Electronic Supplementary Information

Technological data

Table S1 gives an overview of all technological input data with their corresponding references which have been used in the MOO model. The data is grouped according to the different production process steps.

Table S1. Technological input parameters

Parameter	Unit	Value	Reference
General			
Algae farm occupation factor	%	150.00	[1]
Geographical			
Solar irradiation Belgium	$kWh \cdot m^{-2}$	1040.00	[2]
Solar irradiation Iran	$kWh \cdot m^{-2}$	2100.00	[2]
Solar irradiation Cadiz	$kWh \cdot m^{-2}$	1900.00	[2]
Solar irradiation Hawaii	$kWh \cdot m^{-2}$	1868.00	[2]
Solar irradiation Tucson	$kWh \cdot m^{-2}$	2147.00	[2]
Solar irradiation Uttar Pradesh	$kWh \cdot m^{-2}$	1722.00	[2]
Ambient temp. Belgium March-November	°C	12.86	[3]
Ambient pressure	kPa	100.00	
Algae species: General			
Molecular weight	$pg \cdot cell^{-1}$	153.00	[4]
KNO_3 req.	mM	5.00	[5]
Stress stage KNO_3 req.	mM	0.10	[5]
$NaHCO_3$ requirement	mM	2.00	[6]
$MgSO_4$ requirement	mM	2.00	[5]
KH_2PO_4 requirement	mM	0.10	[5]
$FeCl_3.6H_2O$ requirement	mM	0.01	[5]
CO_2 requirement	$g \cdot g\ biomass^{-1}$	1.83	[7]

Percentage growth function	%	67.00	
Percentage growth function stress	%	77.00	
Correction factor stress growth	%	67.00	
Algae species: Dunaliella salina			
Optimal salinity	M	2.00	[5]
Stress stage salinity	M	2.50	[5]
Optimal temperature	°C	25.00	[6]
Stress stage β-carotene content	%	8.8	[4, 6, 8]
Stress stage astaxanthin content	%	0.00	
TAG content	%	10.00	[9, 10]
Stress stage TAG content	%	25.87	[9, 10]
Initial concentration pond	10^6 cell·ml^{-1}	0.40	[4]
Maximum concentration pond	g·l^{-1}	0.50	[4]
Maximum specific growth rate pond	day^{-1}	0.25	[5]
Initial concentration reactor	10^6 cell·ml^{-1}	1.50	[4]
Maximum concentration reactor	g·l^{-1}	2.00	[4]
Maximum specific growth rate reactor	day^{-1}	0.35	[4, 11]
Initial concentration ProviApt	10^6 cell·ml^{-1}	1.50	
Maximum concentration ProviApt	g·l^{-1}	2.00	
Maximum specific growth rate ProviApt	day^{-1}	0.92	
Algae species: Haematococcus pluvialis			
Optimal salinity	M	0.00	
Stress stage salinity	M	0.00	
Optimal temperature	°C	27.00	[12]
Stress stage β-carotene content	%	0.00	
Stress stage astaxanthin content	%	2.90	[13]
TAG content	%	0.11	[14]
Stress stage TAG content	%	1.15	[14]
Initial concentration pond	10^6 cell·ml^{-1}	0.40	[4]

Maximum concentration pond	$g \cdot l^{-1}$	0.50	[4]
Maximum specific growth rate pond	day^{-1}	0.25	[5]
Initial concentration reactor	$g \cdot l^{-1}$	0.50	[15]
Maximum concentration reactor	$g \cdot l^{-1}$	4.10	[15]
Maximum specific growth rate reactor	day^{-1}	0.20	[13]
Initial concentration ProviApt	$g \cdot l^{-1}$	0.50	[15]
Maximum concentration ProviApt	$g \cdot l^{-1}$	4.10	[15]
Maximum specific growth rate ProviApt	day^{-1}	0.52	same rate as for *Nannochloropsis* sp.
Algae species: Nannochloropsis species			
Optimal salinity	$g \cdot kg^{-1}$	22	[16]
Stress stage salinity	$g \cdot kg^{-1}$	34	[16]
Optimal temperature	°C	25.00	[16-18]
Stress stage β-carotene content	%	0.01	[19]
Stress stage astaxanthin content	%	0.03	[19]
TAG content	%	7.00	[20]
Stress stage TAG content	%	38.00	[20]
Initial concentration pond	$g \cdot l^{-1}$	0.20	[21]
Maximum concentration pond	$g \cdot l^{-1}$	1.00	[21]
Maximum specific growth rate pond	day^{-1}	0.17	[21, 22]
Initial concentration reactor	$g \cdot l^{-1}$	0.25	[23]
Maximum concentration reactor	$g \cdot l^{-1}$	2.50	[1]
Maximum specific growth rate reactor	day^{-1}	0.41	[24]
Initial concentration ProviApt	$g \cdot l^{-1}$	0.25	[23]
Maximum concentration ProviApt	$g \cdot l^{-1}$	2.50	[1]
Maximum specific growth rate ProviApt	day^{-1}	1.08	calculated based on [17]
Process: General			
Operation rate	%	70.00	
Process Step: Cultivation 1st stage			
All options			

Pumps in medium supply unit	#	4.00	[25]
Tanks in medium supply unit	#	3.00	[25]
NH_3 emission	% N-fertilizer	4.86	[26]
CO_2 injection energy	$kWh\cdot t\ CO_2^{-1}$	22.20	[27]
Medium preparation energy	$W\cdot m^{-3}\cdot h$	275.00	[28]
Hours of mixing	$h\cdot day^{-1}$	10.00	[29]
Hours of medium preparation	$h\cdot day^{-1}$	6.00	[28]
O_2 emission	$g\cdot g\ biomass^{-1}$	1.07	[7]
Cultivation area	% total	67.00	[1]
Option: Open pond			
CO_2 fixation efficiency	%	41.23	[30, 31]
N_2O emission	% N-fertilizer	0.002	[32]
Mixing energy	$W\cdot m^{-3}$	3.72	[29]
Height pond	m	0.15	[5]
Option: PBR			
CO_2 fixation efficiency	%	71.00	[28, 33]
N_2O emission	% N-fertilizer	0.39	[32]
Mixing energy	$W\cdot m^{-3}$	2500.00	[34]
Heat loss	%	5.00	
Additional heating solar irradiation	°C	5.00	
Volume surface ratio	$m^3\cdot m^{-2}$	0.07	[28]
Option: ProviApt			
CO_2 fixation efficiency	%	71.00	[28, 33]
N_2O emission	%·N-fertilizer	0.39	[32]
Mixing energy	$W\cdot m^{-2}$	5.00	[1]
Heat loss	%	5.00	
Additional heating solar irradiation	°C	5.00	
Volume surface ratio	$l\cdot m^{-2}$	8.66	[17]
Process: Preharvesting			
Option: IPC®			

End concentration	g DW·l^{-1}	10.00	
Energy consumption after open pond	kWh·m^{-3}	0.24	
Energy consumption after reactor	kWh·m^{-3}	0.26	
Maximum recycling ratio	%	100.00	
Process: Cultivation 2nd stage			
All options			
Pumps in medium supply unit	#	4.00	[25]
Tanks in medium supply unit	#	3.00	[25]
NH_3 emission	% N-fertilizer^{-1}	4.86	[26]
CO_2 injection energy	kWh·t CO_2^{-1}	22.20	[27]
Medium preparation energy	W·m^{-3}·h	275.00	[28]
Hours of mixing	h·day^{-1}	10.00	[29]
Hours of medium preparation	h·day^{-1}	6.00	[28]
O_2 emission open pond?	g·g biomass^{-1}	1.07	[7]
Cultivation area	% total	67.00	[1]
Option: Open pond			
CO_2 fixation efficiency	%	41.23	[30, 31]
N_2O emission	% N-fertilizer^{-1}	0.002	[32]
Mixing energy	W·m^{-3}	3.72	[29]
Height pond	m	0.12	[5]
Option: PBR			
CO_2 fixation efficiency	%	71.00	[28, 33]
N_2O emission	% N-fertilizer^{-1}	0.39	[32]
Mixing energy	W·m^{-3}	2500.00	[34]
Heat loss	%	5.00	
Additional heating solar irradiation	°C	5.00	
Volume surface ratio	m^3·m^{-2}	0.07	[28]
Option: ProviApt			
CO_2 fixation efficiency	%	71.00	[28, 33]
N_2O emission	% N-fertilizer^{-1}	0.39	[32]

Mixing energy	W·m^{-2}	5.00	[1]
Heat loss	%	5.00	
Additional heating solar irradiation	°C	5.00	
Volume surface ratio	l·m^{-2}	8.66	[17]
Process: Harvesting			
Option: Centrifuge			
Energy consumption	kWh·m^{-3}	1.40	[35]
Maximum concentration	%	12.00	[36]
Recovery	%	97.00	
Process: Washing			
End salt concentration	g·l^{-1}	4.00	
Mixing time	h	1.00	
Energy consumption mixing	kWh·h·t^{-1}·year·l^{-1}	0.18 Capacity [l]$^{-0.33}$	[37]
Energy consumption centrifuge	kWh·m^{-3}	1.40	[35]
Maximum concentration	%	12.00	[36]
Recovery	%	97.00	
Process: Drying			
Option: Spray Drying			
T_{inlet} air	°C	200.00	[38]
T_{outlet} air	°C	110.00	[38]
T_{outlet} biomass	°C	72.00	Course "Sproeidrogen", Technotrans BV(2001)
Solid content$_{outlet}$	%	94.72	[38]
Biomass recovery	%	95.00	
Correction factor for energy consumption	%	2.90	Course "Sproeidrogen", Technotrans BV(2001)
Total energy consumption	GJ·t(water removed)$^{-1}$	5.20	
Option: Freeze Drying			
Solid content$_{outlet}$	%	93.60	[39]
Biomass recovery	%	95.00	
Energy consumption	kW·kg^{-1}	2.00	[40]

Process: Disruption			
Option: Bead mill			
Energy consumption	$kWh \cdot kg^{-1}$	2.82	41
Disruption time	h	7.00	42
Process: Extraction			
Option: Hexane extraction			
Extraction time	$min \cdot step^{-1}$	60.00	
Carotenoid recovery	%	95.00	
TAG recovery	%	95.00	
Hexane concentration	$l \cdot l^{-1}$	1.00	43
Extraction steps	#	6.00	43
Energy consumption mixing	$kWh \cdot h \cdot t^{-1} \cdot year \cdot l^{-1}$	0.18 Capacity $[l]^{-0.33}$	37
Hexane emission	$g \cdot kg^{-1}$	2.00	44
Other components extracted	%	1.50	
Process: Filtration			
Energy consumption	$kWh \cdot t$ dry material^{-1}	10.00	37
Solvent in residual biomass	%	10.00	
Process: Lipid purification			
Option: Vacuum distillation			
Distillation carotenoids	%	1.00	
Distillation other components	%	1.00	
Distillation water	%	40.00	
Distillation hexane	%	100.00	
Cooling water	$m^3 \cdot kg$ waste solvent^{-1}	0.027	45
Temperature	°C	30.00	46
Steps		3.00	
Time	$min \cdot step^{-1}$	60.00	
Pressure	kPa	24.91	
Distillation energy Belgium	$kWh \cdot t$ recycled^{-1}	1,353.32	
Distillation energy India	$kWh \cdot t$ recycled^{-1}	1,314.21	

Energy efficiency	%	64.00	[37]
Minimum reflux ratio	%	120.00	[37]
Process: Lipid processing			
Option: Transesterification			
Methanol	kg·kg oil^{-1}	0.12	[47]
HCl	kg·kg oil^{-1}	0.04	[47]
NaOH	kg·kg oil^{-1}	0.001	[47]
Phosphoric acid	kg·kg oil^{-1}	0.0006	[47]
Citric acid	kg·kg oil^{-1}	0.0007	[47]
Water	kg·kg oil^{-1}	0.34	[47]
Glycerol production	kg·kg oil^{-1}	0.12	[47]
Biodiesel production	kg·kg oil^{-1}	1.01	[47]
Wastewater	kg·kg oil^{-1}	0.048	[47]
Natural gas	kWh·kg^{-1}	0.24	[47]
Electricity	kWh·kg^{-1}	0.04	[47]
Energy pump	J·kg^{-1}	55.00	[37]
Mxixing time	min	50.00	
Decanter time	min	50.00	
Equipment			[48]
Option: Hydrotreating			
Hydrogen	kg·kg oil^{-1}	0.02	[49]
Phosphoric acid	kg·kg oil^{-1}	0.0019	[49]
Silica	kg·kg oil^{-1}	0.001	[49]
Clay dosing	kg·kg oil^{-1}	0.002	[49]
Water	kg·kg oil^{-1}	0.13	[49]
CO_2 emission	kg·kg oil^{-1}	0.01	[49]
Hydrogen recycling rate	%	89.00	[49]
Renewable diesel production	kg·kg oil^{-1}	0.78	[49]
Naphtha production	kg·kg oil^{-1}	0.02	[49]
Gas production	kg·kg oil^{-1}	0.18	[49]

Propane in gas	%	29.18	49
CO_2 in gas	%	63.12	49
H_2 in gas	%	3.83	49
Waste stream	%	12.50	49
Electricity hydrotreating	$kWh\cdot kg^{-1}$	0.05	50
Natural gas hydrotreating	$kWh\cdot kg^{-1}$	0.05	50
PSA energy	$kWh\cdot kg^{-1}$	0.10	49
Degumming energy	$kWh\cdot kg^{-1}$	0.01	49
Equipment			51
Process: Residue purification			
Option: Evaporation			
Water evaporation	%	40.00	
Solvent evaporation	%	100.00	
Other components evaporation	%	1.00	
Cooling water	$m^3\cdot kg$ waste $solvent^{-1}$	0.027	45
Evaporation energy	$kWh\cdot t$ $recycled^{-1}$	1,153.83	
Energy efficiency	%	64.00	37
Minimum reflux ratio	%	120.00	37
Evaporation time	min	60.00	
Evaporation temperature	K	341.60	
Process: Residue processing			
Option: Pyrolysis			
Biochar fraction	%	63.00	52
Syngas fraction	%	13.00	52
Liquid fraction	%	24.00	52
CO_2 loss	%	9.00	52
CH_4 loss	%	1.50	52
CO loss	%	1.00	52
C_2H_4 loss	%	0.30	52
C_2H_6 loss	%	1.00	52

H_2 loss	%	0.70	[52]
Energy requirement	MJ·kg dry biomass^{-1}	1.24	based on [53]
Energy requirement	MJ·kg water^{-1}	0.14	based on [53]
HHV bio-oil	MJ·kg^{-1}	27.90	[52]
HHV syngas	MJ·kg^{-1}	2.90	[52]
HHV biochar	MJ·kg^{-1}	14.50	[52]
Energy use fluid catalytic cracking	MJ·bbl	401.87	[54]
Biocrude to biochar fluid catalytic cracking	%	19.00	[54]
Energy use hydrotreating	MJ·bbl	446.59	[54]
Biocrude to biochar hydrotreating	%	7.00	[54]
Ratio diesel gasoline refining	%	52.00	[55]
Hydrogen consumption	kg·kg^{-1}	0.12	[56]
Option: Gasification			
Biochar fraction	%	58.00	[57]
Syngas fraction	%	28.00	[57]
Liquid fraction	%	14.00	[57]
Energy requirement	MJ·kg dry biomass^{-1}	1.47	based on [53]
Energy requirement	MJ·kg water^{-1}	0.27	based on [53]
HHV bio-oil	MJ·kg^{-1}	34.10	[57]
HHV syngas	MJ·kg^{-1}	32.90	[57]
HHV biochar	MJ·kg^{-1}	17.50	[57]
Energy use fluid catalytic cracking	MJ·bbl	401.87	[54]
Biocrude to biochar fluid catalytic cracking	%	19.00	[54]
Energy use hydrotreating	MJ·bbl	446.59	[54]
Biocrude to biochar hydrotreating	%	7.00	[54]
Ratio diesel gasoline refining	%	52.00	[55]
Hydrogen consumption	kg·kg^{-1}	0.12	[56]
Option: Torrefaction			
Biochar fraction	%	75.00	[57]
Syngas fraction	%	7.00	[57]

Liquid fraction	%	84.00	[57]
Energy requirement	MJ·kg dry biomass^{-1}	1.05	based on [53]
Energy requirement	MJ·kg water^{-1}	0.28	based on [53]
HHV bio-oil	MJ·kg^{-1}	15.50	[57]
HHV syngas	MJ·kg^{-1}	2.67	[57]
HHV biochar	MJ·kg^{-1}	16.60	[57]
Energy use fluid catalytic cracking	MJ·bbl	401.87	[54]
Biocrude to biochar fluid catalytic cracking	%	19.00	[54]
Energy use hydrotreating	MJ·bbl	446.59	[54]
Biocrude to biochar hydrotreating	%	7.00	[54]
Ratio diesel gasoline	%	52.00	[55]
Hydrogen consumption refining	kg·kg^{-1}	0.12	[56]
Option: HTL			
Pretreatment Temperature	°C	150.00	[54]
Heat exchange efficiency	%	90.00	[54]
Pretreatment energy	MJ·kg water^{-1}	0.58	[54]
Biomass conversion temperature	°C	300.00	[54]
Biomass conversion energy	MJ·kg water^{-1}	0.72	[54]
Biocrude fraction	%	20.00	[54]
Hexane	l·l biocrude^{-1}	0.75	[54]
Energy extraction	MJ·l feed^{-1}	0.02	[54]
Hexane recovery	%	99.50	[54]
Hexane recovery energy	MJ·tonne biocrude^{-1}	2.10	[54]
Biocrude recovery	%	90.00	[54]
Nitrogen in raffinate	%	89.00	[54]
Nitrogen in biomass	%	8.00	[54]
Phosphorus in raffinate	%	94.00	[54]
Phosphorus in biomass	%	1.00	[54]
Nutrient recycle efficiency	%	12.50	[54]
Gas conversion	%	3.00	[54]

CO_2 in gas fraction	%	70.00	[54]
CH_4 in gas fraction	%	30.00	[54]
Solid waste	%	3.00	[54]
Energy use fluid catalytic cracking	MJ·bbl	401.87	[54]
Biocrude to biochar fluid catalytic cracking	%	19.00	[54]
Energy use hydrotreating	MJ·bbl	446.59	[54]
Biocrude to biochar hydrotreating	%	7.00	[54]
Ratio diesel gasoline refining	%	52.00	[55]
Hydrogen consumption	$kg \cdot kg^{-1}$	0.12	[56]
Option: Anaerobic digestion			
Biogas production	m^3 CH_4	0.375	[58]
Methane in biogas	%	70.00	[58]
CO_2 in biogas	%	30.00	[58]
Digestate	$m^3 \cdot kg^{-1}$	0.02	[58]
Liquid digestate	% digestate	93.36	[58]
N liquid digestate	$kg \cdot m^{-3}$	2.94	[58]
P liquid digestate	$kg \cdot m^{-3}$	0.39	[58]
K liquid digestate	$kg \cdot m^{-3}$	0.32	[58]
N solid digestate	$kg \cdot m^{-3}$	4.50	[58]
P solid digestate	$kg \cdot m^{-3}$	0.61	[58]
K solid digestate	$kg \cdot m^{-3}$	0.50	[58]
Water consumption	$m^3 \cdot kg^{-1}$	0.07	[58]
Heat demand	$kWh \cdot kg^{-1}$	0.68	[58]
Power demand	$kWh \cdot kg^{-1}$	0.22	[58]
Volume per feed flow	$m^3 \cdot kg^{-1} \cdot h$	0.25	[49]

Economic data

Table S2 gives an overview of all economic input data with their corresponding references which have been used in the model. The data is grouped in general, investment, operational and revenue data.

Table S2 Economic input parameters

Parameter	Unit	Value	Reference
General			
Evaluation period	Year	10.00	
Site preparation	$\%I_0$	10.00	[59]
Nominal discount rate	%	15.00	[60]
Equity	%	20.00	
Interest loan	%	1.47	[61]
Inflation rate	%	2.00	[62]
Tax rate	%	33.99	[63]
Investment costs			
Process: Cultivation			
All options			
Cost inoculum production system	$EUR \cdot ha^{-1}$	122,595 Capacity $[ha]^{-0.21}$	[25, 64]
Lifetime inoculum production system	year	20.00	[64]
Land cost	$EUR \cdot m^{-2}$	2.62	[65]
Cost medium preparation unit	$EUR \cdot m^{-3} \cdot h$	6,954 Capacity $[m^3 \cdot h^{-1}]^{-0.51}$	[25, 28]
Lifetime medium preparation unit	year	10	[25]
Cost CO_2 supply unit	$EUR \cdot kg^{-1} \cdot h$	436	[28, 66]
Lifetime CO_2 supply unit	year	10.00	[28]
Cost heat exchanger titanium	$EUR \cdot dam^{-3}$	27,085 Capacity $[dam^3]^{-0.4}$	[67]
Cost heat exchanger incoloy	$EUR \cdot dam^{-3}$	21,668 Capacity $[dam^3]^{-0.4}$	[68]
Lifetime heat exchanger	year	15.00	[69]

Option: Open pond			
Cost liners	EUR·ha^{-1}	87,637	[64, 66, 70]
Lifetime liners	year	20.00	[71]
Cost landscaping	EUR·ha^{-1}	8,760	[72]
Cost paddlewheels	EUR·ha^{-1}	11,728	[66, 70, 72]
Lifetime paddlewheels	year	20.00	[72]
Option: PBR			
Cost PBR	EUR·m^{-3}	13,501 Capacity [m³]$^{-0.07}$	[28], price quote commercial supplier
Lifetime PBR	year	10.00	[28]
Cost Blower	EUR·m^{-3}	2,055 Capacity [m³]$^{-0.6}$	[25, 28]
Lifetime blower	year	20.00	[25]
Option: ProviApt			
Reactor installed cost	EUR·ha^{-1}	143,231	[1]
Additional investment	EUR·ha^{-1}	492,500	[1]
Lifetime reactor	year	2.00	[1]
Process: Preharvesting			
Option: IPC®			
Total cost membrane scen Ns FLF	10^6 EUR	176.37	
Total cost membrane scen Hp F	10^6 EUR	13.47	
Total cost membrane scen Ds F	10^6 EUR	6.91	
Total cost membrane scen Hp AD	10^6 EUR	13.47	
Total cost membrane scen Ds AD	10^6 EUR	6.91	
Total cost membrane scen Hp G	10^6 EUR	13.47	
Total cost membrane scen Ds G	10^6 EUR	6.91	
Total cost membrane scen Hp T	10^6 EUR	13.47	
Total cost membrane scen Ds T	10^6 EUR	6.91	
Total cost membrane scen Hp P	10^6 EUR	13.47	
Total cost membrane scen Ds P	10^6 EUR	6.91	
Process: Harvesting			
Option: Centrifuge			

Centrifuge	$EUR \cdot l^{-1} \cdot h$	318,225 Capacity $[m^3 \cdot h^{-1}]^{-0.44}$	price quote commercial supplier
Lifetime centrifuge	year	25.00	[25]
Process: Washing			
Cost tank	$EUR \cdot m^{-3}$	2,417 Input $[m^3]^{-0.43}$	[28]
Lifetime tank	year	10.00	[28]
Cost mixer	$EUR \cdot W^{-1}$	436 Capacity $[W]^{-0.63}$	price quote commercial supplier
Lifetime mixer	year	10.00	
Centrifuge	$EUR \cdot l^{-1} \cdot h$	318,225 Capacity $[m^3 \cdot h^{-1}]^{-0.44}$	price quote commercial supplier
Lifetime centrifuge	year	25.00	[25]
Process: Drying			
Option Spray Drying			
Spray dryer	EUR	188,458 Capacity $[kg_{water\ removed} \cdot h^{-1}]^{-0.4}$	price quote commercial supplier
Lifetime dryer	year	15.00	
Option Freeze Drying			
Freeze dryer	$EUR \cdot kg^{-1} \cdot h$	224,031 Capacity $[kg \cdot h^{-1}]^{-0.4}$	[73]
Lifetime freeze dryer	year	10	
Process: Disruption			
Option: Bead mill			
Bead mill	$EUR \cdot l^{-1} \cdot h$	5,161 Capacity $[l \cdot h^{-1}]^{-0.4}$	price quote commercial supplier
Lifetime bead mill	year	10	
Process: Extraction			
Option: Hexane extraction			
Cost tank	$EUR \cdot m^{-3}$	2,417 Input $[m^3]^{-0.43}$	[28]
Lifetime tank	year	10.00	[28]
Cost mixer	$EUR \cdot W^{-1}$	436 Capacity $[W]^{-0.63}$	price quote commercial supplier
Lifetime mixer	year	10.00	
Process: Filtration			
Filter	$EUR \cdot m^{-2}$	6,139 Capacity $[m^2]^{-0.54}$	[42, 74]
Lifetime filter	year	10.00	
Process: Lipid purification			

Option: Vacuum distillation			
Evaporator	EUR·m^{-3}	192,552 Input $[m^3]^{-0.69}$	price quote commercial supplier
Lifetime evaporator	year	10.00	
Process: Lipid processing			
Option: Transesterification			
Transesterification equipment	EUR·t^{-1}·h	1,874,140 Capacity $[t \cdot h^{-1}]^{-0.4}$	[48]
Lifetime equipment	year	10	
Option: Hydrotreating			
Hydrotreating unit	EUR·l^{-1}·m	2,212,987 Capacity $[l \cdot min^{-1}]^{-0.5}$	[49]
Lifetime hydrotreating unit	year	30	[49]
Pressure swing adsorption (PSA) unit	EUR·l^{-1}·m	484,713 Capacity $[l \cdot min^{-1}]^{-0.4}$	[49]
Lifetime PSA unit	year	30	[49]
Bleaching/degumming unit	EUR·l^{-1}·m	258,514 Capacity $[l \cdot min^{-1}]^{-0.4}$	[49]
Lifetime bleaching/degumming unit	year	30	[49]
Process: Residue purification			
Option: Evaporation			
Evaporator	EUR·m^{-3}	192,552 Input $[m^3]^{-0.69}$	price quote commercial supplier
Lifetime evaporator	year	10.00	
Process: Residue processing			
Option: Pyrolysis			
Pyrolysis equipment	EUR·t^{-1}·h	19,387,234 Input $[t \cdot h^{-1}]^{-0.44}$	[55, 56, 75, 76]
Lifetime pyrolysis unit	year	30	[56]
Hydroprocessing unit	EUR·t^{-1}·day	717,314 Input $[t \cdot day^{-1}]^{-0.40}$	[55]
Lifetime hydroprocessing unit	year	30	[55]
Refining unit	EUR·t^{-1}·day	60,618 Input $[t \cdot day^{-1}]^{-0.40}$	[55]
Lifetime refining unit	year	30	[55]
Option: Gasification			
Gasificiation equipment	EUR·t^{-1}·h	19,387,234 Input $[t \cdot h^{-1}]^{-0.44}$	assumed the same as pyrolysis
Lifetime gasification unit	year	30	assumed the same as pyrolysis
Hydroprocessing unit	EUR·t^{-1}·day	717,314 Input $[t \cdot day^{-1}]^{-0.40}$	[55]

Lifetime hydroprocessing unit	year	30	[55]
Refining unit	EUR·t^{-1}·day	60,618 Input [t·day^{-1}]$^{-0.40}$	[55]
Lifetime refining unit	year	30	[55]
Option: Torrefaction			
Torrefaction equipment	EUR·t^{-1}·h	19,387,234 Input [t·h^{-1}]$^{-0.44}$	assumed the same as pyrolysis
Lifetime torrefaction unit	year	30	assumed the same as pyrolysis
Hydroprocessing unit	EUR·t^{-1}·day	717,314 Input [t·day^{-1}]$^{-0.40}$	[55]
Lifetime hydroprocessing unit	year	30	[55]
Refining unit	EUR·t^{-1}·day	60,618 Input [t·day^{-1}]$^{-0.40}$	[55]
Lifetime refining unit	year	30	[55]
Option: HTL			
HTL equipment	EUR·t^{-1}·h	19,387,234 Input [t·h^{-1}]$^{-0.44}$	assumed the same as pyrolysis
Lifetime HTL unit	year	30	assumed the same as pyrolysis
Hydroprocessing unit	EUR·t^{-1}·day	717,314 Input [t·day^{-1}]$^{-0.40}$	[55]
Lifetime hydroprocessing unit	year	30	[55]
Refining unit	EUR·t^{-1}·day	60,618 Input [t·day^{-1}]$^{-0.40}$	[55]
Lifetime refining unit	year	30	[55]
Option: Anaerobic digestion			
Digester	EUR·m^{-3}	9,257 Input [m^{-3}]$^{-0.40}$	[49]
Lifetime digester	year	30	[49]
Operational costs			
General			
Working rate personnel	EUR·h^{-1}	39.20	[77]
Working hours/day	h·day^{-1}	8.00	
Working days	day	241.00	
Electricity costs (<20,000 MWh year^{-1})	EUR·MWh^{-1}	117.50	[78]
Electricity costs (>20,000 MWh year^{-1})	EUR·MWh^{-1}	93.70	[78]
Natural gas cost	EUR·MWh^{-1}	39.20	[79]
Water purchase cost	EUR·m^{-3}	3.39	[80]
Water disposal cost	EUR·m^{-3}	2.43	[81]

Insurance cost	$\%I_0$	1.00	[82]
Repair/maintenance cost	$\%I_0$	7.00	[82]
Process: Cultivation			
All Options			
Salt price	$EUR \cdot t^{-1}$	75.57	[83]
CO_2 price	$EUR \cdot t^{-1}$	225.00	price quote commercial supplier
KNO_3 price	$EUR \cdot t^{-1}$	1,594.30	[84]
$NaHCO_3$ price	$EUR \cdot t^{-1}$	869.51	[85]
KH_2PO_4 price	$EUR \cdot t^{-1}$	1,992.81	[86]
$FeCl_3.6H_2O$	$EUR \cdot t^{-1}$	488.12	commercial supplier
$MgSO_4$	$EUR \cdot t^{-1}$	797.12	[87]
Option: Open pond			
Personnel on site ponds	person	3+(Area [ha] 10^{-1})	
Option: PBR			
Personnel on site PBR	person	3+(Area [ha] 1^{-1})	
Option: ProviApt			
Personnel on site ProviApt	person	3+(Area [ha] 1^{-1})	[1]
Process: Extraction			
Option: Hexane extraction			
Hexane price	$EUR \cdot t^{-1}$	393.21	[88]
Process: Lipid processing			
Option: Transesterification			
Methanol	$EUR \cdot t^{-1}$	380.00	[89]
NaOH	$EUR \cdot t^{-1}$	181.69	[90]
HCl	$EUR \cdot t^{-1}$	2,378.22	[91]
Phosphoric acid	$EUR \cdot t^{-1}$	717.41	[49]
Citric acid	$EUR \cdot t^{-1}$	2,531.20	[92]
Option: Hydrotreating			
Hydrogen	$EUR \cdot kg^{-1}$	10.00	[93]

Phosphoric acid	EUR·t^{-1}	717.41	[49]
Silica	EUR·kg^{-1}	1.99	[49]
Clay	EUR·kg^{-1}	0.60	[49]
Process: Residue processing			
Option: Pyrolysis			
Hydrogen	EUR·kg^{-1}	10.00	[93]
Option: Gasification			
Hydrogen	EUR·kg^{-1}	10.00	[93]
Option: Torrefaction			
Hydrogen	EUR·kg^{-1}	10.00	[93]
Option: HTL			
Solid waste	EUR·t^{-1}	33.43	[55]
Hydrogen	EUR·kg^{-1}	10.00	[93]
Revenues			
Sale fertilizer	EUR·kg^{-1}	0.39	price quote commercial supplier
Sale larval feed	EUR·kg^{-1}	318.00	[94]
Sale β-carotene	EUR·kg^{-1}	1000.00	commercial sources, [95-99]
Sale astaxanthin	EUR·kg^{-1}	5000.00	[13, 100-104]
Sale biodiesel	EUR·l^{-1}	0.50	[105]
Sale renewable diesel	EUR·l^{-1}	0.50	[105]
Sale glycerol	EUR·t^{-1}	0.17	[48]
Sale gasoline	EUR·l^{-1}	0.48	[105]
Sale naphtha	EUR·kg^{-1}	0.46	[106]
Markets			
Market fertilizer	t·year^{-1}	17,000,000	[107]
Market larval feed	t·year^{-1}	4,000	[108]
Market β-carotene	t·year^{-1}	371.56	[109]
Market astaxanthin	t·year^{-1}	280.00	[110]
Market volume diesel	t·year^{-1}	1,294,000,000	[111]

Market volume glycerol	$t \cdot year^{-1}$	3,551,000	[112]
Market volume gasoline	$t \cdot year^{-1}$	1,286,000000	[111]
Market volume naphtha	$t \cdot year^{-1}$	270,700,000	[113]

Environmental data

Table S3 gives an overview of all environmental input data with their corresponding references which have been used in the model. The data is grouped according to the different production process steps.

Table S3. Environmental input parameters

Parameter	Inventory	Unit		Characterization factor in ecoinvent (Alloc Def, U)	Ref/C
General					
Labour	Energy worker-hour^{-1}	MJ	39.00	Electricity, medium voltage {BE}| market for	[114]
Factory	Sizing factor		0.60		
Factory				Chemical factory, organics {RER}| construction	
Water				Tap water {Europe without Switzerland}| market for	
Water disp.				Wastewater, average {Europe without Switzerland}| market for wastewater, average	
Water em.				Emissions to water: water	
Electricity				Electricity, medium voltage {BE}| market for	
Heat				Heat, district or industrial, natural gas {RER}| market group for	
Land use				Inputs from nature: Occupation, bare area (non-use), BE	
Process: Cultivation 1st stage					
All Options					
Salt				Sodium chloride, powder {GLO}| market for	[a]
CO_2				Carbon dioxide, liquid {RER}| market for	[a]
$NaHCO_3$	Na_2CO_3	$kg\cdot kg^{-1}$	0.66	Soda ash, dense {GLO}| market for	[115]
$NaHCO_3$	CO_2 emission	$kg\cdot kg^{-1}$	$2\cdot10^{-4}$	Emissions to air: Carbon dioxide	[116]
$NaHCO_3$	Water emission	$kg\cdot kg^{-1}$	$6\cdot10^{-4}$	Emissions to air: water	[116]
$NaHCO_3$	Na_2CO_3 emission	$kg\cdot kg^{-1}$	0.0013	Emissions to air: Sodium carbonate	[116]
$NaHCO_3$	CO_2 to water	$kg\cdot kg^{-1}$	0.013	Emissions to water: Carbon dioxide	[116]
$NaHCO_3$	Water to water	$kg\cdot kg^{-1}$	0.0054	Emissions to water: water	[116]

$NaHCO_3$	Na_2CO_3 to water	$kg\cdot kg^{-1}$	0.014	Emissions to water: Sodium	116
$NaHCO_3$	Na_2CO_3 to water	$kg\cdot kg^{-1}$	0.018	Emissions to water: Carbonate	116
$NaHCO_3$	Transport lorry	$tkm\cdot kg^{-1}$	0.10	Transport, freight, lorry, unspecified {GLO}| market for	115
$NaHCO_3$	H_2O	$kg\cdot kg^{-1}$	0.11	Tap water {Europe without Switzerland}| market for	115
$NaHCO_3$	CO_2	$kg\cdot kg^{-1}$	0.28	See CO_2	115
$NaHCO_3$	Electricity	$kWh\cdot kg^{-1}$	0.33	Electricity, medium voltage {BE}| market for	116, 115
$NaHCO_3$	Chemical factory	$p\cdot kg^{-1}$	$4\cdot 10^{-10}$	Chemical factory, organics {RER}| construction	116
$NaHCO_3$	Plastic packaging	$kg\cdot kg^{-1}$	0.002	See Auxiliary: Plastic packaging	117
$NaHCO_3$	Transport train	$tkm\cdot kg^{-1}$	0.60	Transport, freight train {Europe without Switzerland/GLO}| market for	115
KH_2PO_4	P_2O_5	$kg\cdot kg^{-1}$	0.52	Phosphate fertilizer, as P2O5 {GLO}| market for	86
KH_2PO_4	K_2O	$kg\cdot kg^{-1}$	0.34	Potassium fertilizer, as K2O {GLO}| market for	86
KH_2PO_4	Transport lorry	$tkm\cdot kg^{-1}$	0.10	Transport, freight, lorry, unspecified {GLO}| market for	115
KH_2PO_4	Plastic packaging	$kg\cdot kg^{-1}$	0.002	See Auxiliary: Plastic packaging	117
KH_2PO_4	Transport train	$tkm\cdot kg^{-1}$	0.60	Transport, freight train {Europe without Switzerland}| market for	115
KNO_3				Potassium nitrate {GLO}| market for	a
$MgSO_4$				Magnesium sulfate {GLO}| market for	a
$FeCl_3.6H_2O$				Iron (III) chloride, without water, in 40% solution state {GLO}| market for	a
CO_2 em.				Emissions to water: Carbon dioxide	
N_2O em.				Emission to air: Dinitrogen monoxide	
NH_3 em.				Emissions to air: Ammonia	
O_2 em.				Emissions to air: Oxygen	
MPS	Tank	$p\cdot p^{-1}$	1.00	1 p Hot water tank, 600l {CH}| production	a
MPS	Sizing factor		0.57		82
CO_2 supply	Pump	$p\cdot p^{-1}$	1.00	Pump, 40W {CH}| production [a]	a
CO_2 supply	Sizing factor		0.62		b
Heat exch.	Capacity	$kW\cdot p^{-1}$	70.00		67
Heat exch.	Sizing factor		0.60		b
Heat exch.	Transport, lorry	$tkm\cdot p^{-1}$	0.88	Transport, freight, lorry, unspecified {GLO}| market for	115
Heat exch.	Titanium	$kg\cdot p^{-1}$	8.80	Titanium, primary {GLO}| market for	67
Heat exch.	Titanium waste	$kg\cdot p^{-1}$	8.80	See Auxiliary: Titanium waste	

Heat exch.	Packaging plastic	kg·p^{-1}	0.06	See Auxiliary: Plastic packaging	[117]
Heat exch.	Packaging paper	kg·p^{-1}	0.06	See Auxiliary: Paper packaging	[117]
Heat exch.	Transport, train	tkm·p^{-1}	5.28	Transport, freight train {Europe without Switzerland}| market for	[115]
IPS[§]					
Option: Open pond					
Liner	Capacity	ha·p^{-1}	0.81		[72]
Liner	Sizing factor		1.00		[b]
Liner	Material		HDPE		[64]
Liner	Thickness	mil	40.00		[64]
Liner	Width	m	12.20		[72]
Liner	Additional height	m	0.05		
Liner*	Liner depth	m	0.15		[5]
Liner	Transport lorry	tkm·p^{-1}	8,792	Transport, freight, lorry, unspecified {GLO}| market for	[115]
Liner	HDPE	kg·p^{-1}	80,792	Polyethylene, high density, granulate {GLO}| market for	[a]
Liner	HDPE waste	kg·p^{-1}	80,792	See Auxiliary: HDPE waste	
Liner	Transport train	tkm·p^{-1}	48,475	Transport, freight train {Europe without Switzerland}| market for	[115]
PW	Capacity	ha·p^{-1}	0.81		[72]
PW	Sizing factor		1.00		[b]
PW	Paddle width	m·p^{-1}	12.20		[72]
PW	Paddle thickness	m·p^{-1}	0.01		
PW	Paddle radials	#·p^{-1}	8.00		[66]
PW*	Paddle depth	m·p^{-1}	15.00		[5]
PW	Paddle material		HDPE		[118]
PW	Motor material		Steel		[118]
PW	Transport lorry	tkm·p^{-1}	22.43	Transport, freight, lorry, unspecified {GLO}| market for	[115]
PW	HDPE production	kg·p^{-1}	141.31	Polyethylene, high density, granulate {GLO}| market for	[a]
PW	Steel production	kg·p^{-1}	83.00	Steel, chromium steel 18/8 {GLO}| market for	[a, 119]
PW	HDPE waste	kg·p^{-1}	141.31	See Auxiliary: HDPE waste	
PW	Steel waste	kg·p^{-1}	83.00	See Auxiliary: Steel waste	
PW	Transport train	tkm·p^{-1}	134.58	Transport, freight train {Europe without Switzerland}| market for	[115]

	Option: PBR				
PBR	Capacity	$m^3 \cdot p^{-1}$	2.54		[28]
PBR	Int./ext. diam.	$m \cdot m^{-1}$	0.88		[28]
PBR	Transport lorry	$tkm \cdot kg^{-1}$	70.43	Transport, freight, lorry, unspecified {GLO}| market for	[115]
PBR	HDPE	$kg \cdot p^{-1}$	704.26	Polyethylene, high density, granulate {GLO}| market for	[a]
PBR	HDPE waste	$kg \cdot p^{-1}$	704.26	See Auxiliary: HDPE waste	
PBR	Transport train	$tkm \cdot kg^{-1}$	422.56	Transport, freight train {Europe without Switzerland}| market for	[115]
Blower	Pump	$p \cdot p^{-1}$	1.00	Pump, 40W {CH}| production [a]	[a]
	Option: ProviApt				
ProviApt	Width	$m \cdot p^{-1}$	1.25		[120]
ProviApt	Panels	$\# \cdot p^{-1}$	35.00		[120]
ProviApt	Distance panels	m	0.25		[120]
ProviApt	Heigth	m	0.50		[120]
ProviApt	Thickness	m	180.00		[120]
ProviApt	Diameter panels	m	0.02		[120]
ProviApt	HDPE production	$kg \cdot p^{-1}$	13.07	Polyethylene, high density, granulate {GLO}| market for	
ProviApt	HDPE waste	$kg \cdot p^{-1}$	13.07	See Auxiliary: HDPE waste	
ProviApt	Transport, lorry	$tkm \cdot p^{-1}$	1.31	Transport, freight train {Europe without Switzerland}| market for	[115]
ProviApt	Transport, train	$tkm \cdot p^{-1}$	7.84	Transport, freight train {Europe without Switzerland}| market for	[115]
Process: Preharvesting					
	Option: IPC®				
IPC®	Capacity	$m^2 \cdot p^{-1}$	1.00		
IPC®	Sizing factor		1.00		
IPC®	Water	$l \cdot m^{-2}$	20.50	Tap water {Europe without Switzerland}/| market for	
IPC®	Glycerine	$g \cdot m^{-2}$	45.00	Glycerine {GLO}| market for	
IPC®	PES	$g \cdot m^{-2}$	100.00	Polycarbonate {GLO}| market for	
IPC®	PVP	$g \cdot m^{-2}$	50.00	See Auxiliary: PVP prod.	
IPC®	NaOCl	$g \cdot m^{-2}$	5.00	Sodium hypochlorite, without water, in 15% solution state {GLO}| market for	
IPC®	NEP	$kg \cdot m^{-2}$	6,944	N-methyl-2-pyrrolidone {GLO}| market for	
IPC®	Cl2 to air	$g \cdot m^{-2}$	5.00	Emissions to air: Chlorine	

IPC®	AOX to water	$g \cdot m^{-2}$	0.01	Emissions to water: AOX, Adsorbable Organic Halogen as Cl	
IPC®	NaOCl to water	$g \cdot m^{-2}$	5.00	Emissions to water: Sodium hypochlorite	
IPC®	NEP to water	$g \cdot m^{-2}$	305	Emissions to water: Organic compounds (unspecified)	
IPC®	Electricity	$kWh \cdot m^{-2}$	1.11	Electricity, medium voltage {BE}| market for	
IPC®	PVP to waste	$g \cdot m^{-2}$	49.00	See Auxiliary: pl. pack. Waste	
IPC®	PES to waste	$g \cdot m^{-2}$	5.00	See Auxiliary: pl. pack. Waste	
IPC®	Glycerine to waste	$g \cdot m^{-2}$	45.00	Wastewater, average {Europe without Switzerland}| market for wastewater, average	
IPC®	Wastewater+NEP	$l \cdot m^{-2}$	27.81	Wastewater, average {Europe without Switzerland}| market for wastewater, average	
Tanks	Tank	$p \cdot p^{-1}$	1.00	1 p Hot water tank, 600l {CH}| production	[a]
Pumps	Pump	$p \cdot p^{-1}$	1.00	Pump, 40W {CH}| production [a]	[a]
Control eq.	Sizing factor		1.00	Electronic component, passive, unspecified {GLO}| market for	
Laptop	Sizing factor		1.00	Computer, laptop {GLO}| market for	
Process: Harvesting					
Option: Centrifuge					
Centrifuge	Sizing factor		0.56		[b]
Centrifuge	Capacity	$l \cdot h^{-1}$	3,750		[121]
Centrifuge	Steel	$kg \cdot p^{-1}$	3,750	Steel, chromium steel 18/8 {GLO}| market for	[a ,121]
Centrifuge	Steel waste	$kg \cdot p^{-1}$	3,750	See Auxiliary: Steel waste	[121]
Process: Washing					
Tank	Tank	$p \cdot p^{-1}$	1.00	1 p Hot water tank, 600l {CH}| production	[a]
Mixer	Pump	$p \cdot p^{-1}$	1.00	Pump, 40W {CH}| production [a]	[a]
Centrifuge	Centrifuge	$p \cdot p^{-1}$	1.00	See Centrifuge of Process: Harvesting	
Process: Drying					
Option: Spray dryer					
Spray dryer	Capacity	$l \cdot s^{-1}$	1.00		[122]
Spray dryer	Sizing factor		0.60		[b]
Spray dryer	Transport lorry	$tkm \cdot p^{-1}$	29,895	Transport, freight, lorry, unspecified {GLO}| market for	[122]
Spray dryer	Steel	$kg \cdot p^{-1}$	22,900	Steel, chromium steel 18/8 {GLO}| market for	[a, 122]

Spray dryer	Glass fibre	kg·p^{-1}	96	Glass fibre {GLO}| market for	[a ,122]
Spray dryer	Steel waste	kg·p^{-1}	22,900	See Auxiliary: Steel waste	[122]
Spray dryer	Glass fiber waste	kg·p^{-1}	96	See Auxiliary: Glass fibre waste	[122]
Spray dryer	Electric welding	m·kg^{-1}	134	Welding, arc, steel {RER}| processing	[122]
Spray dryer	Rolling steel	kg·kg^{-1}	22,900	Sheet rolling, chromium steel {RER}| processing	[122]
Option: Freeze dryer					
Freeze dryer	Spray dryer	p·p^{-1}	1.00	See Spray Dryer Process: Drying	[a]
Process: Disruption					
Option: Bead mill					
Bead mill	Capacity	l·h^{-1}	500.00		[c]
Bead mill	Sizing factor		0.60		
Bead mill	Steel	kg·p^{-1}	750.00	Steel, chromium steel 18/8 {GLO}| market for	[a,c]
Bead mill	Volume	l	16.50		[c]
Bead mill	Electric welding	m·kg^{-1}	4.39	Welding, arc, steel {RER}| processing	[d]
Bead mill	Rolling steel	kg·kg^{-1}	750.00	Sheet rolling, chromium steel {RER}| processing	[d]
Bead mill	Transport lorry	tkm·p^{-1}	7,027.08	Transport, freight, lorry, unspecified {GLO}| market for	[d]
Bead mill	Steel waste	kg·p^{-1}	750.00	See Auxiliary: Steel waste	
Bead mill	ZrO_2 waste	kg·p^{-1}	4,66.45	See Auxiliary: Steel waste	
Bead mill	Pump	kW	0.55	Pump, 40W {CH}| production [a]	[c]
Beads	Filling	%	85.00	Zirconium oxide {GLO}| market for	[41]
Beads	Lifetime	h	1500.00		[c]
Process: Extraction					
Option: Hexane extraction					
C_6H_{14}				Hexane {GLO}| market for	[a]
Em. C_6H_{14}				Emissions to air: Hexane	
Tank	Tank	p·p^{-1}	1.00	1 p Hot water tank, 600l {CH}| production	[a]
Mixer	Pump	p·p^{-1}	1.00	Pump, 40W {CH}| production [a]	[a]
Process: Filtration					
Membrane	Membrane	p·p^{-1}	1.00	See IPC®	
Process: Lipid purification					

Option: Vacuum distillation					
Distiller	Spray dryer	$p \cdot p^{-1}$	1.00	See Spray Dryer Process: Drying	a
Ref β-car.					123-146
Ref ast.					136, 138, 139, 141, 147-165
Process: Lipid processing					
Option: Transesterification					
Methanol				Methanol {GLO}| market for	
NaOH				Sodium hydroxide, without water, in 50% solution state {GLO}| market for	a
HCl				Hydrochloric acid, without water, in 30% solution state {RER}| market for	
P_2O_5				Phosphate fertiliser, as P_2O_5 {GLO}| market for	
Ref. diesel				Diesel {Europe without Switzerland}| petroleum refinery operation	
Ref. glycerol				Glycerine {GLO}| market for	e
CHOH em.				Emissions to air: Methanol	
NaOH em.				Emissions to air: NaOH	
HCl em.				Emissions to air: HCl	
P_2O_5 em.				Emissions to air: P_2O_5	
TE unit	Pumps	#	9.00	Pump, 40W {CH}| production [a]	a, 48
TE unit	Tanks	#	7.00	1 p Hot water tank, 600l {CH}| production	a, 48
TE unit	Distiller	#	2.00	See Spray Dryer Process: Drying	48
TE unit	Heat exchangers	#	11.00	See Heat exchanger Process: Cultivation	48
TE unit	Sizing factor		0.60		
Option: Hydrotreating					
Hydrogen				Hydrogen, liquid {RER}| market for	
H_3PO_4				Phosphoric acid, industrial grade, without water, in 85% solution state {RER}| purification of wet-process phosphoric acid to industrial grade, product in 85% solution state	
Clay				Clay {RoW}| market for clay	
Silica				Silica sand {GLO}| market for	
Ref. Diesel				Diesel {Europe without Switzerland}| petroleum refinery operation	
Ref. Naphtha				Naphtha {Europe without Switzerland}| petroleum refinery operation	

H_2 em.				Emission to air: H_2	
H_3PO_4 em.				Emission to air: Phosphoric acid	
HT unit	Reactors	#	5.00	1 p Hot water tank, 600l {CH}| production	[a, 51]
HT unit	Separators	#	4.00	See Spray Dryer Process: Drying	[51]
HT unit	Pump	#	1.00	Pump, 40W {CH}| production [a]	[a, 51]
HT unit	Compressor	#	2.00	Pump, 40W {CH}| production [a]	[a, 51]
HT unit	Heat exchanger	#	1.00	See Heat exchanger Process: Cultivation	[51]
HT unit	Sizing factor		0.60		
PSA	Tank	#	1.00	1 p Hot water tank, 600l {CH}| production	[a, 51]
PSA	Sizing factor		0.60		
Pur. Unit	Reactors	#	3.00	1 p Hot water tank, 600l {CH}| production	[a, 51]
Pur. Unit	Centrifuge	#	1.00	See Centrifuge Process: Harvesting	[51]
Pur. Unit	Filters	#	2.00	See IPC®	[51]
Pur. Unit	Sizing factor		0.6		
Process: Residue purification					
Option: Evaporation					
Ref. fert.	N-fertilizer	$kg \cdot kg^{-1}$	0.04	Nitrogen fertiliser, as N {GLO}| market for	[a, 166, e]
Ref. fert.	P-fertilizer	$kg \cdot kg^{-1}$	0.001	Phosphate fertiliser, as P_2O_5 {GLO}| market for	[a, 166, e]
Ref. flf	Electricity boat	$MJ \cdot kg^{-1}$	2.34	Electricity, medium voltage {PE}| market for	[167]
Ref. flf	Aluminium	$kg \cdot kg^{-1}$	0.07	Aluminium, wrought alloy {GLO}| market for	[167]
Ref. flf	Aluminium landfill	%	20.00	Disposal, inert waste, 5% water, to inert material landfill/CH U	[167]
Ref. flf	Steel	$kg \cdot kg^{-1}$	0.07	Steel, chromium steel 18/8 {GLO}| market for	[167]
Ref. flf	Steel landfill	%	90.75	Scrap steel {CH}| treatment of, inert material landfill	[167]
Ref. flf	Steel recycling	%	9.25	See Auxiliary: Recycling steel	[167]
Ref. flf	Plastic	$kg \cdot kg^{-1}$	0.03	Polyethylene, high density, granulate {GLO}| market for	[167]
Ref. flf	Plastic landfill	%	100.00	Disposal, plastics, mixture, 15.3% water, to sanitary landfill/CH U	[167]
Ref. flf	Lead	$g \cdot kg^{-1}$	10.45	Lead {GLO}| market for	[167]
Ref. flf	Lead EoL	%	100.00	Lead concentrate {GLO}| market for	
Ref. flf	Diesel	$MJ \cdot kg^{-1}$	8.09	Diesel, burned in agricultural machinery {GLO}| market for diesel, burned in agricultural machinery	[167]

Ref. flf	Electricity processing	MJ·kg^{-1}	0.56	Electricity, medium voltage {PE}| market for	[167]
Ref. flf	Fuel oil	MJ·kg^{-1}	10.99	Heavy fuel oil {RoW}| market for	[167]
Ref. flf	COD to water	kg·kg^{-1}	0.22	Emission to air: COD	[167]
Evaporator	Spray dryer	p·p^{-1}	1.00	See Spray Dryer Process: Drying	[a]
Process: Residue processing					
Option: Pyrolysis					
Pyr. Unit	Spray dryer	p·p^{-1}	1.00	See Spray Dryer Process: Drying	[a]
Pyr. Unit	Sizing factor		0.60		
Com. bioch.				Hard coal, burned in power plant/BE	[f]
Com. syngas				Natural gas, burned in power plant/BE	[f]
HP eq.	Hydrotreating unit	p·p^{-1}	1.00	See Hydrotreating unit Process: Hydrotreatment	
HP eq	PSA	p·p^{-1}	1.00	See PSA Process: Hydrotreatment	
HP eq	Purification unit	p·p^{-1}	1.00	See Purification unit Process: Hydrotreatment	
HP eq	Sizing facor		0.60		
Hydrogen				Hydrogen, liquid {RER}| market for	
Ref. gasol.				Petrol, unleaded {Europe without Switzerland}| petroleum refinery operation	
Ref. diesel				Diesel {Europe without Switzerland}| petroleum refinery operation	
Option: Gasification					
Gasif. Unit	Spray dryer	p·p^{-1}	1.00	See Spray Dryer Process: Drying	[a]
Gasif. Unit	Sizing factor		0.60		
Com. bioch.				Hard coal, burned in power plant/BE	[f]
Com. syngas				Natural gas, burned in power plant/BE	[f]
HP eq	Hydrotreating unit	p·p^{-1}	1.00	See Hydrotreating unit Process: Hydrotreatment	
HP eq	PSA	p·p^{-1}	1.00	See PSA Process: Hydrotreatment	
HP eq	Purification unit	p·p^{-1}	1.00	See Purification unit Process: Hydrotreatment	
HP eq	Sizing facor		0.60		
Hydrogen				Hydrogen, liquid {RER}| market for	
Ref. gasol.				Petrol, unleaded {Europe without Switzerland}| petroleum refinery operation	
Ref. diesel				Diesel {Europe without Switzerland}| petroleum refinery operation	

Option: Torrefaction					
Tor. Unit	Spray dryer	p·p^{-1}	1.00	See Spray Dryer Process: Drying	a
Tor. Unit	Sizing factor		0.60		
Com. bioch.				Hard coal, burned in power plant/BE	f
Com. syngas				Natural gas, burned in power plant/BE	f
HP eq	Hydrotreating unit	p·p^{-1}	1.00	See Hydrotreating unit Process: Hydrotreatment	
HP eq	PSA	p·p^{-1}	1.00	See PSA Process: Hydrotreatment	
HP eq	Purification unit	p·p^{-1}	1.00	See Purification unit Process: Hydrotreatment	
HP eq	Sizing facor		0.60		
Hydrogen				Hydrogen, liquid {RER}| market for	
Ref. gasol.				Petrol, unleaded {Europe without Switzerland}| petroleum refinery operation	
Ref. diesel				Diesel {Europe without Switzerland}| petroleum refinery operation	
Option: HTL					
HTL unit	Spray dryer	p·p^{-1}	1.00	See Spray Dryer Process: Drying	a
Hydrogen				Hydrogen, liquid {RER}| market for	
Solid waste				Final waste flow: solid waste	
Ref. gasol.				Petrol, unleaded {Europe without Switzerland}| petroleum refinery operation	
HTL unit	Sizing factor		0.60		
HP eq	Hydrotreating unit	p·p^{-1}	1.00	See Hydrotreating unit Process: Hydrotreatment	
HP eq	PSA	p·p^{-1}	1.00	See PSA Process: Hydrotreatment	
HP eq	Purification unit	p·p^{-1}	1.00	See Purification unit Process: Hydrotreatment	
HP eq	Sizing facor		0.60		
Hydrogen				Hydrogen, liquid {RER}| market for	
Ref. gasol.				Petrol, unleaded {Europe without Switzerland}| petroleum refinery operation	
Ref. diesel				Diesel {Europe without Switzerland}| petroleum refinery operation	
Option: Anaerobic digestion					
Digester	Spray dryer	p·p^{-1}	1.00	See Spray Dryer Process: Drying	a
Ref. CO_2				Carbon dioxide, liquid {RER}| market for	a
Ref. CH_4				Methane, 96% by volume {GLO}| market for	

N-fertillizer				Nitrogen fertiliser, as N {GLO}| market for	
P-fertilizer	P to P_2O_5 ratio	$kg \cdot kg^{-1}$	2.41	Phosphate fertiliser, as P_2O_5 {GLO}| market for	
K-fertilizer	K to K_2O ratio	$kg \cdot kg^{-1}$	4.58	Potassium fertiliser, as K_2O {GLO}| market for	
Digester	Sizing factor		0.60		
Auxiliary					
Pl. Waste	Transport lorry	$tkm \cdot kg^{-1}$	0.019	Transport, freight, lorry, unspecified {GLO}| market for	g
Pl. Waste	Transport train	$tkm \cdot kg^{-1}$	0.011	Transport, freight train {Europe without Switzerland}| market for	g
Pl. Waste	Recycled plastic	$kg \cdot kg^{-1}$	0.85	See Auxiliary: Plastic recycling	168
Pl. Waste	Incinerated plastic	$kg \cdot kg^{-1}$	0.11	Disposal, polyethylene, 0.4% water, to municipal incineration/CH	168
Pl. Waste	Landfilled plastic	$kg \cdot kg^{-1}$	0.05	Disposal, plastics, mixture, 15.3% water, to sanitary landfill/CH	168
Pl. recycl.	Replaced pl. (QF)	$kg \cdot kg^{-1}$	0.75	Packaging film, low density polyethylene {GLO}| market for	169
Pl. recycl.	Electricity	$kWh \cdot kg^{-1}$	0.60	Electricity, medium voltage {BE}| market for	h
Tit. waste	Transport lorry	$tkm \cdot kg^{-1}$	0.019	Transport, freight, lorry, unspecified {GLO}| market for	i
Tit. waste	Transport train	$tkm \cdot kg^{-1}$	0.011	Transport, freight train {Europe without Switzerland}| market for	i
Tit. waste	Recycled tit.	$kg \cdot kg^{-1}$	0.9998	See Auxiliary: Tit. Recycle.	168
Tit. waste	Landfilled tit.	$kg \cdot kg^{-1}$	0.0002	Disposal, inert waste, 5% water, to inert material landfill/CH U	168
Tit. rec.	Replaced tit. (QF)	$kg \cdot kg^{-1}$	1.00	Titanium, primary {GLO}| market for	169
Tit. rec.	Electricity	$GJ \cdot kg^{-1}$	0.026	Electricity, medium voltage {BE}| market for	170
P. Waste	Transport, lorry	$tkm \cdot kg^{-1}$	0.019	Transport, freight, lorry, unspecified {GLO}| market for	g
P. Waste	Transport train	$tkm \cdot kg^{-1}$	0.011	Transport, freight train {Europe without Switzerland}| market for	g
P. Waste	Recycled paper	$kg \cdot kg^{-1}$	0.9994	Paper (waste treatment) {GLO}| recycling of paper	168
P. Waste	Incinerated paper	$kg \cdot kg^{-1}$	0.0005	Disposal, packaging paper, 13.7% water, to municipal incineration/CH U	168
P. Waste	Recycled paper	$kg \cdot kg^{-1}$	0.14	Paper (waste treatment) {GLO}| recycling of paper	171
P. Waste	Landfilled paper	$kg \cdot kg^{-1}$	0.86	Disposal, packaging paper, 13.7% water, to sanitary landfill/CH U	171
HDPE waste	Transport lorry	$tkm \cdot kg^{-1}$	0.019	Transport, freight, lorry, unspecified {GLO}| market for	g
HDPE waste	Transport train	$tkm \cdot kg^{-1}$	0.011	Transport, freight train {Europe without Switzerland}| market for	g
HDPE waste	Recycled HDPE	$kg \cdot kg^{-1}$	0.85	See Auxiliary: HDPE recycle.	168
HDPE waste	Incinerated HDPE	$kg \cdot kg^{-1}$	0.11	Disposal, polyethylene, 0.4% water, to municipal incineration/CH U	168
HDPE waste	Landfilled HDPE	$kg \cdot kg^{-1}$	0.05	Disposal, polyethylene, 0.4% water, to sanitary landfill/CH U	168

HDPE rec.	Electricity	kWh·kg^{-1}	0.60	Electricity, medium voltage {BE}| market for	h
HDPE rec.	Replaced HDPE (QF)	kg·kg^{-1}	0.75	Polyethylene, high density, granulate {GLO}| market for	a, 169
Steel waste	Transport lorry	tkm·kg^{-1}	0.0193	Transport, freight, lorry, unspecified {GLO}| market for	i
Steel waste	Transport train	tkm·kg^{-1}	0.011	Transport, freight train {Europe without Switzerland}| market for	i
Steel waste	Recycled Steel	kg·kg^{-1}	0.9998	See Auxiliary: Recycle steel	168
Steel waste	Landfilled Steel	kg·kg^{-1}	0.0002	Scrap steel {CH}| treatment of, inert material landfill	168
Rec. Steel	Electricity	GJ·kg^{-1}	0.023	Electricity, medium voltage {BE}| market for	i, 170
Rec. Steel	Replaced steel (QF)	kg·kg^{-1}	1.00	Steel, chromium steel 18/8 {GLO}| market for	a, 169
PVP prod.	1,4-butanediol	kg·kg^{-1}	0.80	Butane-1,4-diol {GLO}| market for	172
PVP prod.	Acetylene	kg·kg^{-1}	0.23	Acetylene {GLO}| market for | Alloc Def, U	172
PVP prod.	Hydrogen to air	kg·kg^{-1}	0.04	Emissions to air: Hydrogen	172
PVP prod.	Water to water	kg·kg^{-1}	0.16	Emissions to water: water	172
PVP prod.	Ammonia	kg·kg^{-1}	0.15	Ammonia, liquid {RER}| market for	172
Gl. f. waste	Transport lorry	tkm·kg^{-1}	0.0193	Transport, freight, lorry, unspecified {GLO}| market for	i
Gl. f. waste	Transport train	tkm·kg^{-1}	0.011	Transport, freight train {Europe without Switzerland}| market for	i
Gl. f. waste	Recycled gl. f.	kg·kg^{-1}	0.94	See Auxiliary: Glass recycling	168
Gl. f. waste	Incinerated gl.f.	kg·kg^{-1}	0.01	Waste glass {Europe without Switzerland}| treatment of waste glass, municipal incineration	168
Gl. f. waste	Landfilled gl. f.	kg·kg^{-1}	0.05	Disposal, glass, 0% water, to inert material landfill/CH U	168
Gl. f. rec.	Replaced gl. f. (QF)	kg·kg^{-1}	1.00	Glass fibre {GLO}| market for	a, 169

Abbreviations: Ref/C = Reference/Comment; pack. = packaging; rec. = recycling; pl. = plastic; QF = quality factor; em. = emission; exc. = exchanger; tit. = titanium; p. = paper; prod. = production; PW: paddlewheel; eq. = equipment; transf. = transformation; MPS = medium preparation system; fr. = fraction; sep. = separation; SSP = single superphosphate; TSP = triple superphosphate; Int./ext. diam. = internal/external diameter; Tor. = Torrefaction; Gas. = Gasification; Gasol.= Gasoline; Pyr. = Pyrolysis; TE = Transesterification; HP = Hydroprocessing; HT = Hydrotreatmen; eq = equipment; com = combustion; bioch. =biochar; flf = fish larvae feed; pur. = purification. [§] IPS = Inoculum production system; the impact of the first cultivation stage of the PBR cultivation option is scaled to produce the corresponding amount of inoculum; * In second cultivation stage: height = 12 m; [a] = adapted to Belgian conditions; [b] = economic regression function; [c] = Information supplier; [d] = adapted from spray dryer; [e] = removed the transport emissions; [f] = Input at zero; [g] = Waste polyethylene {Europe without Switzerland}| market for waste polyethylene; [h] = PE (waste treatment) {GLO}| recycling of PE; [i] = Scrap steel {Europe without Switzerland}| market for scrap steel.

Equations

The original MOMINLP problem can be formulated as follows:

$$Max\ NPV(b_{g,h}, a) \qquad \forall\, g \in G, h \in H \qquad (1)$$

$$Max\ \Delta HH(b_{g,h}, a) \qquad \forall\, g \in G, h \in H \qquad (2)$$

$$Max\ \Delta ED(b_{g,h}, a) \qquad \forall\, g \in G, h \in H \qquad (3)$$

$$Max\ \Delta RA(b_{g,h}, a) \qquad \forall\, g \in G, h \in H \qquad (4)$$

$$s.t. \sum_{h \in H} b_{g,h} = 1, \qquad \forall\, g \in G \qquad (5)$$

$$s.t.\, 0 \le a \ \le Maximum\ scale \qquad (6)$$

$$s.t.\, b\ \in \{0,1\} \qquad (7)$$

In the MOO problem, equations (1-4) are the objectives, equation (5) ensures that for each process step exactly one option is chosen and equation (6) and (7) determine the bounds on the variables.

The transformed MILP problem is formulated as follows:

$$Max\ NPV(x_{g,h,j,k,p}) = npv_{g,h,j,k,p} * x_{g,h,j,k,p} \qquad \forall\, g \in G, h \in H, j \in J, k \in k, p \in P \qquad (8)$$

$$s.t. \sum_{h \in H} a_{g,h}^{input} = \sum_{h \in H} a_{g-1,h}^{output} \qquad \forall\, g \in G \qquad (9)$$

$$s.t.\ a_{g,h}^{ouput} = a_{g,h}^{input} * \gamma_{g,h} \qquad \forall\, g \in G, h \in H \qquad (10)$$

$$s.t.\, 0 \ \le\ a_{g,h,j} \le\ M_{g,h,j} * b_{g,h} \qquad \forall\, g \in G, h \in H, j \in J \qquad (11)$$

$$s.t. \sum_{h \in H} b_{g,h} = 1 \qquad \forall\, g \in G \qquad (12)$$

$$s.t. \sum_{p \in P} d_{g,h,k,p} = 1 \qquad \forall\, g \in G, h \in H, k \in k \qquad (13)$$

$$s.t. \sum_{p \in P} c_{g,h,k,p} = Scale_{g,h,k}(x_{g,h,j}) \qquad \forall\, g \in G, h \in H, j \in J, k \in k \qquad (14)$$

$$s.t.\, PP_{g,h,k,p-1} d_{g,h,k,p} \le c_{g,h,k,p} \le PP_{g,h,k,p} d_{g,h,k,p} \qquad \forall\, g \in G, h \in H, k \in k, p \in P \qquad (15)$$

$$s.t.\, hh_{g,h,j,k,p} * x_{g,h,j,k,p} \ge \varepsilon_{it-\Delta HH,g,h,j,k,p} \qquad \forall\, g \in G, h \in H, j \in J, k \in k, p \in P \qquad (16)$$

$$s.t.\, ed_{g,h,j,k,p} * x_{g,h,j,k,p} \ge \varepsilon_{it-\Delta EQ,g,h,j,k,p} \qquad \forall\, g \in G, h \in H, j \in J, k \in k, p \in P \qquad (17)$$

$$s.t.\, ra_{g,h,j,k,p} * x_{g,h,j,k,p} \ge \varepsilon_{it-\Delta RS,g,h,j,k,p} \qquad \forall\, g \in G, h \in H, j \in J, k \in k, p \in P \qquad (18)$$

$$s.t.\, b_{g,h}, d_{g,h,k,p} \in \{0,1\} \qquad \forall\, g \in G, h \in H, k \in k, p \in P \qquad (19)$$

$$s.t.\, b_{g,h}, a_{g,h,j}, c_{g,h,k,p}, d_{g,h,k,p}\ \subset\ x_{g,h,j,k,p} \qquad \forall\, g \in G, h \in H, j \in J, k \in k, p \in P \qquad (20)$$

The two matrices (*Aq* and *Aeq*) and seven vectors (*Bq*, *Beq*, x_0, *npv*, *hh*, *eq*, *rs*) which are used to transfer the problem from Excel to Matlab are formulated as follows (where *npv* can be replaced by *hh*, *eq* or *rs*):

$$Max\ npv * x_{g,h,j,k,p} \qquad \forall\, g \in G, h \in H, j \in J, k \in K, p \in P \qquad (21)$$

$$Aeq * x_{g,h,j,k,p} = Beq \qquad \forall\, g \in G, h \in H, j \in J, k \in K, p \in P \qquad (22)$$

$$Aq * x_{g,h,j,k,p} \leq Bq \qquad \forall\, g \in G, h \in H, j \in J, k \in K, p \in P \qquad (23)$$

$$s.t.\, b_{g,h}, d_{g,h,k,p} \in \{0,1\}, \qquad \forall\, g \in G, h \in H, j \in J, k \in K, p \in P \qquad (24)$$

$$s.t.\, b_{g,h}, a_{g,h,j}, c_{g,h,k,p}, d_{g,h,k,p} \subset x \qquad \forall\, g \in G, h \in H, j \in J, k \in K, p \in P \qquad (25)$$

Process flow diagrams

Figures S1-S11 are the process flow diagrams of the Pareto-optimal scenarios of the MOO case study.

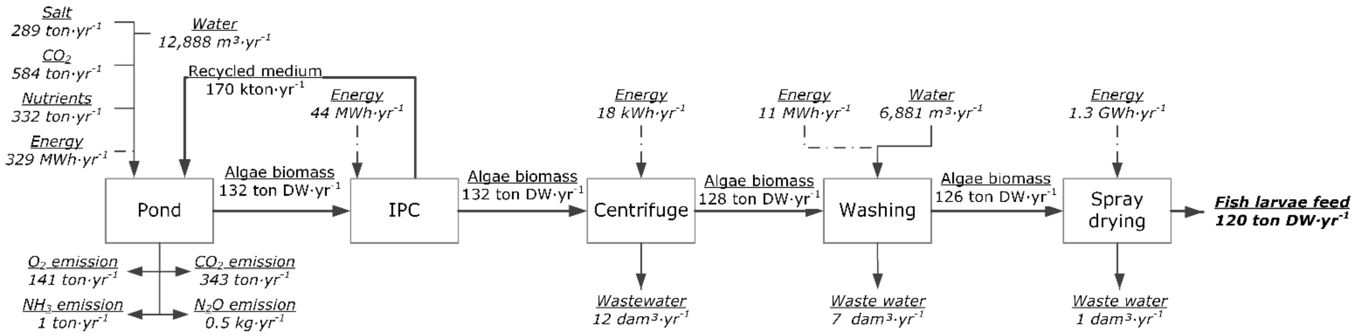

Fig. S1 PFD Ns FLF scenario

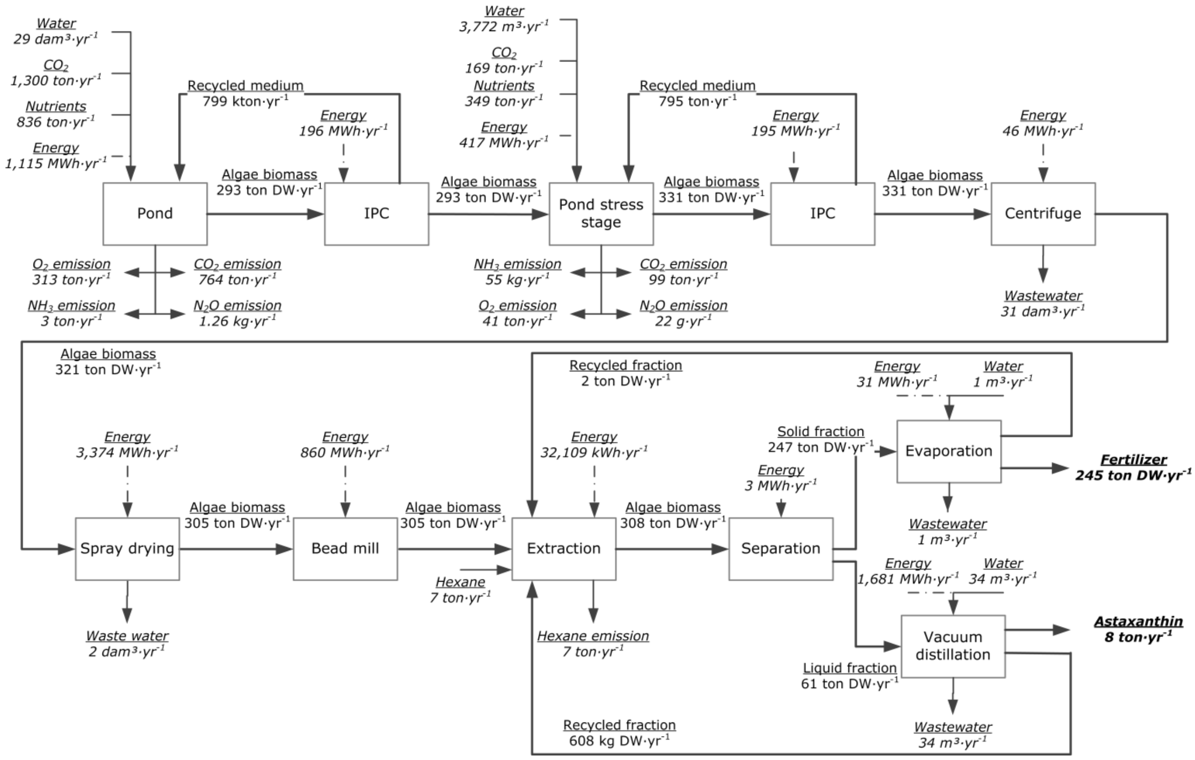

Fig. S2 PFD Hp F scenario

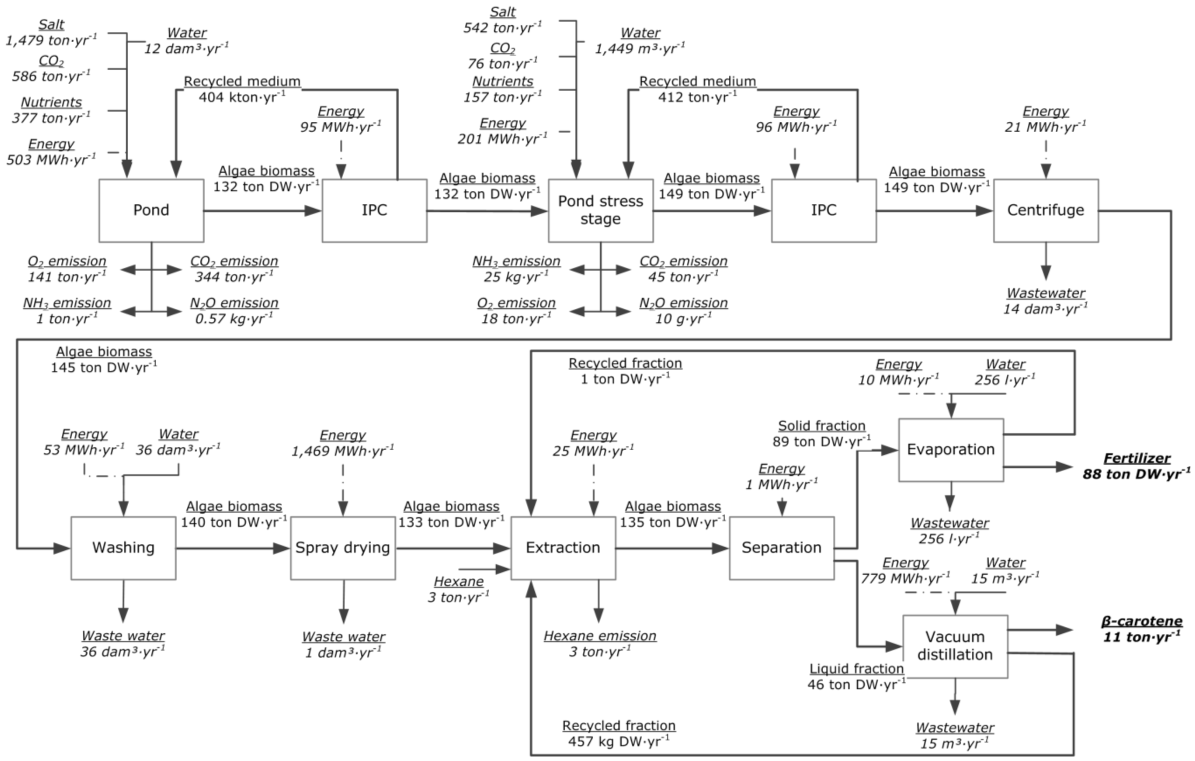

Fig. S3 PFD Ds F scenario

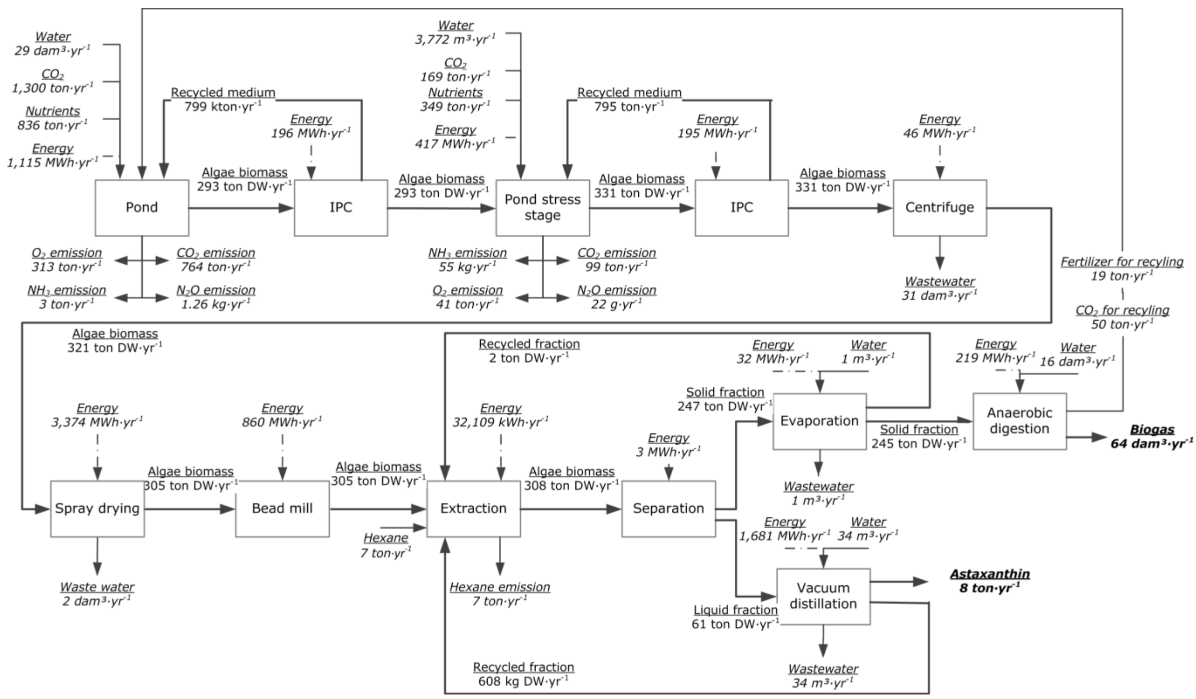

Fig. S4. PFD Hp AD scenario

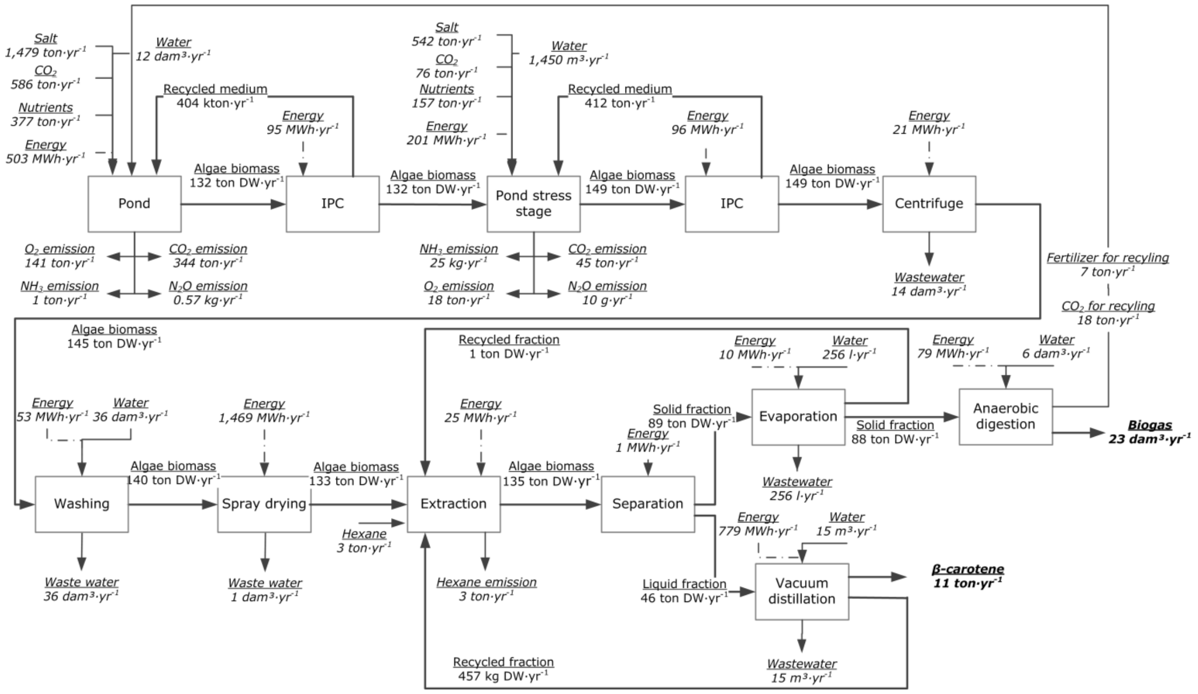

Fig. S5 PFD Ds AD scenario

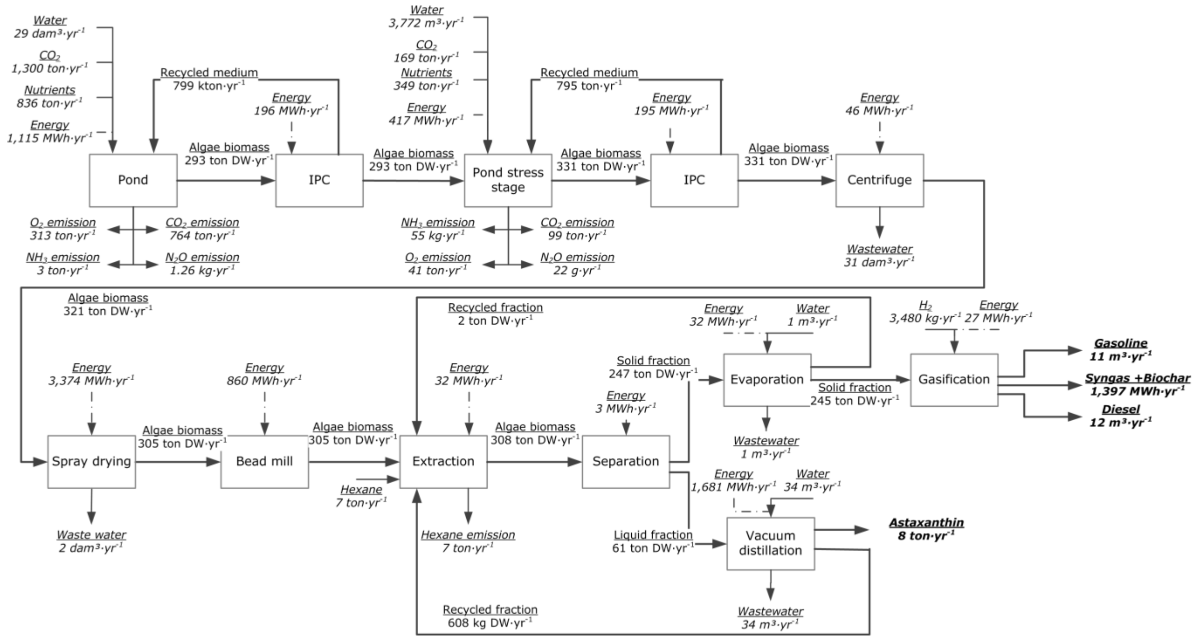

Fig. S6 PFD Hp G scenario

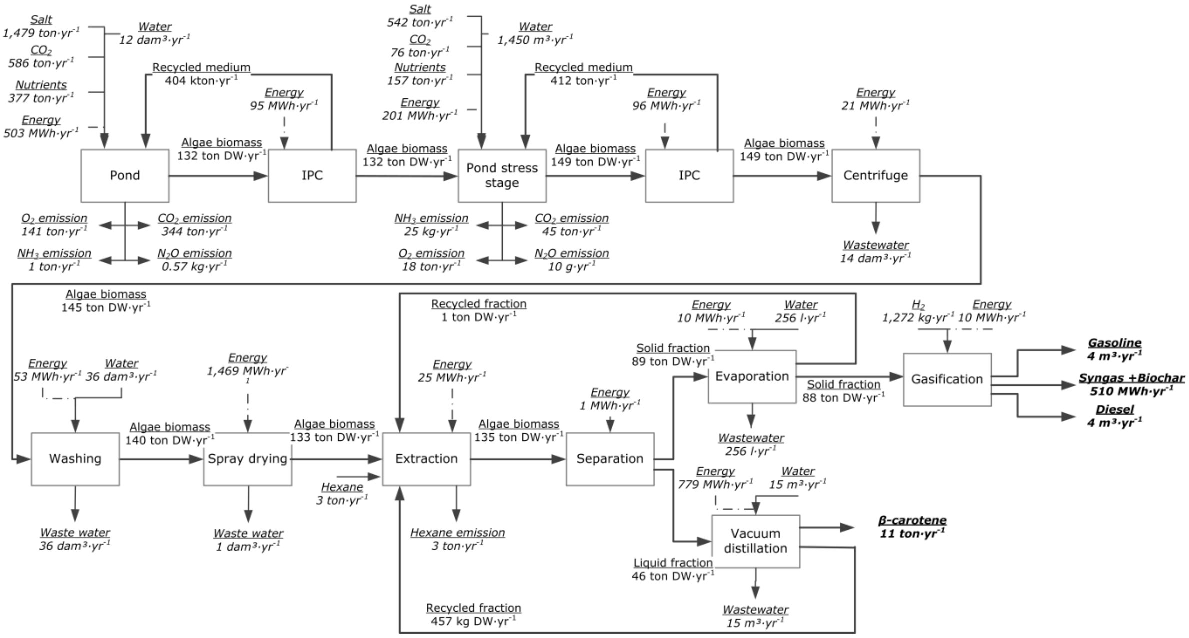

Fig. S7 PFD Ds G scenario

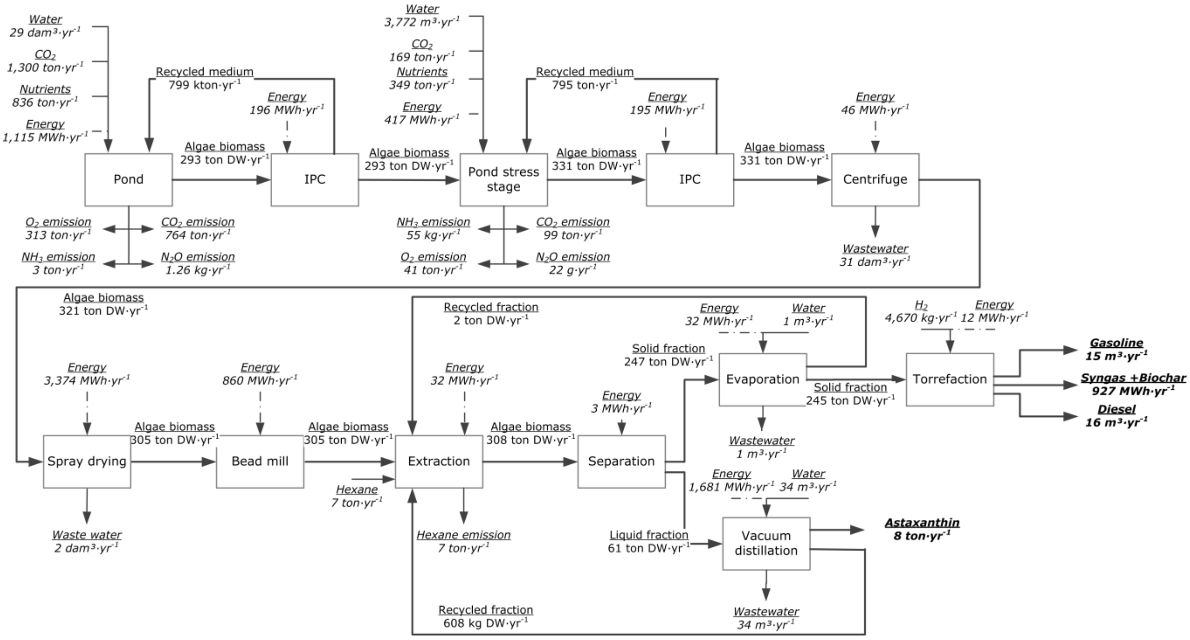

Fig. S8 PFD Hp T scenario

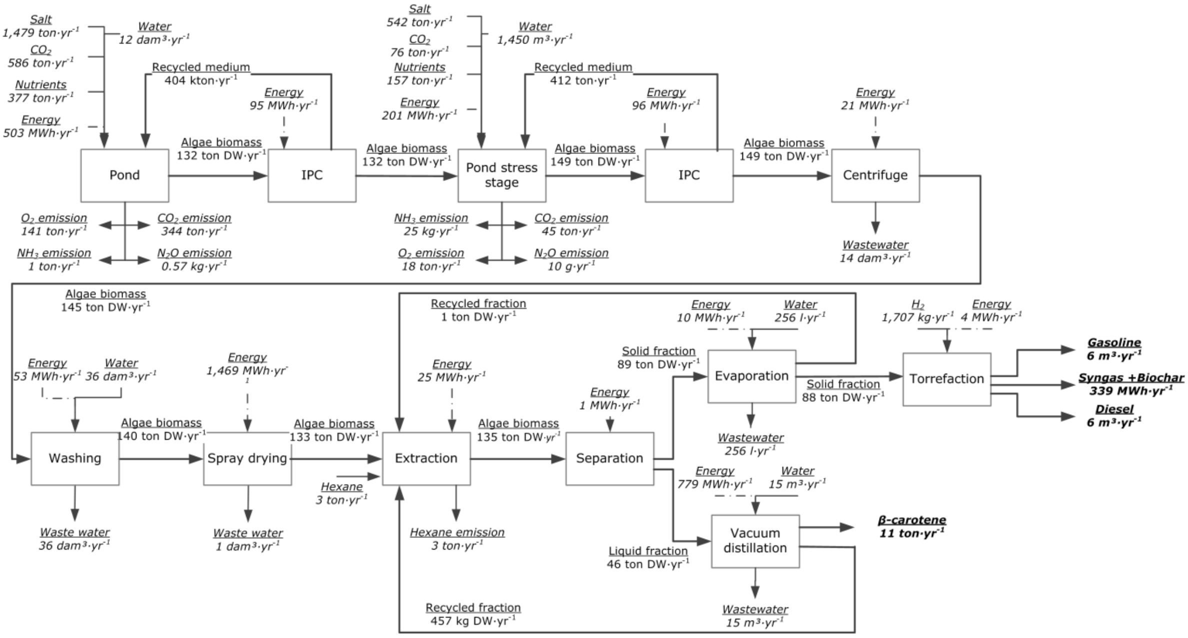

Fig. S9 PFD Ds T scenario

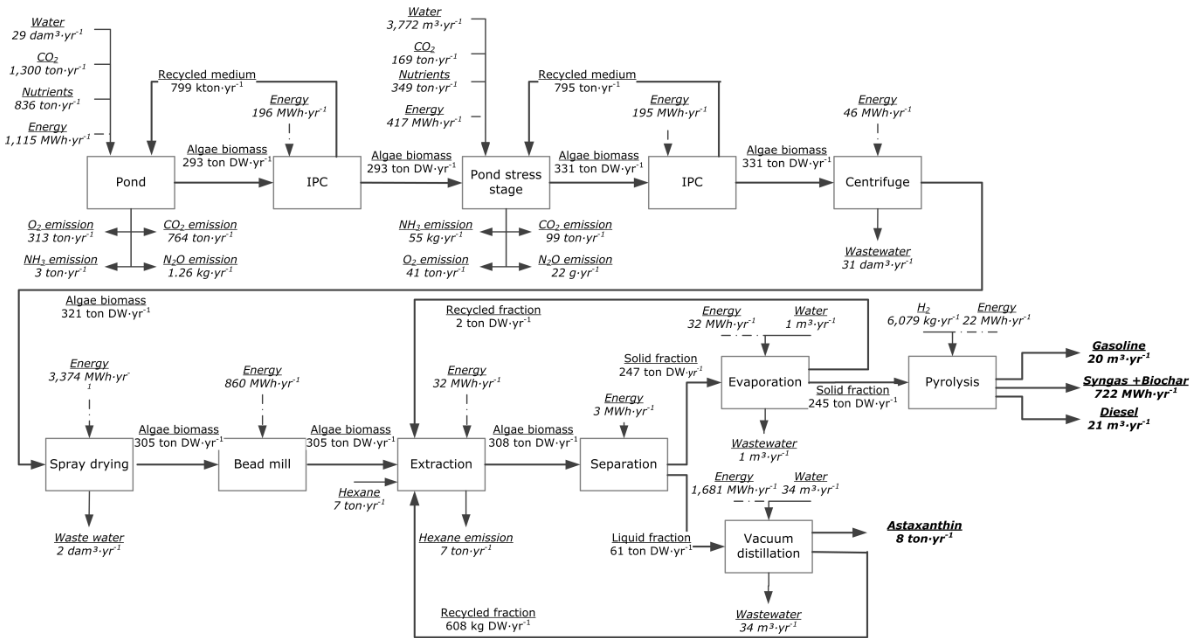

Fig. S10 PFD Hp P scenario

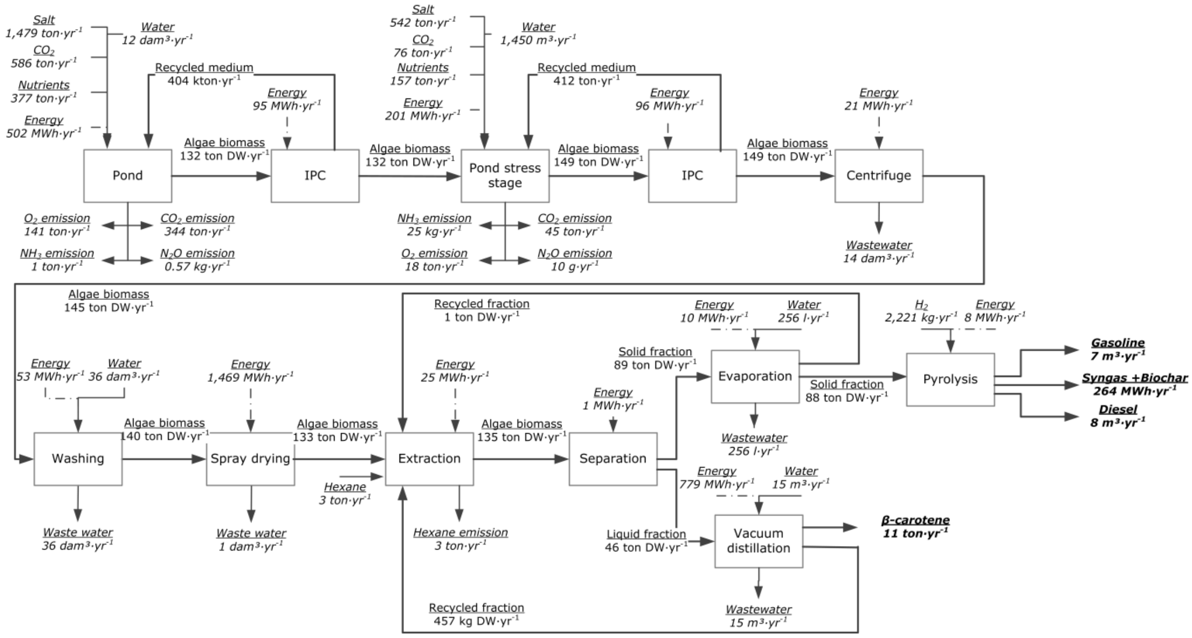

Fig. S11 PFD Ds P scenario

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