydrogen produced is 2 MW**
Steam cycle	**$1,600,000**	**1,261,265**	**843,203**	
Balance of Plant	$6,500,000	5,123,890	600,914	9% of TIC based on reference
Total Installed Capital Cost (TIC)	**$75,500,000**	**59,515,951**	**6,676,819**	
Building, site development, add'l piping (18.5% TIC)	$12,400,000	9,774,805	1,235,211	
Total Direct Costs (TDC)	**$87,900,000**	**$69,290,756**	**7,912,030**	
Indirect Costs (60% TDC)	**$52,800,000**	**41,621,752**	**4,747,218**	
Fixed Capital Investment (FCI=TDC+Indirect Cost)	**$140,700,000**	**$110,912,508**	**12,659,248**	
Working Capital (5%FCI)	$7,000,000	5,518,035	632,962	
Land (included in feedstock cost)	$2,700,000	2,128,385	2,128,385	
Total Capital Investment (TCI)	**$150,400,000**	**118,558,929**	**15,420,596**	

Table A14 Operating costs for biocrude upgrading plant for Concept 2

Variable	**Value**	**Total Cost (2014), million USD/year**	**Million Euro 2014 /year**	**Million Euro 2018/year**	**1/10th of the original capacity presented in the study of Snowden Swan et al. 2017**	**Comments**
Hydrotreating catalyst, $/lb (2014$) (2 year life)	16.6	0.4	0.29	0.3	0.03	Assumed to be the same

Hydrocracking catalyst, $/lb (2014$) (5 year life)	16.6	0.03	0.02	0.02	0.002	Assumed to be the same
Hydrogen plant catalyst, $/1000scf H2 (2014$) (5 year life)	0.0205	0.06	0.04	0.04	-	No need of natural gas
Natural gas, $/1000scf (2014$)	5.62	2.79	2.04	2.08	-	No need of natural gas
Cooling tower chemical, $/lb (2007$)	1.36	0.01	0.01	0.01	0.001	Assumed to be the same
Boiler chemical, $/lb (2007$)	2.27	0.01	0.01	0.01	0.001	Assumed to be the same
Electricity, ¢/kWh (2014$)	7.09	0.92	0.67	0.69	0.20	Electricity need is re-calculated
Water makeup, $/ton (2001$)	0.2	0.05	0.04	0.04	0.004	Assumed to be the same
Wastewater fee, $/ton (2001$)	0.48	0.07	0.05	0.05	0.005	Assumed to be the same
Total		**4.34**	**3.17**	**3.24**	**0.24**	
Fixed operating costs		2.19	1.6	1.63	0.16	Assumed to be the same
Overhead & maintenance	90% of labor & supervision	1.97	1.44	1.47	0.15	Assumed to be the same
Maintenance capital	3% of TIC	4.05	2.96	3.02	0.30	Assumed to be the same
Insurance and taxes	0.7% of FCI	0.99	0.72	0.74	0.07	Assumed to be the same
Total Fixed Operating Costs		9.18	6.71	6.84	0.69	Assumed to be the same

Part 3: LCA data

Table A15 LCA factors (source Ecoinvent database, https://ecoinvent.org/)

Upstream processes(Ecoinvent)	GWP100 (kg CO2-Eq/kg of product)
market for natural gas, from high pressure network (1-5 bar), at service station, GLO,	0.61
market for natural gas, high pressure, RoW m3	0.26
market for tap water, Europe without Switzerland (kg)	2.00E-5
water production, deionised, Europe without Switzerland (kg)	2.86E-04
market for water, deionised, Europe without Switzerland	2.86E-04
market group for electricity, medium voltage, RER kwh	0.40
market for electricity, medium voltage, DK	0.24
market for process-specific burdens, residual material landfill Europe without Switzerland (kg)	0.003
process-specific burdens, inert material landfill, RoW kg	0.003
treatment of wastewater, average, capacity 1.1E10l/year Wastewater purified in a moderatly large municipal wastewater treatment plant (capacity class 2), with an average capacity size of 71100 per-captia-equivalents PCE, treatment of wastewater, average, capacity 1.1E10l/year, CH (m3)	0.327
market for wastewater, average, Europe without Switzerland/The wastewater, average is treated in the same place as it is produced. That is why regional market activities are in this case adequate (m3)	0.476
hydrogen cracking, APME, RER (kg)/ hydrogen liquid	1.69
chlor-alkali electrolysis, diaphragm cell, RER kg/ hydrogen liquid	12.45
hydrogen production, gaseous, petroleum refinery operation Europe without Switzerland	1.55
glycerine production, from epichlorohydrin, RER	4.04
market for potassium carbonate	2.66
quicklime production, milled, loose, RoW	1.17
chlor-alkali electrolysis, mercury cel RER	3.49
chemical production, organic GLO chemical, organic [kg]	1.93
treatment, sewage, to wastewater treatment, class 2, CH, [m3] (#2276)	0.35

The assumptions used on LCA are the following:

- All output streams crossing the system boundaries of the presented cases should have been characterized for their destiny either directed to another treatment facility or to the environment.
- The Aqueous Phase (AP) produced by the HTL reaction stage is either sent directly to a central waste treatment facility under the assumption that there is no need of ammonia removal (Scenario 1b) or treated via ammonia stripping and the resulting wastewater stream is sent again to a central WWTP (Scenario 1a) or sent to an AD plant (Scenario 1c) the wastewater of which is

also sent to a WWTP (Scenario 1c). All other wastewater streams are assumed to be sent to a central WWTP.

- The WWTP can be the plant that supplies the sludge to the whole study system (i.e. the boundaries) and therefore the produced wastewater streams are assumed to be burdened by the treatment impacts of the WWTP without however affecting the produced amount of sludge. The design of the WWTP is not considered as part of the environmental and technoeconomic analysis of the particular study therefore a process model “Wastewater, average {CH}| treatment of, capacity 1.1E10l/year | APOS, U” was used in order to attribute treatment emissions.
- In addition, the sewage sludge comes to the entrance to the boundaries with no impacts allocated from the wastewater plant model. “Wastewater, average {CH}| treatment of, capacity 1.1E10l/year | APOS, U” was used in order to attribute treatment emissions”
- Ecoinvent considers the sludge biogenic according to the model assumption. “Wastewater, average {CH}| treatment of, capacity 1.1E10l/year | APOS, U” was used in order to attribute treatment emissions”
- We assume that the returned wastewaters to the WWTP is of very low quantity compared to the treated wastewaters without any operational impact to the plant.
- Waste models from Ecoinvent are not sensitive to the quality but only to the quantity.
- The benefits of sludge incineration as considered in the Ecoinvent model are not considered in the case study.
- The AD technology performance has been obtained from the study of Tews et al., (2014) which considers that the input stream to the AD unit includes 25% organics after dewatering of the initial stream that has 4% organics. The dewatering process reduces the initial water content by 90%. This reduction percentage has been considered for the current study assuming that the initial stream (11800kg/hr) exiting the HTL unit contains 75% organics which after reducing the water content by 90% reaches a content of 45% to organics (final weight 1851kg/hr). This stream is considered to be converted (by %wt). to gas by (23%), wastewater (76%) and solids (1%). The estimated gas quantity is then multiplied by a factor of 62% representing the content of biogas in methane (https://www.iea.org/reports/outlook-for-biogas-and-biomethane-prospects-for-organic-growth/an-introduction-to-biogas-and-biomethane)
- The impacts of the process that does the dewatering has not taken into account in the calculations of the current study neither in the study of Tews et al (2014).
- Some parameters like to efficiency of the AD plant to gas might be subjected to sensitivity analysis given that the streams of the reference study are not of the same composition to the current study but this is out of scope.
- The separation of the gas stream into pure methane that the is used internally in the HTL process and to hydrogen production in Scenario 1c has not taken into account

Assumptions for system boundaries

- System boundaries start from the entrance of sewage sludge until the biofuels (diesel, gasoline or HDO biocrude), assuming that feedstock enters boundaries with no impacts allocated from the wastewater plant model. The Life Cycle Assessment is on cradle to gate analysis expressed on 1 kg of biofuel as a functional unit.
- A cradle to grave approach is done for the GWP indicator which is expressed on the whole life cycle of the fuel blend (diesel and gasoline) considering as

avoided impacts the fossil based fuels production plus the fossil emissions from combustion.

- Transportation is not included in the calculations and any kind of logistics-related impacts, i.e transporting sludge to HTL and the biocrude to the upgrading unit.
- The sizing of each HTL plant is assumed to be of such capacity so as to be coupled with a WWTP from which it is supplied with sewage sludge and therefore corresponds to the population equivalent that the WWTP covers. The same goes for the sizing of the central hydrogen upgrading plant that receives input from 10 different HTL plants. The selected WWTP plant size in this study roughly corresponds to a population equivalent of 2-4 millions, which for example represents big WWTP from a European perspective. Thus, considering one HTL plant for each WWTP and one upgrading plant serving 10 such HTL/WWTP plants already refers to a very high scale, making further scaling-up scenarios rather improbable. Scaling down would be more likely and this would affect linearly the LCA impacts, which will not be the case for technoeconomic analysis. On the other hand, ramping-up the technology (i.e., installing more plants of the same size in various locations worldwide) would affect both LCA and TEA by improving efficiencies, decreasing installation and productions costs according to the learning by doing concept. However, this type of prospective analysis lies outside the scope of the present study.
- Hydrogen that is needed for upgrading is 958kg/hr that corresponds to 33MW (using LHV equal to 33 kWh/kg (Fuels - Higher and Lower Calorific Values (engineeringtoolbox.com)). It is assumed that this quantity is covered by electrolysis technology without estimating the number of plants of a particular size needed to cover this requirement. For example (Selma Brynolf 2018), gives the size of alkaline electrolysis 1.1-5.3MW and PEM 0.10-1.2MW.

Values of impacts for Hydrotreating and Hydrocracking for Scenarios presented in Figures 8 and 9

	GWP (kg CO2-eq/kg biofuel blend	
	Hydrotreating &	Hydrocracking (Scrubber)
Scenario 1b	5.7E-05	3.3E-04
Scenario 1c	5.7E-05	3.3E-04
Scenario 2	5.7E-05	-
Scenario 3	5.7E-05	-
Scenario 4	5.7E-05	

Abbreviations: Global warming (GWP), Stratospheric ozone depletion (ODP), Ionizing radiation (IRP), Ozone formation, Human health (HOFP), Fine particulate matter formation (PMFP), Ozone formation, Terrestrial ecosystems (EOFP), Terrestrial acidification (TAP), Freshwater eutrophication (FEP), Marine eutrophication (MEP), Terrestrial ecotoxicity (TAP), Freshwater ecotoxicity (FETP), Marine ecotoxicity (METP), Human carcinogenic toxicity (HTPc), Human non-carcinogenic toxicity (HTPnc), Land use (LOP), Mineral resource scarcity (SOP), Fossil resource scarcity (FFP), Water consumption (WCP)