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D3.7 Update of LCA-LCC in ABP treatment by HTL pyrolysis process

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ACRONYMS AND ABBREVIATIONS

Acronym/Abbreviation	Description
ABP	Animal by-products
HTL	Hydrothermal liquefaction
UA	University of Alicante
EU	European Union
LCA	Life cycle assessment
LCC	Life cycle cost
LCI	Life cycle inventory
AP	Aqueous phase
GC/MS	Gas chromatography / Mass detector
TGA	Thermogravimetric analysis

1. Summary

In this report, the Life Cycle Assessment and Life Cycle Cost for an ABP hydrothermal liquefaction plant have been developed. Simultaneously, a similar analysis for a conventional pyrolysis plant has been prepared, to compare the environmental impacts produced in both cases as well as the costs of both plants.

Inputs and outputs involved in both processes have been estimated. In the LCA, 7 main categories have been selected to define the burdens in the life cycle inventory: gas, bio-crude, aqueous phase, power, solid, water and nitrogen. The ReCiPe 2008 method has been selected to calculate life cycle impact category indicators.

Capital as well as operational costs for HTL and pyrolysis plants have been considered in the LCC.

From both points of view, environmental and economic aspects, choice of HTL is favoured versus the conventional pyrolysis for this type of material and the plant configuration proposed.

2. Introduction

Deliverable D3.6 related with LCA-LCC in ABP treatment by HTL process was presented in the month 30 of the project. Some conclusions were obtained about the environmental impacts of the process and the items that could mainly affect. Nevertheless, as was indicated in that report, the study performed by that time was considered a preliminary study. In this deliverable, a more extended analysis is presented. Thus, the total amount of nitrogen and phosphorous in each phase has been determined and included in the analysis. The addition of free water at the steady state in the HTL has been removed, since the raw material has high water content, although the purge has been necessary to increase up to 14.7%. These facts modify some of the values obtained in the previous LCA, although many of the conclusions deduced in that report are still valid. The LCA of a conventional pyrolysis of animal by-products has been also performed in order to compare these two technologies. The LCC for both processes has been also included in this deliverable.

Figures 1 and 2 show the schemes of both technologies compared in this report: HTL and pyrolysis process. All the values in this deliverable are referred to a treatment of 5000 kg/h of ABP which is an average value of this type of sub-products generated in a medium size province in Spain.

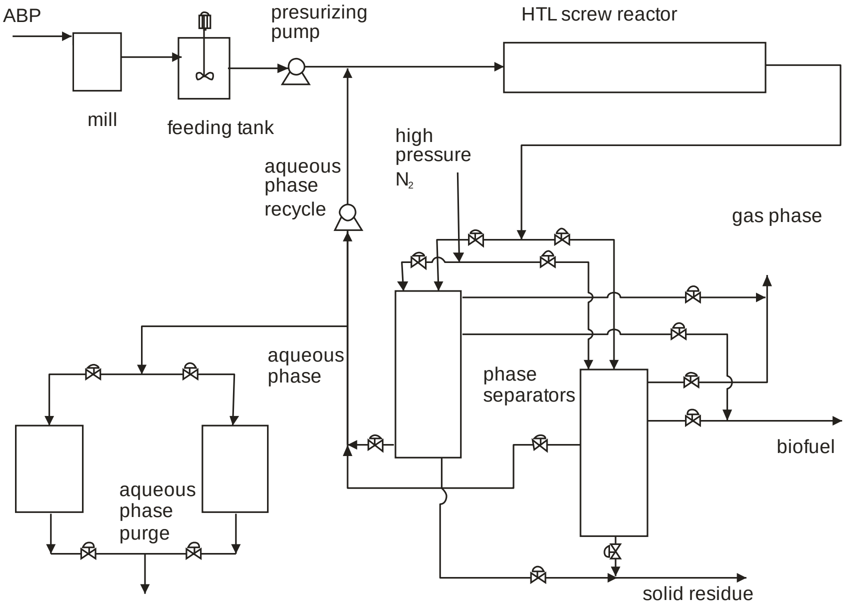


Figure 1 Scheme for HTL process

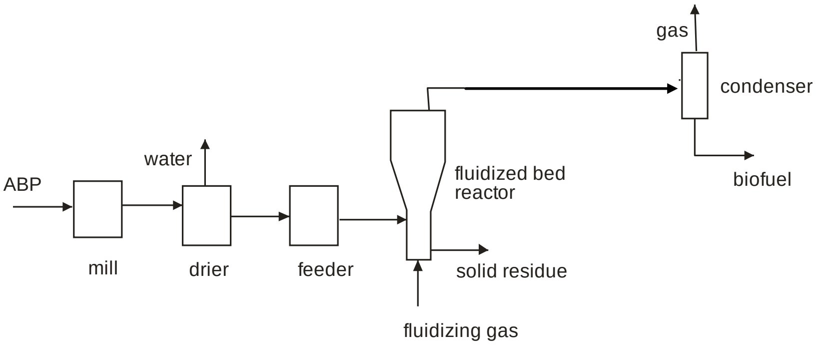


Figure 2 Scheme for pyrolysis process

The yields of the fractions obtained in the HTL process are (expressed as kg fraction/100 kg raw material):

% gas: 0.57
% biocrude: 42.1
% aqueous phase: 43.3
% solid: 14

For the case of the pyrolysis process, these values are (expressed in the same units):

% gas: 11.6
% liquid: 33.6
% solid: 17.7

The difference up to 100 corresponds to the water removed in the drying process (37.1%).

The operational parameters selected present the following values:

HTL:

Final moisture in the process (%): 80
Preactor (atm). 170
Pinitial (atm): 1
Paqueous phase recycling (atm): 165
Treactor (ºC). 250
Tinitial (ºC): 25
Taqueous phase recycling (ºC): 225

Pyrolysis:

Preactor (atm): 1
Tdryer (ºC): 120
Treactor (ºC). 525

3. Life Cycle Assessment

The LCA developed follows the same methodology as that used in the preliminary study.

The burdens included in the Life Cycle Inventory (LCI) for both processes are shown in Tables 1 and 2.

Table 1 Life Cycle Inventary of the HTL and Pyrolysis processes

Data LCA Animal by-products (ABP)		
LCI	**HTL**	**PYROLYSIS**
Animal by-products (kg/h)	5000	5000
Drying power (kW)	-	1467
Milling+ mixing power (kW)	72	69
Pump power (kW)	36	-
Heating power (kW)	1035	774
Water (kg/h)	-	2110
N_2 (kg/h)	-	106
Solids (kg/h)	700	885

Table 2 Components included in each category of the LCI of the HTL and Pyrolysis processes

EMISSIONS

PYROLYSIS

#	GAS PHASE	FLOW (kg/h)
1	Ammonia	0.71
2	carbon dioxide	412.10
3	carbon monoxide	63.42
4	methane	30.73
5	ethane	24.37
6	ethylene	21.30
7	Ethyne	0.07
8	propane	26.71
9	propylene	25.37
10	isobutane	5.03
11	n-butane	6.73
12	1-butylene	18.36
13	propyne	0.21
14	1,3-butadiene	16.02
15	cis-2-butene	1.93
16	trans-butene	1.59
17	isobutene	0.19
18	isopentane	5.33
19	n-pentane	1.30
20	1-pentene	2.19
21	1-butyne	0.29
22	isoprene	2.21
23	n-hexane	0.67
24	2-butyne	14.15
25	1-hexene	0.83
26	cis-2-hexene	0.34
27	heptane	0.73
28	Benzenepropanenitrile	0.58
29	acetaldehyde	2.37
30	1-heptene	3.12
31	2,2-dimethylhexane	1.12
32	acraldehyde	5.81
33	propionaldehyde	63.38
34	toluene	5.24
	Biocrude	**FLOW (kg/h)**
35	N total (Elemental analysis)	142.2
36	1H-Pyrrole	158.8
37	Toluene	52.3
38	1H-Pyrrole, 3-methyl-	123.9
39	Phenol	37.1
40	2-Pyridinamine	85.4
41	Phenol, 4-methyl-	25.2
42	Benzyl nitrile	9.8
43	2,5-Pyrrolidinedione, 3-methyl-	86.4
44	Piperidinone	74.3
45	Benzenepropanenitrile	12.3
46	2,4-Imidazolidinedione, 5-methyl-	32.8
47	1H-Indole	280.4
48	1,3-Cyclopentanedione	10.6
49	Pyrrole-2-carboxamide	100.9
50	7-Methylindole	99.6
51	1-Piperidinepropanenitrile	82.9
52	2(1H)-Pyrimidinone, 4-amino-	167.8
53	Pyrimidine, 2,4,5-triamino-	160.2
54	1,4-Benzenediol, 2,3,5-trimethyl-	4.8
55	Pentadecane	6.3
56	N-dimethyl-3-methyl-3-nonamine	6.3
57	8-Heptadecene	9.6
58	Tetradecanoic acid	7.9
59	2-Heptadecanone	8.4
60	3,9-diazatricyclo[7.3.0.0(3,7)]dodecan-2,8-dione	71.0
61	Hexadecanoic acid	56.3
62	6-Tetradecyne	8.9
63	3,5-dioxocycloundecane-1-carbonitrile	11.9
64	8-Octadecenoic acid, methyl ester	1.4
65	2-Nonadecanone-	2.6
66	9-Octadecenoic acid (Z)-	30.2
67	Octadecanoic acid-	7.7
68	Hexadecanamide	7.1
	Solids	**FLOW (kg/h)**
69	N total (Elemental analysis)	14.63
70	Phosphoro total	36.9
	Services	**FLOW (kg/h)**
71	Electricity (medium voltage)	2258
72	Tap water	2110
73	N2	279

HTL

#	GAS PHASE	FLOW (kg/h)
1	Ammonia	0.035
2	carbon dioxide	28.011
3	carbon monoxide	0.120
4	methane	0.007
5	ethane	0.010
6	ethylene	0.013
7	propane	0.006
8	propylene	0.003
9	isobutane	0.004
10	n-butane	0.008
11	1-butylene	0.001
12	propyne	0.000
13	1,3-butadiene	0.003
14	isopentane	0.058
15	n-pentane	0.005
16	1-butyne	0.001
17	n-hexane	0.002
18	Acetaldehyde	0.013
	Biocrude	**FLOW (kg/h)**
19	N total (Elemental analysis)	121.5
20	Tetradecanoic acid	14.9
21	9-Hexadecenoic acid	35.8
22	Palmitic acid (Hexadecanoic acid)	196.1
23	Oleic acid	394.9
24	Octadecanoic acid	31.4
25	Hexanedioic acid, dioctyl ester	44.1
26	9-Octadecenoic acid (Z)-, 2-hydroxy-1-(hydroxymethyl)ethyl ester	120.9
27	Octadecanoic acid, 2-hydroxy-1-(hydroxymethyl)ethyl ester	18.9
28	Tetradecanamide	8.9
29	8-hexadecenamide (Z)	27.7
30	Hexadecanamide	71.9
31	9-Octadecenamide, (Z)	162.6
32	Octadecanamide	32.9
33	9-Octadecenamide, N,N-dimethyl	13.1
34	Oleic diethanolamide	19.7
35	N ,N-DIMETYLPALMITAMIDE	8.9
36	Hexanal, O-methyloxime	12.9
37	1H-Indole-3-acetic acid, ethyl ester	11.9
38	1H-Indene, 2-butyl-3-hexyl- (PAH)	19.5
39	2-Methyl-3-(4-methoxybenzoyl)indole	213.0
40	Pyrrolidine, 1-(1-oxo-9-octadecenyl)-,	46.8
41	Lanol (Cholest-5-en-3-ol)	20.0
42	3,9-DIAZATRICYCLO[7.3.0.0(3,7)]DODECAN-2,8-DIONE	27.5
	Aqueous phase	**FLOW (kg/h)**
43	N total (Elemental analysis)	3.19
44	OCTANOIC ACID	0.15
45	Acetamide	0.07
46	Propanamide	0.04
47	2,4(1H,3H)-Pyrimidinedione, 5-methyl-	0.36
48	Pyrrolidine	0.46
49	N-Ethylpyrrrolidine	0.52
50	2-pyrrolidinone	0.18
51	2,5-Pyrrolidinedione,1-methyl	0.11
52	Pyrrolo[1,2-a]pyrazine-1,4-dione, hexahydro-	3.91
53	Pyrrolo[1,2-a]pyrazine-1,4-dione, hexahydro-3-(2-methylpropyl)-	0.53
54	3-benzyl-1,4-diaza-2,5-dioxobicyclo[4.3.0]nonane	0.74
55	3,9-DIAZATRICYCLO[7.3.0.0(3,7)]DODECAN-2,8-DIONE	1.60
56	1,4-diaza-2,5-dioxobicyclo[4.3.0]nonane	8.84
57	Piperidine	0.01
58	2-piperidinone	0.76
59	2,5-Piperazinedione, 3-methyl-6-(1-methylethyl)-	0.54
60	2,5-Piperazinedione, 3-methyl-6-(phenylmethyl)-	1.07
61	2,5-Piperazinedione, 3-(phenylmethyl)-	1.64
62	2,5-Piperazinedione, 3-benzyl-6-isopropyl-	0.20
63	2-benzyl-3,6-dioxo-5-isopropylpiperazine	0.15
64	1,4,5,6-TETRAHYDRO-1,3,5-TRIMETHYL-AS-TRAZINE	0.12
65	maltol (3-hidroxi-2-metil-4H-piran-4-ona)	0.45
66	Glicerina	4.64
67	Caprolactam	0.13
68	Ornithine	1.13
69	2H-Azepin-2-one, 3-aminohexahydro-	0.64
70	2-(dimethylhydrazono)butanal	1.24
71	2,4-Imidazolidinedione, 1-methyl-	1.08
72	4-cyanomethylquinoline	1.29
73	3-ETHOXY-4-METHOXYPHENOL	1.19
74	Phenol, 3,5-dimethoxy-	4.92
75	[1,1'-Biphenyl]-3-ol	2.15
76	2-Methyl-9-hydroxyphenalenone	0.91
77	Hydantoin, 1-butyl-	0.41
78	2,5-Cyclohexadiene-1,4-dione, 2,5-dihydroxy-3-methoxy-6-methyl-	1.04
79	4-oxo-2,2a,3,4-tetrahydrophenaleno[1,9-bc]furan	0.94
80	prolylleucyl anhydride	1.38
	Solids	**FLOW (kg/h)**
81	N total (Elemental analysis)	14.63
82	Phosphorous (total)	36.9
	Services	**FLOW (kg/h)**
83	Electricity (medium voltage)	1092

In this study 7 categories have been included: gas phase, biocrude, aqueous phase, power, solids, water and nitrogen. The last two only affects the conventional pyrolysis and the aqueous phase is only formed in the HTL process. The model developed includes all the different components of each category. As in the preliminary analysis, contributions of the infrastructures needed and the effect of CO_2 transport are neglected in this study.

As in deliverable D3.6, the energy consumed in the HTL process has been estimated as the energy needed to heat the solution up to the process temperature, the energy consumed in the reactor inlet pump and the energy required in grinding. In the case of the pyrolysis process, the total energy needed includes also the energy required to dry the raw material.

In order to build the LCA model, the ReCiPe 2008 methodology has been selected to calculate life cycle impact category indicators. Eighteen impact categories are included in this model (Table 3). Initially, a mid-point level with a hierarchist perspective (H) has been selected. The impact factors corresponding to the different burdens have been obtained from the Ecoinvent Data Base 3.3. (Swiss Centre for Life Cycle Inventories) and ReCiPe methodology.

Table 3 Impact categories

Impact categories at midpoint level	**Unit**	
terrestrial acidification (TAP)	kg SO2-Eq	(to air)
terrestrial ecotoxicity (TETP)	kg 1,4-DC. -Eq	(to industrial soil)
freshwater eutrophication (FEP)	kg P-Eq-Eq	(to fresh water)
freshwater ecotoxicity (FETP)	kg 1,4-DC. -Eq	(to fresh water)
marine eutrophication (MEP)	kg N-Eq	(to fresh water)
marine ecotoxicity (METP)	kg 1,4-DC. -Eq	(to marine water)
agricultural land occupation (ALOP)	m^2 x y	(agricultural land)
urban land occupation (ULOP)	m^2 x y	(urban land)
natural land transformation (NLTP)	m^2	(natural land)
climate change (GWP)	kg CO2-Eq	(to air)
human toxicity (HTP)	kg 1,4-DC. -Eq	(to urban air)
photochemical oxidant formation (POFP)	kg NMVOC-Eq	(to air)
ozone depletion (ODP)	kg CFC-11. -Eq	(to air)
particulate matter formation (PMFP)	kg PM10-Eq	(to air)
ionising radiation (IRP)	kg U235-Eq	(to air)
fossil depletion (FDP)	kg oil-Eq	(oil)
metal depletion (MDP)	kg Fe-Eq	(Fe)
water depletion (WDP)	m^3	(water)

The LCA has been developed in collaboration with the research group COnCEPT (Computer Optimization of Chemical Engineering Processes and Technologies) of the University of Alicante.

Table 4 shows the equivalence used between the compounds identified in the products and those used in the present LCA using ReCiPe methodology.

Table 4 Compounds identified in products and the ones used for factors in ReCiPe

	EMISSIONS	
	PYROLYSIS	
	Identified Compounds of Products	Selected Compounds in ReCiPe
#	GAS PHASE	
1	Ammonia	Ammonia
2	carbon dioxide	Carbon dioxide
3	carbon monoxide	Carbon monoxide
4	methane	Methane
5	ethane	Ethane
6	ethylene	Ethene
7	Ethyne	Hydrocarbons, aliphatic, alkanes, cyclic
8	propane	Propane
9	propylene	Propene
10	isobutane	Isobutane
11	n-butane	Butane
12	1-butylene	1-Butene
13	propyne	Hydrocarbons, aliphatic, alkanes, cyclic
14	1,3-butadiene	Butadiene
15	cis-2-butene	2-Butene (cis)
16	trans-butene	2-Butene (trans)
17	isobutene	Isobutene
18	isopentane	Isopentane
19	n-pentane	Pentane
20	1-pentene	1-Pentene
21	1-butyne	1-Pentene
22	isoprene	Isoprene
23	n-hexane	Hexane
24	2-butyne	Hydrocarbons, aliphatic, alkanes, cyclic
25	1-hexene	Hexane
26	cis-2-hexene	Hexane
27	heptane	Heptane
28	Benzenepropanenitrile	Benzene
29	acetaldehyde	Acetaldehyde
30	1-heptene	1-Hexene
31	2,2-dimethylhexane	Hexane, 3 methyl
32	acraldehyde	Aldehydes, unspecified
33	propionaldehyde	Propanal
34	toluene	Toluene
	Biocrude	
35	N total (Elemental analysis)	Nitrogen, organic bound
36	1H-Pyrrole	Pyrrole
37	Toluene	Toluene
38	1H-Pyrrole, 3-methyl-	2-Acetyl-1-methylpyrrole
39	Phenol	3,4-dimethylphenol
40	2-Pyridinamine	4,6-Dimethyl-2-pyridinamine
41	Phenol, 4-methyl-	3,4-dimethylphenol
42	Benzyl nitrile	ACETONITRILE
43	2,5-Pyrrolidinedione, 3-methyl-	2-Pyrrolidinone
44	Piperidinone	piperine
45	Benzenepropanenitrile	lactonitrile
46	2,4-Imidazolidinedione, 5-methyl-	1-n-butylimidazole
47	1H-Indole	Indole
48	1,3-Cyclopentanedione	Cyclopentanone
49	Pyrrole-2-carboxamide	6-Amino-3-pyridinecarboxamide
50	7-Methylindole	3-Methylindole
51	1-Piperidinepropanenitrile	N-Nitrosopiperidine
52	2(1H)-Pyrimidinone, 4-amino-	5-((3,4,5-trimethoxyphenyl)methyl)-2,4-pyrimidinediamine
53	Pyrimidine, 2,4,5-triamino-	5-((3,4,5-trimethoxyphenyl)methyl)-2,4-pyrimidinediamine
54	1,4-Benzenediol, 2,3,5-trimethyl-	tert-butylhydroquinone
55	Pentadecane	n-decane
56	N-dimethyl-3-methyl-3-nonamine	nonylamine
57	8-Heptadecene	n-decane
58	Tetradecanoic acid	2-Ethylhexanoic acid
59	2-Heptadecanone	2-Decanone
60	3,9-diazatricyclo[7.3.0.0(3,7)]dodecan-2,8-dione	1,4-diazobicyclo[2.2.2]octane
61	Hexadecanoic acid	(E)-2-Hexenoic acid
62	6-Tetradecyne	n-decane
63	3,5-dioxocycloundecane-1-carbonitrile	4-biphenylcarbonitrile
64	8-Octadecenoic acid, methyl ester	Dibutyl adipate
65	2-Nonadecanone-	2-Decanone
66	9-Octadecenoic acid (Z)-	(E)-2-Hexenoic acid
67	Octadecanoic acid-	2-Ethylhexanoic acid
68	Hexadecanamide	Hexanamide
	Solids	
69	N total (Elemental analysis)	Fertiliser, applied (N component)
70	Phosphoro total	Phosphorus, total
	Services	
71	Electricity (medium voltage)	Market Electricity medium voltage
72	Tap water	Market Tap Water
73	N_2	Nitrogen, liquid

	EMISSIONS	
	HTL	
	Identified Compounds of Products	Selected Compounds in ReCiPe
#	GAS PHASE	
1	Ammonia	Ammonia
2	carbon dioxide	Carbon dioxide
3	carbon monoxide	Carbon monoxide
4	methane	Methane
5	ethane	Ethane
6	ethylene	Ethene
7	propane	Propane
8	propylene	Propene
9	isobutane	Isobutane
10	n-butane	Butane
11	1-butylene	1-Butene
12	propyne	Hydrocarbons, aliphatic, alkanes, cyclic
13	1,3-butadiene	Butadiene
14	isopentane	Isopentane
15	n-pentane	Pentane
16	1-butyne	Hydrocarbons, aliphatic, alkanes, cyclic
17	n-hexane	Hexane
18	Acetaldehyde	Acetaldehyde
	Biocrude	
19	N total (Elemental analysis)	Nitrogen, organic bound
20	Tetradecanoic acid	2-Ethylhexanoic acid
21	9-Hexadecenoic acid	(E)-2-Hexenoic acid
22	Palmitic acid (Hexadecanoic acid)	2-Ethylhexanoic acid
23	Oleic acid	(E)-2-Octenoic acid
24	Octadecanoic acid	2-Ethylhexanoic acid
25	Hexanedioic acid, dioctyl ester	Dibutyl adipate
26	9-Octadecenoic acid (Z)-, 2-hydroxy-1-(hydroxymethyl)ethyl ester	Lactic acid, Isopropyl ester
27	Octadecanoic acid, 2-hydroxy-1-(hydroxymethyl)ethyl ester	Lactic acid, Isopropyl ester
28	Tetradecanamide	Hexanamide
29	8-hexadecenamide (Z)	Hexanamide
30	Hexadecanamide	Hexanamide
31	9-Octadecenamide, (Z)	Hexanamide
32	Octadecanamide	Hexanamide
33	9-Octadecenamide, N,N-dimethyl	Armeen DM 16D
34	Oleic diethanolamide	Hexanamide
35	N ,N-DIMETYLPALMITAMIDE	Armeen DM 16D
36	Hexanal, O-methyloxime	Acetoxime
37	1H-Indole-3-acetic acid, ethyl ester	Indole-3-acetic acid
38	1H-Indene, 2-butyl-3-hexyl- (PAH)	PAH, polycyclic aromatic hydrocarbons
39	2-Methyl-3-(4-methoxybenzoyl)indole	4,9-Dihydro-7-methoxy-1-methyl-3H-pyrido(3,4-b)indole
40	Pyrrolidine, 1-(1-oxo-9-octadecenyl)-,	N-methylpyrrolidine
41	Lanol (Cholest-5-en-3-ol)	Vitamin A acid
42	3,9-DIAZATRICYCLO[7.3.0.0(3,7)]DODECAN-2,8-DIONE	1,4-diazobicyclo[2.2.2]octane
	Aqueous phase	
43	N total (Elemental analysis)	Nitrogen, organic bound
44	OCTANOIC ACID	(E)-2-Octenoic acid
45	Acetamide	ACETAMIDE
46	Propanamide	ACETAMIDE
47	2,4(1H,3H)-Pyrimidinedione, 5-methyl-	epsilon-caprolactam
48	Pyrrolidine	N-methylpyrrolidine
49	N-Ethylpyrrrolidine	N-methylpyrrolidine
50	2-pyrrolidinone	2-Pyrrolidinone
51	2,5-Pyrrolidinedione,1-methyl	2-Pyrrolidinone
52	Pyrrolo[1,2-a]pyrazine-1,4-dione, hexahydro-	2-Pyrrolidinone
53	Pyrrolo[1,2-a]pyrazine-1,4-dione, hexahydro-3-(2-methylpropyl)-	2-Pyrrolidinone
54	3-benzyl-1,4-diaza-2,5-dioxobicyclo[4.3.0]nonane	1,4-diazobicyclo[2.2.2]octane
55	3,9-DIAZATRICYCLO[7.3.0.0(3,7)]DODECAN-2,8-DIONE	1,4-diazobicyclo[2.2.2]octane
56	1,4-diaza-2,5-dioxobicyclo[4.3.0]nonane	1,4-diazobicyclo[2.2.2]octane
57	Piperidine	piperine
58	2-piperidinone	piperine
59	2,5-Piperazinedione, 3-methyl-6-(1-methylethyl)-	1-n-butylimidazole
60	2,5-Piperazinedione, 3-methyl-6-(phenylmethyl)-	1-(Phenylmethyl)-1H-imidazole
61	2,5-Piperazinedione, 3-(phenylmethyl)-	1-(Phenylmethyl)-1H-imidazole
62	2,5-Piperazinedione, 3-benzyl-6-isopropyl-	1-Benzylpiperazine
63	2-benzyl-3,6-dioxo-5-isopropylpiperazine	1-Benzylpiperazine
64	1,4,5,6-TETRAHYDRO-1,3,5-TRIMETHYL-AS-TRAZINE	Atrazine
65	maltol (3-hidroxi-2-metil-4H-piran-4-ona)	3-Hydroxy-2-phenyl-4H-1-benzopyran-4-one
66	Glicerina	1,2,3-Propanetriol
67	Caprolactam	epsilon-caprolactam
68	Ornithine	11-Aminoundecanoic acid
69	2H-Azepin-2-one, 3-aminohexahydro-	Dinitrosohomopiperazine
70	2-(dimethylhydrazono)butanal	Isovaleraldehyde
71	2,4-Imidazolidinedione, 1-methyl-	1-n-butylimidazole
72	4-cyanomethylquinoline	6-Nitroquinoline
73	3-ETHOXY-4-METHOXYPHENOL	2-methoxy-4-methylphenol
74	Phenol, 3,5-dimethoxy-	2-methoxy-4-methylphenol
75	[1,1'-Biphenyl]-3-ol	4,4'-biphenyldiol
76	2-Methyl-9-hydroxyphenalenone	phenanthrenequinone
77	Hydantoin, 1-butyl-	5,5-Dimethylhydantoin
78	2,5-Cyclohexadiene-1,4-dione, 2,5-dihydroxy-3-methoxy-6-methyl-	5,5-Dimethyl-1,3-cyclohexanedione
79	4-oxo-2,2a,3,4-tetrahydrophenaleno[1,9-bc]furan	5-(Hydroxymethyl)-2-furancarboxaldehyde
80	prolylleucyl anhydride	1-(Phenylmethyl)-1H-imidazole
	Solids	
81	N total (Elemental analysis)	Fertiliser, applied (N component)
82	Phosphorous (total)	Phosphorus, total
	Services	
83	Electricity (medium voltage)	Market Electricity medium voltage

Figure 3 compares the contribution of each burden at each of the 18 impact categories for both processes.

Before analysing the results obtained, it must be clarified that the LCA has been performed considering the schemes proposed in Figures 1 and 2. Therefore, the analysis of the use of product streams has not been included in the assessment.

In the LCA, aspects such as ecotoxicity or eutrophication are evaluated as if the product streams were poured with no control. But that is not the case. The production of most of the streams generated is the target of the process; therefore the products obtained are going to be used and they cannot be considered as waste. A full LCA would imply to know the use of each one of these products and the impacts generated in their use. This type of analysis would need a wider experimental study in order to get the required information, which is out of the limits of this project.

Qualitatively it can be said that, in the case of the HTL, the use of the aqueous phase as fertilizer could be interesting, as well as the extraction of some compounds with added value, such as glycerine. On the other hand, the main objective of the process is the production of biocrude to be used as fuel, therefore energy will be recovered from this stream. A similar analysis can be performed with the products generated in the pyrolysis process, where biocrude as well as gas phase are potential energy sources.

All these aspects must be kept in mind when the results of the LCA developed are interpreted.

According to Figure 3, as can be seen, the energy consumption represents the main contribution in 11 impact categories for both processes; in all of them, the value in the pyrolysis process is higher than that of the HTL due to the drying step of the sample previous to the pyrolysis step. It must be remained that, as shown in Figure 1, the water used in the HTL process is recycled before cooling down the product.

In those categories affected by gas phase significantly, such as photochemical oxidant or climate change, pyrolysis shows always a higher influence, since the yield of gas generated in pyrolysis is much higher than that produced in the HTL process. A mistake has been detected in this category in data presented in last deliverable (D3.6), where gas phase data expressed as percentage were used as if they were expressed per unit. That error has been corrected in this report, which has been already prepared with right and coherent units.

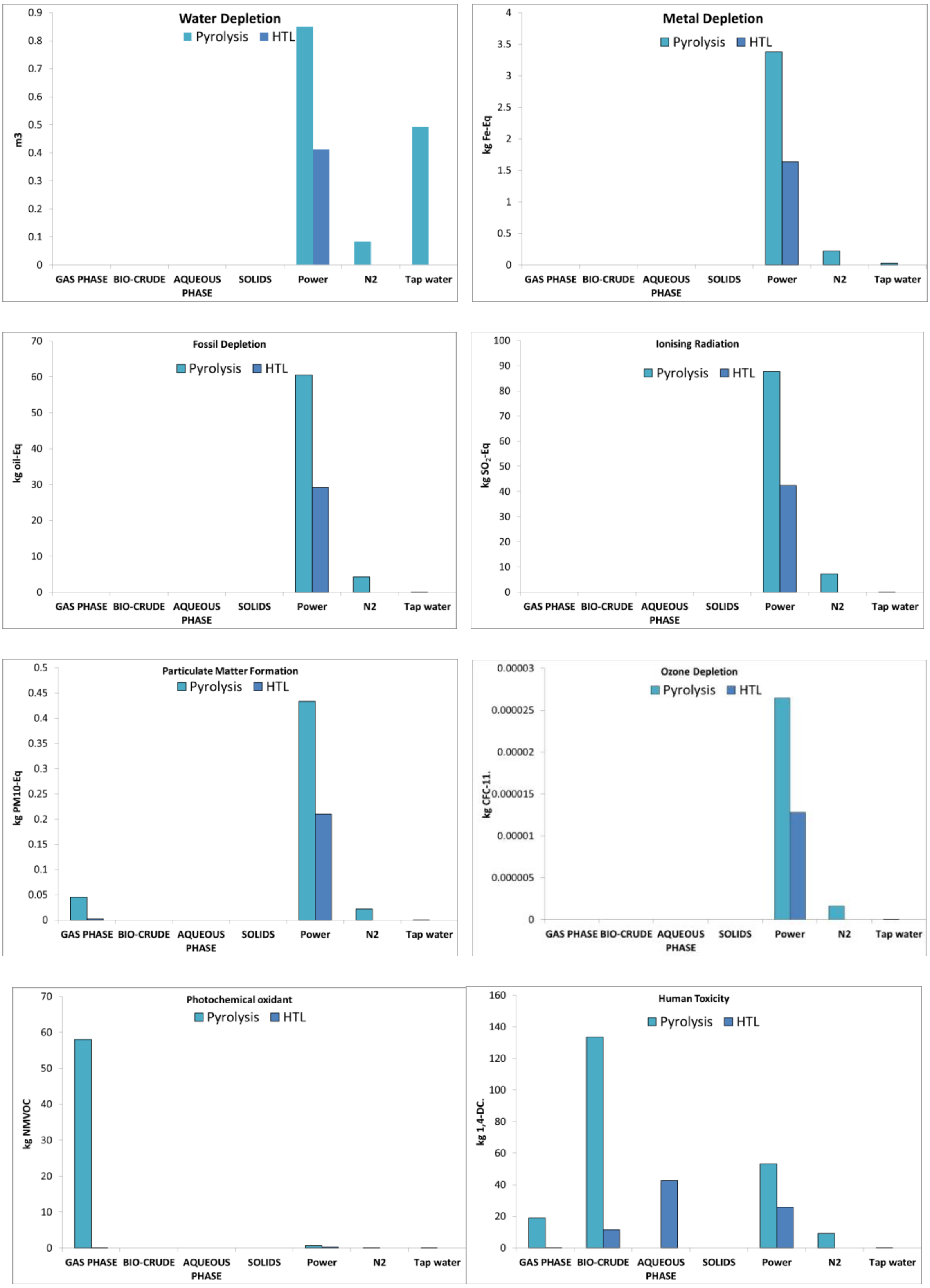


Figure 3 Contribution of each burden at the impact categories (midpoint level)

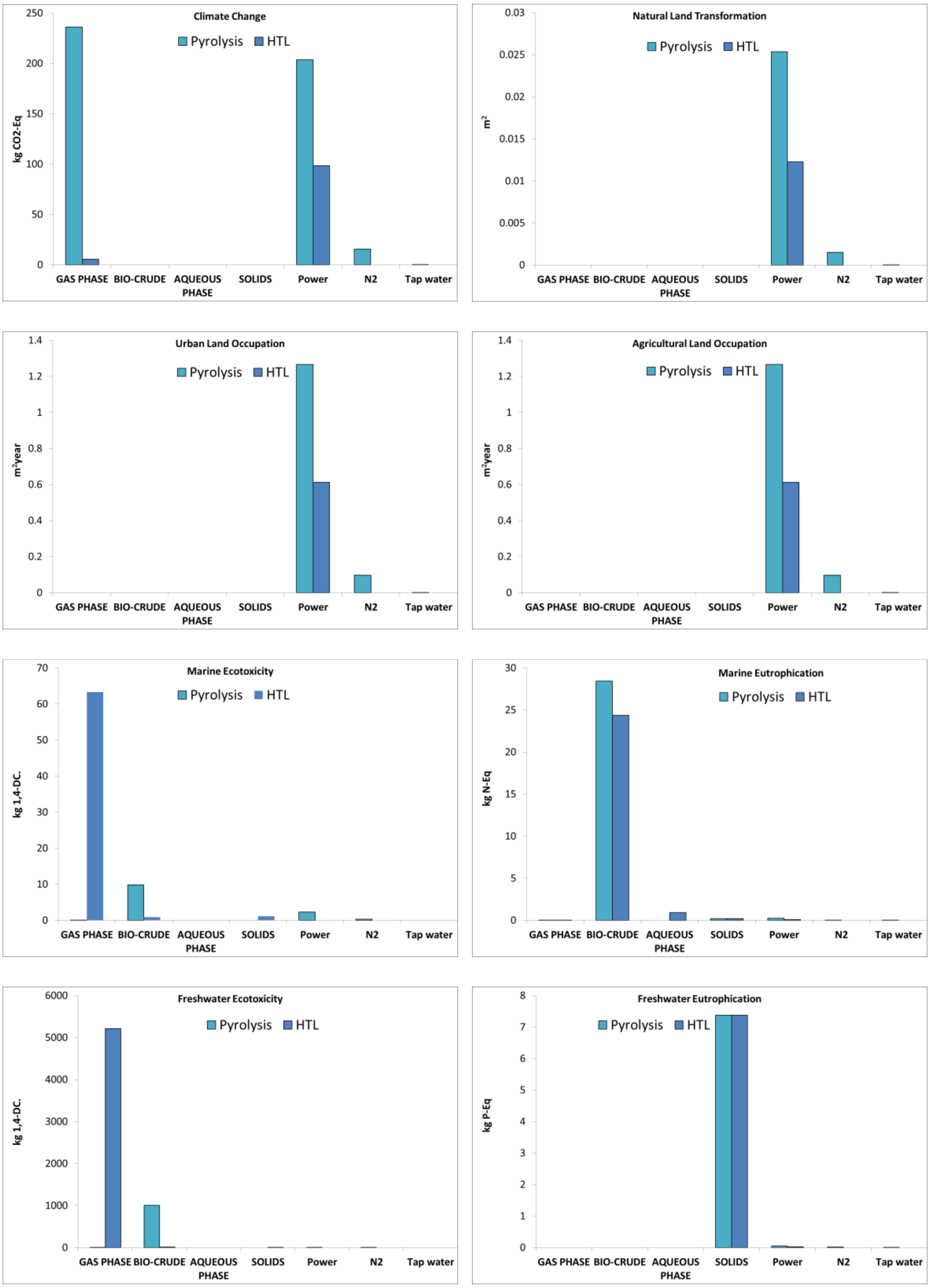


Figure 3 Contribution of each burden at the impact categories (midpoint level) (continued)

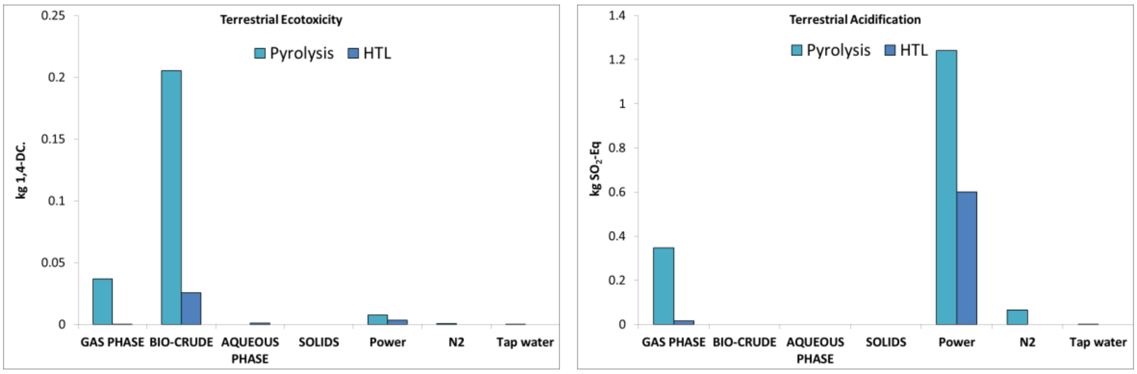


Figure 3 Contribution of each burden at the impact categories (midpoint level) (continued)

In categories related with eutrophication (freshwater and marine) the inclusion of new data of nitrogen and phosphorous content in solids has changed the effect of burdens, comparing with the analysis in D3.6. In the case of the freshwater eutrophication, solids play the main role (in case they were poured with no control). The phosphorous content in the raw material remains in the solid in pyrolysis as well as in HTL; therefore, the effect on the eutrophication would be the same in both processes. When marine eutrophication is analysed, the nitrogen present in all the phases must be considered. In this case, nitrogen compounds in the biocrude produced reach the highest values. Although both processes yield similar values, the effect of pyrolysis is higher.

In case of the biocrude stream was poured, this burden would show the highest effect on the categories related with ecotoxicity (terrestrial, freshwater and marine). In the case of terrestrial, the pyrolysis shows the main impact, while in the case of freshwater and marine ecotoxicity the biocrude coming from the HTL process shows the main weight, due to the significant yield of lanol (Cholest-5-en-3-ol) in this product. All the phases affect the human toxicity, biocrude being the main one. In this case, the effect of pyrolytic biocrude is higher than that of the HTL product, due to the formation of phenol and nitrile derivatives.

According to the results obtained, the LCA performed allows concluding that, from 18 impact categories studied, 15 categories are more affected by a conventional pyrolysis than by the HTL process, 1 of them is affected similarly by both processes and in 2 categories (freshwater and marine ecotoxicity) HTL shows higher impacts.

If it is considered that the biocrude obtained from both processes is a fuel that is going to be burnt for energy, the products obtained at the end of the global process are very similar. However, although the calorific value of the biocrude obtained in a conventional pyrolysis is not available in literature, due to the characteristics of both processes, it cannot be higher than the one obtained in the HTL process, since the water produced in the pyrolysis remains in the biocrude, without being separated in an aqueous phase. Moreover, it is known that the percentage of biocrude obtained in the HTL is higher than that generated in the pyrolysis (about 25% higher). These aspects indicate that the energy obtained from HTL process will be always higher than the one from pyrolysis. Thus, all these aspects, not considered in the LCA developed, would additionally reduce the impact of HTL biocrude vs. that of the pyrolysis and would also favor the choice of HTL vs. conventional pyrolysis for this type of raw material. Consequently, we can conclude from this study that HTL is a very attractive alternative, compared to conventional pyrolysis, for treating this type of residues.

Figures 4 and 5 show the contribution of each component considered in the LCI in the corresponding impact at midpoint level for both processes. These figures allow detecting which components show the higher effect on each impact category (numbers listed in these figures correspond with number and names listed in table 2). Thus, for example, in HTL process it can be seen that compounds such as lanol or pyridine derivatives (coloured in red) stand out among others together with the presence of N in the biocrude and the consumption of power. In the case of pyrolysis, compounds generated such as propionaldehyde and indole together with the presence of P in solids and the power consumption are emphasised.

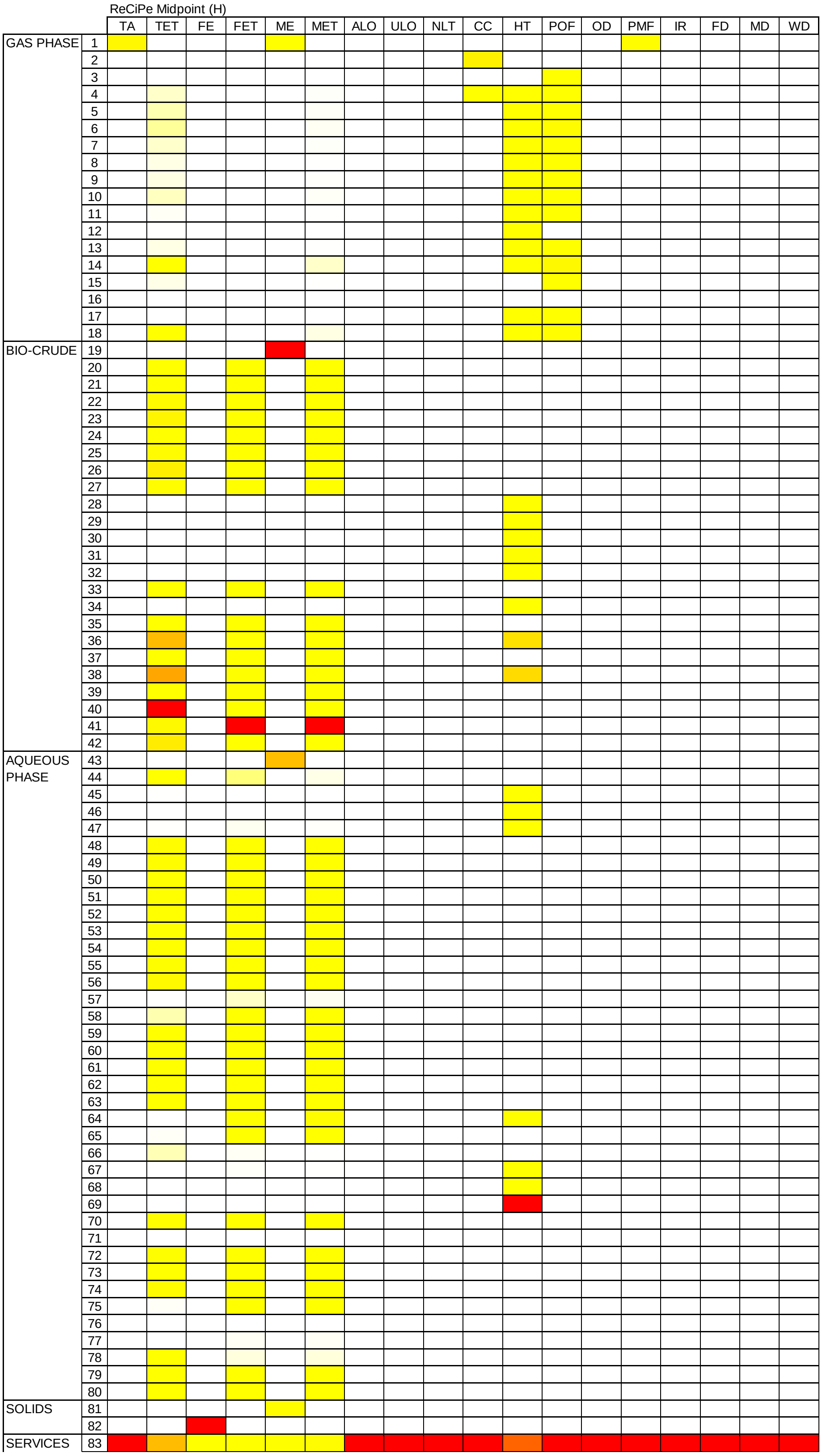


Figure 4 Heatmap of the contribution of each component of the LCI in the corresponding impact at mitpoint level, ReCiPe midpoint (H) for HTL process.

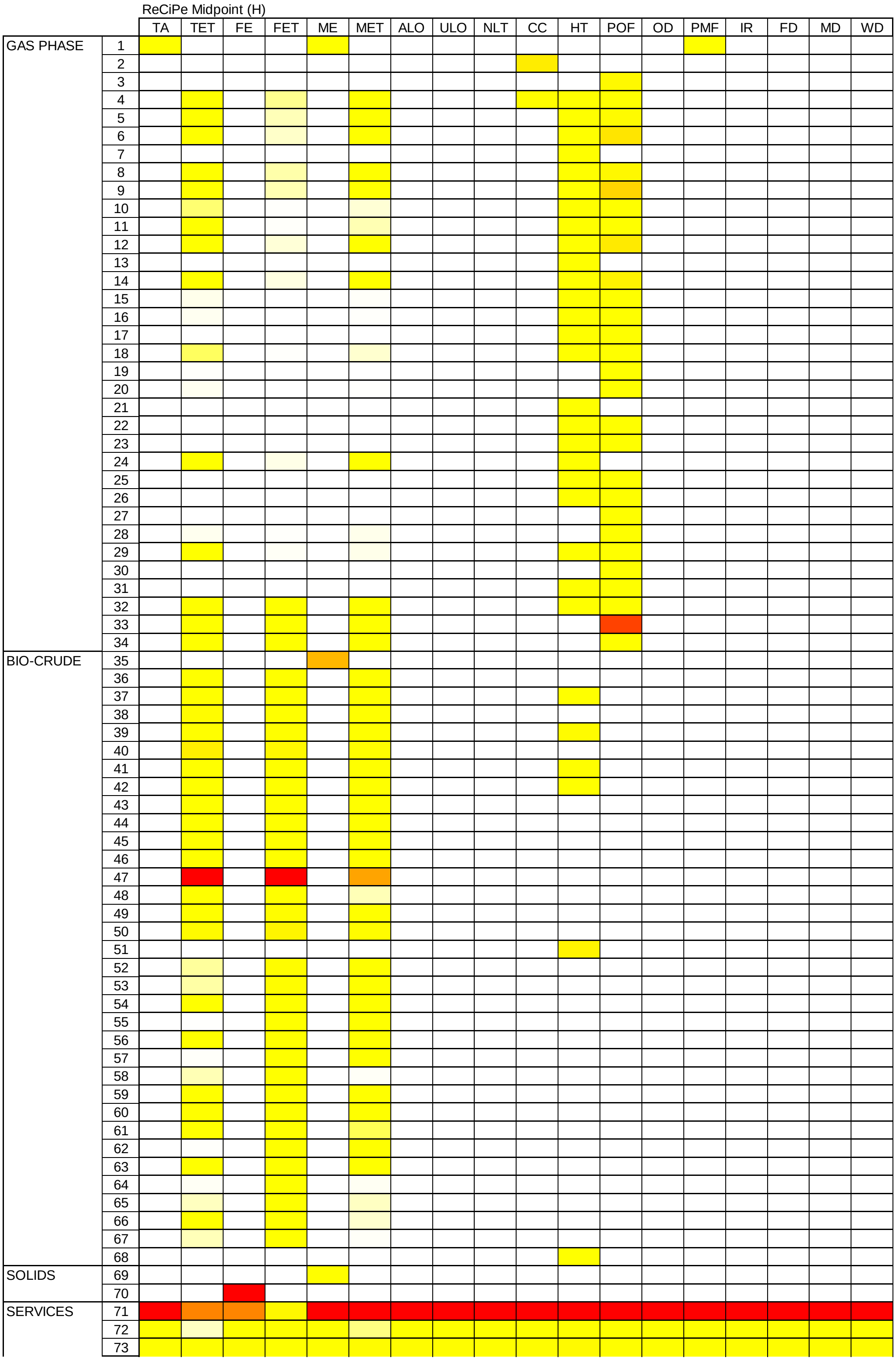


Figure 5 Heatmap of the contribution of each component of the LCI in the corresponding impact at mitpoint level, ReCiPe midpoint (H) for Pyrolysis process.

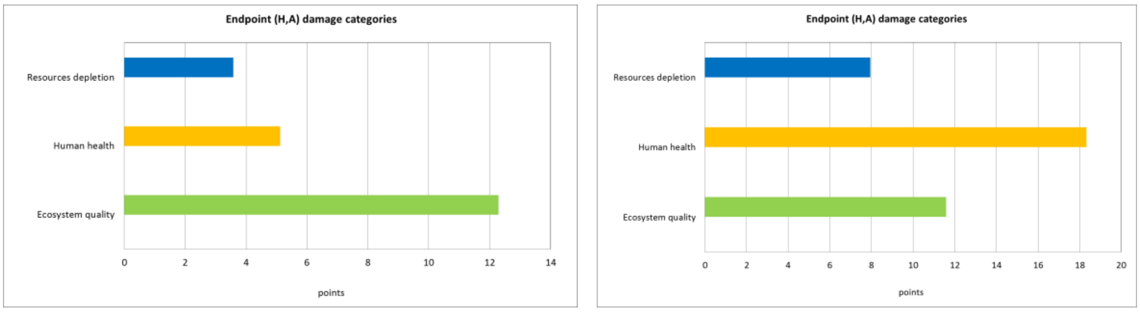
As in the previous deliverable, the analysis at the 'end point level' has been performed, where the midpoint impact categories are converted and aggregated into three endpoint categories: damage to human health, damage to ecosystem diversity and damage to resource availability (Table 5).

Table 5 Endpoint categories

Endpoint categories	Unit	
damage to human health	DALY	(disability-adjusted loss of life)
damage to ecosystem diversity	Species.yr	(loss of species during a year)
damage to resource availability	$	(increased cost)

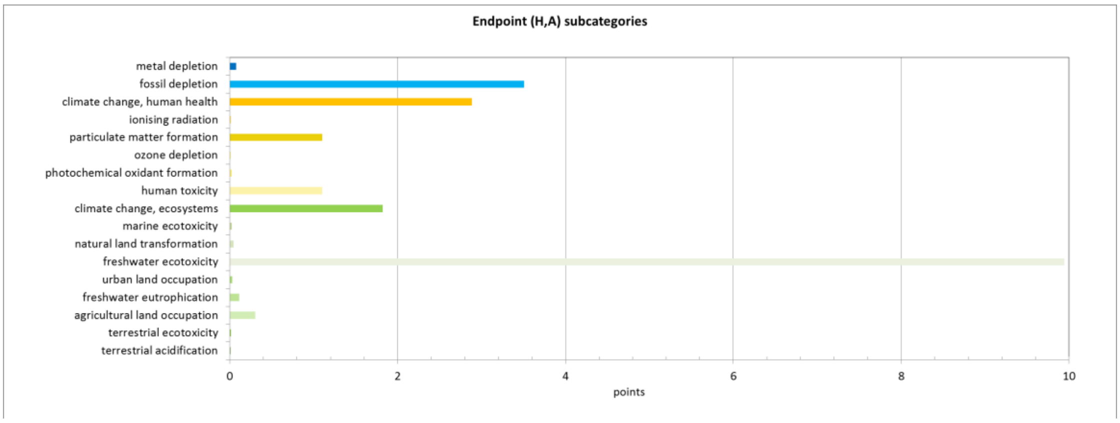
Figure 6 compares the results obtained at the endpoint level (H) for both processes. The units used in this case are 'arbitrary points' (normalized and weighted by using the recommended average (A) weights). Figure 7 shows the contribution of each subcategory (impact categories in the midpoint level). The colour of each subcategory indicates in which endpoint category is included.

As can be seen, HTL process shows much lower impact (around 55-70% lower) on the resources depletion and human health categories than the conventional pyrolysis. Regarding to the ecosystem quality, HTL is around 7% higher. As was commented on previously, most of the streams generated in the process will be valorised and used in other plants and those that could not be used will be treated before their disposal.

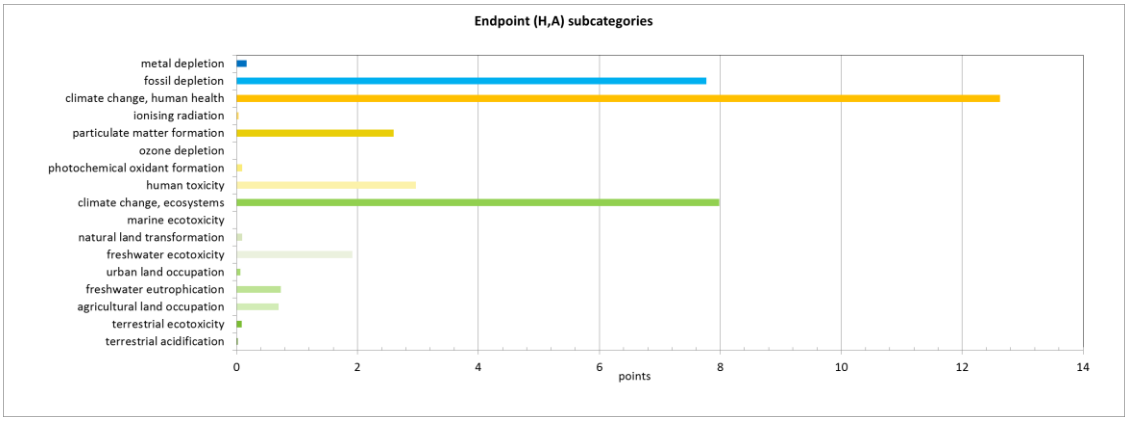


(a) (b)

Figure 6 Damage evaluation of the process according to the endpoint categories (a) HTL, (b) Pyrolysis



(a)



(b)

Figure 7 Contribution of each subcategory on the endpoint damage evaluation a) HTL, (b) Pyrolysis

References related to LCA of hydrothermal liquefaction process [1-3] and fast pyrolysis [4-5] have been found for other types of biomass different from ABP.

4. Life Cycle Cost

Similarly to the life cycle assessment developed, a life cycle cost has been also performed. The HTL LCC has been compared to that of the pyrolysis process.

As in the case of LCA, all the values are referred to a treatment of 5000 kg/h of ABP.

The items taken into account to develop the LCC of both processes have been a) capital costs, which includes the equipments needed in both cases and b) operational costs, which mainly considers the energy consumed in the processes as well as other consumables such as cooling water. In the case of the pyrolysis process, N_2 as carrier gas is used for the fluidized bed reactor.

Due to the flow rates needed for the plant capacity considered, the best option would be to install a plant to produce N_2 from air, generating also O_2 that could be sold [6]. The cost of this plant has been included in the capital costs and the cooling water and power required have been listed in the operational costs. The value of salaries for workers has not been included in the analysis, since it has been considered that it would be similar in both cases.

4.1 Capital costs

Tables 6 and 7 show the list of equipments considered for both processes as well as their capacity and costs. The capacity value has been calculated from the volumetric flow (estimated from the mass flow and the density of the sample) and the residence time of the sample in each equipment. In the case of the condenser needed in the pyrolysis process, the heat transfer area has been calculated taking into account the energy that must be removed in the condensation process, using water as refrigerant. Annex 1 shows the calculations performed to estimate these capacity values.

The cost values in the tables are approximate. In the case of the HTL process, they have been estimated from real costs at pilot plant scale and scaling factors provided by suppliers. Based on lab scale data and scaling factors, cost values for the pyrolysis plant have been also estimated.

In this report, proposals for the dimensions of some equipments have been included, but a more rigorous analysis would have to be developed to decide the best configuration of the plant from a technical and economic point of view. Due to the high working pressure used in the HTL, which increases significantly the cost of big size equipments, it would be interesting considering the possibility of working with two smaller parallel systems, but that study is beyond the limits of this analysis.

Table 6 Capacity and costs of equipments in a HTL process

	Capacity	Costs (€)
Mill+mixer	1.4 m^3	97000
Pump (170 atm)	5000 kg/h	270000
Pump (water recycled; 170 atm)	10725 kg/h	200000
Reactor (screw reactor) (dimensions proposal: L= 13m; D_{int} shell= 0.6 m; D_{axis} screw=0.22m)	3.2 m^3	510000
Outlet vessel (high P) (2 units)	4.7 m^3/unit	315000
Water outlet vessel (high P) (2 units)	0.56 m^3/unit	50000
Valves, pipes, instrumentation and control	-	120000
TOTAL		**1562000**

Table 7 Capacity and costs of equipments in a pyrolysis process

	Capacity	Costs (€)
Mill	2.7 m^3	60000
Dryer (dimensions proposal: 1.5 x 1 x 2m)	2.7 m^3	60000
Reactor (fluidized bed reactor) (including feeder and solid extractor)	3 m^3	330000
Condenser	13 m^2	30000
Outlet vessel for liquids (2 units)	1 m^3/unit	10000
Outlet vessel for solids (2 units)	0.5 m^3/unit	5000
N_2 production plant	106 kg N_2/h	30000
Valves, pipes, instrumentation and control	-	100000
TOTAL		**625000**

As was expected, the capital costs for HTL plant is much higher than that for the conventional pyrolysis.

4.2 Operational costs

Tables 8 and 9 show the items taken into account to estimate the operational costs of both processes. In the case of the HTL technology, these data are only related to the power consumed by the equipments. In the case of the pyrolysis process, the cooling water flow used in the condenser as well as the auxiliary plant needed for the N_2 production has been also considered. Annex 2 shows the calculations performed to obtain the values.

Table 8 Operational costs in a HTL process

Energy demanded by	**Cost (€/h)**
Mill	8.5
Mixer	0.4
Pump (170 atm)	3.4
Pump (water recycled; 170 atm)	1.1
Reactor (screw reactor)	127.8
TOTAL	**141**

Table 9 Operational costs in a pyrolysis process

		Cost (€/h)
Mill	**Energy**	8.5
Dryer		181
Reactor (fluidized bed reactor)		95.5
N_2 production plant		8.6
Condenser	**Cooling water**	2.5
N_2 production plant		0.9
TOTAL		**297**

As can be seen, the operational costs in the pyrolysis process is higher than twice the costs in the HTL process providing that the water used in the HTL process is recycled.

If the water flow used in the process were not recycled, the operational cost for the HTL process would increase up to 527 €/h, since the energy consumed to heat the water needed would be much higher.

4.3 Total annual costs

In order to transform capital costs into annual costs, the following expression has been used [7]:

where i is the fractional interest rate per year and n the number of years. In this report it has been assumed that the capital has been borrowed over a period of 8 years at a rate of 10% of interest.

Table 10 compares the total annual costs of both processes, considering that the plants are operating for 8000 h/year

Table 10 Total annual costs in both processes

	Total cost (€/year)
HTL	1421872
Pyrolysis	2493013

According to these results, the annual cost of treated 5000 kg/h of animal by-products by HTL is lower than 57% the cost of the treatment by conventional pyrolysis.

4.4 Energy recovered from the products obtained

As commented on previously, data for calorific value of bio-oil obtained from animal by-products with the pyrolysis technology have not been found. However the characteristics of this process as well as the yields obtained, allow guarantee the fact that the energy obtained from HTL process will be always higher than the one from pyrolysis (see comments on LCA section). Therefore, if this item could be quantified in the analysis, it would favor the choice of the HTL process vs. the pyrolysis one.

5. Conclusions

The LCA of ABP hydropyrolysis carried out previously has been extended and that for the conventional pyrolysis process has been also developed. The ReCiPe 2008 methodology has been selected to calculate the corresponding environmental impacts and compare both processes from an environmentally point of view. Similarly the LCC for both processes has been also performed, in order to compare the annual costs for the technologies proposed.

According to the results obtained, the energy consumption represents the main contribution in most of the environmental impact categories as well as in the process costs, being this consumption mainly associated to the sample heating, in the case of the HTL process and to the sampling drying in the case of the pyrolysis.

This study shows that, from an environmental as well as economic point of view, HTL with water recycling is a very attractive alternative compared to conventional pyrolysis, for treating and valorizing animal by-products.

6. References:

[1] Liu X, Saydah B, Eranki P, Colosi LM, Mitchell BG, Rhodes J, Clarens AF (2013) Pilot-scale data provide enhanced estimates of the life cycle energy and emissions profile of algae biofuels produced via hydrothermal liquefaction. Bioresource Technology 148:163-171

[2] Zhu Y, Biddy MJ, Jones SB, Elliott DC, Schmidt AJ (2014)Techno-economic analysis of liquid fuel production from woody biomass via hydrothermal liquefaction (HTL) and upgrading. Applied Energy 129:384-394.

[3] Benavente V, Fullana A, Berge ND (2016). Life cycle analysis of hydrothermal carbonization of olive mill waste: Comparison with current management approaches. Journal of Cleaner Production
http://dx.doi.org/10.1016/j.jclepro.2016.11.013

[4] Iribarren D, Peters JF, Dufour J (2012) Life cycle assessment of transportation fuels from biomass pyrolysis. Fuel 97: 812-821.

[5] Chan YH, Tan RR, Yusup S, Lam HL, Quitain AT (2016) Comparative life cycle assessment (LCA) of bio-oil production from fast pyrolysis and hydrothermal liquefaction of oil palm empty fruit bunch (EFB). Clean Techn Environ Policy 18: 1759-1768.

[6] Web page N_2 production. Revision in May, 2017
https://www.alibaba.com/product-detail/CANGAS-Cryogenic-Low-Price-Liquid-Nitrogen_60466204342.html

[7] Smith, R. (1995) Chemical Process Design. McGraw Hill.

[8] Peters, S. and Timerhaus, D. (2003) Plants Design and Economics for Chemical Engineers. McGraw Hill.

[9] Web page energy price. Revision in May, 2017.

https://www.ipsom.com/2017/01/repaso-de-los-precios-y-estado-de-la-energia-en-europa-en-el-2016/

[10] Web page water price. Revision in May, 2017. http://www.aiguesdebarcelona.cat/facturadelaigua/pdfs/factura_comercial_2017_2_es.pdf

7. ANNEX 1. Calculations of equipment capacity

Original data: Basis (kg ABP/h): 5000

Initial raw material moisture (%): 37.1

Density of raw material (kg/L): 1.1

Density of mixture (raw material+water) (kg/L): 1

Cp raw material (kJ/kgºC): 2.3

In the case of the HTL technology, taking into account the value of the initial moisture in the sample as well as the value required in the process (80%), the amount of water that must be added can be calculated. This water (10725 kg/h) will be recycled.

Table A1.1 shows the mass flow rate (M) and residence time (□) considered for each equipment. It also includes the calculated values of volumetric flow rate (Q) and volume (V). The expressions used in those calculations have been also included in the head of the corresponding columns. The volume of the screw reactor corresponds to the volume between the shell and the screw. The dimensions of the reactor estimated are: length=13m, shell internal diameter: 0.6m and screw diameter: 0.22m. An oversize volume (V_{real}) has been estimated, especially in the deposits to allow a more flexible operation, by increasing the calculated volume by 20%.

Table A1. 1 Capacity of equipments in a HTL process

HTL	M (kg/h)	Q (m^3/h) (M/□)	□(min)	V (m^3) (□ x Q)	V_{real} (m^3)
Mill+mixer	5000	4.5	15	1.14	1.4
Pump (170 atm)	5000	4.5	-	-	-
Pump (water recycled; 170 atm)	10725	10.7	-	-	-
Reactor (screw reactor)	15725	15.7	12	3.2	3.2
Outlet vessel (high P) (2 units)	15725	15.7	15	3.93	4.7
Water outlet vessel (high P) (2 units)	1855	1.9	15	0.46	0.56

A similar analysis was performed to analyze the pyrolysis process, taking into account that in this case, instead of adding water, sample must be initially dried. Table A1.2 shows similar information to that of Table A1.1 for the pyrolysis process. In this case, the reactor selected for the pyrolysis process is a fluidized bed reactor. The dimensions estimated of the reactor are: 1.2m x 2.7m.

Table A1. 2 Capacity of equipments in a pyrolysis process

PYROLYSIS	M (kg/h)	Q (m^3/h) (M/□)	□(min)	V (m^3) (□ x Q)	V_{real} (m^3)
Mill	5000	4.5	30	2.27	2.7
Dryer	5000	4.5	30	2.27	2.7
Reactor (fluidized bed reactor)	3145	3.1	10	0.52	$3_{(1)}$
Condenser	1680			10.9 $m^2{}_{(2)}$	13 m^2
Outlet vessel for liquids (2 units)	1680	1.7	30	0.83	1
Outlet vessel for solids (2 units)	885	0.9	30	0.43	0.5

(1) The volume includes the fluidized inert bed

(2) Instead of a volume, in this case the value corresponds to the exchange area of the heat exchange needed to condense the liquid fraction.

The area of the condenser has been calculated considering the use of cooling water as a refrigerant, in a shell and tubes condenser, and a heat transfer coefficient value of 750 W/m^2ºC, typical value when the cold fluid is water and the hot one is a low viscosity organic liquid [8]. Difference of temperature for cooling water, between entrance and exit, has been considered of 30ºC.

8. ANNEX 2. Operational costs

Costs considered in this annex are:

Energy: 0.1234 €/kWh [9]

Cooling water: 1.59 €/m^3 [10]

In the case of the HTL process, the operational costs correspond to the power consumed in the equipments. For each equipment, the energy demanded is calculated according to their specifications:

Mill: obtained from commercial information about industrial mills. Data calculated from interpolation in a range from 60 to 7000 kg/h.

Mixer: obtained from commercial information about industrial mixers, with helixes up to 12 m.

Pump: calculated by considering the pressure difference between entry and exit of the pump. An efficiency of 85% has been considered for this equipment.

Reactor: energy necessary to heat the mass flow of raw material from room temperature to reactor temperature, to add the heat loss of the recirculated water and to vaporize the gas fraction (to estimate this value, the pyrolysis enthalpy has been considered (400 kJ/kg) [a]).

Table A2.1 shows the results obtained in this case.

Table A2. 1 Operational costs in a HTL process

HTL	**Power (kW)**	**Cost (€/h)**
Mill	69	8.5
Mixer	3	0.4
Pump (high P; from 1 to 170 atm)	27.6	3.4
Pump (water recycled; from 165 to 170 atm)	8.8	1.1
Reactor (screw reactor)	1035.4	127.8
TOTAL	1143.7	**141**

In the case of the pyrolysis process, the operational costs must include other additional items, such as the energy required in the dryer, the cooling water needed in the condenser and the carrier gas in the fluidized bed reactor. The specifications are as follows:

Dryer: energy needed to heat the raw material from room temperature to 120ºC and to evaporate its moisture.

Reactor: energy necessary to heat the mass flow of dried raw material (from 120ºC to 525ºC) and the pyrolysis enthalpy (400 kJ/kg)

Refrigerant in condenser: the amount of cooling water needed to condense the liquid fraction obtained. The cooling water will be cold down in a cooling tower and, at the steady state, only the amount of evaporated water will be fed.

Nitrogen as carrier gas: The energy and cooling water needed to get the fluidizing gas required. As in the previous case, only the amount of water evaporated in the cooling water has been considered.

Table A2.2 shows the operational costs for the pyrolysis process.

Table A2. 2 Operational costs in a pyrolysis process

PYROLYSIS			**Cost (€/h)**
Mill	**Energy (kW)**	69	8.5
Dryer		1466.5	181
Reactor (fluidized bed reactor)		774	95.5
N_2 production plant		70	8.6
Condenser	**Cooling water (kg/h)**	1555	2.5
N_2 production plant		555	0.9
TOTAL			**297**

[a] Fernández González, J., Gutiérrez Martín, F., Del Río González, P., San Miguel Alfaro, G., Bahillo Ruiz, A., Sánchez Hervás, JM., Ballesteros Perdices, M., Vázquez Minguela, JA., Rodríguez Antón, LM., Aracil Mira, J. (2015) Tecnologías para el uso y transformación de biomasa energética. Mundi-Prensa.