Electronic Supplementary Material (ESI) for Sustainable Energy & Fuels.

Life cycle analysis (LCA) and economic evaluation of catalytic fast pyrolysis: Implication of co-product's end-usage, catalyst type, and process parameters

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S1. Bio-oil combustion

Bio-oil produced from pyrolysis is combusted to provide energy to the end-user.

Assumptions:

1. Atmospheric air comprising of 21% oxygen and 79% nitrogen was used during combustion.
2. 50% excess air was utilized to ensure complete oxidation.
3. All the nitrogen contained in combustion air is inert and only bio-oil based nitrogen goes to NOx.
4. Nitrogen (N) in bio-oil goes to NO and NO_2.

5. Only 5-10% NO_2 is formed in comparison to NO (NO_2/NO = 10% (assumed)).

6. Sulfur (S) in bio-oil completely converts to SO_2.

Reaction:

$$CH_aO_bN_cS_d + \frac{1}{2}(\frac{11a + 24c + 44d}{22} - b)O_2 \rightarrow CO_2 + \frac{a}{2}H_2O + \frac{c}{1.1}NO + \frac{c}{11}NO_2 + dSO_2 \quad \text{(S1)}$$

Calculation of gaseous emissions:

Suppose M is bio-oil molecular weight and m is the mass of bio-oil (in kg).

CO_2 produced during bio-oil combustion = $44 * \frac{m}{M}$

H_2O produced during bio-oil combustion = $\frac{a}{2} * 18 * \frac{m}{M}$

NO produced during bio-oil combustion = $\frac{c}{1.1} * 30 * \frac{m}{M}$

NO_2 produced during bio-oil combustion = $\frac{c}{11} * 46 * \frac{m}{M}$

SO_2 produced during bio-oil combustion = $d * 64 * \frac{m}{M}$

O_2 fed inside the combustor (50% excess) = $\frac{1}{2}(\frac{11a + 24c + 44d}{22} - b) * 32 * \frac{m}{M} * 1.5$

N_2 present inside combustion air = $\frac{1}{2}(\frac{11a + 24c + 44d}{22} - b) * 32 * \frac{m}{M} * 1.5 * \frac{79}{21} * \frac{28}{32}$

Air fed for bio-oil combustion =

$$\{[\frac{1}{2}(\frac{11a+24c+44d}{22}-b) * 32 * \frac{m}{M} * 1.5] + [\frac{1}{2}(\frac{11a+24c+44d}{22}-b) * 32 * \frac{m}{M} * 1.5 * \frac{79}{21} * \frac{28}{32}]\}$$

(S2)

O_2 unreacted = Total O_2 fed to the combustor - O_2 reacted

Total flue gas produced = CO_2 + H_2O + NO + NO_2 + SO_2 + O_2 + N_2 (S3)

Energy provided for preheating air =

$$\{[\frac{1}{2}(\frac{11a+24c+44d}{22}-b) * 32 * \frac{m}{M} * 1.5] + [\frac{1}{2}(\frac{11a+24c+44d}{22}-b) * 32 * \frac{m}{M} * 1.5 * \frac{79}{21} * \frac{28}{32}]\} * 1.005 * (500-25)$$

(S4)

Bio-oil LHV have been calculated by using eqn (S5). [1]

$$LHV\ (in\ MJ/kg) = HHV - 0.212H - 0.0245M - 0.008Y \quad (S5)$$

Where, LHV is the low heating value of bio-oil (in MJ/kg)

HHV is the high heating value of bio-oil (in MJ/kg)

H is the hydrogen content in bio-oil (in wt.%).

M is moisture content in bio-oil (in wt.%).

Y is the oxygen content in bio-oil (in wt.%).

Elemental composition and high heating value (HHV) of bio-oil is being adopted from past literature. [2,3]

Then, total energy released from bio-oil combustion = bio-oil produced (in kg) * bio-oil LHV (in MJ/kg). (S6)

S2. Biochar combustion

Different percentage of biochar was combusted in different scenarios to provide process energy.

Assumptions:

1. Atmospheric air comprising of 21% oxygen and 79% nitrogen was used during combustion.
2. 50% excess air was utilized to ensure complete oxidation.
3. All the nitrogen contained in combustion air is inert and only biochar-based nitrogen goes to NOx.
4. Nitrogen (N) in biochar goes to NO and NO_2.
5. Only 5-10% NO_2 is formed in comparison to NO (NO_2/NO = 10% (assumed)).
6. Sulfur (S) in biochar completely converts to SO_2.

Reaction:

$$CH_aO_bN_cS_d + \frac{1}{2}(\frac{11a + 24c + 44d}{22} - b)O_2 \rightarrow CO_2 + \frac{a}{2}H_2O + \frac{c}{1.1}NO + \frac{c}{11}NO_2 + dSO_2 \quad \text{(S7)}$$

Calculation of gaseous emissions:

Suppose M is biochar molecular weight and m is the mass of biochar (in kg).

CO_2 produced during biochar combustion = $44 * \frac{m}{M}$

H_2O produced during biochar combustion = $\frac{a}{2} * 18 * \frac{m}{M}$

NO produced during biochar combustion = $\frac{c}{1.1} * 30 * \frac{m}{M}$

NO_2 produced during biochar combustion = $\frac{c}{11} * 46 * \frac{m}{M}$

SO_2 produced during biochar combustion = $d * 64 * \frac{m}{M}$

O_2 fed inside the combustor (50% excess) = $\frac{1}{2}(\frac{11a + 24c + 44d}{22} - b) * 32 * \frac{m}{M} * 1.5$

N_2 present inside combustion air = $\frac{1}{2}(\frac{11a + 24c + 44d}{22} - b) * 32 * \frac{m}{M} * 1.5 * \frac{79}{21} * \frac{28}{32}$

Air fed for biochar combustion =

$$\{[\frac{1}{2}(\frac{11a + 24c + 44d}{22} - b) * 32 * \frac{m}{M} * 1.5] + [\frac{1}{2}(\frac{11a + 24c + 44d}{22} - b) * 32 * \frac{m}{M} * 1.5 * \frac{79}{21} * \frac{28}{32}]\}$$

(S8)

O_2 unreacted = Total O_2 fed to the combustor - O_2 reacted

Total flue gas produced = $CO_2 + H_2O + NO + NO_2 + SO_2 + O_2 + N_2$ (S9)

Energy provided for preheating air =

$$\{[\frac{1}{2}(\frac{11a+24c+44d}{22}-b) * 32 * \frac{m}{M} * 1.5] + [\frac{1}{2}(\frac{11a+24c+44d}{22}-b) * 32 * \frac{m}{M} * 1.5 * \frac{79}{21} * \frac{28}{32}]\} * 1.005 * (500-25)$$

(S10)

Biochar LHV was utilized for calculating energy released during combustion, which has been calculated from the following well established correlation (eqn (S11)): [4]

$$LHV\ (MJ/kg) = HHV * (1-w/100) - (w/100) * 2.444 - 2.444 * (h/100) * 8.936 * (1-w/100) \tag{S11}$$

Where, LHV is lower heating value (in MJ/kg).

HHV is higher heating value (in MJ/kg).

w is the moisture percentage in biochar (in wt.%).

h is the hydrogen percentage in biochar (in wt.%).

Biochar composition (both ultimate and proximate) and HHV has been taken from the previous studies on the same biomass. [5]

Then, total energy released from biochar combustion = biochar combusted (in kg) * biochar LHV (in MJ/kg). (S12)

S3. Non-condensable gas combustion

NCG released during pyrolysis were combusted to provide energy to the process. NCG composed of CO, CO, CH_4 and H_2, out of which CO, CH_4 and H_2 are combustible, and CO_2 is non-combustible.

Assumptions:

1. Atmospheric air comprising of 21% oxygen and 79% nitrogen was used during combustion.
2. 50% excess air was provided for ensuring complete combustion to occur.
3. CO is assumed to be negligible in exhaust gas due to the occurrence of complete oxidation in the presence of excess air.
4. N_2 is inert and doesn't react to NOx

Reactions:

$$CO + 1/2O_2 \rightarrow CO_2 \quad \text{(S13)}$$

$$CH_4 + 2O_2 \rightarrow CO_2 + 2H_2O \quad \text{(S14)}$$

$$H_2 + 1/2O_2 \rightarrow H_2O \quad \text{(S15)}$$

Composition (in mol%) of NCG released during non-catalytic, Al_2O_3 catalyzed and Ni/Al_2O_3 catalyzed pyrolysis has been appended below (based on our previous lab-scale studies): [2,3]

Table S1 Composition of NCG (in mol%) evolved from non-catalytic, Al_2O_3 catalyzed and Ni/Al_2O_3 catalyzed pyrolysis. [2,3]

	Non-catalytic pyrolysis	Al_2O_3 catalyzed pyrolysis	Ni/Al_2O_3 catalyzed pyrolysis
CO_2	46.12	40.06	33.54
CO	31.66	34.41	37.10
CH_4	12.37	13.57	14.62
H_2	9.85	11.96	14.74

Amount of flue gases produced during NCG combustion can be calculated using reactions (S13-S15) occurred during combustion process and composition of NCG (Table S1) (as given above).

Amount of air fed to the combustor = $\frac{29}{32} * \frac{1}{0.21} * O_2\, required\, (50\%\, excess)$ (S16)

Energy released during combustion is dependent on the fuel lower heating value (LHV), which has been calculated by using the following correlation: [6]

$$LHV\ (MJ/Nm^3) = 0.001(126.36 * CO + 107.98 * H_2 + 358.18 * CH_4) \quad \text{(S17)}$$

Density of non-condensable gases can be predicted from its mass fraction composition using eqn (S18):

$$Density\left(\frac{kg}{Nm^3}\right) = \dot{m}_{CO2} * \rho_{CO2} + \dot{m}_{CO} * \rho_{CO} + \dot{m}_{CH4} * \rho_{CH4} + \dot{m}_{H2} * \rho_{H2} \quad \text{(S18)}$$

Energy required (in MJ) to preheat air to combustion temperature of NCG = m*1.005*(600-25) (S19)

Where, m represents the total amount of NCG combusted in kg.

Total energy released during combustion = LHV (MJ/kg) * m (kg) (S20)

Table S2 depicts the attributes of NCG combustion calculated for all 3 processes.

Table S2 Different attributes of NCG combustion from non-catalytic, Al_2O_3 catalyzed and Ni/Al_2O_3 catalyzed pyrolysis (for functional unit of 1 MJ energy production from bio-oil).

	Non-catalytic pyrolysis	**Al_2O_3 catalyzed pyrolysis**	**Ni/Al_2O_3 catalyzed pyrolysis**
LHV (MJ/kg)	6.260	7.119	8.077
Pre-heating energy required (MJ)	0.0349	0.0455	0.0444
Total combustion energy released (MJ)	0.126	0.160	0.151
Air fed (Nm^3)	0.0501	0.0654	0.0368
Exhaust released (kg)	0.0804	0.101	0.0956

S4. Condenser 1 and 2

Specific heat capacity of NCG, $C_{p,NCG}$ = $\dot{m}_{CO2} * C_{p,\ CO2} + \dot{m}_{CO} * C_{p,CO} + \dot{m}_{CH4} * C_{p,CH4} + \dot{m}_{H2} * C_{p.H2}$

(S21)

Specific heat capacity of bio-oil [7], $C_{p,bio\text{-}oil}$ = 2.435 kJ/kg K (S22)

Specific heat capacity of bio-oil, $C_{p,volatiles}$ = $\dot{m}_{bio-oil} * C_{p,\ bio-oil} + \dot{m}_{NCG} * C_{p,NCG}$

(S23)

Total heat of condensation of volatiles = $m_{volatiles} * C_{p,volatiles} * (550\text{-}25)$ (S24)

Applying energy balance on condenser:

$m_{volatiles} * C_{p,volatiles} * (550\text{-}25) = m_{water} * C_{p,water} * (T_{water,\ out} - T_{water,\ in})$ (S25)

Using eqn (S25), mass of condensation water (m_{water}) can be calculated for a given amount of volatiles and inlet and outlet water temperature.

Table S3 Inventory input-output data utilized for LCA of non-catalytic pyrolysis in the 4 different scenarios.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Remarks
Functional unit	1 MJ energy produced	1 MJ energy produced	1 MJ energy produced	1 MJ energy produced	
Inputs					
Pine needles (kg)	0.117	0.117	0.117	0.117	
DE: Diesel mix at refinery (biomass transportation) (kg)	0.00046	0.00046	0.00046	0.00046	Ecoinvent 3.8[a]
DE: Thermal energy from natural gas (drying) (MJ)	0.0256	0.0256	0.0256	0.0256	[4]
DE: Electricity grid mix (chopping) (MJ)	0.00287	0.00287	0.00287	0.00287	[8,9]
DE: Electricity grid mix (grinding) (MJ)	0.0204	0.0204	0.0204	0.0204	[10]
DE: Thermal energy from natural gas (pyrolysis) (MJ)	0.543	0.417	0.17	-	[11–13]
DE: Tap water from groundwater (condenser 1) (kg)	0.211	0.211	0.211	0.211	Using eqn (S25)

DE: Tap water from groundwater (condenser 2) (kg)	0.0705	0.0705	0.0705	0.0705	Using eqn (S25)
DE: Diesel mix at refinery (bio-oil transportation) (kg)	0.000212	0.000212	0.000212	0.000212	Ecoinvent 3.8[a]
DE: Thermal energy from natural gas (bio-oil combustion) (MJ)	0.255	0.255	0.255	0.116	Using eqn (S4)
GLO: Air (bio-oil combustion) (Nm^3)	0.443	0.443	0.443	0.443	Using eqn (S2)
DE: Thermal energy from natural gas (NCG combustion) (MJ)	-	0.0349	0.0349	0.0349	Using eqn (S19)
GLO: Air (NCG combustion) (Nm^3)	-	0.0501	0.0501	0.0501	Using eqn (S16)
GLO: Air (biochar combustion) (Nm^3)	-	-	0.147	0.331	Using eqn (S8)
Output					
Biochar (kg)	0.0316	-	-	-	[2]
Non-condensable gases (NCG) (kg)	0.0201	-	-	-	[2]
Off-gases (bio-oil combustion) (kg)	0.587	0.587	0.587	0.587	Using eqn (S3)
Off-gases (NCG combustion) (kg)	-	0.0804	0.0804	0.0804	Using eqn (S13-15)

					and Table S1
Off-gases (biochar combustion) (kg)	-	-	0.191	0.431	Using eqn (S9)
Biochar to coal credit (kg)	-	0.0316	0.0189	0.00316	Table 1

[a] GLO, Truck (diesel driven), Euro 6, up to 7.5t gross weight and 2.7t payload capacity.

Table S4 Inventory input-output data utilized for LCA of Al_2O_3 catalyzed pyrolysis in the 4 different scenarios.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Remarks
Functional unit	1 MJ energy produced	1 MJ energy produced	1 MJ energy produced	1 MJ energy produced	
Inputs					
Pine needles (kg)	0.116	0.116	0.116	0.116	
DE: Diesel mix at refinery (biomass transportation) (kg)	0.000453	0.000453	0.000453	0.000453	Ecoinvent 3.8[a]
DE: Thermal energy from natural gas (drying)	0.0252	0.0252	0.0252	-	[4]

(MJ)					
DE: Electricity grid mix (chopping) (MJ)	0.00283	0.00283	0.00283	0.00283	[8,9]
DE: Electricity grid mix (grinding) (MJ)	0.02	0.02	0.02	0.02	[10]
DE: Thermal energy from natural gas (pyrolysis) (MJ)	0.534	0.374	0.166	-	[11–13]
EU: Alumina (Al_2O_3) (catalyst) (kg)	0.104	0.104	0.104	0.104	Ecoinvent 3.8[b]
DE: Tap water from groundwater (condenser 1) (kg)	0.208	0.208	0.208	0.208	Using eqn (S25)
DE: Tap water from groundwater (condenser 2) (kg)	0.0694	0.0694	0.0694	0.0694	Using eqn (S25)
DE: Diesel mix at refinery (bio-oil transportation) (kg)	0.000198	0.000198	0.000198	0.000198	Ecoinvent 3.8[a]
DE: Thermal energy from natural gas (bio-oil combustion) (MJ)	0.253	0.253	0.253	0.166	Using eqn (S4)
GLO: Air (bio-oil combustion) (Nm^3)	0.44	0.44	0.44	0.44	Using eqn (S2)
DE: Thermal energy from natural gas (NCG	-	0.0455	0.0115	-	Using eqn (S19)

combustion) (MJ)					
GLO: Air (NCG combustion) (Nm^3)	-	0.0654	0.0654	0.0654	Using eqn (S16)
GLO: Air (biochar combustion) (Nm^3)	-	-	0.144	0.325	Using eqn (S8)
Output					
Biochar (kg)	0.031	-	-	-	[3]
Non-condensable gases (NCG) (kg)	0.0225	-	-	-	[3]
Off-gases (bio-oil combustion) (kg)	0.581	0.581	0.581	0.581	Using eqn (S3)
Off-gases (NCG combustion) (kg)	-	0.101	0.101	0.101	Using eqn (S13-15) and Table S1
Off-gases (biochar combustion) (kg)	-	-	0.188	0.423	Using eqn (S9)
Biochar to coal credit (kg)	-	0.031	0.0186	0.0031	Table 1

[a] GLO, Truck (diesel driven), Euro 6, up to 7.5t gross weight and 2.7t payload capacity.

[b] EU-28, Alumina production 2015, production of smelter grade alumina, single route, at plant (3.94 g/cm^3).

Table S5 Inventory input-output data utilized for LCA of Ni/Al_2O_3 catalyzed pyrolysis in the 4 different scenarios.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4	Remarks
Functional unit	1 MJ energy produced	1 MJ energy produced	1 MJ energy produced	1 MJ energy produced	
Inputs					
Pine needles (kg)	0.0863	0.0863	0.0863	0.0863	
DE: Diesel mix at refinery (biomass transportation) (kg)	0.000338	0.000338	0.000338	0.000338	Ecoinvent 3.8[a]
DE: Thermal energy from natural gas (drying) (MJ)	0.0188	0.0188	0.0188	0.0112	[4]
DE: Electricity grid mix (chopping) (MJ)	0.00211	0.00211	0.00211	0.00211	[8,9]
DE: Electricity grid mix (grinding) (MJ)	0.015	0.015	0.015	0.015	[10]
DE: Thermal energy from natural gas (pyrolysis) (MJ)	0.399	0.247	0.124	-	[11–13]
EU: Alumina (Al_2O_3) (catalyst) (kg)	0.0706	0.0706	0.0706	0.0706	Ecoinvent 3.8[b]
DE: Water (desalinated; deionised) (catalyst impregnation) (kg)	0.706	0.706	0.706	0.706	[3]

DE: Electricity grid mix (catalyst impregnation) (MJ)	0.0224	0.0224	0.0224	0.0224	Using instrument power rating
DE: Thermal energy from natural gas (catalyst drying) (MJ)	0.0373	0.0373	0.0373	0.0373	Using instrument power rating
DE: Electricity grid mix (catalyst calcination) (MJ)	0.00932	0.00932	0.00932	0.00932	Using instrument power rating
DE: Tap water from groundwater (condenser 1) (kg)	0.155	0.155	0.155	0.155	Using eqn (S25)
DE: Tap water from groundwater (condenser 2) (kg)	0.0518	0.0518	0.0518	0.0518	Using eqn (S25)
DE: Diesel mix at refinery (bio-oil transportation) (kg)	0.000138	0.000138	0.000138	0.000138	Ecoinvent 3.8[a]
DE: Thermal energy from natural gas (bio-oil combustion) (MJ)	0.241	0.241	0.179	0.124	Using eqn (S4)
GLO: Air (bio-oil combustion) (Nm^3)	0.419	0.419	0.419	0.419	Using eqn (S2)
DE: Thermal energy from natural gas (NCG	-	0.0444	0.0444	-	Using eqn (S19)

combustion) (MJ)					
GLO: Air (NCG combustion) (Nm^3)	-	0.0368	0.0368	0.0368	Using eqn (S16)
GLO: Air (biochar combustion) (Nm^3)	-	-	0.0918	0.206	Using eqn (S8)
Output					
Biochar (kg)	0.0237	-	-	-	[3]
Non-condensable gases (NCG) (kg)	0.0188	-	-	-	[3]
Off-gases (bio-oil combustion) (kg)	0.54	0.54	0.54	0.54	Using eqn (S3)
Off-gases (NCG combustion) (kg)	-	0.0956	0.0956	0.0956	Using eqn (S13-15) and Table S1
Off-gases (biochar combustion) (kg)	-	-	0.144	0.323	Using eqn (S9)
Biochar to coal credit (kg)	-	0.0237	0.0142	0.00237	Table 1

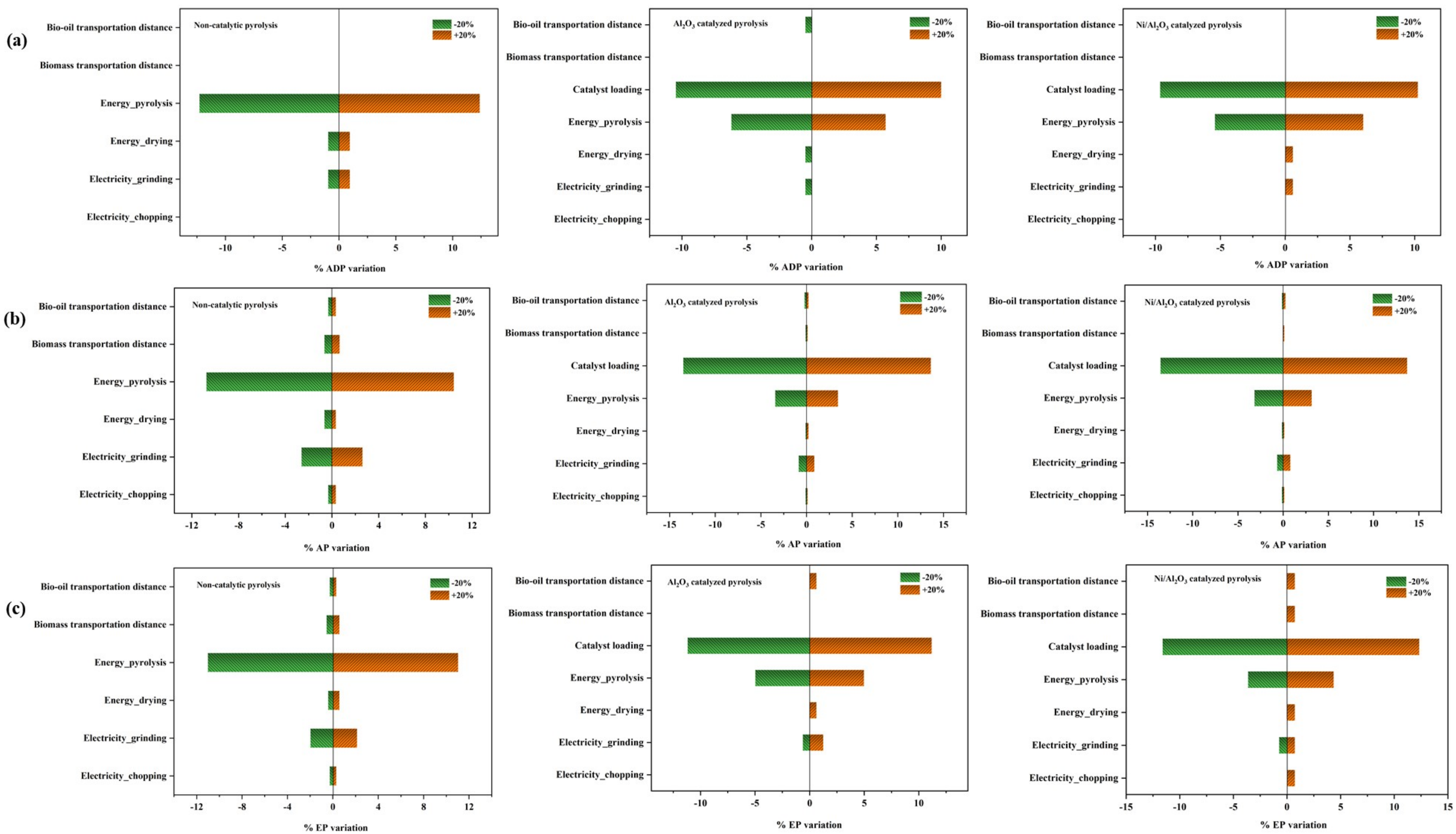
[a] GLO, Truck (diesel driven), Euro 6, up to 7.5t gross weight and 2.7t payload capacity.

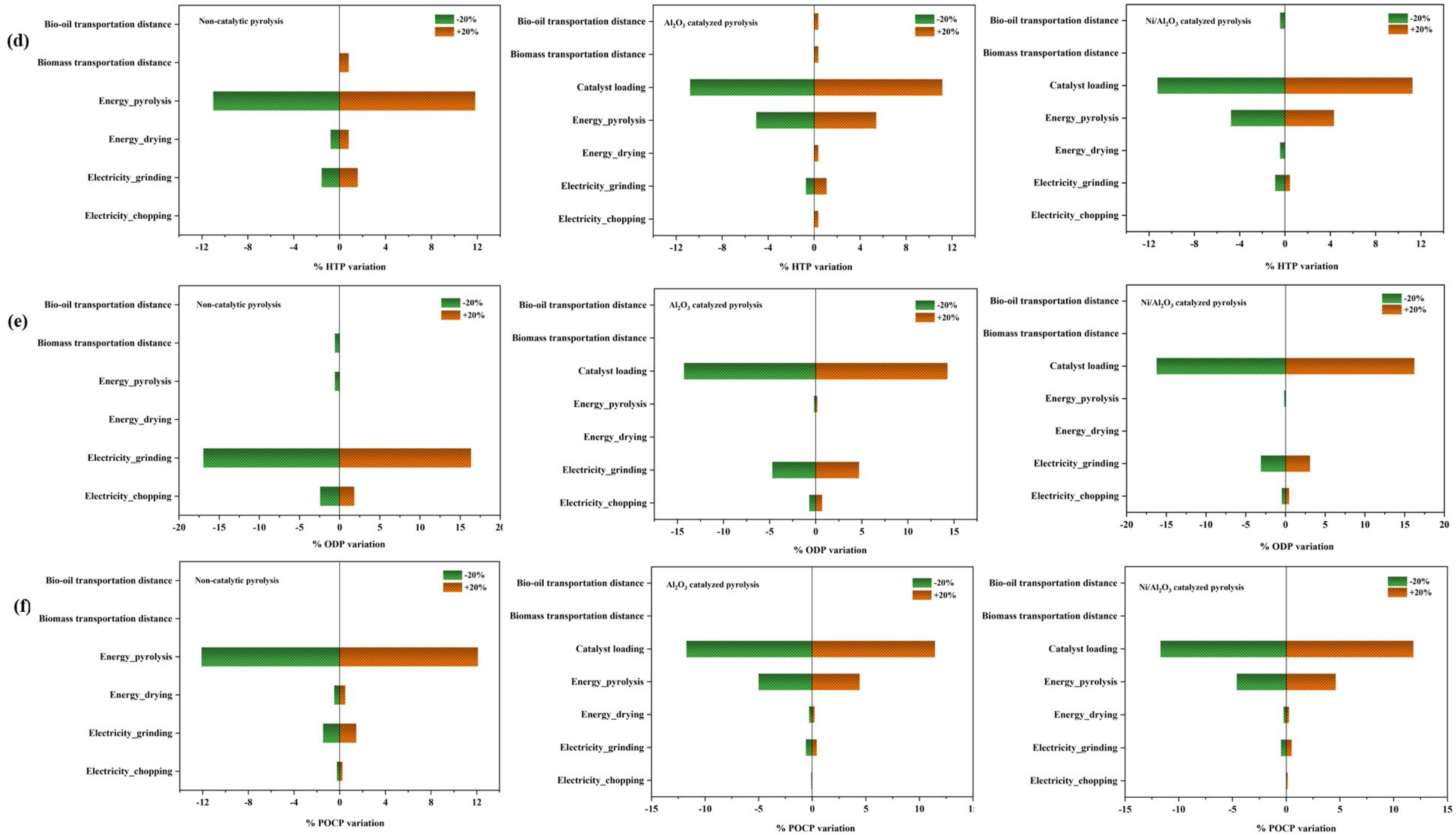
[b] EU-28, Alumina production 2015, production of smelter grade alumina, single route, at plant (3.94 g/cm^3).

Table S6 Ecoinvent 3.8 inventory datasets employed for non-catalytic and catalytic pyrolysis system

Inventories	Inventory database names*
Diesel	DE│Diesel mix at refinery│from crude oil and bio components│production mix, at refinery│10 ppm sulfur, 6.19% bio components
Truck	GLO│Truck (diesel driven), Euro 6│up to 7.5t gross weight, 2.7t payload capacity
Thermal energy from natural gas	DE│Thermal energy from natural gas│technology mix regarding firing and flue gas cleaning│production mix, at plant heat│100% efficiency
Electricity	DE│Electricity grid mix│AC, technology mix│consumer mix, to consumer
Alumina	EU-28│Alumina production 2015│production of smelter grade alumina│single route, at plant│3.94 g/cm^3
Water (for catalyst preparation)	DE│Water (desalinated; deionised) │ via ion exchange│single route, at plant│1000 kg/m^3, 18 g/mol
Water (for condensation)	DE│Tap water from groundwater│filtration, disinfection, ion removement, etc.│production mix, at plant│1000 kg/m^3, 18 g/mol
Air	GLO│Compressed air 7 bar (low power consumption)│7 bar, high efficiency│consumer mix, at plant│low electricity consumption

*DE: Germany; GLO: Global; EU: European Union


(a)
Non-catalytic pyrolysis
-20%
+20%
Bio-oil transportation distance
Biomass transportation distance
Energy_pyrolysis
Energy_drying
Electricity_grinding
Electricity_chopping
-10
-5
0
5
10
% ADP variation
Al_2O_3 catalyzed pyrolysis
-20%
+20%
Bio-oil transportation distance
Biomass transportation distance
Catalyst loading
Energy_pyrolysis
Energy_drying
Electricity_grinding
Electricity_chopping
-10
-5
0
5
10
% ADP variation
Ni/Al_2O_3 catalyzed pyrolysis
-20%
+20%
Bio-oil transportation distance
Biomass transportation distance
Catalyst loading
Energy_pyrolysis
Energy_drying
Electricity_grinding
Electricity_chopping
-10
-5
0
5
10
% ADP variation
(b)
Non-catalytic pyrolysis
-20%
+20%
Bio-oil transportation distance
Biomass transportation distance
Energy_pyrolysis
Energy_drying
Electricity_grinding
Electricity_chopping
-12
-8
-4
0
4
8
12
% AP variation
Al_2O_3 catalyzed pyrolysis
-20%
+20%
Bio-oil transportation distance
Biomass transportation distance
Catalyst loading
Energy_pyrolysis
Energy_drying
Electricity_grinding
Electricity_chopping
-15
-10
-5
0
5
10
15
% AP variation
Ni/Al_2O_3 catalyzed pyrolysis
-20%
+20%
Bio-oil transportation distance
Biomass transportation distance
Catalyst loading
Energy_pyrolysis
Energy_drying
Electricity_grinding
Electricity_chopping
-15
-10
-5
0
5
10
15
% AP variation
(c)
Non-catalytic pyrolysis
-20%
+20%
Bio-oil transportation distance
Biomass transportation distance
Energy_pyrolysis
Energy_drying
Electricity_grinding
Electricity_chopping
-12
-8
-4
0
4
8
12
% EP variation
Al_2O_3 catalyzed pyrolysis
-20%
+20%
Bio-oil transportation distance
Biomass transportation distance
Catalyst loading
Energy_pyrolysis
Energy_drying
Electricity_grinding
Electricity_chopping
-10
-5
0
5
10
% EP variation
Ni/Al_2O_3 catalyzed pyrolysis
-20%
+20%
Bio-oil transportation distance
Biomass transportation distance
Catalyst loading
Energy_pyrolysis
Energy_drying
Electricity_grinding
Electricity_chopping
-15
-10
-5
0
5
10
15
% EP variation



(d)
Non-catalytic pyrolysis
Al$_2$O$_3$ catalyzed pyrolysis
Ni/Al$_2$O$_3$ catalyzed pyrolysis
-20%
+20%
Bio-oil transportation distance
Biomass transportation distance
Catalyst loading
Energy_pyrolysis
Energy_drying
Electricity_grinding
Electricity_chopping
% HTP variation
(e)
% ODP variation
(f)
% POCP variation

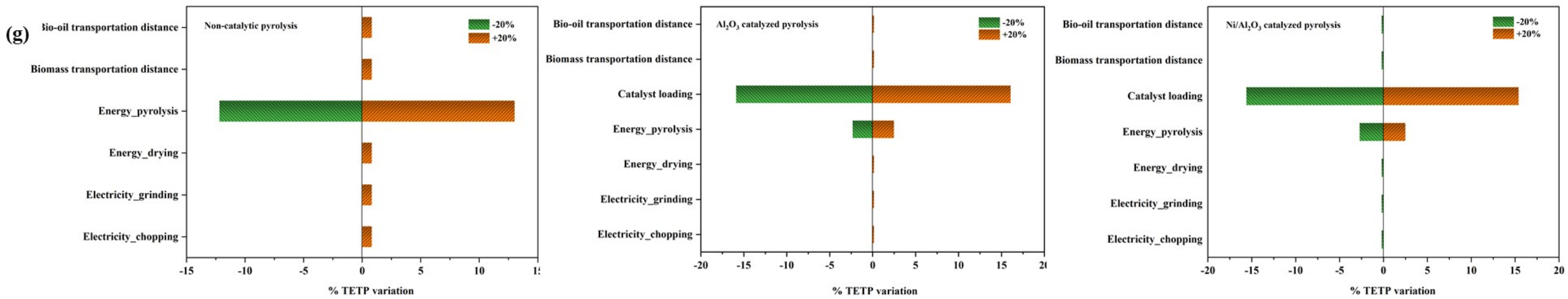


Fig. S1. Parameter sensitivity analysis in (a) ADP, (b) AP, (c) EP, (d) HTP, (e) ODP, (f) POCP and (g) TETP impact categories for non-catalytic, Al_2O_3 and Ni/Al_2O_3 catalyzed pyrolysis using CML 2001 – August 2016 method.

Table S7 Impact of introducing two different energy mix databases (Germany and India) on the environmental metrices of non-catalytic pyrolysis as per CML 2001 – Aug 2016 method

	Sc 1		Sc 2		Sc 3		Sc 4	
	Germany	**India**	**Germany**	**India**	**Germany**	**India**	**Germany**	**India**
ADP fossil	1.05	1.12	0.057	0.13	0.12	0.17	0.19	0.23
AP	3.07E-05	0.000166	-6.68E-05	6.20E-05	-3.63E-05	7.50E-05	1.78E-06	9.13E-05
EP	7.08E-06	2.38E-05	-7.41E-06	7.72E-06	-3.65E-06	7.32E-06	1.05E-06	6.82E-06
FAETP inf.	4.23E-05	4.49E-05	-9.55E-06	-6.95E-06	3.27E-06	5.96E-06	1.93E-05	2.21E-05
GWP	0.061	0.069	-0.033	-0.026	-0.014	-0.0085	0.0089	0.013
HTP inf.	0.0013	0.0032	-0.0008	0.0012	-0.00035	0.0016	0.00021	0.0022
MAETP inf.	0.59	10.6	-4.49	5.50	-2.52	7.48	-0.061	9.96
ODP, steady state	1.65E-16	3.75E-17	1.54E-16	2.74E-17	1.56E-16	3.08E-17	1.59E-16	3.49E-17
POCP	4.13E-06	1.32E-05	-4.73E-06	3.75E-06	-2.49E-06	4.34E-06	3.02E-07	5.07E-06
TETP inf.	0.00012	2.25E-05	6.01E-05	-2.88E-05	4.62E-05	-1.00E-05	2.88E-05	1.34E-05

Table S8 Impact of introducing two different energy mix databases (Germany and India) on the environmental metrices of Al_2O_3 catalyzed pyrolysis as per CML 2001 – Aug 2016 method

	Sc 1		**Sc 2**		**Sc 3**		**Sc 4**	
	Germany	**India**	**Germany**	**India**	**Germany**	**India**	**Germany**	**India**
ADP fossil	2.09	2.25	1.09	1.24	1.15	1.29	1.22	1.35
AP	9.33E-05	0.00039	-3.06E-06	0.00028	2.68E-05	0.00029	6.42E-05	0.00031
EP	1.61E-05	4.95E-05	1.72E-06	3.32E-05	5.41E-06	3.28E-05	1.00E-05	3.23E-05
FAETP inf.	8.96E-05	0.000108	3.80E-05	5.62E-05	5.06E-05	6.89E-05	6.63E-05	8.47E-05
GWP	0.15	0.17	0.056	0.071	0.075	0.089	0.098	0.11
HTP inf.	0.0028	0.0074	0.00072	0.0054	0.0011	0.0058	0.0017	0.0064
MAETP inf.	1.79	25.31	-3.20	20.32	-1.27	22.26	1.14	24.69
ODP, steady state	5.74E-16	2.77E-16	5.64E-16	2.67E-16	5.66E-16	2.70E-16	5.68E-16	2.74E-16
POCP	9.96E-06	2.90E-05	1.15E-06	1.94E-05	3.34E-06	2.00E-05	6.09E-06	2.07E-05
TETP inf.	0.00060	0.00042	0.00054	0.00037	0.00052	0.00039	0.00051	0.00041

Table S9 Impact of introducing two different energy mix databases (Germany and India) on the environmental metrices of Ni/Al_2O_3 catalyzed pyrolysis as per CML 2001 – Aug 2016 method

	Sc 1		**Sc 2**		**Sc 3**		**Sc 4**	
	Germany	**India**	**Germany**	**India**	**Germany**	**India**	**Germany**	**India**
ADP fossil	1.66	1.82	0.87	1.03	0.91	1.06	0.97	1.11
AP	7.59E-05	0.00039	1.63E-06	0.00031	2.45E-05	0.00032	5.31E-05	0.00033
EP	1.38E-05	4.30E-05	2.69E-06	3.00E-05	5.51E-06	2.97E-05	9.04E-06	2.94E-05
FAETP inf.	7.95E-05	0.00010	3.94E-05	6.53E-05	4.91E-05	7.50E-05	6.11E-05	8.71E-05
GWP	0.12	0.13	0.045	0.060	0.059	0.074	0.076	0.089
HTP inf.	0.0023	0.0083	0.00069	0.0067	0.0010	0.0070	0.0015	0.0075
MAETP inf.	1.86	32.08	-1.97	28.26	-0.49	29.74	1.35	31.59
ODP, steady state	6.47E-16	2.69E-16	6.39E-16	2.61E-16	6.40E-16	2.64E-16	6.42E-16	2.67E-16
POCP	8.03E-06	2.69E-05	1.21E-06	1.93E-05	2.89E-06	1.98E-05	4.98E-06	2.03E-05
TETP inf.	0.00044	0.00031	0.00039	0.00028	0.00038	0.00029	0.00036	0.00031

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