

Article

Opportunities and Challenges of the European Green Deal for the Chemical Industry: An Approach Measuring Innovations in Bioeconomy

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Supplementary Materials

S.1. Materials and methods

S.1.1. System definition and identification of system boundaries

Table S1. Overview of constant and variable input parameters for the evaluation of relevant biomass resources.

Exogenous		Endogenous
a. Constant spatial terms		
		<u>Plant specifications</u> <ul style="list-style-type: none">Input of feedstock equivalent to 150 000 gross tonne straw/year
b. Variable spatial terms		
<u>Plant biomass (feedstock) characteristics</u> <ul style="list-style-type: none">Moisture content of feedstock on wet basis (wt %)<ul style="list-style-type: none">Agricultural residuesEnergy cropsForestry residues from coniferous treesForestry residues from non-coniferous treesLower heating value (MJ/kg)<ul style="list-style-type: none">Agricultural residuesEnergy cropsForestry residues from coniferous treesForestry residues from non-coniferous trees <u>Biomass availability and identification of plant location</u> <ul style="list-style-type: none">Technical potential of feedstock per NUTS 3 region (gross tonne DM/km²)<ul style="list-style-type: none">Primary residues from forest<ul style="list-style-type: none">Logging residues from final fellings & thinnings<ul style="list-style-type: none">Final felling from non-coniferous treesFinal fellings from coniferous treesThinnings from non-coniferous treesThinnings from coniferous treesStumps from final fellings & thinnings<ul style="list-style-type: none">Final felling from non-coniferous treesFinal fellings from coniferous treesEnergy crops<ul style="list-style-type: none">Primary production of lignocellulosic biomass crops: Energy grasses, annual & perennial crops<ul style="list-style-type: none">Miscanthus (Perennial grass)Switchgrass (Perennial grass)Giant reed (Perennial grass)Reed Canary Grass (Perennial grass)Agricultural residues<ul style="list-style-type: none">Straw<ul style="list-style-type: none">Cereals strawOil seed rape straw		<u>Plant biomass (feedstock) input</u> <ul style="list-style-type: none">Share of biomass input per plant location (%)<ul style="list-style-type: none">Agricultural residuesEnergy cropsForestry residues from coniferous treesForestry residues from non-coniferous trees

<ul style="list-style-type: none"> ○ Maize stover ○ Sugarbeet leaves ○ Sunflower straw <p><u>Energy crop farming (miscanthus)</u></p> <ul style="list-style-type: none"> • Diesel for non-road application (agriculture tractor diesel HP 600) (MJ) • Electricity (MJ) • Nitrogen (t) • Phosphoric acid P205 (t) • Potassium oxide (t) • Herbicides (t) • Calcium carbonate (t) <p><u>Field treatment, drying, collection, handling and storage (miscanthus)</u></p> <ul style="list-style-type: none"> • High density polyethylene (t) <p><u>Agriculture residues (MJ)</u></p> <ul style="list-style-type: none"> • Carbon dioxide • Diesel, combusted • Agrochemicals • Phosphorous • Gasoline • Nitrogen • Quicklime • Water <p><u>Forestry residues – Forwarding with forwarder</u></p> <ul style="list-style-type: none"> • Diesel for non-road application (high sulphur content, tractor) (MJ) • Lubricants (t) <p><u>Forestry residues – Loading and unloading of loose residues</u></p> <ul style="list-style-type: none"> • Diesel for non-road application (high sulphur content, tractor) (MJ) • Lubricants (t) <p><u>Forestry residues – Chipping (including residue feeding to chipper)</u></p> <ul style="list-style-type: none"> • Diesel for non-road application (high sulphur content, tractor) (MJ) • Lubricants (t) 	
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Table S2. Overview of constant and variable input parameters for the evaluation of relevant biomass provisions and logistics.

	Exogenous	Endogenous
a. Constant spatial terms		
	<u>Truck specifications</u> <ul style="list-style-type: none"> • Owners interest (%) • Loan interest (%) • Loading and unloading time (truck) (h) <ul style="list-style-type: none"> - Chips - Straw - Oil • Average speed on private/unsealed road (km/h) • Average speed on public/sealed road (km/h) • Truck operation mode (single or fleet operation mode) • Truck fuel consumption (L/100 km) <ul style="list-style-type: none"> - Highway - Forest - 60 gross tonne truck off highway - Private/Unsealed road • Truck and trailer (€/y) <ul style="list-style-type: none"> - Residual value of purchase price truck (%) - Residual value of purchase price truck (%) - Oil consumption (L/1 000km) - Front axle: new (km/tyre) - Drive tyre: new (km/tyre) - Trailer tyre: new (km/tyre) - Number of front axle tyres - Number of drive tyres - Number tyres trailer - Percentage new drive tyres (%) - Percentage new trailer tyres (%) - Distance on retread compared to new tyre (%) - Garage distance truck per day (km) <u>Biomass and oil characteristics</u> <ul style="list-style-type: none"> • Packing fraction of input biomass and oil (m³/m³) <ul style="list-style-type: none"> - Chips - Straw - Oil <u>Working conditions</u> <ul style="list-style-type: none"> • Wet days – no adequate working conditions (d) • Protective equipment allowance paid to workers (€) <u>Toll fees</u> <ul style="list-style-type: none"> • Road user charges/toll/maut (€/1 000 km) 	<u>General assumptions</u> <ul style="list-style-type: none"> • Inflation is neglected • Focus on normal trucks, no heavy load trucks • Standard payload • Terrain type is neglected • Three central collection sites per plant location
b. Variable spatial terms		
	<u>Fuel and engine oil prices</u> <ul style="list-style-type: none"> • Gasoline price for transportation (€/L) • Diesel price for transportation (€/L) • Engine oil (€/L) <u>Biomass harvesting costs</u> <ul style="list-style-type: none"> • Residue harvesting costs (€/gross tonne) <ul style="list-style-type: none"> - Cutover - Landing - Steep cutover <u>Working conditions (truck)</u> <ul style="list-style-type: none"> • Max. shift hours (truck) (h) • Driver wages (€/h) • Average wages (of workers) (€/h) • Accident insurance of transport (€/€100) • Total paid days per year (d) • Bank/saturation holidays (d) • Sick leave (d) • Leave per year (d) 	<u>Type of truck according to transported good</u> <ul style="list-style-type: none"> • Chips • Straw • Oil <u>Average transportation distance (km)</u> <ul style="list-style-type: none"> • On private/unsealed road • On public/sealed road

Truck specifics

- Truck driver tyres per year (€)
- Truck trailer tyres per year (€)
- Truck tyre retread per year (€)
- Trailer tyre retread per year (€)
- Chip truck costs (€)
- Chip truck trailer costs (€)
- Straw truck costs (€)
- Straw truck trailer costs (€)
- Oil truck costs (€)
- Oil truck trailer costs (€)
- Registration of truck (€/y)
- Truck and trailer annual maintenance costs (€/km)
 - Truck (€/km)
 - Trailer (€/axle/100 000km)
 - Turntables & Couplings (€/100 000 trailer km)
 - No. of trailer axles
 - No. of couplings & turn tables
 - Scale Repairs (€/100 000 combined km)
 - Structural Repairs (€/100 000 combined km)
 - Crane Repairs (€/100 000 truck km)
 - Painting (€/y)

Overhead costs (truck)

- Overhead costs (€/y)
 - Office costs
 - Parking lease
 - Office equipment
 - Postage, telephone, etc.
 - Office staff costs
 - Accountancy and legal fees
 - Bank and finance charges
 - Public liability insurance
 - Operating supplies
 - Fire equipment
 - Radio equipment
 - First aid
 - Safety
 - Tools
 - other
 - Training

Vehicle to drive workers to collection sites

- Toyota Hilux (€/a)
 - Vehicle kilometres per day (km/d)
 - Type: Petrol/diesel
 - Capacity (cc)
 - Year purchased (y)
 - Delivery price (€)
 - Current new price (€)
 - Expected life (km)
 - Current used price (€)
 - Tyre life (km)
 - New tyre price (set of 4) (€)
 - Proportion of ACI as loan (l)
 - Proportion of ACI as owners equity
 - R + M as % of depreciation
 - Taxation per km

Additional machine

- Tractor 4 wheel drive
 - Power (kw)
 - Year purchased
 - Delivery price
 - Current new price
 - Hours to be owned
 - Current used price

<ul style="list-style-type: none"> - Tyre life (hrs) - New tyre price (set of 4) - Proportion of allowance for credit losses as loan - Proportion of allowance for credit losses as owners equity - R + M as % of depreciation - Registration / taxation per km - Fuel consumption (l/kW/hr) <p><u>Biomass characteristics and biomass (feedstock) costs</u></p> <ul style="list-style-type: none"> • Physical density of transported goods (kg/m³).¹Constant: spatial <ul style="list-style-type: none"> - Pyrolysis oil¹ - Biodiesel¹ - Wood chips - Energy crops (perennial grass)¹ - Agricultural residues¹ • Costs per type of input biomass (€/t) <ul style="list-style-type: none"> - Agricultural residues - Energy crops - Forestry residues from coniferous trees - Forestry residues from non-coniferous trees 	
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Table S3. Overview of constant and variable input parameters for the evaluation of relevant biomass conversion route.

Exogenous	Endogenous
a. Constant spatial terms	
<p><u>Catalysts specifications/ composition (environmental focus)</u></p> <ul style="list-style-type: none"> • Type of catalyst <ul style="list-style-type: none"> - Aluminium oxide <ul style="list-style-type: none"> ▪ Bauxite mining <ul style="list-style-type: none"> ○ Bauxite ore (t) ○ Residual oil (mmBTU) ○ Electricity (mmBTU) ○ Water mining (gal) ○ Diesel for non-road applications (mmBTU) ▪ Bauxite refining <ul style="list-style-type: none"> ○ Residual oil (mmBTU) ○ Natural gas (mmBTU) ○ Coal average (mmBTU) ○ Electricity (mmBTU) ○ Lime (t) ○ Water process (gal) ○ Sodium hydroxide (t) ○ Bauxite (t) - Zeolite <ul style="list-style-type: none"> ▪ ZSM-5 (t) ▪ SiO₂ gel (t) ▪ Kaolin (t) - Molybdenum <ul style="list-style-type: none"> ▪ Natural gas (mmBTU) ▪ Conventional diesel (mmBTU) ▪ MoS₂ (t) ▪ Ammonium hydroxide (t) - Cobalt <ul style="list-style-type: none"> ▪ Cobalt oxide (t) ▪ Nitric acid (t) - Nickel <ul style="list-style-type: none"> ▪ Nickel (t) ▪ Nitric acid (t) 	<p><u>Technology readiness level (TRL)</u></p> <ul style="list-style-type: none"> • No. of technology readiness level <p><u>General assumptions</u></p> <ul style="list-style-type: none"> • Plant life (operational) (y) • Operating days per year (h) • Plant life (economical) (y) • Interest rate (%) • Maintenance costs (%) <p><u>Catalysts specifications</u></p> <ul style="list-style-type: none"> • Type of catalyst • Price (€/kg) • Required quantity (kg catalyst / gross tonne feed-stock) • Recycling rate catalysts (%) <p><u>Biomass</u></p> <ul style="list-style-type: none"> • Tolerable moisture content (wt%) <p><u>Parameter of plant concepts (environmental focus)</u></p> <ul style="list-style-type: none"> • Input (MJ/kg) <ul style="list-style-type: none"> - Biomass (rhizomes) - Natural gas - Electricity - Diesel - Steam • Output (MJ/kg) <ul style="list-style-type: none"> - Gasoline - Diesel - Electricity - Char - Steam <p><u>Plant output (MJ/kg) (technical focus)</u></p> <ul style="list-style-type: none"> • HHV diesel • HHV gasoline • HHV off-gas • HHV char • Biomass input dry • Biomass input wet • Fast pyrolysis product

	<ul style="list-style-type: none"> Hydrotreated pyrolysis oil HHV natural gas <u>Additional plant input and outputs (MJ/MJ)</u> <ul style="list-style-type: none"> Plant electricity <ul style="list-style-type: none"> Plant electricity use Plant purchased electricity Electricity sold to grid Co-products <ul style="list-style-type: none"> Co-product sold (char) Co-product sold (steam) Plant natural gas use Plant diesel use Steam use
b. Variable spatial terms	
<u>Biomass input</u> <ul style="list-style-type: none"> Feedstock costs (€/odt) <u>Energy prices</u> <ul style="list-style-type: none"> Natural gas (€/GJ) Diesel (€/L) Electricity sold (€/kWh) Electricity purchased (€/kWh) Gasoline (€/L) Fuel oil (€/L) <u>Additional costs</u> <ul style="list-style-type: none"> Price for sand (€/y) Costs for waste disposal (€/y) <u>Labour prices and working days per year</u> <ul style="list-style-type: none"> Production labour (€/hr) Foreman labour (€/hr) Specialist labour (€/hr) Office Staff (€/yr) Management staff (€/yr) Working days per year (d/y) Tax rate (EBIT) (%)	<u>Biomass input</u> <ul style="list-style-type: none"> Feedstock mix (%)

S.1.2. Biomass provision

A general overview of biomass provision is provided in Figure S1, displaying the system boundaries for feedstock production from lignocellulosic biomass. This includes site preparation, planting, stand tending and harvesting of the biomass. After felling or cutting of the biomass, it is, if required, bundled and subsequently forwarded to a collection site, e.g., an interim storage at the edge of the field or in the wood, where the forestry residues, agricultural residues and energy crops are sized and prepared for collection. Typical parameters affecting supply and availability of biomass are its characteristics and cultivation. The specifics about different types of biomass include, e.g., the harvesting window, the crop yield, crop residue-to-grain or seed ratios, biomass volume, biomass density, biomass moisture content and biomass availability. The cultivation processes of biomass comprises crop tillage practices, fertilizer use, pesticide use, water use, energy for irrigation, machinery including fuel energy and infrastructure (e.g., tractors, harvesters and sheds)[1–7].

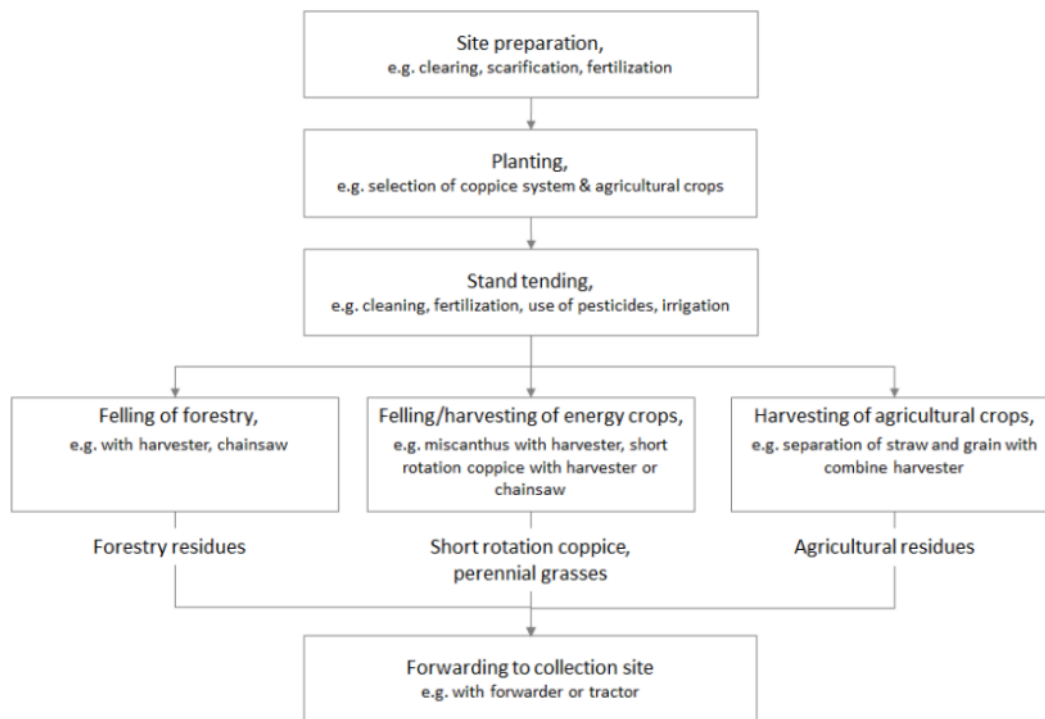


Figure S1. Simplified process scheme of the raw material supply chain from lignocellulosic biomass.

S.2. Case study

S.2.1. System definition

Determination of relevant biomass provision and logistics

Table S4. General input variables for biomass provision and logistics.

Parameter	Unit	All regions
<i>Operational details (trucks)</i>		
Load time		
Chips	h	0.67
Straw	h	0.77
Oil	h	0.50
Unload time		
Chips	h	0.33
Straw	h	0.50
Oil	h	0.67
<i>Physical density</i>		
Pyrolysis oil	kg/m ³	1 240
Biogenic diesel	kg/m ³	880
Wood chips	kg/m ³	190
Energy crops ¹	kg/m ³	140
Agricultural residues	kg/m ³	155
<i>Additional operational details</i>		
Maximum shift hours	h	12
Average speed on unsealed roads	km/h	35
Average speed on sealed roads	km/h	70

¹Perennial grasses.

Table S5. Costs components of transportation.

Costs component	Unit	Northern Europe	Central Europe	Southern Europe
<i>Fuel</i>				
Gasoline	€/l	1.41	1.31	1.17
Diesel	€/l	1.33	1.09	1.01
Engine oil	€/l	3.23	3	2.68
<i>Wages and labor aspects</i>				
Driver	€/h	24.59	20.84	13.95
Average wages	€/h	37.26	31.58	21.14
Total paid days per year	d	260	260	260
Bank holidays	d	11	11	14
Sick leave	d	19	18.4	18.6
Leave in days	d	26	24	23
<i>Truck costs</i>				
Chip truck	€	298 307	273 448	265 493
Chip trailer	€	59 400	54 450	52 866
Oil truck	€	298 307	273 448	245 827
Oil trailer	€	199 800	183 150	164 650
Straw truck	€	298 307	273 448	265 493
Straw trailer	€	59 400	54 450	52 866
<i>Truck fuel consumption</i>				
Highway	l/100km	47.62	47.62	47.62
Unsealed road	l/100km	60	60	60

<i>Toll fee</i>				
Truck	€/1,000km	75	75	75
Trailer	€/1,000km	75	75	75
<i>Truck specifications</i>				
Truck payload ¹	t	28.25	24.50	24.50
Truck volume ¹	m ³	95	95	95
<i>Overhead costs</i>				
Office costs	€/a	3 110.40	2 851.20	2 563.20
Parking lease	€/a	1 036.80	95.40	854.40
Postage, telephone and bills	€/a	1 555.20	1 425.60	1 281.60
Office staff costs	€/a	3 061.80	2 806.65	2 523.15
Accountancy and legal fees	€/a	540.00	495.00	445.00
Public liability insurance	€/a	13 086.36	11 995.83	10 784.13
Operating supplies ²	€/a	552.96	506.88	455.68
<i>Vehicle costs³</i>				
Type		Diesel	Diesel	Diesel
Capacity	cc	2 611	2 393	2 151
Year purchased		2017	2017	2017
Delivery price	€	26825	24590	22106
Expected life	km	150 000	150 000	150 000
Current used price	€	16 364	15 000	13 485
Tyre life	km	40 000	40 000	40 000
New tyre price ⁴	€	772	708	636
Registration/taxation per year	€	0.0012	0.0011	0.0010
Fuel consumption	l/km	0.07	0.07	0.07
Taxation	km	0.0008	0.0007	0.0007
<i>Maintenance of trucks</i>				
Repairs	€/100,000km	1 347.84	1 235.52	1 110.72
Painting	€/a	1 382.40	1 267.20	1 139.20

¹For all kind of trucks, i.e. bin, chip, straw and oil trucks, ²Fire equipment, radio equipment, first aid, safety, tools and other,

³Toyota Hilux, ⁴Set of four tyres.

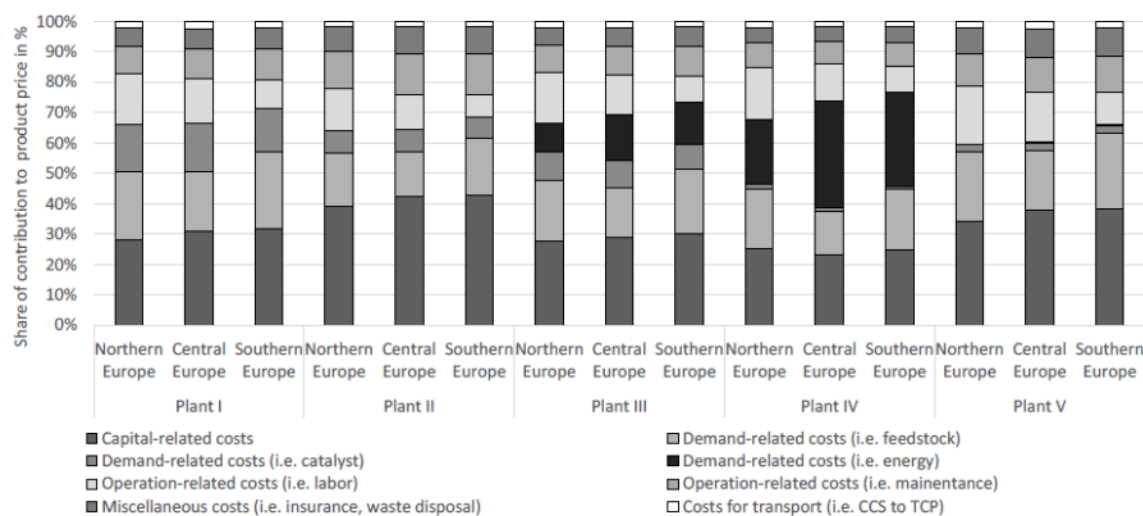


Figure S2. Share of contribution to the product price from cradle to plant gate, excluding potential co-products.

Determination of relevant biomass conversion routes

Table S6. Selected technical parameters for the five plant concepts.

Parameter	Unit	Plant I	Plant II	Plant III	Plant IV	Plant V
<i>Calorific value</i>						
Biomass _{DM} ²	MJ/kg ¹	17.21	17.82	17.21	19.22	17.65
Biomass (wet matter) ²	MJ/kg ¹	12.05	11.74	12.05	9.61	13.24
Char	MJ/kg ¹	-	-	28.81	25.00	-
<i>Performance</i>						
Diesel		2.43	3.00	5.75	6.06	5.00
Gasoline		6.43	3.12	4.60	6.98	2.11
Sum blendstock		8.86	6.12	10.35	13.04	7.12
Ratio diesel/gasoline	%	27.45	49.00	55.55	46.45	70.30
Electricity use	MJ/kg ¹	-	-	0.44	1.52	-
Electricity credit	MJ/kg ¹	0.22	0.67	-	-	0.60
Natural gas use	MJ/kg ¹	0.01	-	2.08	3.28	0.09
Char credit	MJ/kg ¹	-	-	-	1.57	-
Steam use	MJ/kg ¹	-	-	-	-	0.00d
Steam credit		-	-	-	0.75	-
Diesel use ³		0.01	-	-	-	-

¹Per kg dry feedstock, ²The calorific value for plant concept II was assumed to be the average value of the other four plants concepts, ³Diesel no.2, ⁴Rounded value.

S.2.2. Methodological assessment

Economic assessment – Equipment costs summary

Table S7. Equipment costs summary and specifications for the current status, calculations based on [8–16].

Equipment	Description	Total Equipment Costs for the Current Status in €	Installed Costs for the Current Status in €
Plant I			
Pretreatment	Flue gas blower, cross flow pellet dryer, hopper feeder, screener feeder conveyor, radial stacker conveyor, dryer feed screw conveyor, biomass feed screw conveyor, hydraulic truck dump with scale, hammermill, front end loaders, magnetic head	55 017	107 950
	pulley, vibratory conveyor, dump hopper, hammermill surge bin, dryer feed bin, dried biomass hopper, lock hopper, feed hopper		
Thermo-chemical conversion		8 777 165	26 576 024
<i>Fast pyrolysis</i>	Fluidizing gas recycle compressor, combustor air compressor, catalytic fluidized bed reactor, char combustor, catalyst cooler, catalyst steam stripper, primary cyclone, secondary cyclone, char combustor primary cyclone, char combustor secondary cyclone, depleted catalyst and ash storage bin, catalyst feed bin	8 777 165	26 576 024
	Downstream processing	8 335 144	14 440 345
<i>Product condensation and separation</i>	Heavy fraction condenser adsorber, light fraction condenser adsorber, vapor heat exchanger, feed cooler, feed/overhead exchanger, liquid feed chiller, heavy fraction heat exchanger, quench circulating chiller, bottoms pump, circulating filter charge pump, aqueous filter charge pump, organic product pump, quench recycle pump, bottoms filter, bottoms decanter, quench circulation filter, aqueous phase filter, organic product surge tank, circulating surge tank	1 095 505	1 748 466
	<i>Hydrogen recycle and water gas shift</i>		
<i>Whole oil hydroprocessing</i>	Post-WGS heat exchanger, post-WGS cooler, PSA compressor: multistage, PSA, compressor condensate pump, High temperature WGS, PSA compressor suction knock-out, PSA compressor disch knock-out, compressor condensate tank	3 763 210	6 523 523
	Feed-effluent exchanger, feed furnace, high temperature product heat exchanger, high temperature product cooler, 1st quench hydrogen cooler, 2nd quench hydrogen cooler, hydrogen makeup compressor, hydrogen recycle compressor, HT feedpump, hydrotreater, vapor knock-out drum, high pressure, high temperature effluent flash, low pressure, high temperature effluent flash	1 943 555	3 205 120
<i>Oil Fractionation</i>	Gasoline column, diesel column, condenser, reboiler, gasoline product cooler, diesel product heat exchanger, diesel product cooler, overhead vapor cooler, 1 st reflux pump, 2 nd reflux pump, 1 st overhead accumulator, 2 nd overhead accumulator	240 952	561 294
<i>Hydrocracking</i>	Feed-effluent exchanger, feed furnace, hydrocracking product heat exchanger, HC product cooler, 1 st quench hydrogen cooler,	1 291 922	2 401 942

	2 nd quench hydrogen cooler, hydrogen makeup compressor, hydrogen recycle compressor, hydrocracking feed pump, hydrocracker, vapor knock-out drum, high pressure effluent flash, low pressure effluent flash		
Miscellaneous		26 934 953	50 864 982
<i>Hydrogen plant</i>	Water-gas-shift effluent, water-gas-shift cooler, pyrolysis offgas compressor to reformer, compressor condensate pump, steam reformer package, low temperature separation reactor, compressor condensate tank, reformer combustor air flow, PSA compressor multistage, PSA, water-gas-shift reactor, compressor suction knockout drum, PSA compressor discharge knockout drum	20 431 987	38 647 502
<i>Steam system & Power generation</i>	Steam turbine condenser, blowdown cooler, boiler feed water electrode ionization, polishing, 1 st stage steam turbine generator, 2 nd stage steam turbine generator, startup boiler, makeup pump, condensate pump, electrode ionization pump, boiler feed water pump, condensate collection tank, blowdown flash drum, condensate collection tank, condensate surge tank, deaerator, deaerator packed column, steam drum, steam turbine condensate tank	5 139 549	9 433 020
<i>Cooling water & other utilities</i>	Plant air compressor, cooling tower system, hydraulic truck dump with scales, flue gas scrubber, flue gas stack, chilled water system, product loading rack, cooling water pump, firewater pump, diesel pump, ammonia pump, caustic pump, boiler feed water chemical pump, flue gas scrubber circulation pump, gasoline product pump, diesel product pump, instrument air dryer, plant air receiver, firewater storage tank, purchased diesel storage tank, ammonia storage tank, caustic storage tank, boiler feed water chemical storage tank, gasoline product storage tank, diesel product storage tank	1 363 417	2 784 461
Total		44 102 279	91 989 301
Plant II			
Pretreatment	Conveyor belt, truck scales, bale unwrapping conveyor, magnetic separator, chopper, dryer, silo with screw conveyor	2 038 687	6 992 695
	Thermo-chemical conversion	8 045 067	27 594 580
<i>Fast pyrolysis</i>	Twin screw mixing reactor, vibration sieve, pneumatic lift, collecting bin, screw conveyor, pyrolysis gas burner, combustion air fan, air preheater, isolation, cyclone, filter, quench, gas cooler, pump, condensate cooler, cooling water pump, pyrolysis gas filter, pyrolysis gas blower, tank for solids, tank for liquids, colloid mixer, screw conveyor, colloid mill, pump, tank for slurry	8 045 067	27 594 580
	Downstream processing	38 499 884	132 054 603
<i>Slurry pretreatment</i>	Slurry unloading, slurry tank, slurry conveyor, 1 st slurry homogenization tank, 2 nd slurry homogenization tank, slurry feeding	731 010	2 507 363
<i>Gasification agent provision</i>	Air compressor, rectification column, oxygen compressor, nitrogen compressor	3 854 074	13 219 476
<i>Condensate and quench water system</i>	Condensate pump, condensate heat exchanger, waste water treatment, waste water demineralization, tank for treated water, high pressure pump for quench	340 336	1 167 353

<i>Gasification and auxiliaries</i>	Furnace pump, furnace heat exchanger, inert gas provision, entrained flow gasifier	3 658 561	12 548 863
<i>Product gas conditioning</i>	Gas cleaner, water-gas-shift reactor, gas scrubber, condensate pump, filter, heat exchanger, gas cooler	1 829 440	6 274 978
<i>Synthesis gas cleaning</i>	Sour gas cleaner, heat exchanger	2 258 239	7 745 759
<i>Slag treatment</i>	Slag drainage, slag filter, slag conveyor, slag storage, slag loading	786 308	2 697 036
<i>Fischer-Tropsch synthesis</i>	Heat exchanger, turbine, Fischer-Tropsch synthesis reactor, heat exchanger	2 768 603	9 496 308
<i>Product recovery</i>	Degassing column, decanter, hydrocarbon fractionation, pressure swing adsorption, H ₂ compressor, raw product hydrotreater, raw product reformer, distillate hydrotreater, wax hydrocracking, fuel gas compressor	22 273 314	76 397 467
Total		48 583 638	166 641 878
Plant III			
Pretreatment¹		2 886 575	10 239 515
Thermo-chemical conversion		39 478 612	40 237 219
<i>Fast pyrolysis</i>	CFB pyrolyzer, quench & auxiliaries, pyrolysis oil filters, filtrate screw feeder, steam generator- char burner exhaust, boiler feed water heater (char burner exhaust), air compressor for char exhaust (cooling)	39 478 612	40 237 219
Downstream processing		17 450 090	33 564 197
<i>Fast pyrolysis oil upgrading</i>	Feed pump, stabilizer, 1 st stage reactors, 2 nd stage reactors, sulfur agent pump, stabilizer product flash, 2 nd stage three phase separator, hydrotreating oil flash, expander, stabilized oil cooler, 1 st feed/product heat exchanger, 2 nd feed/product heat exchanger, hydrotreating oil product heat recovery, hydrotreating oil product cooler, PSA feed heater, blowdown dryer, fired heater, air cooler, light columnfeed heater, reboiler, condenser, light column, reflux drum, stabilized product pump, PSA, PSA off gas compressor, stabilier gas product compressor, makeup hydrogen compressor, hydrogen compressor	12 644 080	28 426 699
<i>Product separation and hydrocracking</i>	Naphtha splitter, product splitter, reboiler, fired reboiler, 1 st air cool condenser, 2 nd air cool condenser, 1 st reflex drum, 2 nd reflex drum, 1 st bottom product pump, 2 nd bottom product pump, hydrocracker unit (fired heater, hydrocracker vessel, feed/product exchanger, air cooler, trim collar, high pressure flash, low pressure flash, fuel gas compressor), gasoline product cooler, diesel product cooler	4 806 010	5 137 498
Miscellaneous		19 089 746	20 261 192
<i>Hydrogen plant</i>	<i>Steam reformer system</i>	17 547 564	17 547 564
<i>Utilities and wastewater treatment plant</i>	Wastewater aerobic digestion, constructed treatment wetlands water pumps, plant air compressor, hydraulic truck dump with scale, firewater pump, diesel pump, instrument air dryer, plant air receiver, firewater storage tank, sulfur agent storage tank, feed storage, product storage, steam reformer costs: ammonia pump, hydrazine pump, ammonia storage tank, hydrazine storage tank, flare	1 542 182	2 713 627
Total		78 905 023	104 302 123

Plant IV			
Pretreatment	Pyrolysis dryer and mill	6 553 035	25 100 747
	Thermo-chemical conversion	5 846 584	22 394 755
<i>Fast pyrolysis</i>	Catalyst (sand) in pyrolysis reactor, 1 st heat exchanger, 2 nd heat exchanger, pumps, quench , Flash,1 st pyrolysis compressor ,2 nd pyrolysis compressor, 3 rd pyrolysiscompressor , Pyrolysis reactor, gas and char combustor	5 846 584	22 394 755
	Downstream processing	11 617 617	44 923 931
<i>Biorefinery unit</i>	Catalysts, 1 st - 4 th heat exchanger hydrotreating, 1 st - 3 rd heat exchanger hydrocracking,1 st - 3 rd heat exchanger steam reforming , hydrotreating pump, 1 st - 2 nd hydrocracking pump, Steam reforming pump, hydrotreating flash, hydrocrackingflash, Steam reforming condenser, hydrotreating compressor, hydrocracking compressor,1 st - 2 nd steam refoming compressor, 1 st - 2 nd hydrocracking distillation,1 st - 2 nd hydrotreating reactor, hydrocracking reactor , steam reforming reactor ,steam reforming water gas shift, steam reforming PSA	11 617 617	44 923 931
Total		24 017 237	92 419 433
Plant V			
Pretreatment	Bale transport conveyor, bale unwrapping conveyor, truck scales, magnetic separator, chopper, chopper conveyor, chopper screen with recycle conveyor, dryer, grinder, grinder conveyor, grinder screen with recycle conveyor	2 899 559	8 756 668
	Thermo-chemical conversion	13 153 758	31 166 721
<i>Gasification</i>	Combustor-Steam boiler, entrained flow, slagging gasifier, slag collector, direct quench syngas cooler, biomass receiving hopper, lock hopper, biomass feeding bin	8 733 322	20 523 306
<i>Syngas cleaning</i>	High pressure amine system, sour water gas shift stream compressor, sour water gas shift reactor, liquid oxidation catalyst absorber, liquid oxidation catalyst oxidizer vessel, carbon dioxide compressor, liquid collection tank, direct quench syngas cooler, venturi scrubber	4 420 436	10 643 415
	Downstream processing	5 524 269	16 804 943
<i>Fuel synthesis</i>	Booster syngas compressor, recycle syngas booster compressor, PSA booster compressor, syngas heater, syngas cooler, recycle syngas preheater, Fischer-Tropsch reactor, ZnO sulfur removal beds, pressure swing adsorption unit, FT knock-out column, water separator	5 524 269	16 804 943
Miscellaneous		17 752 258	53 611 818
<i>Hydroprocessing</i>	Hydroprocessing unit, gasoline 30-day storage tank, diesel 30-day storage tank	3 166 737	9 563 546
<i>Power generation</i>	Combustion turbine- electric generator, cooling water pump, heat recovery steam generator, high pressure steam pump, high pressure steam/water separation, combined steam turbine- electric generator, air compressor	10 558 795	31 887 560
<i>Air separation Unit²</i>	Air compressor, air cooler, oxygen compressor cooler, oxygen compressor, high pressure column condenser, high pressure column condenser accumulator, high pressure column reflux pump, high pressure column tower,1 st air compressor inter-cooler, 2 nd air compressor intercooler, 3 rd air compressor inter-cooler, low pressure column reboiler, low pressure column	4 026 726	12 160 711

tower, water knock-out drum, gas expander, water knock-out drum

Total	39 329 844	110 340 150
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¹Pretreatment costs: 0.93% of feedstock costs [8].

Economic assessment – Demand-related costs summary

Table S8. Energy prices for industrial consumers and sellers [17].

Costs component	Unit	Northern Europe	Central Europe	Southern Europe
<i>Purchasing</i>				
Natural gas	€/GJ	7.93	8.30	7.66
Electricity	€/kWh	0.06	0.15	0.11
<i>Selling</i>				
Diesel	€/l	0.50	0.42	0.46
Gasoline	€/l	0.45	0.44	0.48
Electricity basic price without taxes and levies	€/kWh	0.0585	0.0813	0.1078
Electricity basic price taxes and levies other than VAT	€/kWh	0.0005	0.0680	0.0055
Electricity selling price ¹	€/kWh	0.0146	0.0369	0.0280

¹The electricity price for selling is assumed to be 24,7 % of the total electricity price for industrial consumers in 2015 [18].

Economic assessment – Catalyst prices

Table S9. Catalyst prices [8-12,19] and expert knowledge.

Plant concept	Unit	Northern Europe	Central Europe	Southern Europe
Plant I	€/t _{DM}	32.56	29.77	26.67
Plant II	€/t _{DM}	20.37	18.62	16.68
Plant III	€/t _{DM}	22.68	20.74	18.58
Plant IV	€/t _{DM}	3.42	3.12	2.80
Plant V	€/t _{DM}	4.91	4.49	4.02

Environmental assessment – Allocation methodology

The results of the life cycle assessment can be significantly affected by the choice of allocation methodology since based on the allocation methodology applied a broad variety of results can be gained. The allocation methodology for agricultural residues and main products and co-products generated of the conversion processes are defined in the following.

Agricultural residues. The allocation methodology for the agricultural residues is the cereal unit allocation approach, to distinguish between the wheat grain and wheat straw produced. The results for the different allocation methods are listed in Table S10.

Table S10. Selected allocation methods for grain and straw [20].

Type of allocation	Unit	Grain	Straw
Mass allocation	%	56	44
Energy allocation	%	55	45
Economic allocation	%	77	23
Cereal unit allocation	%	72	25

In general, the results of life cycle assessments can be highly influenced by the choice of allocation approach. Biomass provision systems are especially influenceable by allocation due to their co-products. Hence, if the allocation methodology is not aligned properly for the different products from the same biomass provision system, methodological inconsistencies may appear. This may cause that for instance parts of the environmental burden of a product or co-product might be either unaccounted or wrongly accounted for. The cereal unit allocation approach is based on the principle of quantifying the products and co-products dependent on the nutritional value for livestock [20].

Products and co-products. The allocation factors of the products and co-products of the conversion processes are displayed in Figure S3. The allocation is based on the energy content (i.e. MJ).

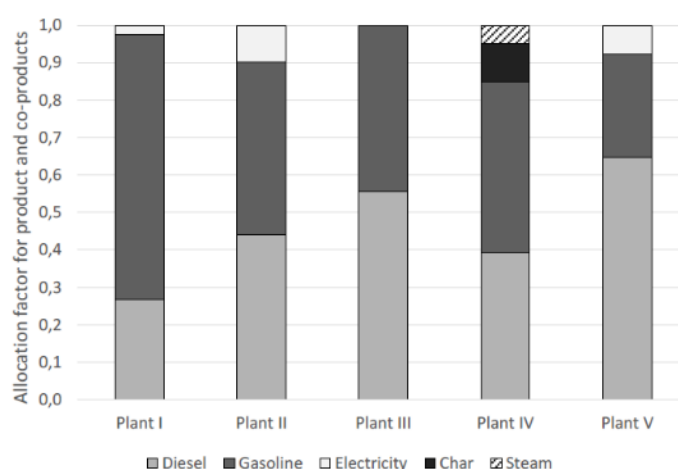


Figure S3. Allocation factors for the selected plant concepts per product (i.e. diesel) and co-product (i.e. gasoline, electricity, char and steam).

S.2.3. Results

Evaluation of relevant biomass resources

Table S11. Technical potential of forestry residues, agricultural residues and energy crops in selected NUTS-3 regions for the current status, calculated based on [21].

Parameter	Unit	Northern Europe	Central Europe	Southern Europe
Country		Sweden	Germany	Spain
Location		Skane län	Mecklenburgische Seenplatte	Ciudad Real
NUTS-3-region		SE224	DE80J	ES422
Forestry residues ¹	t _{DM} /km ²	67.5	46.6	7.8
Agricultural residues ²	t _{DM} /km ²	216.0	230.3	52.2
Energy crops ³	t _{DM} /km ²	0.4	0.4	130.8
Forestry residues	€/t _{DM}	51.4	39.8	32.2
Agricultural residues	€/t _{DM}	46.3	36.7	33.6
Energy crops	€/t _{DM}	106.2	62.3	52.7

¹Logging residues and stumps from final fellings and thinnings from coniferous and non-coniferous trees; ²Cereal straw, oil seed rape straw, maize stover, sugar beet leaves, sunflower straw; ³Primary production of lignocellulosic biomass crops, i.e., energy grasses, annual and perennial crops, e.g., miscanthus, switchgrass, giant reed, reed canary grass.

Evaluation of relevant biomass provision and logistics

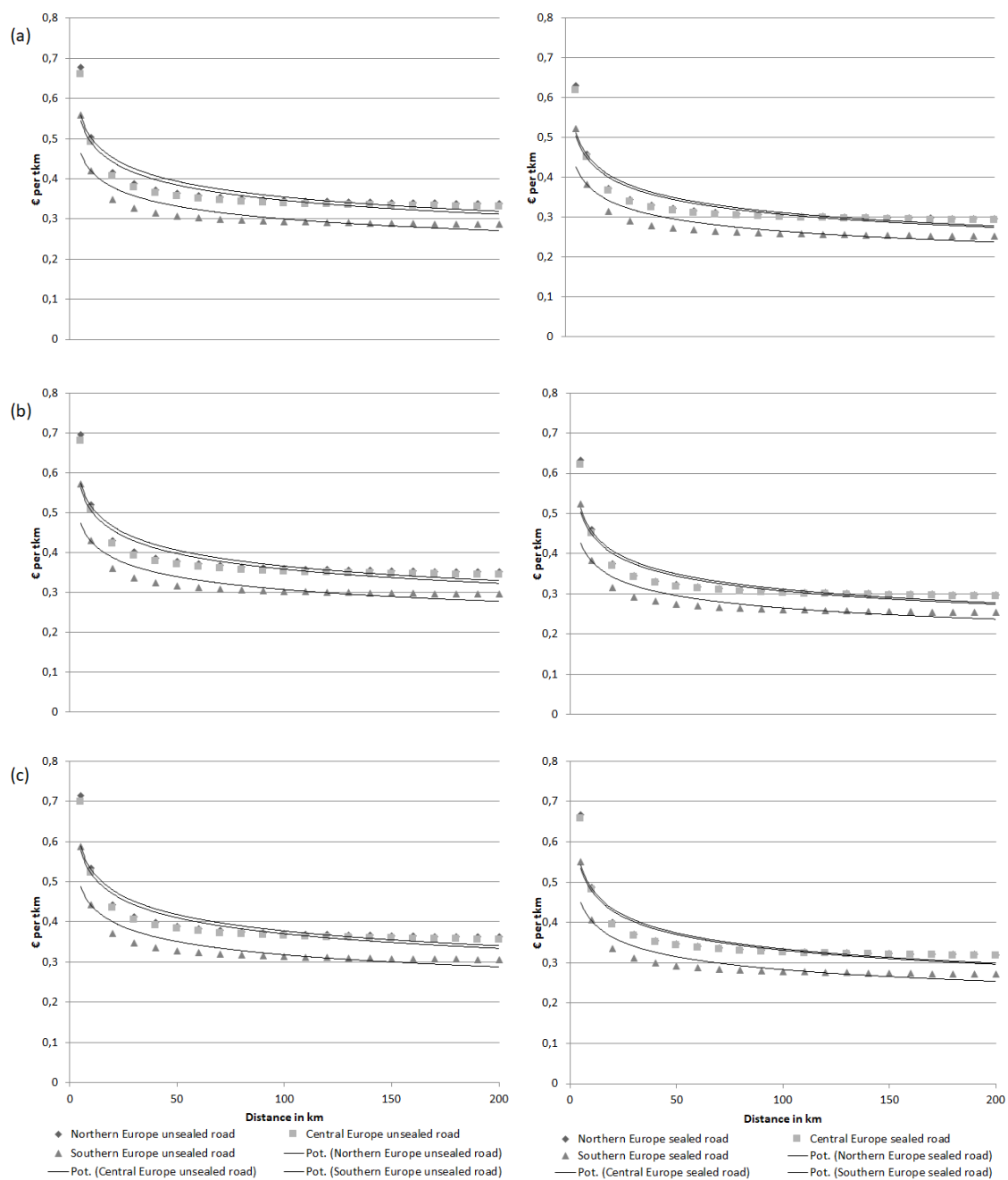


Figure S4. Transportation costs for for (a) chip, (b) straw and (c) oil trucks on sealed and unsealed road.

Economic assessment – Parameter variation

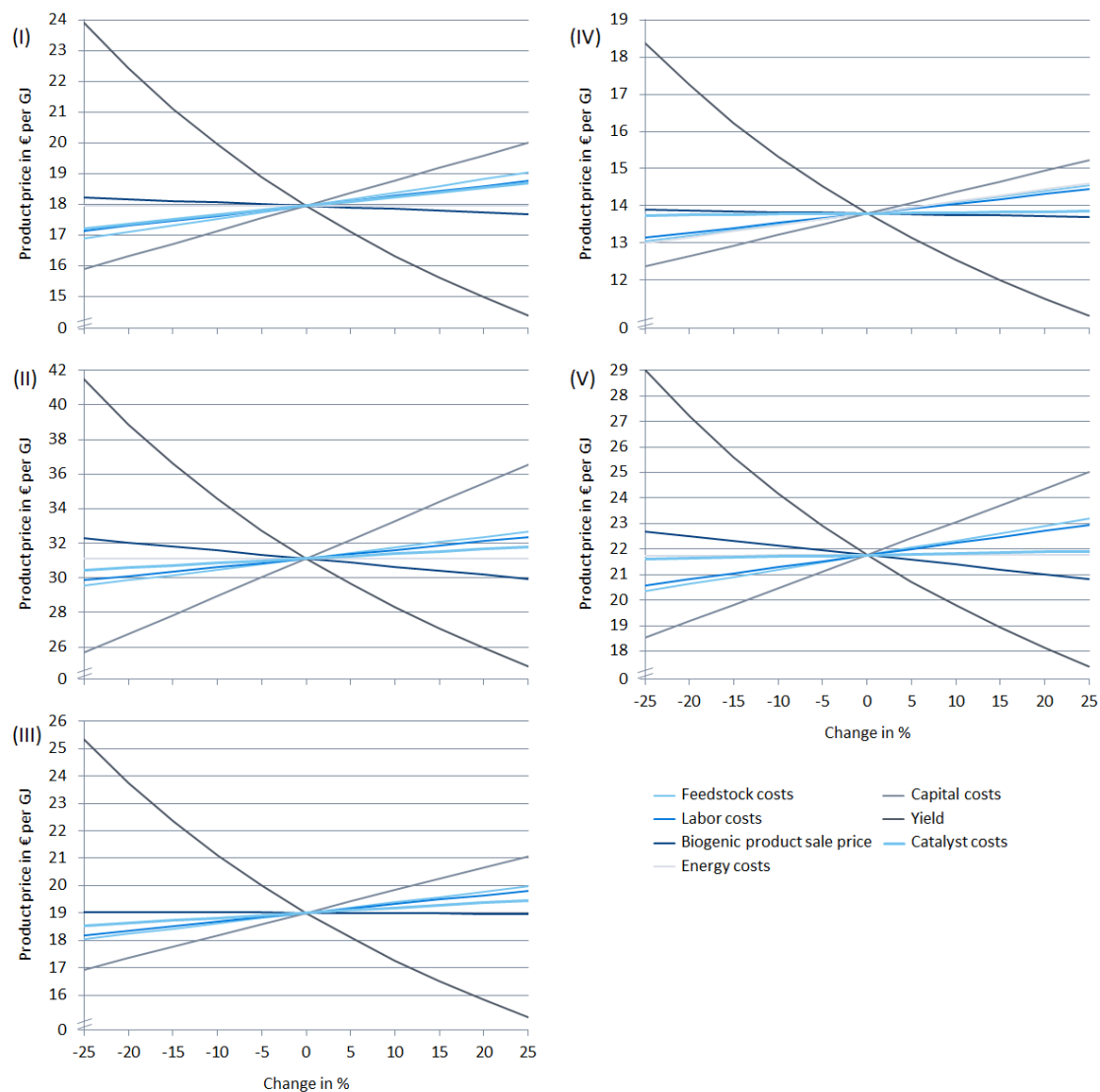


Figure S5. Variation of the parameters (i) feedstock costs, (ii) labor costs, (iii) fuel sale price, (iv) energy costs, (v) capital costs, (vi) yield and (vii) catalyst costs for the five plant concepts in Northern Europe.

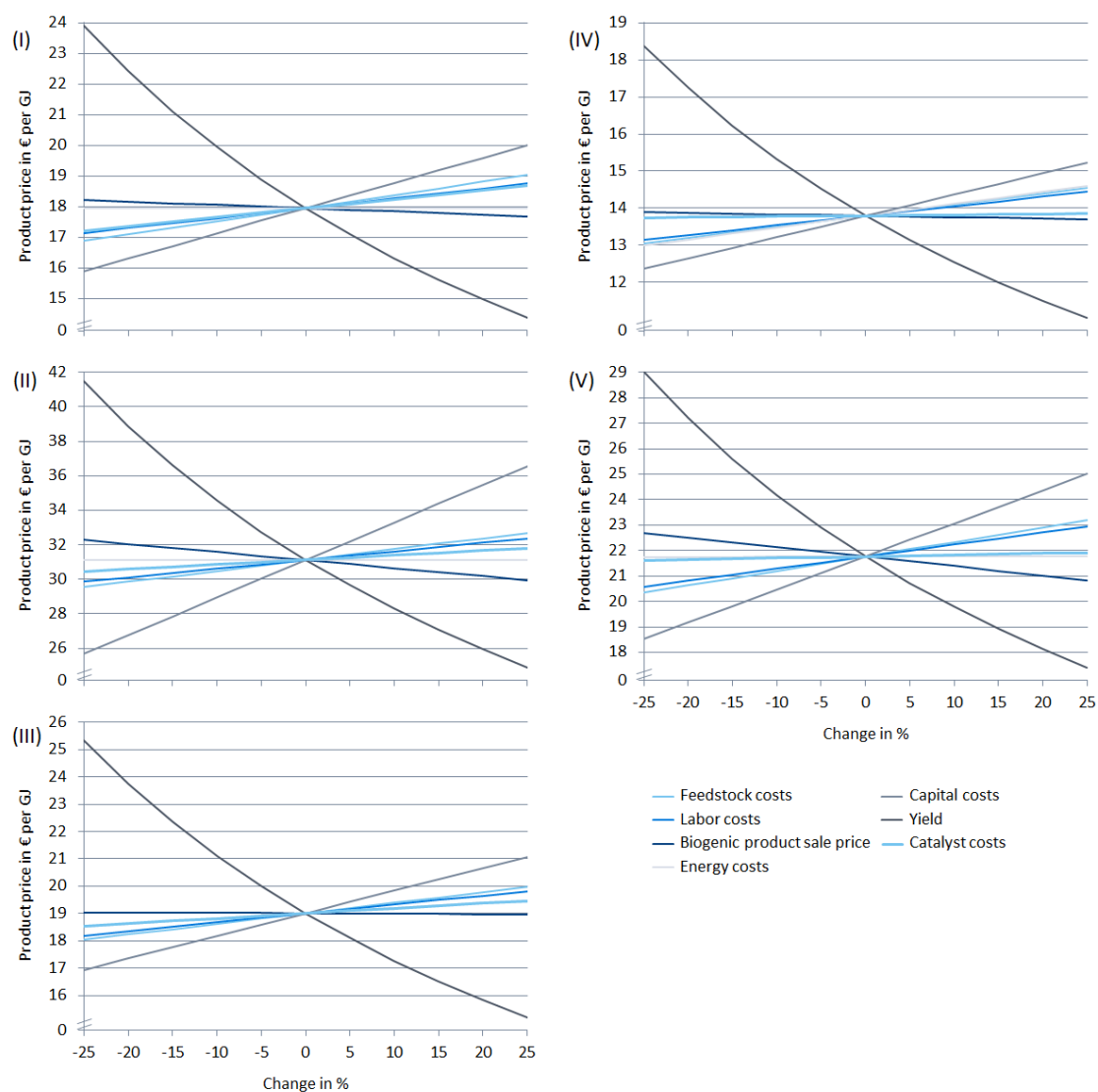


Figure S6. Variation of the parameters (i) feedstock costs, (ii) labor costs, (iii) fuel sale price, (iv) energy costs, (v) capital costs, (vi) yield and (vii) catalyst costs for the five plant concepts in Central Europe.

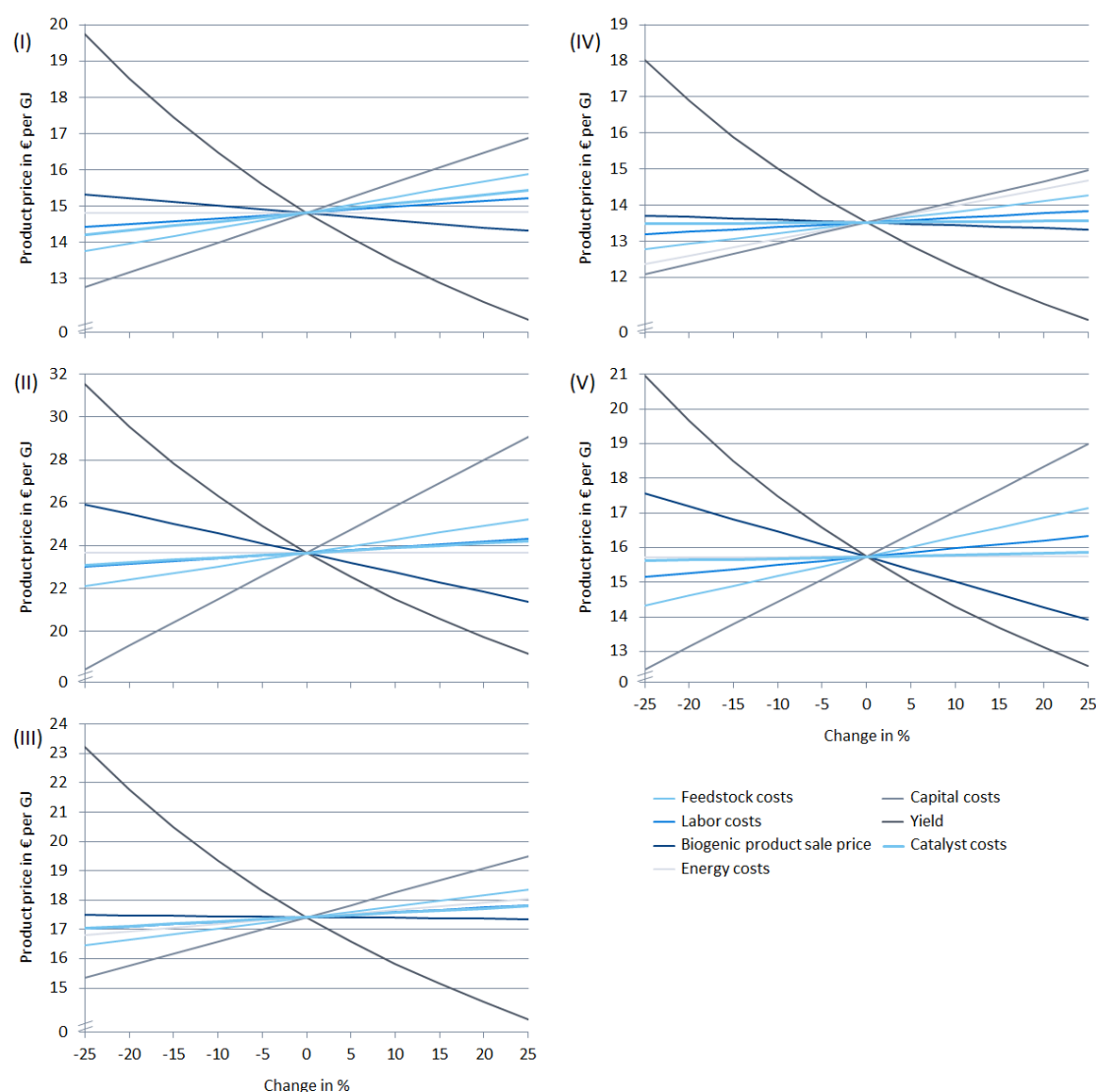


Figure S7. Variation of the parameters (i) feedstock costs, (ii) labor costs, (iii) fuel sale price, (iv) energy costs, (v) capital costs, (vi) yield and (vii) catalyst costs for the five plant concepts in Southern Europe.

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