

Supplementary Materials: Economic and Environmental Assessment of Catalytic and Thermal Pyrolysis Routes for Fuel Production from Lignocellulosic Biomass

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Section S1: Process Information

1.1. Process Flow Diagram

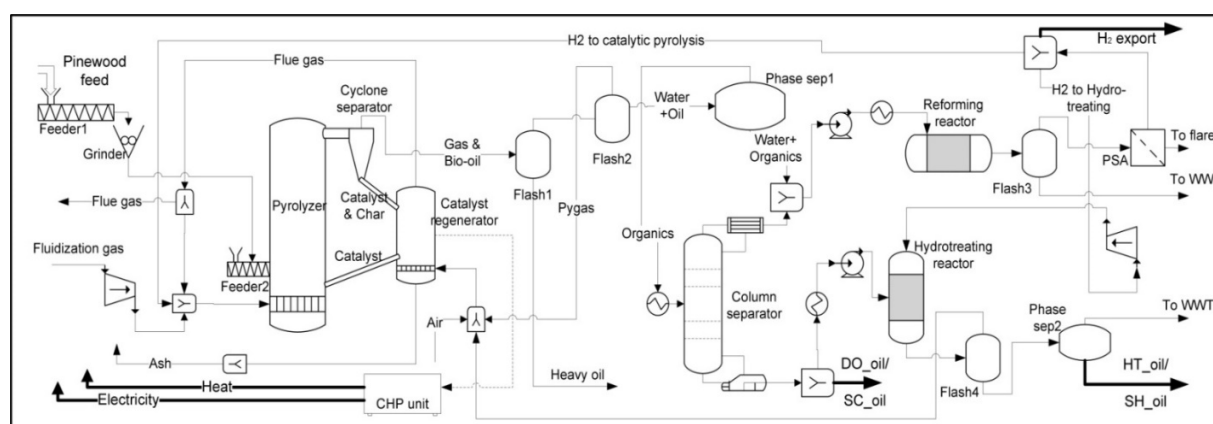


Figure S1. Process flow diagram.

1.2. Process Input and Output Mass Flows

Please refer to the LCA inventory data in section S3 for mass flows per unit product for all the inputs and outputs in all the cases and scenarios.

Section S2: Process Economics Data

2.1. Process Equipment, Sizing and Cost Information.

Table S1. Information about the process equipment, sizing and cost information. The scaling exponent and installation factor are provided as well.

Process Unit	Design Capacity	Units	Purchase Cost (EUR) in 2018	Scaling Exponent	Installation Factor
Pretreatment					
Conveyer—Woodchips feed to process	33,443 ¹	kg/h	658,503	0.6	1.7
Grinder—Ball mill/crusher	33,443	kg/h	978,962	0.7	2.96
Grinding screen	2	m ²	38,131	0.3	2.9
Screw feeder—Pyrolyzer	20,000	kg/h	1203	0.46	2.5
Pyrolysis					
Pyrolyzer	20,000	kg/h	4,427,309	0.53	1.5
Carrier gas compressor	26	kW	21,544	0.9	2.26
Carrier gas heater	1	m ²	11,357	0.14	2.72
Screw extractor—char/ash removal	3655	kg/h	550	0.46	2.5
Aerosol mixer	17,345	kg/h	2690	0.5	1
Cyclone—char/ash removal	17,345	kg/h	113,138	0.82	1.7
Oil separation					
Flash 1—WatOil extraction	14,449	kg/h	18,746	0.72	2.47
Flash 2—Aq. Org extraction	6336	kg/h	10,355	0.72	2.47
Heatex—WatOil preheater	8112	kg/h	67,533	0.7	1
Oil spec dist column	325	Multi	405,094	0.81	3.24
Dist column internals	162	Multi	166,958	0.78	1
Heatex—Column reboiler	685	kg/h	100,592	0.7	1
Heatex—Column condenser	766	kg/h	29,142	0.7	1
Heatex—Oil product cooler	685	kg/h	20,302	0.7	1
Hydrogen production					
Inline Aq. Org mixer	7420	kg/h	1,60	0.5	1
Pump—H ₂ prod feed	7	kW	2838	0.29	1.52
Heatex—H ₂ prod feed	62	m ²	47,539	1.83	2.97
Reforming reactor	7420	kg/h	1,009,088	0.6	2.7
Flash 3—H ₂ prod liquids removal	7420	kg/h	11,601	0.72	2.47
Pressure Swing Adsorption unit—H ₂ separation	308	m ³ /h H ₂	156,399	0.65	2.47
Combined heat and power (CHP)					
Inline mixer—combustor feed	9145	kg/h	1953	0.5	1
Screw feeder—combustor char feed	5509	kg/h	665	0.46	2.5
Air inlet fan/propeller	8	m ³ /s	9544	0.93	1.75
Combustor/Catalyst regenerator	52,971	kg/h	1,754,789	0.6	1.58
Turbine	14,343	kW	1,599,974	0.6	1.8
Generator	14,343	kW	4,730,063	0.6	1.8
Cooling tower	44	kg/h	218,263	0.6	1.8
Cyclone—flue gas clean up	42,971	kg/h	238,056	0.82	1.7
Flue gas stack	42,971	kg/h	56,020	0.5	2.93
Hydrotreating					
H ₂ Compressor 1	3	kW	3491	0.9	2.26
H ₂ Compressor 2	8	kW	7245	0.9	2.26
Oil feed pump	29	kW	4296	0.29	1.52
Heatex—HTRX feed preheater	2	m ²	12,890	0.14	2.72
Hydrotreating reactor	696	kg/h	243,859	0.6	2.7
Work recovery Turbine	31	kW	40,121	0.6	1.8
Flash gas sep	696	kg/h	2110	0.72	2.47
Oil water phase sep	28	m ³ /h	99,831	0.65	2.47
EcoQuil cooler	696	kg/h	63,485	0.7	1

<i>Storage</i>					
Biomass storage	20,000	kg/h	649,319	0.5	1
Ash storage	1800	kg/h	194,796	0.5	1
Bio-oil storage	2112	m ³	347,728	0.7	2.47
Hydrogen storage	1377	m ³	1,324,454	0.7	1.99
Oil product storage	246	m ³	157,104	0.7	1.7

¹ includes recycle of biomass within the grinding circuit.

2.2. Operating Cost Components (Material and Utility Price Assumptions)

Table S2. Operating Cost Components (Material and Utility Price Assumptions).

Material/Utility	Price*	Units	Descriptors
Pinewood chips	80	EUR/MT	@38.48 MJ/m ³
Hydrogen	1200	EUR/MT	
Electricity	0.1	EUR/kWh	Selling price is 95% of the purchase price
Steam	27	EUR/tonne	Selling price is 80% of the purchase price
Ash	100	EUR/MT	20% of the purchase price of NPK fertilizer
Process water	1	EUR/m ³	demineralized
Cooling water (river water)	0.05	EUR/m ³	5 deg C max heating
Wastewater treatment	5	EUR/MT	

* all the prices are at average 2018 price levels.

2.3. Catalyst Composition and Cost Data

Table S3. Catalyst composition and cost data.

	Pyrolysis catalysts			Hydrogen production catalysts	Hydrotreating catalysts	
	EUR/kg	Cs/ASA	Na-Alumina	HYZeolite	Ni/Al2O3	NiO/MoO3/Al2O3
Ni	15.08				0.035	0.12
Pt	37348.21					
Mo	24.42				0.155	
Co	35.91					
Cs	45.04	0.1				
Na	0.59		0.12			
Y-Zeolite	1.08			0.99		
H ion	1.23			0.01		
Support	0.00					
Al2O3	4.10	0.55	0.88		0.81	0.88
CNT	4.10					
ASA	4.10	0.35				
Mfg.	4.10	1	1	1	1	1
Support+Mfg.	8.19					
Amount required [kg catalyst/(kg feed/hr)]		0.5	0.5	0.5	1.67	1.67

2.4. Capital and Operating Cost Breakdown for Each Case and Scenario

Table S4. Capital costs (in million EUR).

Process Sections (Installed Costs)	DO_oil				SH_oil				SC_oil			HT_oil			
	Cs/AS A	Na-Al	HY-Z	Thermal	Cs/AS A	Na-Al	HY-Z	Thermal	Cs/ASA	Na-Al	HY-Z	Cs/AS A	Na-Al	HY-Z	Thermal
Pretreatment	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4	3.4
Pyrolysis	9.6	9.6	9.6	9.6	9.6	9.6	9.6	9.6	9.6	9.6	9.6	9.6	9.6	9.6	9.6
Oil separation	2.5	2.4	2.4	2.7	2.5	2.4	2.4	2.7	2.5	2.4	2.4	2.5	2.4	2.4	2.7
Hydrogen production	4.6	4.1	4.4	6.5	4.6	4.1	4.4	6.5	4.6	4.1	4.4	4.6	4.1	4.4	6.5
CHP unit	20.7	22.6	23.4	16.4	20.7	22.6	23.4	16.4	20.7	22.6	23.4	20.7	22.6	23.4	16.4
Hydrotreating	0.0	0.0	0.0	0.0	1.2	1.3	1.0	2.8	0.0	0.0	0.0	1.5	1.9	1.6	0.0
Storage	6.5	5.3	5.5	11.3	6.5	5.3	5.5	11.2	6.5	5.3	5.5	6.4	5.1	5.3	11.3
Total Installed Equipment Cost	33.9	34.0	35.0	35.8	34.8	34.9	35.7	37.8	33.9	34.0	35.0	35.0	35.2	36.0	35.8
Total Direct and Indirect Costs	53.3	53.6	55.0	55.9	54.6	54.9	56.0	58.7	53.3	53.6	55.0	54.8	55.3	56.4	55.9
Contingency	10.7	10.7	11.0	11.2	10.9	11.0	11.2	11.7	10.7	10.7	11.0	11.0	11.1	11.3	11.2
Fixed Capital Investment (FCI)	64.0	64.4	66.0	67.1	65.5	65.9	67.2	70.4	64.0	64.4	66.0	65.8	66.4	67.7	67.1
Working Capital	9.6	9.7	9.9	10.1	9.8	9.9	10.1	10.6	9.6	9.7	9.9	9.9	10.0	10.2	10.1
Total Capital Investment	73.6	74.0	75.9	77.1	75.3	75.8	77.3	81.0	73.6	74.0	75.9	75.7	76.3	77.9	77.1

Table S5. Operating costs (in million EUR/year).

	DO_oil				SH_oil				SC_oil			HT_oil			
	Cs/ASA	Na-Al	HY-Z	Thermal	Cs/ASA	Na-Al	HY-Z	Thermal	Cs/ASA	Na-Al	HY-Z	Cs/ASA	Na-Al	HY-Z	Thermal
Feedstock	13.44	13.44	13.44	13.44	13.44	13.44	13.44	13.44	13.44	13.44	13.44	13.4	13.44	13.44	13.44
Utilities	0.13	0.10	0.12	0.06	0.13	0.10	0.12	0.06	0.13	0.10	0.12	0.1	0.11	0.12	0.06
Waste disposal	0.40	0.41	0.48	0.26	0.40	0.41	0.48	0.26	0.40	0.41	0.48	0.4	0.41	0.48	0.26
Labor costs	2.35	2.30	2.30	2.30	2.30	2.30	2.30	2.30	2.30	2.30	2.30	2.3	2.30	2.30	2.30
Overhead and maintenance (O&M)	2.09	2.06	2.08	2.10	2.07	2.08	2.09	2.13	2.06	2.06	2.08	2.1	2.08	2.10	2.10
Catalyst costs	0.19	0.16	0.19	0.32	0.21	0.18	0.20	0.37	0.19	0.16	0.19	0.2	0.18	0.20	0.32
Other	0.54	0.54	0.55	0.57	0.55	0.55	0.57	0.60	0.54	0.54	0.55	0.6	0.56	0.57	0.57
Total expenses before credit	19.12	19.02	19.16	19.04	19.10	19.07	19.20	19.17	19.05	19.02	19.16	19.1	19.08	19.21	19.04
By-product credit	18.17	19.21	20.32	18.24	18.08	19.18	20.30	18.06	18.10	19.20	20.31	17.9	18.97	20.08	18.24
Net total expenses	0.95	−0.19	−1.16	0.81	1.02	−0.11	−1.10	1.11	0.95	−0.18	−1.15	1.2	0.11	−0.87	0.81

Section S3: LCA Data

3.1. LCA Impact Data

Table S6. LCA impact data.

Parameter	Unit	CED (MJ/unit)	GHG (kg CO ₂ eq./unit)
Steam	kg	1.9	9.0×10^{-2}
Electricity	MJ	3.1	1.9×10^{-1}
Hydrogen	kg	2.3×10^2	$1.3E \times 10^1$
Woodchips	m ³	3.5×10^3	5.3×10^{-2}
Nitrogen	kg	1.8	8.8×10^{-2}
Water, for cooling, decarbonized	kg	9.1×10^{-5}	7.8×10^{-6}
Water, boiler/process softened	kg	3.0×10^{-4}	2.4×10^{-5}
Wastewater, untreated, in treatment	kg	2.5×10^{-1}	8.3×10^{-2}
Lorry	tkm	1.8	1.1×10^{-1}
River barge	tkm	6.6×10^{-1}	4.6×10^{-2}
Ash	kg	3.0	1.8×10^{-1}

3.2. LCA Inventory Data

Table S7. LCA inventory data.

		DO_oil				SH_oil				SC_oil				HT_oil			
Parameter	Unit	Cs/ASA	Na-Al	HY-Z	Thermal	Cs/ASA	Na-Al	HY-Z	Thermal	Cs/ASA	Na-Al	HY-Z	Cs/ASA	Na-Al	HY-Z	Thermal	
Product																	
Biofuel	MJ	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	
Avoided product																	
Hydrogen	kg	1.1×10^{-2}	7.2×10^{-3}	1.3×10^{-2}	1.2×10^{-2}	1.2×10^{-2}	7.3×10^{-3}	1.3×10^{-2}	1.2×10^{-2}	1.2×10^{-2}	7.3×10^{-3}	1.3×10^{-2}	1.1×10^{-2}	6.0×10^{-3}	1.0×10^{-2}	9.6×10^{-3}	
Electricity	MJ	1.6	1.9	3.2	3.8×10^{-1}	1.6	1.9	3.2	3.8×10^{-1}	1.6	1.9	3.2	1.5	1.7	2.8	3.3×10^{-1}	
Steam	kg	8.5×10^{-1}	1.1	1.9	7.3×10^{-2}	8.6×10^{-1}	1.1	1.9	7.0×10^{-2}	8.6×10^{-1}	1.1	1.9	8.2×10^{-1}	1.0	1.6	6.1×10^{-2}	
Ash	kg	6.7×10^{-2}	6.8×10^{-2}	1.1×10^{-1}	2.5×10^{-2}	6.8×10^{-2}	6.9×10^{-2}	1.1×10^{-1}	2.4×10^{-2}	6.8×10^{-2}	6.9×10^{-2}	1.1×10^{-1}	6.4×10^{-2}	6.3×10^{-2}	9.7×10^{-2}	2.1×10^{-2}	
Inputs																	
Woodchips	M3	4.4×10^{-3}	4.5×10^{-3}	7.2×10^{-3}	1.6×10^{-3}	4.5×10^{-3}	4.5×10^{-3}	7.3×10^{-3}	1.6×10^{-3}	4.5×10^{-3}	4.5×10^{-3}	7.3×10^{-3}	4.2×10^{-3}	4.2×10^{-3}	6.4×10^{-3}	1.4×10^{-3}	
Nitrogen	kg	3.7×10^{-2}	3.8×10^{-2}	6.0×10^{-2}	1.4×10^{-2}	3.8×10^{-2}	3.8×10^{-2}	6.1×10^{-2}	1.4×10^{-2}	3.8×10^{-2}	3.8×10^{-2}	6.1×10^{-2}	3.6×10^{-2}	3.5×10^{-2}	5.4×10^{-2}	1.2×10^{-2}	
Boiler Feed water	kg	1.5	1.7	2.9	3.9×10^{-1}	1.5	1.8	2.9	3.9×10^{-1}	1.5	1.8	2.9	1.4	1.6	2.6	3.4×10^{-1}	
Cooling water	kg	1.1×10^1	9.2	1.7×10^1	2.0	1.2×10^1	9.5	1.7×10^1	2.1	1.1×10^1	9.4	1.7×10^1	1.1×10^1	8.9	1.5×10^1	1.9	
Transport lorry >32t	Tkm	5.1×10^{-1}	5.2×10^{-1}	8.3×10^{-1}	1.9×10^{-1}	5.2×10^{-1}	5.2×10^{-1}	8.4×10^{-1}	1.9×10^{-1}	5.2×10^{-1}	5.3×10^{-1}	8.4×10^{-1}	4.9×10^{-1}	4.8×10^{-1}	7.4×10^{-1}	1.6×10^{-1}	
Transport river barge	Tkm	8.1×10^{-1}	8.3×10^{-1}	1.3	3.0×10^{-1}	8.3×10^{-1}	8.4×10^{-1}	1.3	3.0×10^{-1}	8.3×10^{-1}	8.4×10^{-1}	1.3	7.8×10^{-1}	7.7×10^{-1}	1.2	2.6×10^{-1}	
Wastewater	kg	1.6×10^{-1}	1.7×10^{-1}	3.1×10^{-1}	3.8×10^{-2}	1.6×10^{-1}	1.7×10^{-1}	3.2×10^{-1}	3.8×10^{-2}	1.6×10^{-1}	1.7×10^{-1}	3.2×10^{-1}	1.5×10^{-1}	1.6×10^{-1}	2.8×10^{-1}	3.4×10^{-2}	