Annex: Sustainable biofeedstock supply chains for advanced biofuels in Europe towards 2050

Sustainable biofeedstock supply chains for advanced biofuels in Europe towards 2050

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At the request of:

Concawe Special Task Force on Sustainable Bio-feedstock Availability (RT/STF-3)

Brussels
November 2025

KEYWORDS

Biomass supply chains, biomass supply chain optimisation, biomass availability, lignocellulosic feedstocks, biofuel supply chain costs, biomass logistics, advanced biofuels, advanced biofuel techno-economics, refinery integration

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ANNEX A: BIOMASS PROPERTIES, POTENTIALS, AND COSTS

A.1: METHODOLOGY

A.1.1: Biomass properties

Table 1 Biomass feedstock characteristics (moisture content and net calorific value). Source: S2Biom (Lammens et al., 2016).

Category	Category in the supply chain model	LHV (wb) (GJ/t_{wb})	LHV (dry) (GJ/t_{dry})	Moisture content [% w/w]
Agricultural residues	Agriculture residues	13.7	16.5	15.0
Wheat straw		13.2	16.0	15.0
Maize stover		14.1	17.0	15.0
Prunings		10.2	17.2	35.5
Residues from vineyards		10.5	17.5	35.0
Residues from fruit tree plantations		9.4	17.2	40.0
Residues from olive tree plantations		10.9	17.2	32.0
Residues from citrus tree plantations		10.0	16.7	35.0
Grassy crops	Energy crops	11.8	17.1	24.9
Reed canary grass		9.6	17.4	39.1
Switchgrass		12.7	16.5	9.1
Miscanthus		14.9	16.6	11.6
Woody crops		10.0	18.3	40.0
SRC other (incl. eucalyptus)		9.9	18.1	40.0
SRC willow		10.1	18.4	40.0
SRC poplar		10.1	18.4	40.0
Primary forest residues	Primary forest residues	9.3	19.0	51.0
Logging residues from broadleaf trees		10.2	18.7	48.3
Logging residues from conifer trees		8.4	19.2	53.6
Secondary forest residues	Secondary forest residues and PCW	14.9	18.4	33.3
Sawdust from conifers		14.7	18.8	50.0
Sawdust from non-conifers		14.7	18.8	50.0
Sawmill residues, conifers (excl. sawdust)		13.6	18.0	50.0
Sawmill residues, non-conifers (excl. sawdust)		13.6	18.0	50.0
Residues industries producing semi-finished wood-based panels		16.0	18.4	10.0
Residues from further wood processing		16.0	18.4	10.0
Non-hazardous post-consumer wood (PCW)		16.0		13.1
Stemwood	Low grade stemwood	11.6	19.1	51.0
Stemwood from thinnings, broadleaf trees		11.5	19.0	48.3
Stemwood from thinnings, conifers trees		11.6	19.2	53.6
MSW*	n/a	10.8	7.9	27.2

*) used to calculate the potential, but not included in the supply chain model.

A.1.2: Land availability for lignocellulosic energy crops

Land use/cover projections are essential to map biomass availability (and other indicators) for 2030 and 2050. The land use/cover projections are derived from the Land-Use-based Integrated Sustainability Assessment modelling platform (LUISA (Lavalle et al., 2016) for each reference year. The LUISA model, developed by the European Commission, evaluates both the direct and indirect impacts of EU policies related to territorial aspects. The model covers all EU-27 + UK countries, and the projections are based on economic, demographic, and political drivers (Baranzelli et al., 2014). The reference scenario of LUISA is based on the improved version of the 2018 LUISA base map. This map integrates data from the CORINE Land Cover (CLC) 2018 dataset.

The LUISA land use/cover projections aggregate several land use/cover categories based on the CLC classification[1]. For instance, the LUISA category "Forest/Transitional woodland-shrub" combines the CLC categories of Coniferous Forest, Mixed-forest, and Transitional woodland-shrubs. The aggregation of categories poses limitations when estimating the available land, as some categories within the aggregated ones can either meet or fail to comply with RED II/III sustainability criteria. For example, categories such as forest (within the aggregated "Forest/Transitional woodland-shrub" category) fail to meet RED II/III criteria sustainability criteria. In contrast, shrublands (within the aggregated "Forest/Transitional woodland-shrub" category) could potentially comply. To address this limitation, specific land use/cover categories from the LUISA projections are disaggregated or aggregated into a new classification based on the most recent version (2018) of the CLC dataset (EEA, 2020), see Table 2.

Table 2 Land use/cover classification based on LUISA database and aggregation/disaggregation based on CLC. Adapted from Vera et al., 2021.

Land use/cover categories classification in this study		LUISA land use/cover categories		Corine land cover land use/cover categories used for aggregation/ disaggregation	Description of aggregation/disaggregation
1	Artificial	1 2 7 10	Urban Industry, Commercial and Services Infrastructures and urban green leisure		LUISA land use/cover categories *Urban; Industry, Commercial and Services; Infrastructures and Urban green leisure* are aggregated to a single land use/cover category *'Artificial'*
2	Agriculture	3	Agriculture		No aggregation / disaggregation
3	Forest	4	Forest/Transitional woodland-shrubland	3.1.1 Broad leaved forest 3.1.2 Coniferous Forest 3.1.3 Mixed Forest	LUISA land use/cover category *'Forest/Transitional woodland-shrubland'* is disaggregated to *'Forest'* and *'Shrubland'*. All areas classified as forest in CLC 2018 (categories 3.1.1, 3.1.2 and 3.1.3) that overlap with *'Forest/Transitional woodland-shrubland'* in LUISA are classified as *'Forest'*. [A]

[1] For more information see https://land.copernicus.eu/user-corner/technical-library/corine-land-cover-nomenclature-guidelines/html

					- All areas that on a previous time step are categorized as *'Forest'* and on the subsequent time step as *"new energy crops"* are classified as *'Forest'* B
4	Natural grassland	6	Natural land		LUISA land use/cover category '*Natural land*' is disaggregated to '*Natural grassland*'; '*Open space suitable*' and '*Open space unsuitable*'. - All areas of '*Natural land*' not classified as *'Open space suitable' or 'Open space unsuitable*' are classified as *'Natural grassland'*. - All areas that on a previous time step are categorized as *'Natural grassland'* and on the subsequent time step as *"new energy crops"* are classified as *'Natural grasslands'* B
5	Open space suitable	5	New energy crops		LUISA land use/cover category "5. New energy crops" - All areas that remain "new energy crops" over each subsequent time step.
6	Wetlands		8 Wetlands		No aggregation / disaggregation
7	Water bodies		9 Water		No aggregation / disaggregation
8	Shrublands	4	Forest/Transitional woodland-shrubland		LUISA land use/cover category *'Forest/Transitional woodland-shrubland'* is disaggregated to *'Forest'* and '*Shrubland*'. The area not categorised as *'Forest'* (3) is classified as 'Shrubland'. - All areas that on a previous time step are categorized as *'Shrubland'* and on the subsequent time step as *"new energy crops"* are classified as *'Shrubland'* B
5	Open space unsuitable	6	Natural land	3.3.1 Beaches-dunes-sands 3.3.2 Bare rocks 3.3.5 Glaciers and perpetual snow	LUISA land use/cover category '*Natural land*' is disaggregated to '*Natural grassland*'; '*Open space suitable*' and *'Open space unsuitable'* - The CLC 2018 land use/cover categories *'Beaches-dunes-sands*'; *'Bare rocks*'; and' *Glaciers and perpetual snow'* that spatially overlap with '*Natural land*' of the LUISA projections are classified as *'Open space unsuitable'* C - All areas that on a previous time step are categorized as 'Open space unsuitable' and on the subsequent time step as *"new energy crops"* are classified as *'Open space unsuitable'* B

5	Open space suitable	6	Natural land	3.2.2 Moors and heathland 3.2.3 Sclerophyllous vegetation 3.3.3 Sparsely vegetated areas	LUISA land use/cover category '*Natural land*' is disaggregated to '*Natural grassland*'; '*Open space suitable*' and '*Open space unsuitable*' - The CLC 2018 land use/cover categories' *Moors and heathland*'; '*Sclerophyllous vegetation*', '*Sparsely vegetated areas*' and 'Burnt areas' that spatially overlap with '*Natural land*' of the LUISA projections are classified as '*Open space suitable*' [D] - All areas that on a previous time step are categorized as 'Open space suitable' and on the subsequent time step as "*new energy crops*" are classified as '*Open space suitable*' [B]
10	Abandoned land	5	New energy crops		LUISA land use/cover category '*New energy crops*' which was previously agricultural land, is reclassified as abandoned agricultural land.

[A] It is assumed that areas classified as '*Forest*' in CLC 2018 remain constant over time until 2050.
[B] the disaggregation of "New energy crops" is required to assure that the LUC dynamics and therefore land availability meets RED II/III sustainability and marginal land criteria for all categories and each point in time.
[C] land with physical constraints for lignocellulosic energy crops production
[D] land with no-physical constraints for lignocellulosic energy crop production

Once the land use/covers are established for each relevant year, RED II/III sustainability criteria are overlayed into land exclusion parameters and applied to the land use/cover projections (Figure 1, step 2). For example, under RED II/III, agricultural land is restricted from being used to produce lignocellulosic energy crops. These criteria are in place to avoid displacement effects of food and feed crops (avoid the risk of indirect land use change). The land exclusion parameters based on RED II/III are presented in

Table ***3***. Afterward, the data from Marginal Lands for Growing Industrial Crops project (Elbersen et al., 2020) is applied to distinguish the areas under land marginality (Figure 1, step 3). The marginal land data applied in this study provides land classified as marginal (regardless of land use/cover) based on six different biophysical constraints, such as adverse climate, adverse chemical composition of soil and adverse terrain[2].

[2] For more information see https://magic-h2020.eu/

Figure 1 Land availability for lignocellulosic energy crops approach, adapted from (Vera et al., 2021).

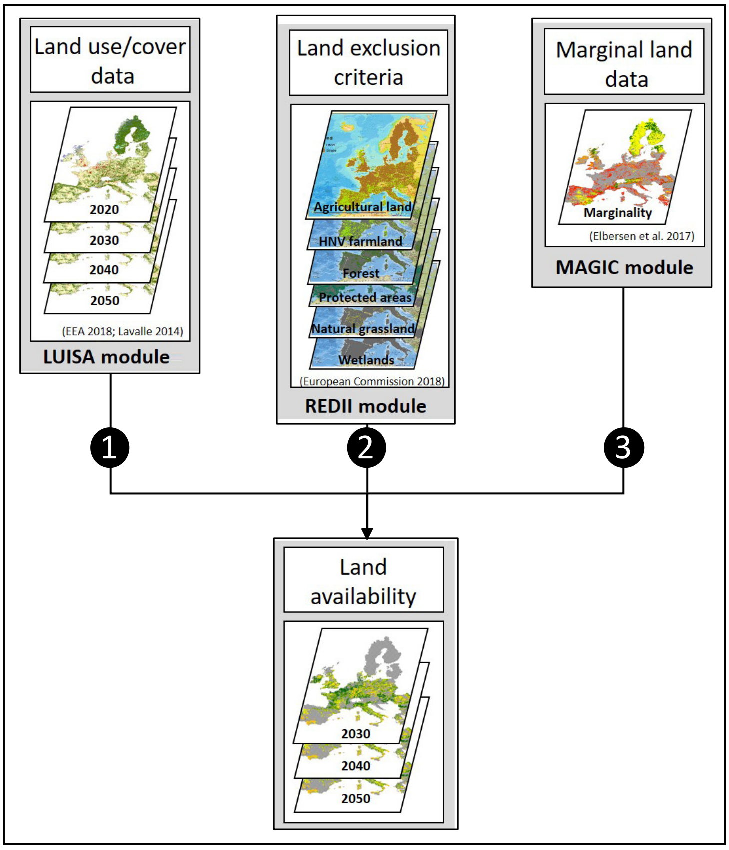


Table 3 Summary of the RED II/III sustainability criteria as laid down in the directive and the correspondence into land exclusion parameters. Adapted from (Vera et al., 2021).

RED II sustainability criteria for land use [a]	Translation of criteria into exclusion parameters
• RED II Article 2, definition 37 Reducing the risk of indirect land- use change: "low indirect land- use change-risk biofuels, bioliquids and biomass fuels' means biofuels, bioliquids and biomass fuels, the feedstock of which was produced within schemes which avoid displacement effects of food and feed-crop based biofuels, bioliquids, and biomass fuels through improved agricultural practices as well as through the cultivation of crops on areas which were previously not used for cultivation of crops, and which were produced in accordance with the sustainability criteria for biofuels, bioliquids, and biomass fuels laid down in Article 29"	Exclusion of all land dedicated to food, feed and fibre production to avoid the risk of indirect land-use change. All land categorized as "Agriculture" in the land cover dataset is excluded, including [b]: • Non- irrigated arable land • Permanently irrigated land • Rice fields • Vineyards • Fruit trees and berry plantations • Olive groves • Pastures • Annual crops associated with permanent crops

	• Complex cultivation patterns • Land principally occupied by agriculture, with significant areas of natural vegetation • Agro- forestry areas
REDII Article 29: Sustainability and greenhouse gas emissions saving criteria for biofuels, bioliquids, and biomass fuels	
• Paragraph 2:"Biofuels, bioliquids and biomass fuels produced from agricultural biomass... shall not be made from raw material obtained from land with a high biodiversity value..."	Exclusion of land with a High Nature Value, targeted to HNV farmland [c]: • Farmland with a high proportion of semi-natural vegetation • Farmland with a mosaic of low- intensity agriculture and natural and structural elements • Farmland supporting rare species or a high proportion of European or World populations
• Paragraph 3, subsection a and b: "...primary forest and other wooded land, namely forest and other wooded land of native species..." "...highly biodiverse forest and other wooded land which is species- rich and not degraded, or has been identified as being highly biodiverse by the relevant competent authority..."	Exclusion of land categorized as "Forest" in the land cover dataset, including [b]: • Broad-leaved forest • Coniferous forest • Mixed forest
• Paragraph 3, subsection c: "...areas designated by law or by the relevant competent authority for nature protection purposes..." "...For the protection of rare, threatened or endangered ecosystems or species recognised by international agreements or included in lists drawn up by intergovernmental organisations or the International Union for the Conservation of Nature..."	Exclusion of all areas dedicated to achieve long-term conservation of nature with its associated ecosystem services and cultural values. Exclusion of all areas designated with a protected status under European policy, mainly [d]: • The Natura 200 network • The Emerald network of areas of special conservation interest • Wetlands under the Ramsar convention
• Paragraph 3, subsection d: "...highly biodiverse grassland...namely grassland that would remain grassland in the absence of human intervention..."	Exclusion of land categorized as "Natural grasslands" in the land cover dataset [b]
• Paragraph 4, subsection a, b, and c: "...land with high- carbon stock, namely land that had one of the following status...wetlands, namely land that is covered with or saturated by water permanently, ..." • "Continuously forested areas"	Exclusion of land categorized as "Wetlands" and "Forest" in the land cover dataset, including [b]: • Inland marshes • Peat bogs • Salt marshes • Saline

	• Intertidal flats • Broad-leaved forest • Coniferous forest • Mixed forest
• Paragraph 5: "...shall not be made from raw material obtained from land that was peatland in January 2008..."	Exclusion of land categorized as "Wetlands" in the land cover dataset, mainly [b] • Peat bogs
[a](European Commission, 2018) [b](Baranzelli et al., 2014; EEA, 2020) [c] All farmland is excluded for every time step with the land cover dataset category "Agriculture". This includes all farmland, either with an HNV status or not. [d](EEA, 2023a, 2023b)	

Table 4 Biomass type yield mineral content, adapted from (Agronomic Crops Netwtok Ohio State University, 2017; Dees et al., 2017; Rees et al., 2017).

Lignocellulosic energy crop	N content (kg t_{dry}^{-1})	P_2O content (kg t_{dry}^{-1})	K_2O content (kg t_{dry}^{-1})	CaO content (kg t_{dry}^{-1})
Miscanthus	6.3	2.0	8.1	5.7
Switchgrass	4.7	2.0	11.8	1.2
Giant Reed	9.9	1.1	8.8	20.5
Reed Canary grass	5.0	0.3	2.9	7.4
Cardoon	13.0	2.3	2.4	3.1
Willow	4.0	0.4	3.5	7.7
Poplar	3.0	0.1	1.4	5.3
Eucalyptus	11.0	0.6	24.1	3.2
Cereal straw	4.5	1.2	8.2	NA
Maize stover	6.9	1.6	13.9	NA

A.1.3: Lignocellulosic energy crops biomass potentials

Gross biomass potential
The gross biomass potentials are calculated with

Equation 1, representing the relation between crop-specific phenological characteristics and climate conditions. The crops' phenological characteristics are the length of the growing season, crop growth stage, cumulative evapotranspiration for each crop growth stage and water use efficiency. These parameters are summarized for each lignocellulosic energy crop in Table 5.

Equation 1

$$AB_{t,i} = \sum_j ET_j \cdot Kc_{i,j} \cdot WP_i$$

Where:

AB_t = Theoretical water-constrained above ground biomass potential, t_{dry}/ha year
i = Crop type
j = Crop growth stage
ET = Reference evapotranspiration, m^3
Kc = Crop coefficient, incorporates crop specific characteristics and averaged effects of evaporation from the soil, dimensionless
WP = Water use efficiency, t_{dry}/ (m^3 ha)

Table 5 Crop phenological characteristics, adapted from (Ramirez-Almeyda et al., 2017; Vera et al., 2021).

Lignocellulosic energy crop	Growing season (days)	Start day of growing season (day)	Length of growth stage (Cumulative fraction of length of season)				Crop coefficient per growth stage (Kc)				Water use efficiency (t_{dry} m^{-3} ha^{-1})	Harvest index
			Initial	Development	Mid	Late	Initial	Development	Mid	Late		
Miscanthus	210	80	0.21	0.34	0.84	1	0.48	1.05	1.41	0.95	33	0.7
Switchgrass	210	80	0.18	0.31	0.80	1	0.50	0.99	1.30	0.80	30	0.6
Giant reed	220	90	0.21	0.32	0.78	1	0.54	1.01	1.74	1.10	31	0.7
Cardoon	250	90	0.10	0.20	0.80	1	0.50	0.70	1.00	0.95	31	0.6
Willow	300	80	0.16	0.39	0.84	1	0.40	1.00	1.50	0.50	30	0.65
Poplar	300	80	0.16	0.39	0.84	1	0.40	1.00	1.50	0.40	29	0.6
Eucalyptus	300	90	0.16	0.39	0.84	1	0.40	1.00	1.50	0.40	27	0.65

Daily evapotranspiration is estimated spatially explicitly for the reference points in time following the widely applied Penman-Monteith equation (Monteith, 1965). This equation is the FAO's sole recommended method to estimate reference evapotranspiration[3]. Climatic parameters (such as wind speed, humidity and temperature) to estimate daily reference evapotranspiration are derived from the HadGEM2-ES (Gordon et al., 2000) global climatic model under the Representative Concentration Pathway (RCP) 2.6 (Van Vuuren et al., 2011). This scenario considers mitigation actions aiming to limit the increase of global mean temperature to 2°C. Daily global projections (between 2030 and 2050) on temperature, precipitation, relative humidity, shortwave radiation, and wind speed are collected from the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP2b; (Warszawski et al., 2014)).

Biomass potentials, including agroecological suitability

The impact of location-specific biophysical conditions on crop growth is assessed by applying crop-specific agroecological suitability maps. These maps are generated based on ten distinct biophysical parameters. Agroecological suitability is expressed as a percentage of the theoretical maximum achievable yield, which spans from 0 (unsuitable conditions) to 100 (highly favourable conditions), as illustrated in Equation 2. These suitability maps are computed individually for each crop and for

[3] For more information please see Chapter 2 - FAO Penman-Monteith equation

the reference points in time, utilizing the methodologies outlined in (Perpiña Castillo et al., 2015). The considered biophysical parameters are:

1. Soil pH
2. Soil texture
3. Soil depth
4. Soil type
5. Soil drainage
6. Slope
7. Temperature
8. Precipitation
9. Frost Free Days (FFD)
10. Length Growing Period temperature (LGPt)

Parameters 1 to 6 are assumed to remain constant. Parameters 7 – 10 are assessed following the climate change projections under the RCP 2.6 scenario. Further details and crop-specific scores for each suitability parameter can be found in Table 6

Equation 2

$$AB_{s,i} = AB_{t,i} \cdot S_i$$

Where:

AB_s = Above ground biomass potential considering biophysical factors, t_{dry}/ha year
i = Crop type
AB_t = Theoretical water-constrained above ground biomass potential, t_{dry}/ha year
S = Suitability index for specific location, %

Table 6 Crops suitability scores adapted from (Perpiña Castillo et al., 2015).

Biophysical variables	Classes	Lignocellulosic energy crops suitability to biophysical variables (%)							
		Miscanthus	Switchgrass	Reed canary grass	Giant Reed	Cardoon	Willow	Poplar	Eucalyptus
Soil pH	0-4	0	0	0	0	0	0	0	0
	4-5	40	40	40	20	20	20	20	20
	5-6	80	60	60	80	60	60	60	60
	6-7	100	100	100	100	100	100	100	100
	7-8	60	40	80	60	80	80	80	80
LGPt (days)	0	0	0	0	0	0	0	0	0
	1-59	0	0	0	0	0	0	0	0
	60-149	100	100	100	100	100	0	0	0
	150-209	100	100	100	100	100	100	100	100
	210-269	100	100	100	100	100	100	100	100
	270-365	100	100	100	100	100	100	100	100
FFD (days)	0-100	0	0	0	0	0	0	0	0
	100-200	80	80	80	0	80	0	0	0
	200-300	80	80	100	80	100	100	100	100

Biophysical variables	Classes	Lignocellulosic energy crops suitability to biophysical variables (%)							
		Miscanthus	Switchgrass	Reed canary grass	Giant Reed	Cardoon	Willow	Poplar	Eucalyptus
	>300	100	100	100	100	100	100	100	100
Soil texture	Coarse	60	60	20	60	40	40	60	60
	Medium	80	100	100	100	100	100	100	100
	Medium fine	100	100	100	100	100	100	100	100
	Fine	40	60	60	80	60	60	40	60
	Very fine	20	0	20	60	0	0	0	60
	No mineral soils	0	0	0	0	0	0	0	0
Soil depth (cm)	<10	0	0	0	0	0	0	0	0
	10-20	0	0	0	0	0	0	0	0
	20-40	0	0	20	0	0	0	0	0
	40-60	20	20	40	0	20	0	40	40
	60-80	60	60	60	60	60	60	60	60
	80-100	60	60	80	80	60	60	60	60
	100-120	80	80	100	100	80	80	80	80
	120-150	100	100	100	100	100	100	100	100
Soil type	Alluvial deposits	80	80	80	80	80	80	80	80
	Other rocks	0	0	0	0	0	0	0	0
	Sandy materials	100	100	100	100	100	100	100	100
	Clayey materials	100	100	100	100	100	100	100	100
	Crystalline rocks	40	40	40	40	40	40	40	40
	Volcanic rocks	0	0	0	0	0	0	0	0
	Loamy materials	100	100	100	100	100	100	100	100
	Calcareous rocks	60	60	80	60	60	60	60	60
	Detrital formations	60	60	60	60	60	60	60	60
Soil drainage	Excessively well drained	100	100	100	100	100	100	100	100
	Imperfectly drained	0	0	0	0	0	40	0	0
	Moderately drained	60	60	60	80	60	60	60	60
	Poor drained	0	0	0	0	0	40	20	0
	Temporary drained	40	40	40	40	40	40	40	40
	Very Poor drained	0	0	0	0	0	0	0	0
	Well drained	80	80	80	80	80	80	80	80
Temperature (˚C)	0- (-)15	0	0	40	0	0	0	40	0
	0-4	0	0	60	0	0	20	40	0
	4-6	20	20	60	0	0	20	60	0
	6-8	100	60	60	0	0	80	100	0
	8-10	100	100	80	20	20	100	100	20
	10-15	100	100	100	100	100	100	100	100
	15-20	20	20	40	100	100	40	40	100

Biophysical variables	Classes	Lignocellulosic energy crops suitability to biophysical variables (%)							
		Miscanthus	Switchgrass	Reed canary grass	Giant Reed	Cardoon	Willow	Poplar	Eucalyptus
	>20	0	0	40	100	100	0	20	100
Precipitation (mm)	0-200	0	0	0	0	0	0	0	0
	200-400	0	0	60	0	40	0	0	40
	400-500	0	60	60	40	60	0	0	60
	500-600	40	60	60	60	60	0	0	60
	600-800	60	80	80	80	80	80	80	80
	800-1000	80	100	100	100	100	100	100	100
	>1000	100	100	100	100	100	100	100	100
Slope (%)	0-2	100	100	100	100	100	100	100	100
	2-5	80	80	80	80	80	80	80	80
	5-8	60	60	60	60	60	60	60	60
	8-16	40	40	40	40	40	40	40	40
	16-30	20	20	20	20	20	20	20	20
	>30	0	0	0	0	0	0	0	0

Biomass potentials, including harvestable yields

Crop-specific harvest indexes are applied to estimate the final crop yield at each location; see Equation 3. Harvest indexes are presented in Table 5.

Equation 3

$$Y_i = AB_{s,i} \cdot HI_i$$

Where:

Y = Harvestable Yield, t_{dry}/ (ha year)
i = Crop type
AB_s = Above ground biomass potential considering biophysical factors, t_{dry}/ (ha year)
HI = Harvest index, dimensionless

Water Balance (Deficit) of Lignocellulosic Energy Crops

The water balance of lignocellulosic energy crops is assessed following the methods of (Brouwer & Heibloem, 1986) for each reference point in time. While this approach lacks a direct indicator for determining potential water depletion in crop production areas, it does provide a reliable estimate of the amount of additional water (i.e., irrigation) needed by each crop type to achieve the potential biomass yields.

Equation 4 describes the water balance approach. The crop Water Balance (WB) is assessed for each crop by comparing its evapotranspiration rates with effective Precipitation during the growing season. Effective Precipitation (EP) represents the share of Precipitation retained in the soil that becomes available for the crop growth. EP is calculated using Equation 5.

Equation 4

$$WB_i = \sum_{GC} ET_0 * Kc_{i,j} - \sum_{jGC} EP$$

Where:

- WB= Water balance, mm/year
- i = Crop type
- GC= Grow cycle
- j= Crop growing stage
- ET_0 = Evapotranspiration, mm/day
- Kc = Crop coefficient
- EP = Effective Precipitation, mm/day

Equation 5

$$EP = P \cdot \frac{125 - 0.2P}{125} \; for \; P_{month} < 250mm$$

Or

$$EP = 125 + 0.1 \; P \; for \; P_{month} > 250 \; mm$$

Where:

EP= Effective precipitation, mm/day
P = Precipitation, mm/day

The methods to determine daily evapotranspiration from lignocellulosic energy crops have been covered in the biomass potential section. The same climatic projection data (RCP 2.6) is considered. The water balance results are expressed in mm/year over each crop growing cycle. In addition, to provide a holistic comparison, the water balance results are compared spatially explicitly with the water stress projections under the same RCP 2.6 scenario from AQUEDUCT water risk atlas (Kuzma et al., 2023). Water stress is defined as “the ratio of total water demand to available renewable surface and groundwater supplies. Water demand includes domestic, industrial, irrigation, and livestock uses. Available renewable water supplies include the impact of upstream consumptive water users and large dams on downstream water availability. Higher values indicate more competition among users” (Kuzma et al., 2023). Given data availability, the WB results are only compared with water stress projections for 2030 and 2050.

A.1.4: Agricultural residues biomass potential

Yields for wheat, rye, barley oats, triticale, sorghum and maize are estimated for each location following production trends, agroclimatic yield maps and agroecological suitability maps.

1) Country and crop-specific yields are retrieved for the last years (2012-2022) to reflect yield dynamics (Eurostat, 2024). Using the historical yield data, an average (between 2012 and 2022) yield (country dependent) is estimated and extrapolated until 2025 by following the annual crop-specific yield increase. This process is carried out until 2025 to avoid the overestimation of attainable yields in already high-yield countries.

2) After 2025, average country and crop-specific yields are extrapolated with the support of agroclimatic potential yield maps. Agroclimatic yield maps describe the possible upper agronomic limit for producing individual crops under specific

agroclimatic, soil, inputs and terrain conditions. Agroclimatic yield projection maps with high input under the RCP 2.6 scenario for wheat, rye, barley oats, sorghum and maize were retrieved for each relevant point in time from the Global Agro-Ecological Zones (GAEZ)[4] modelling framework and database developed by FAO and IIASA. No map is available for triticale; thus, the wheat map was used as a proxy, given that triticale is a hybrid between wheat and rye with yields more similar to wheat.

3) An average country-specific agroclimatic yield was estimated for each reference point in time and crop. Note that the average agroclimatic yield was computed as the average yield of each country plus one standard deviation to avoid including low-yield locations that would not reflect EU members' cereal production trends. Depending on each scenario, yields are estimated for each relevant point in time in order to reduce the percentual gap between 2025 yields and agroclimatic yields for 2030, 2040, and 2050. This process is carried out to avoid overestimating country-specific attainable yields over time. Once average yields for each point in time, country and crop type are estimated, yields are subsequently mapped from agroecological suitability maps (scores).

Agroecological suitability maps provide the suitability of each crop on a specific location expressed as a percentage of the theoretical maximum achievable yield, which spans from 0 (indicating unsuitable conditions) to 100 (indicating highly favourable conditions). Agroecological suitability projection maps under the RCP 2.6 scenario for wheat, rye, barley oats, sorghum and maize are retrieved from the GAEZ framework[5]. It was assumed that each country and crop-specific average yield16F[6] corresponds directly to the average agroecological suitability for the reference points in time (step 3). Once this correlation was established, yields were derived from each location's suitability score.

The difference in yield increases between countries (see Section 3.2.2 in the main report) is assumed to reflect historical trends on cereal yields (Eurostat, 2024), in which a relative increase in yields over time is higher in countries with a low yield compared to countries with high base yields. As a result, low-yield countries have more room for yield improvement. In addition, historical trends also reflect that such yield increases for low-yielding countries occur in a shorter period of time. Generally, once high yields are obtained, yield increases experience a plateau trend over time. These trends are reported in statistics and scientific publications (Eurostat, 2024; Schils et al., 2018; Tian et al., 2021).

Once yields are assessed and mapped for each crop, location and point in time, residues are calculated following Equation 6. Table 7 includes a description of each ratio and the applied removal ratios for each residue type.

Equation 6

$$ARY_i = Y_i \cdot RR \cdot DM \cdot TA \cdot SR$$

Where:

ARY = Available residue yield, t_{dry}/ha year
i = Crop type
Y = Yield, tonne/ha

[4] For more information please see GAEZ v4 Data Portal (fao.org)
[5] For more information please see GAEZ v4 Data Portal (fao.org)
[6] Given the impossibility of distinguishing within the LUISA land cover projections crops land uses, a weighted average is applied for each country to estimate cereals yields while considering wheat, rye, barley, oats, triticale, and sorghum yields and the share of land dedicated historically to that crop. The same process is done with suitability maps.

RR = Residue to yield ratio, %
DM = Dry matter content, %
TA= Technical availability factor, %
SR = Sustainable potential removal, %

Table 7 Applied ratios for each residues type, adapted from (Eurostat, 2024; García-Condado et al., 2019; Panoutsou & Maniatis, 2021a).

Parameter	Cereals	Grain Maize
Residue to yield ratio (%)	100	110
Dry matter content (%)	85	85
Technical availability factors (%)	40:45:50 depending on supply scenario	40:45:50 depending on supply scenario
Sustainable potential removal (%)	40	45

A.1.5: Comparison with the ICL and Concawe Report

In the Sustainable biomass availability in the EU toward 2050 report (Panoutsou & Maniatis, 2021), lignocellulosic energy crops are estimated to vary between 36 to 108 million tons for 2030 and 42 to 127 million tonnes for 2050, depending on the scenario. Cereal straw is estimated to vary between 118 to 141 million tonnes in 2030 and 130 to 156 million tonnes in 2050. Maize stover is projected to vary between 25 to 28 million tonnes in 2030 and 28 to 31 million in 2050. The main differences in potentials between this assessment and the Sustainable biomass availability in the EU toward 2050 report study are driven by the following parameters provided in Table 8.

Table 8 Comparison of relevant parameters for lignocellulosic crops and agricultural residues.

	Mid-term report Sustainable biomass feedstock supply chains for advanced biofuels	**Sustainable biomass availability in the EU to 2050 report**
Lignocellulosic energy crops assessed	Miscanthus, Switchgrass, RCG, Giant Reed, Willow, Poplar and Eucalyptus	Fiber Sorghum, Kenaf, Miscanthus, Switchgrass, Cardoon Poplar and Willow
Assessment type	Spatially explicit (yields) while considering biophysical conditions and crop phenological characteristics align with climate projections based on IPCC climatic models.	Statistics - country level
Land availability for lignocellulosic energy crops	Using 50% for the low scenario, 75% for the medium scenario and 100% for the High scenario of the available land that is considered marginal, meets RED II/III land sustainability criteria and the crop adaptability to each land location's specific biophysical conditions.	Using 25% of the available marginal land in the Low Scenario, 50% in the Medium Scenario (Scenario 2) and 75% in the High Scenario (Scenario 3).
Crops mix potential	The maximum-yield biomass potential is quantified by selecting the lignocellulosic energy crop for each location with the highest attainable yield.	Not specified
Yield increases for lignocellulosic energy crops	0.5% for the Low, 0,75% for the Medium and 1% for the High scenario annual increase	1% for the Low, 1% for the Medium and 2% for the High scenario annual increase
Yield increases for crops related to agricultural residues	Low: 30% of the yield difference between 2025 actual yield and 2050 agroclimatic attainable yield is covered Medium: 60% of the yield difference between 2025 actual yield and 2050 agroclimatic attainable yield is covered High: 90% of the yield difference between 2025 actual yield and 2050 agroclimatic attainable yield is covered	1,9% annual increase divided into 0.9% for crop yield improvements and 1% for management practice improvements
Removal rate of field residues	40% for the Low, 45% for the Medium and 50% for the High scenario	40% for the Low, 45% for the Medium and 50% for the High scenario

In this assessment, the biomass potential of lignocellulosic energy crops is higher than the one given by the Sustainable biomass availability in the EU to 2050 report. This difference between studies is driven by the additional crop types considered, the amount of land dedicated for producing these crops and yield assumptions. In the Sustainable biomass availability in the EU toward 2050 report, for 2030, approximately 20 million ha (14.5 low quality + 5.5 high quality) of marginal land are available to produce lignocellulosic energy crops. Furthermore, the average yield (regardless of crop type) for the entire EU27 + UK is assumed to be 6.6 t/ha for low-quality and 8.8 t/ha for high-quality marginal lands. Considering the high Sustainable biomass availability in the EU toward 2050 report study scenario (75% of marginal land is used), 15 million ha are used to produce 108 million tonnes of lignocellulosic energy crops for 2030. In this assessment, approximately 20.5 million ha of marginal land is available in 2030 that complies with RED II/III sustainability criteria (Vera et al., 2021). However, when considering the suitability of crops to agroecological and climatic conditions across the EU27 + UK, 8 million ha are estimated to be available for lignocellulosic energy crop production. For the High availability scenario in this study (100% of marginal land used), 118 million tonnes of lignocellulosic energy crops can be produced while selecting the crop type with the highest attainable yield for each location. Therefore, differences between reports are also driven by the spatial difference of crops to achieve yields under specific geophysical conditions (see section 3.2 of the main report).

There are also differences in the reports between cereal straw potentials, with higher availability potentials given by the Sustainable biomass availability in the EU to 2050 report. These differences are attributed to the assumptions related to crop yield increase. In the Sustainable biomass availability in the EU toward 2050 study, 156 million tonnes of cereal straw are available for the High scenario in 2050. These results are driven by the assumption that crops yield will annually increase by 1.9% as a result of crop and management improvements; this translates into a 38% increase (1.9% yield annual yield increase over 20 years) for the cereal straw biomass potential in for the High scenario by 2050. Therefore, even countries with a currently high yield for cereals will still increase their yields by almost 40% by 2050. In this report, the High scenario assumed that 90% of the cereals yield gap (2050 agroclimatic attainable yield – 2025 actual yield) is covered by 2050. This means that for each location, the yield increases to meet 90% of the agroclimatic attainable yield in 2050 compared to the actual yield in 2025. For maize stover, the results are similar between the two studies.

A.1.6: Biomass costs at roadside

Roadside cost of lignocellulosic energy crops and agricultural residues

Machinery costs for agricultural activities are composed by 3 parameters:

- **Fixed costs:** These are based on the replacement value (€) of each machine and include the annual costs as a percentage of the replacement values expressed in terms of residual value (€). These costs cover depreciation (€), interests (€), accommodation (€), levies (€), technical control/general inspection (€) maintenance and repair (€). The fixed costs are estimated at an hourly rate for each machine based on the specific potential use per year (h/years). The selection of machines was done following the approach present in (Dees et al., 2017), and middle-end machines were selected for each agricultural activity. Specific cost machinery data was retrieved from the MaKost database[7]. The MaKost database provides the fixed and variable costs, as well as the energy consumption of more than 2000 agricultural machines (as of 2020) (KTBL, 2023).
- **Variables costs:** These correspond mainly to fuel inputs. Variables costs are estimated based on each machine's fuel consumption (l/h) (KTBL, 2023) and country-specific diesel prices. Diesel prices for each country are retrieved from the European Commission Oil Bulletin (European Commission, 2023). To avoid the use of extreme fuel prices driven by recent events such as war and geopolitics, an average of the last 3 years was applied.
- **Labour costs:** hourly labour costs are retrieved for each country based on national statistics (Eurostat, 2023b; UK office for national statistics, 2023).

The use of machinery is directly related to each lignocellulosic energy crop's production and management practices. Note that the production and management practices vary per crop type and are considered over the entire crop rotation cycle. Table 9 includes the number of activities carried out over each crop rotation cycle.

7 For more information please see MaKost (ktbl.de).

Table 10 provides the machine cost characteristics used for each activity. The number of hours (h/ha) dedicated to each agricultural activity is required to obtain the final machinery cost per crop type over the entire rotation cycle. This data was retrieved from different studies (Escobar et al., 2017; Fazio & Monti, 2011; Forte et al., 2015; González-García et al., 2012; Krzyżaniak et al., 2016; KTBL, 2023; Livingstone et al., 2022; Mathanker & Hansen, 2015; Meys et al., 2021; Monti et al., 2009).

The cost of fertilizers is based on the nutrient input rate, which is directly proportional to what is removed by harvesting the crop. The nutrient content for each crop/biomass type is present in Table 4. Fertilizer prices for urea, DAP and potassium chloride are retrieved from the World Bank commodities prices data set (The World Bank, 2023). The nutrient content of each fertilizer is considered. For example, 46% of the urea content corresponds to nitrogen. The cost of herbicides is based on the commercial cost of MCPA. **Error! Reference source not found.** contains the herbicide application rates.

The cost of land is estimated as a percentage of the actual agricultural land renting prices for each country. There is no direct relation between the land renting costs for a marginal and a non-marginal land. However, it is acknowledged that the rent of a marginal land is lower (Wagner et al., 2019). Therefore, it is assumed that marginal land renting prices are half of the prices of agricultural land. Agricultural land renting prices are retrieved from Eurostat (Eurostat, 2023a).

Table 9 Crop/biomass specific agricultural activities (Dees et al., 2017).

Biomass type	Rotation period (years)	Activity (# of time over rotation period)							
		Cleaning /clearing field	Ploughing	Disking/ Harrowing	Planting	Sowing	Fertilizer application	Weed control	Harvesting /mowing/bailing residues
Miscanthus	20	1	1	1	1	0	17	1	18
Switchgrass	15	1	1	1	0	1	14	1	14
RCG	15	1	1	1	0	1	14	1	14
Giant reed	15	1	1	1	1	0	14	1	14
Willow	20	1	1	1	1	1	7	3	7
Poplar	20	1	1	1	1	1	7	3	7
Eucalyptus	20	1	1	1	1	1	7	3	7
Agricultural residues	1	-	-	-	-	-	-	-	1

Table 10 Machinery cost data (KTBL, 2023)

Activity	Equipment type	Replacement value (€)	Depreciation (€)	Interests (€)	Accommodation (€)	Levies (€)	Technical control, general inspection (€)	Maintenance and repair (€)	Potential use per year (h/y)	Diesel use (l/h)
Tractor	Standardtraktor, Allradantrieb, Lastschaltgetriebe, 40 km/h, 83 (75-92) kW	80000	5333	1440	154	605	36	5833	833	9.7
Cleaning/clearing field	Rotationsmähwerk, angebaut, Front, 2,5 m	10500	840	189	67	-	-	561	300	-
	Schlegelmulcher, Landschaftspflege, Heck/Front, 2,0 m	8900	1187	160	53	-	-	600	300	-
Ploughing	Drehpflug, angebaut, 3 Schare, 1,05 m	11000	629	198	50	-	-	1179	380	-
Disking/ harrowing	Scheibenegge, angebaut, 3,0 m	17000	971	306	172	-	-	1071	300	-
Planting (rhizomes)	Scheibenpflanzmaschine, 3-reihig	8600	573	155	84	-	-	350	160	-
Sowing	Rotationsmähwerk, angebaut, Front, 2,1 m	9000	600	162	126	-	-	458	160	-
Fertilizer application	Disk spreader 3000l	14000	1400	280	120	-	-	420	600	-
Weed control	Pflanzenschutzspritze, aufgebaut, ohne Spritzgestänge, 1500 l	13000	1040	234	108	-	-	39	300	-
	Spritzgestänge, 15 m	13700	1096	247	-	-	30	300	300	-

Mowing (Giant reed)	Schlegelmulcher, Front/Heck 4,0 m	17000	1360	306	96	-	-	203	300	-
Bailing residues	Quaderballenpresse, 120 x 90 cm, Tandemachse	175000	11667	3150	331	-	-	6.250	320	-
	Ballentransportwagen, 40 km/h, zweiachsig, 10,5 t (8 t)	10000	533	180	403	-	-	600	250	-

		Depreciation (€/h)	Interests (€/h)	Levies (€/h)	Maintenance and repair (€/h)	Diesel use (l/h)
Planting (SRC)	Schlaggröße: 1.0 ha, Bodenbearbeitungswiderstand: leicht, Entfernung zum Schlag: 1.0 km, Menge: 900.0 Stück/ha, Arbeitsbreite: 4.5 m	51.714	13.9604	1.3328	19.72	16.5
Harvesting (SRC)	Pappel-/Weidenernte mit Feldhäcksler, Feldhäcksler 275 kW, 2-reihig Doppelzug je 10 t, Dreiseitenkippanhänger; 67 kW	127.3725	29.7108	9.5661	59.0004	39.4
Harvesting perennial grasses	Miscanthus mit Feldhäcksler auf Schwad legen	130.392	31.1184	7.4736	47.52	12
Bailing perennial grasses	Miscanthusstroh Pressen mit Quaderballenpresse	46.2931	12.5132	3.6162	37.5683	5.84

Table 11 Herbicide application per crop type

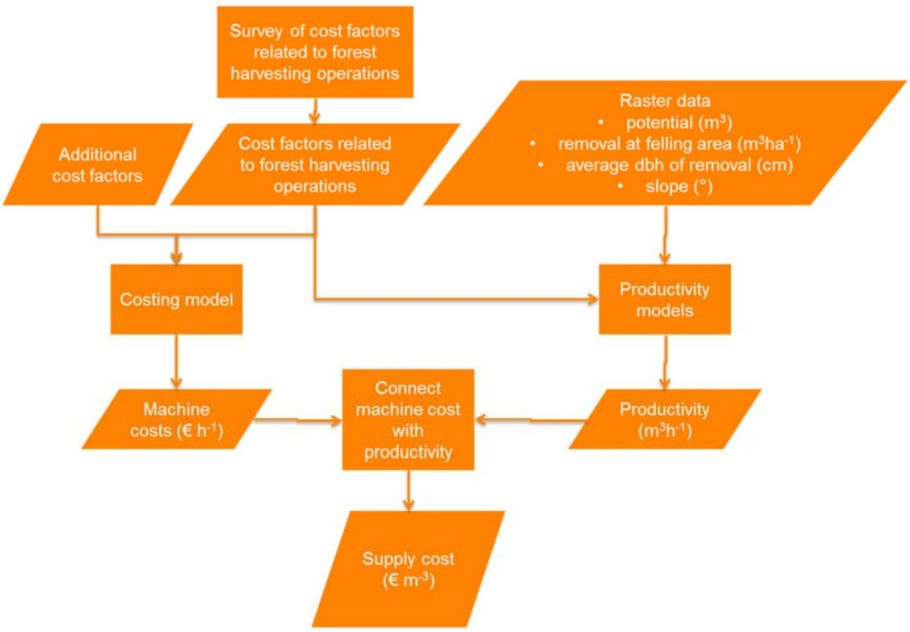
Lignocellulosic energy crop	Pesticides (Kg ha^{-1} $year^{-1}$)
Miscanthus	0.3[A]
Switchgrass	0.2[A]
Giant Reed	0.2[A]
Reed Canary grass	0.2[A]
Cardoon	0.2[A]
Willow	4.0[B]
Poplar	4.0[C]
Eucalyptus	1.6[C]

A (Fazio & Monti, 2011)
B Based on data for Poplar (Giuntoli et al., 2017)
C (Giuntoli et al., 2017)
D (Rettenmaier et al., 2018)
E (Järveoja et al., 2013)
F (Schmidt et al., 2015)

Roadside cost of forest biomass

The general Activity Based Calculation method for forest biomass is shown in Figure 2. First, supply chains were standardised, assuming roadside chipping of stemwood and primary logging residues. Stumps are extracted and assumed to be crushed by a mobile grinder. A detailed explanation of each supply chain and the cost calculations is provided in Dees et al. (2017).

Figure 2 General workflow of forest biomass cost calculations (Dees et al. 2017).



A.2: RESULTS

The results of the modelling work on agricultural biomass availability potentials and biomass roadside costs for 2030 and 2050 are presented in the following sections for the Low and Medium scenarios. The results for the High scenario are available in the main report.

In the case of energy crops, while moving from the Low to the Medium and High scenarios and improvements in yields due to innovation and enhanced management practices are assumed, the EU average yields remain relatively stable across scenarios. This is because, as the scenario ambition increases, a larger share of marginal lands across the EU-27 + UK is assumed to be utilised for energy crop production (Low: 50%, Medium: 75%, High: 100%). As more land is brought into use, less productive and lower-yielding areas are included, which counteracts the yield improvements assumed in the model for the Medium and High scenarios. Nevertheless, as illustrated in the figures below, the range and variability of possible yields becomes significantly wider from Low to Medium and High scenarios. This is due to the greater geographical spread and heterogeneity of marginal land use, encompassing both high- and low-performing areas.

A.2.1: Agricultural biomass availability potential

Low Scenario:

Figure 3 Biomass potentials (for all markets) of lignocellulosic energy crops, cereal straw and maize stover for the Low availability scenario in the EU-27 + UK. The Max-yield biomass potential represents the case based on which the lignocellulosic energy crop with the highest attainable yield is selected for each location. The individual energy crop bars represent the case when all marginal lands are dedicated to a single crop.

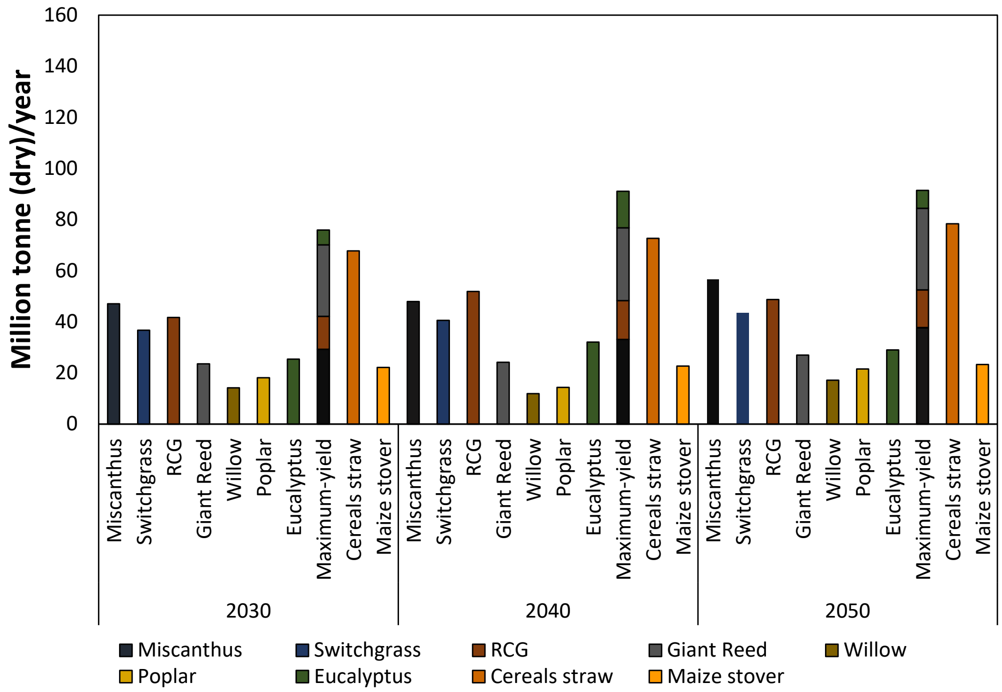
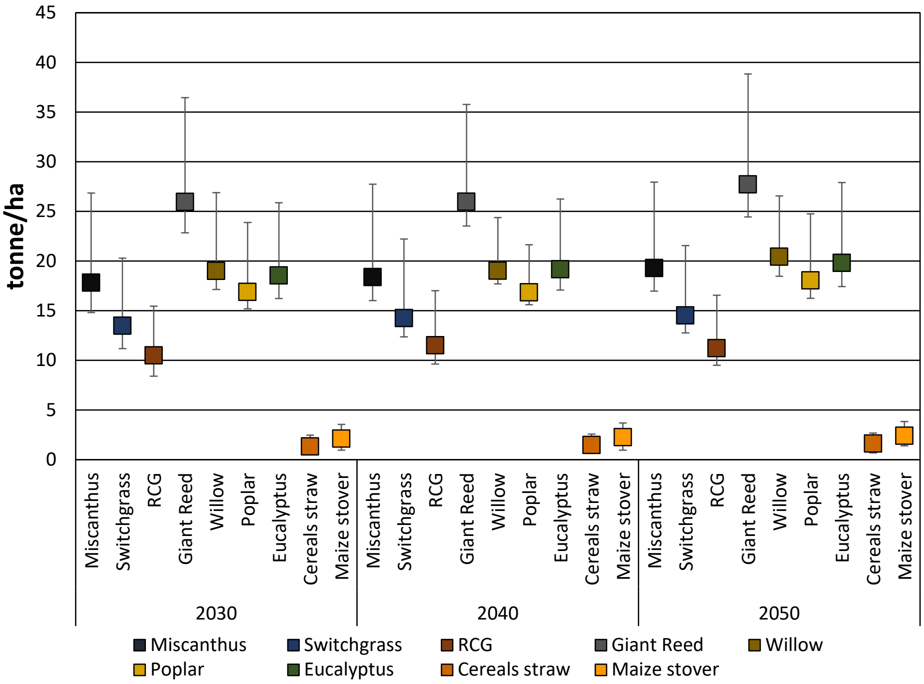


Table 12 Average yield for each crop in the Low availability scenario while considering all the potential locations suitable for each crop type in EU-27 + UK.

Crop	2030 (t/ha)	2040 (t/ha)	2050 (t/ha)
Miscanthus	17.8	18.4	19.3
Switchgrass	13.5	14.2	14.5
RCG	10.5	11.5	11.2
Giant Reed	25.9	26.0	27.7
Willow	19.0	19.0	20.4
Poplar	16.9	16.8	18.0
Eucalyptus	18.5	19.1	19.8

Figure 4 Biomass yield range of lignocellulosic energy crops, cereal straw and maize stover for the Low scenario while considering all the potential locations suitable for each crop type in EU-27 + UK.



Medium Scenario:

Figure 5 Biomass potentials (for all markets) of lignocellulosic energy crops, cereal straw and maize stover for the Medium availability scenario in the EU-27 + UK. The Max-yield biomass potential represents the case based on which the lignocellulosic energy crop with the highest attainable yield is selected for each location. The individual energy crop bars represent the case when all marginal lands are dedicated to a single crop.

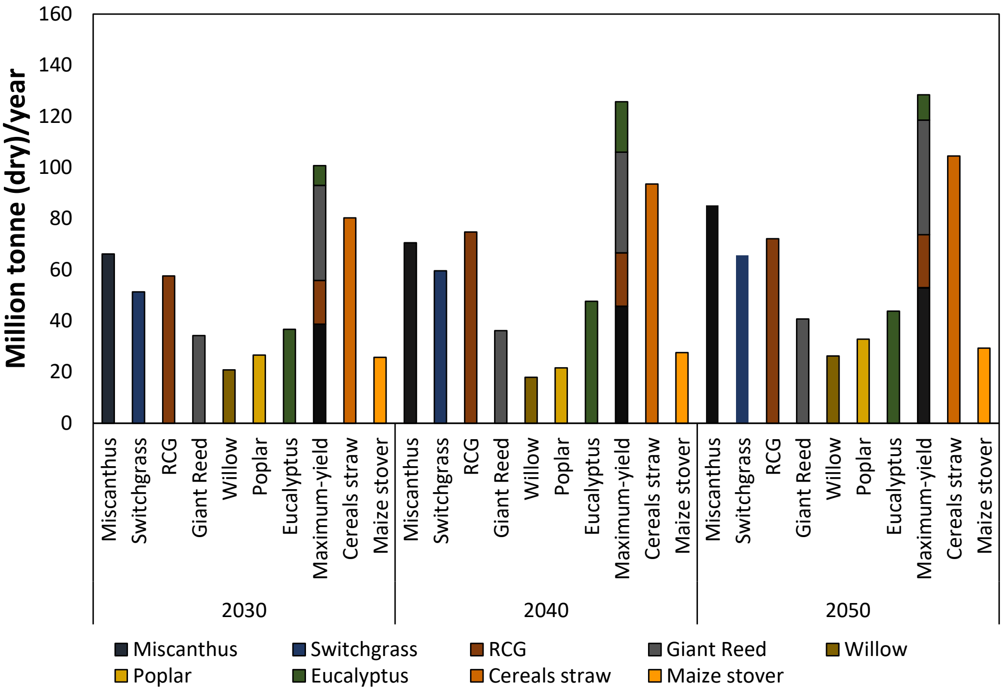
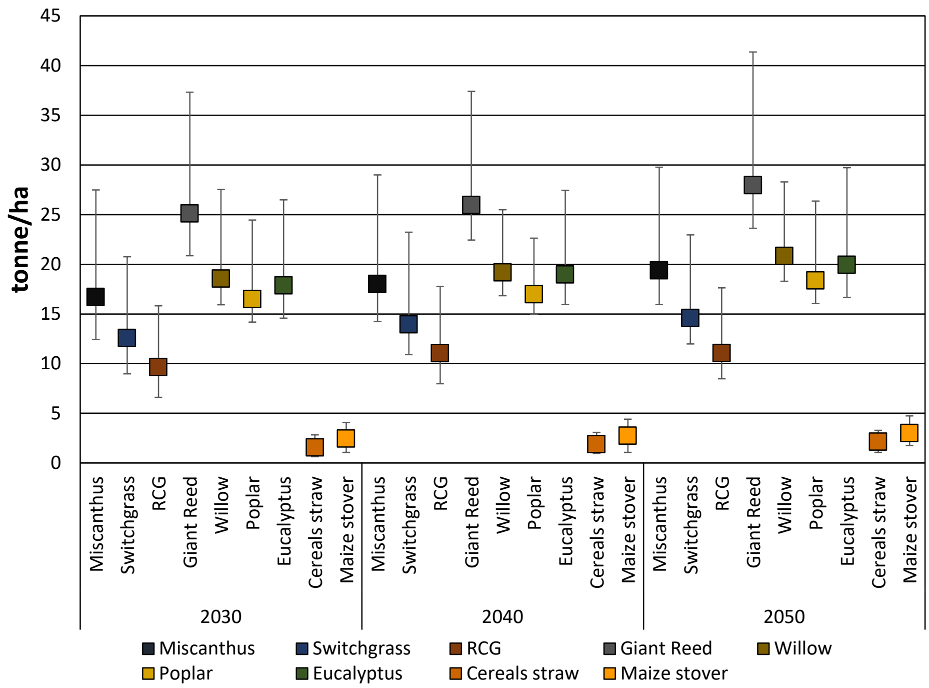


Table 13 Average yield for each crop in the low availability scenario while considering all the potential locations suitable for each crop type in EU-27 + UK.

Crop	2030 (t/ha)	2040 (t/ha)	2050 (t/ha)
Miscanthus	16.7	18.0	19.4
Switchgrass	12.6	13.9	14.6
RCG	9.7	11.0	11.1
Giant Reed	25.1	26.0	28.0
Willow	18.6	19.2	20.8
Poplar	16.5	17.0	18.4
Eucalyptus	17.9	19.0	19.9

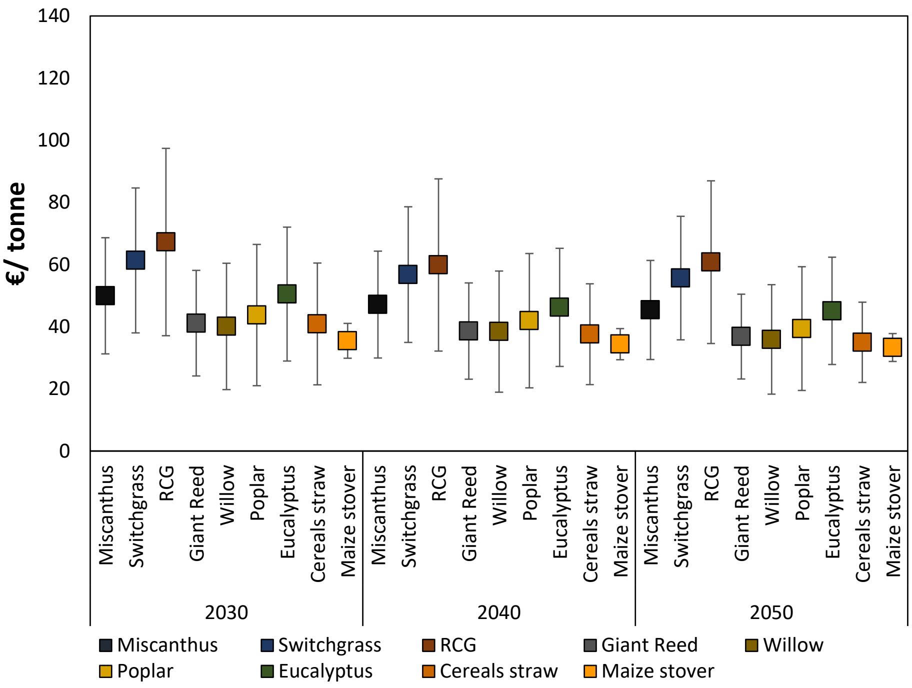
Figure 6 Biomass yield range of lignocellulosic energy crops, cereal straw and maize stover for the Medium scenario while considering all the potential locations suitable for each crop type in EU-27 + UK.



A.2.4: Agricultural biomass roadside costs

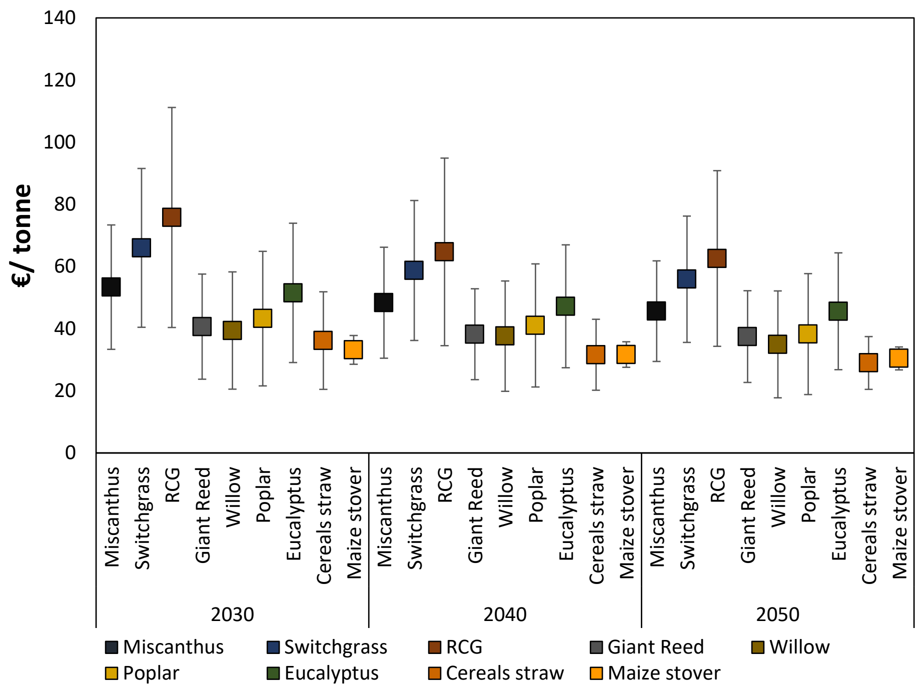
Low Scenario:

Figure 7 EU-27 + UK average costs of production and harvesting of lignocellulosic energy crops and collection of agricultural residues for the Low availability scenario (in €/t_{dry}). The ranges indicate the spatial variability of cost due to the heterogeneity of yields.



Medium Scenario:

Figure 8 EU-27 + UK average costs of production and harvesting of lignocellulosic energy crops and collection of agricultural residues for the Medium availability scenario (in €/t_{dry}). The ranges indicate the spatial variability of cost due to the heterogeneity of yields.



ANNEX B: BIOFUEL PLANT PRODUCTION COST

B.1: GENERAL COST ASSUMPTIONS

All costs and prices were adjusted to 2023 euros (€$_{2023}$). The Chemical Engineering Plant Cost Index (CEPCI) index was used to adjust equipment costs to 2023. CEPCI is a widely used index in the field of chemical engineering to adjust and estimate the capital costs of industrial processes and plants over time. Utilities and consumables were adjusted using harmonized indices of consumer prices (HICP) (Eurostat 2024). Key cost assumptions used as inputs for the economic calculations are provided in Table 14.

Table 14 Labour, material and utilities costs

Materials and utilities	Unit	Value
Labour cost (EU average)[1]	€/h	32.2
Electricity (EU average)[1]	€/kWh	0.13
Natural gas (EU average)[1]	€/m^3	0.53
	€/MWh	60
Steam[2]	€/MWh	67
Hydrogen 2030[3]	€/t	3500
Hydrogen 2050[4]	€/t	4500
Water[5]	€/m^3	0.50
Waste water discharge cost[5]	€/m^3	0.05
Ash disposal[6]	€/t	26.9

1) Average labour cost in industry and energy prices for non-household consumers (EUROSTAT 2024) - prices were adjusted at levels before the European energy crisis.
2) Calculated based on the natural gas price and a boiler efficiency of 90%.
3) Cost of hydrogen production from steam methane reforming of natural gas (SMR) in 2023, Source: Clean Hydrogen Partnership (2024).
4) All hydrogen used in 2050 is assumed to be green at 4500 €/t (S&P, 2025).
5) Source: CONCAWE (indicative values) - 2016 Survey of Effluent Quality and Water Use at European Refineries
6) Source: de Jong et al (2015), adjusted to €$_{2023}$

B.2: COSTING METHODOLOGY

The biofuel plant costs in this study were calculated using the factorial calculation tool SCENT (Standardized Cost Estimation for New Technology). SCENT was developed by Eerev and Patel (2012) based on the Lang factor, a ratio that relates the cost of major process plant equipment (Total purchased equipment cost, TPEC) to the total capital investment (TCI):

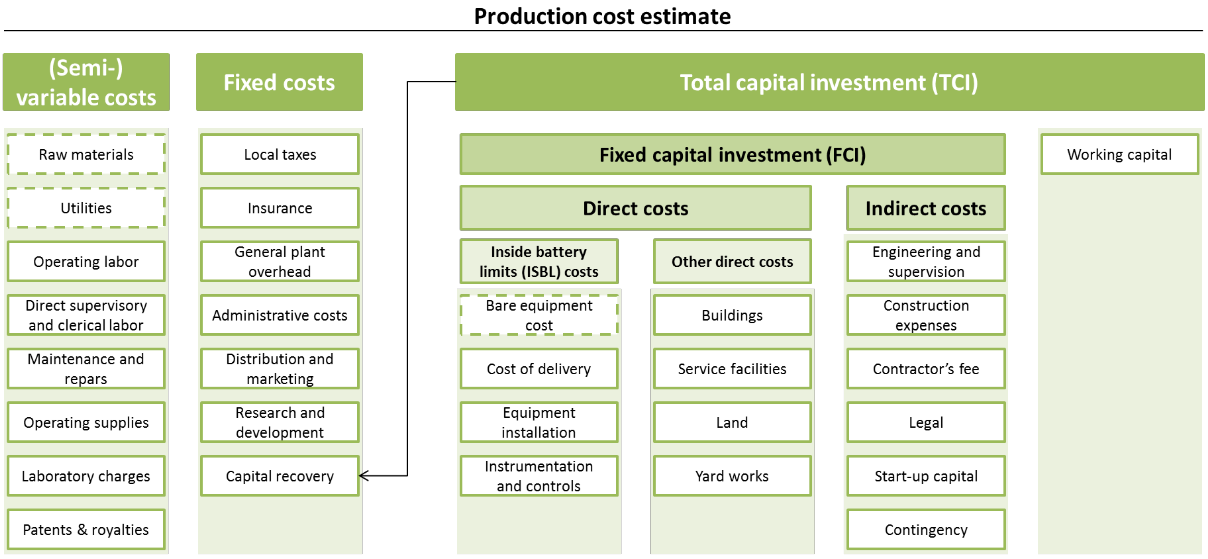
$$TCI = TPEC \cdot Lang\ factor$$

This method provides cost estimates with an accuracy range of ±30% for average conditions and does not reflect on location-specific factors (Eerev and Patel, 2012).

It is, however, useful for process industries to generate preliminary cost estimates for emerging technologies, such as advanced biofuel plants. The main benefits of this method are:

- It accounts for both (semi-)variable and fixed costs, encompassing multiple cost components, as illustrated in Figure 9.
- Cost estimates can be made on a limited amount of data for bare equipment costs, raw materials and utilities (dashed boxes in Figure 9).
- By adapting the factorial approach of the SCENT for outside battery limits (OSBL) costs, it can be used to estimate the benefits of integration strategies that apply to generalized locations, including co-location or retrofitting.

Figure 9 Approach to determine (semi-)variable and fixed production costs (de Jong et al 2015). Solid-lined boxes are based on a factorial approach, and dashed boxes are calculated based on input data.



De Jong et al. (2015) used the SCENT tool to quantify the general benefits of integration with existing industrial facilities in biofuel production, by adapting the factorial approach of the SCENT method for different cost components. Greenfield cost factors were based on the SCENT tool. For co-production strategies, direct cost factors were decreased to reflect synergies between the host and co-located facility. These include shared infrastructure such as buildings, service facilities, land, and yard works. As a result, the Lang factor, here defined as the ratio between total purchased equipment cost (TPEC) and Total Capital Investment (TCI), reduces from 5.39 for a greenfield location to 4.98 for co-location and 4.51 for retro-fitting (see Table 15).

Labour cost reductions were also considered and calculated assuming integrated production compared to two individual sites based on the assumption that the host site has twice the capacity of the co-located facility (de Jong et al 2015).

Table 15 Cost factors for greenfield, co-location, and retro-fitting facilities, based on de Jong et al. (2015).

Cost components	Unit	Green-field	Co-location	Retro-fitting	Re-purpose
Direct cost					
Bare equipment cost		100%			
Total purchased equipment cost (TPEC)		**100% (new equipment only)**			
Delivery	% of TPEC	10%			
Total delivered equipment cost (TDEC)	Relative to TPEC	**110%**			
Buildings[1]	% of TPEC	47%	29%	7%	0%
Service facilities[1]	% of TDEC	55%	42%	42%	0%
Land[2]	% of TDEC	6%	4%	0%	0%
Yard Works[1]	% of TDEC	12%	12%	0%	0%
Equipment installation[3]	% of TPEC	39%			
Instrumentation and controls	% of TDEC	26%			
Indirect cost					
Engineering and supervision	% of TDEC	32%			
Construction expenses	% of TDEC	34%			
Contractor's fee	% of TDEC	19%			
Legal	% of TDEC	4%			
Contingency	% of TDEC	37%			
Total direct and indirect cost (TDIC)	Relative to TPEC	**424%**	**392%**	**370%**	**316%**
Start-up capital[4]	% of TDIC	6%			
Depreciable Capital Investment (DCI)	Relative to TPEC	**449%**	**415%**	**392%**	**335%**
Fixed Capital Investment (FCI) (Lang factor)	Relative to TPEC	**469%**	**433%**	**392%**	**335%**
Working capital[5]	% of FCI	15%			
Total Capital Investment (TCI)	Relative to TPEC	**539%**	**498%**	**451%**	**385%**
OPEX reductions					
Operating labor[6]	% Reduction compared to greenfield	0%	41%	41%	41%

1) Cost factors for buildings, service facilities and yard work are decreased because they are shared with the host side.
2) A co-located facility is assumed to use two-thirds of the land of the incubator facility, and retrofitted equipment is assumed to be integrated into the incubator facility, eliminating the need for extra land.
3) Average EU, based on construction labour and a weighted average (based on equipment cost) of the material and labour installation factor as reported in SCENT (Eerev and Patel 2012).
4) Factors for estimating the start-up capital are based on the total fixed-capital investment: 6% for TPEC > 25 $M€_{2023}$.
5) Deviates from de Jong et al. (2015) but is in line with SCENT (15%) and petrochemical plants.
6) Approximate estimation: Labour cost reductions were calculated compared to two individual sites using Wessel's method based on the assumption that the host site is twice the size of the co-located facility (de Jong et al. 2015).

B.3: COST ESTIMATES AT REFERENCE SCALE

This section provides the detailed input techno-economic assumptions for the advanced biofuel production plant configurations and integration options at the reference scale for 2030 and 2050. These are used to calculate the cost of biofuel production at different scales using scaling factors (see Section 5.4 of the main report). Section B.4 shows the results for all systems used in the mixed-integer linear (MILP) model to calculate capital investment cost and scale-dependent OPEX.

- **Cost estimates at reference scale: Gasification and Fischer-Tropsch (GFT)**

Table 16 Detailed input data for Gasification and Fischer-Tropsch (GFT) at reference scale in 2030: 164 MW fuel output (5.2 PJ/y or 124 ktoe/y), 428 MW (13.5 PJ/y or 323 ktoe/y) feedstock input.

Cost item	Unit	Centralized: Gasification and Fischer-Tropsch		
Host site		Intermodal terminal	Pulp mill / existing biofuel plant	Oil refinery
Input		Biomass	Biomass	Biomass
Output		Biofuel	Biofuel	Biofuel
Production data				
Yield[1]	GJ_{output} / GJ_{input}	0.383	0.383	0.383
Electricity demand[2]	$GJ/GJ_{biofuel}$	0.10	0.10	0.10
Electricity generation[2]	$GJ/GJ_{biofuel}$	0.25	0.25	0.25
Net electricity demand (negative: export to grid)[2]	$GJ/GJ_{biofuel}$	-0.15	-0.15	-0.15
CAPEX[3]				
Air separation unit	M€	9.8	9.8	9.8
Feed prep and drying	M€	11.7	11.7	11.7
Gasification with tar reforming and heat recovery	M€	37.5	37.5	37.5
Syngas cleanup and steam reforming	M€	27.8	27.8	27.8
FT synthesis	M€	17.1	17.1	17.1
Hydrocracking and product separation	M€	20.5	20.5	20.5
Steam system and power generation	M€	10.3	10.3	10.3
Remainder OSBL	M€	0.0	0.0	0.0
Total purchased equipment cost (TPEC)	M€	**134.6**	**134.6**	**134.6**
Co-location strategy		Greenfield	Co-location	Retrofitting
Lang factor[4]		5.39	4.98	4.51
Total capital investment (TCI)	M€	726	670	606
Specific capital costs	$€/kW_{output}$	4425	4084	3697
Total annualized CAPEX[5]	$€/GJ_{biofuel}$	**16.5**	**15.2**	**13.8**
OPEX				
Catalyst and chemicals[6]	$€/GJ_{biofuel}$	0.06	0.06	0.06
Water[6]	$€/GJ_{biofuel}$	0.22	0.22	0.22
Waste water treatment[6]	$€/GJ_{biofuel}$	0.01	0.01	0.01
Wet ash disposal[6]	$€/GJ_{biofuel}$	0.29	0.29	0.29
Labor cost[7]	$€/GJ_{biofuel}$	0.95	0.55	0.55
CAPEX-dependent OPEX[8]	$€/GJ_{biofuel}$	14.31	13.21	11.96
Other[8]	$€/GJ_{biofuel}$	0.87	0.79	0.72
Credits (electricity sales)	$€/GJ_{biofuel}$	5.39	5.39	5.39
Total OPEX (incl. electricity sale credits[9])	$€/GJ_{biofuel}$	**11.32**	**9.75**	**8.43**
CAPEX + OPEX (excl. feedstock)	$€/GJ_{biofuel}$	**22.88**	**21.01**	**19.07**

1) Yield based on wood to liquid hydrocarbons in Edwards et al. (2017) used for default GHG emission calculations from biofuels in EU legislation. De Jong et al. (2015) and Zhu et al. (2011) consider the co-production of naphtha, which is not in the scope of the model. The overall energy efficiency (electricity plus fuels) of the plant is 44%.
2) Electricity consumption and co-generation are based on de Jong et al (2015), original source: Zhu et al. 2011. Surplus electricity is assumed to be exported to the grid.
3) Total purchased equipment costs were taken from de Jong et al (2015), original source: Zhu et al. (2011). Costs were adjusted from €2013 to €2023 using the CEPCI index (CE 2024).
4) The Lang factor reflects co-location/integration benefits (see also Annex B.2).
5) Discount rate: 10%, plant lifetime: 20 years,
annuity factor: 0.1175, load factor:90%.
6) Calculated based on quantities of materials and utilities from de Jong et al. (2015) and their prices (see Annex B1).
7) Labor requirement calculated according to Wessel's method (see de Jong et al. 2015) with an average EU labor cost (32.20 €/h). Reduced labor costs at locations with co-location benefits (see Annex B2).
8) Calculated similarly to de Jong et al (2015, 2017): CAPEX-dependent OPEX (maintenance and repairs, operating supplies, local taxes, and insurance) are calculated as a factor equal to 10.2% of TCI. Others (distribution, marketing, patents, royalty fees) are calculated as 5.5% of total OPEX.
9) Calculated based on electricity export (to grid) and electricity prices (Annex B1).

Table 17 Detailed input data for Gasification and Fischer-Tropsch (GFT) at reference scale in 2050: 164 MW fuel output (5.2 PJ/y or 124 ktoe/y), 428 MW (13.5 PJ/y or 323 ktoe/y) feedstock input.

Cost item	Unit	Centralized: Fischer-Tropsch			
Host site		**Intermodal terminal**	**Pulp mill / existing biofuel plant**	**Oil refinery**	**Oil refinery (repurpose)**
Input		Biomass	Biomass	Biomass	Biomass
Output		Biofuel	Biofuel	Biofuel	Biofuel
Production data					
Yield[1]	$GJ_{biofuel}/GJ_{biomass}$	0.450	0.450	0.450	0.450
Electricity demand[2]	$GJ/GJ_{biofuel}$	0.09	0.09	0.09	0.09
Electricity generation[2]	$GJ_{biofuel}/GJ_{biomass}$	0.21	0.21	0.21	0.21
Net electricity demand (negative: export to grid)[2]	$GJ/GJ_{biofuel}$	-0.13	-0.13	-0.13	-0.13
CAPEX[3]					
Air separation unit	M€	6.6	6.6	6.6	6.6
Feed prep and drying	M€	7.8	7.8	7.8	7.8
Gasification with tar reforming and heat recovery	M€	25.2	25.2	25.2	25.2
Syngas cleanup and steam reforming	M€	18.7	18.7	18.7	18.7
FT synthesis	M€	11.5	11.5	11.5	11.5
Hydrocracking and product separation	M€	13.8	13.8	13.8	6.9
Steam system and power generation	M€	6.9	6.9	6.9	6.9
Remainder OSBL	M€	0.0	0.0	0.0	0.0
Total purchased equipment cost (TPEC)	M€	**90.4**	**90.4**	**90.4**	**83.5**
Co-location strategy		Greenfield	Co-location	Retro-fitting	Re-purpose
Lang factor[4]		5.39	4.98	4.51	3.85
Total capital investment (TCI)	M€	488	450	407	322
Specific capital costs	$€/kW_{output}$	2973	2744	2484	1963
Total annualised CAPEX	**$€/GJ_{biofuel}$**	**11.1**	**10.2**	**9.3**	**7.3**

OPEX[4]					
Catalyst and chemicals	€/GJ$_{biofuel}$	0.06	0.06	0.06	0.06
Water	€/GJ$_{biofuel}$	0.19	0.19	0.19	0.19
Waste water treatment	€/GJ$_{biofuel}$	0.01	0.01	0.01	0.01
Wet ash disposal	€/GJ$_{biofuel}$	0.25	0.25	0.25	0.25
Labor cost	€/GJ$_{biofuel}$	0.95	0.55	0.55	0.55
CAPEX-dependent OPEX	€/GJ$_{biofuel}$	9.62	8.87	8.03	6.35
Other	€/GJ$_{biofuel}$	0.61	0.55	0.50	0.41
Credits (electricity sales)	€/GJ$_{biofuel}$	4.59	4.59	4.59	4.59
Total OPEX (incl. electricity sale credits)	€/GJ$_{biofuel}$	**7.09**	**5.90**	**5.01**	**3.23**
CAPEX + OPEX (excl. feedstock)	**€/GJ$_{biofuel}$**	**16.33**	**14.94**	**13.57**	**10.83**

1) Today's overall energy efficiency for biomass conversion to FT products ranges from 40% to 55% (Brown et al. 2020) but could increase to over 60% in the future due to catalyst improvement, process optimization, and heat and energy recovery. A fuel yield of 45% and overall conversion efficiency of 51% (fuel plus electricity) is therefore considered achievable.
2) Net electricity demand is assumed the same as for 2030.
3) Based on a capital cost reduction of 32.8% compared to 2030 (see section 5.4.4 of the main report).
4) CAPEX-dependent OPEX is reduced with CAPEX. Other OPEX components are assumed the same as for 2030.

- ### Cost estimates at reference scale: HTL centralised

Table 18 Detailed input data for centralized HTL and upgrading at reference scale in 2030: 73 MW fuel output (2.3 PJ/y or 53 ktoe/y), 156 MW feedstock input (4.92 PJ/y or 117 ktoe/y).

Cost item	Unit	Centralized: HTL conversion plus upgrading		
Host site		**Intermodal terminal**	**Pulp mill / existing biofuel plant**	**Oil refinery**
Input		Biomass	Biomass	Biomass
Output		Biofuel	Biofuel	Biofuel
Production data				
Yield[1]	GJ$_{fuel}$/GJ$_{biomass}$	0.47	0.47	0.47
Electricity demand[2]	GJ/GJ$_{biofuel}$	0.083	0.083	0.083
Electricity generation[2]	GJ/GJ$_{biofuel}$	0.034	0.034	0.061
Net electricity demand[2]	GJ/GJ$_{biofuel}$	0.049	0.049	0.022
Natural gas demand[3]	GJ/GJ$_{biofuel}$	0.06	0.06	
Hydrogen demand[3]	GJ/GJ$_{biofuel}$			0.15
Steam production[3]	GJ/GJ$_{biofuel}$			0.09
CAPEX[4]				
Feedstock handling	M€	0.85	0.42	0.42
Biomass conditioning	M€	5.14	5.14	5.14
HTL reactor	M€	9.77	9.77	9.77
Hydrotreater	M€	12.70	12.70	12.70
Hydrocracker	M€	4.70	4.70	4.70
Hydrogen plant	M€	5.09	5.09	
Utilities	M€	4.13	4.13	4.13
Missing equipment (10%)	M€	4.24	4.19	3.69
Total purchased equipment cost (TPEC)	M€	**46.61**	**46.14**	**40.54**

Co-location strategy		Greenfield	Co-location	Retrofitting
Lang factor[5]		5.39	4.98	4.51
Total capital investment (TCI)	M€	251	230	183
Specific capital costs	€/kW_{output}	3441	3144	2501
Total annualised CAPEX[6]	**€/$GJ_{biofuel}$**	**12.8**	**11.7**	**9.3**
OPEX				
Electricity[7]	€/$GJ_{biofuel}$	1.77	1.77	0.79
Catalyst and chemicals[8]	€/$GJ_{biofuel}$	0.63	0.63	0.63
Waste disposal[8]	€/$GJ_{biofuel}$	1.55	1.55	1.55
Hydrogen[7]	€/$GJ_{biofuel}$			4.37
Natural gas[7]	€/$GJ_{biofuel}$	1.00	1.00	
Labor cost[9]	€/$GJ_{biofuel}$	1.58	0.93	0.93
CAPEX-dependent OPEX[10]	€/$GJ_{biofuel}$	11.13	10.17	8.09
Other[10]	€/$GJ_{biofuel}$	0.97	0.88	0.90
Steam sales (credit)[7]	€/$GJ_{biofuel}$			-1.67
Total OPEX	€/$GJ_{biofuel}$	**18.63**	**16.92**	**15.60**
CAPEX + OPEX (excl. feedstock)	**€/$GJ_{biofuel}$**	**31.45**	**28.63**	**24.92**

1) Based on a biomass to biocrude yield of 0.247 kg/kg dry wood for a water catalyst at 300 ºC system (Tzanetis et al. 2017) and a biocrude to biofuel yield of 1.06 GJ/GJ (de Jong et al. 2017). The biocrude yield assumed in de Jong et al. (2017) was considered too optimistic, therefore, not considered in this study.
2) Electricity consumption and generation are taken from de Jong et al. (2017). Steam and electricity are produced from anaerobic digestion gas and off-gases from the HTL reactor. For the centralized system at a refinery location with hydrogen supply and decentralized HTL conversion, off-gases are not used for hydrogen production, but are used to generate more electricity.
3) Based on de Jong et al (2017): hydrogen required from refinery sites for biocrude upgrading: 1.35 kg/GJ biocrude. Natural gas required for hydrogen production in distributed supply chains: 0.1649 GJ/kg hydrogen. In centralized supply chains (apart from refinery locations), hydrogen is produced from off-gases from the HTL conversion process.
4) Total purchased equipment costs were taken from de Jong et al. (2017) and adjusted from $€_{2015}$ to $€_{2023}$ using the CEPCI index (CE 2024).
5 The Lang factor reflects co-location/integration benefits (see also Annex B.2).
6) Discount rate: 10%, plant lifetime: 20 years, annuity factor: 0.1175, load factor: 90%.
7) Calculated based on utility prices (Annex B.1).
8) Taken from de Jong et al. (2017), and adjusted from $€_{2015}$ to $€_{2023}$ using the Harmonised Index of Consumer Prices (HICP) (EUROSTAT 2024).
9) Labor requirement calculated according to Wessel's method (see de Jong et al. 2015) and average EU labor cost (32.50 €/h). Reduced labor costs at locations with co-location benefits (see Annex B.2).
10) Calculated similar to de Jong et al (2017): CAPEX-dependent OPEX (maintenance and repairs, operating supplies, local taxes, and insurance) are calculated as a factor equal to 10.2% of TCI. Others (distribution, marketing, patents, royalty fees) are calculated as 5.5% of total OPEX.

Table 19 Detailed input data for centralized HTL and upgrading at reference scale in 2050: 73 MW fuel output (2.3 PJ/y or 53 ktoe/y), 112 MW feedstock input (3.5 PJ/y or 84 ktoe/y). The SMR unit is replaced with ex-situ green hydrogen supply.

Cost item	**Unit**	**Centralized: HTL conversion plus upgrading**			
Host side		**Intermodal terminal**	**Pulp mill / existing biofuel plant**	**Oil refinery**	**Oil refinery (repurpose)**
Input		Biomass	Biomass	Biomass	Biomass
Output		Biofuel	Biofuel	Biofuel	Biofuel
Production data					
Yield[1]	$GJ_{fuel}/GJ_{biomass}$	0.66	0.66	0.66	0.66
Electricity demand	$GJ/GJ_{biofuel}$	0.083	0.083	0.083	0.083
Electricity generation	$GJ/GJ_{biofuel}$	0.034	0.034	0.061	0.061
Net electricity demand	$GJ/GJ_{biofuel}$	0.049	0.049	0.022	0.022
Natural gas demand	$GJ/GJ_{biofuel}$				
Hydrogen demand	$GJ/GJ_{biofuel}$	0.15	0.15	0.15	0.15
Steam production	$GJ/GJ_{biofuel}$		0.09	0.09	0.09
CAPEX[2]					
Feedstock handling	M€	0.57	0.28	0.28	0.28
Biomass conditioning	M€	3.49	3.49	3.49	3.49
HTL reactor	M€	6.63	6.63	6.63	6.63
Hydrotreater	M€	8.62	8.62	8.62	4.31
Hydrocracker	M€	3.19	3.19	3.19	1.59
Hydrogen plant	M€	0.00	0.00		
Utilities	M€	2.80	2.80	2.80	2.80
Missing equipment (10%)	M€	2.53	2.50	2.50	1.91
Total purchased equipment cost (TPEC)	M€	**27.83**	**27.51**	**27.51**	**21.02**
Co-location strategy		Greenfield	Co-location	Retro-fitting	Re-purpose
Lang factor		5.39	4.98	4.51	3.85
Total capital investment (TCI)	M€	150	137	124	81
Specific capital costs	$€/kW_{output}$	2055	1875	1698	1109
Total annualised CAPEX	$€/GJ_{biofuel}$	**7.7**	**7.0**	**6.3**	**4.1**
OPEX					
Electricity	$€/GJ_{biofuel}$	1.77	1.77	0.79	0.79
Catalyst and chemicals	$€/GJ_{biofuel}$	0.63	0.63	0.63	0.63
Waste disposal	$€/GJ_{biofuel}$	1.55	1.55	1.55	1.55
Hydrogen	$€/GJ_{biofuel}$	5.62	5.62	5.62	5.62
Natural gas	$€/GJ_{biofuel}$				
Labor cost	$€/GJ_{biofuel}$	1.58	0.93	0.93	0.93
CAPEX-dependent OPEX	$€/GJ_{biofuel}$	6.65	6.06	5.49	3.59
Other	$€/GJ_{biofuel}$	0.98	0.91	0.83	0.72
Steam sales (credit)	$€/GJ_{biofuel}$		-1.67	-1.67	-1.67
Total OPEX	$€/GJ_{biofuel}$	**18.78**	**15.81**	**14.17**	**12.17**
CAPEX + OPEX (excl. feedstock)	$€/GJ_{biofuel}$	**26.43**	**22.79**	**20.50**	**16.30**

1) Based on a biomass-to-biocrude yield of 0.345 kg/kg dry wood for a Na_2CO_3(aq.) catalyst at 300 °C system (Tzanetis et al. 2017) and a biocrude-to biofuel yield of 1.06 GJ/GJ (de Jong et al. 2017).
2) Based on a capital cost reduction of 32% from short- and long-term cost reductions (see section 5.4.4 of the main report).

- **Plant Cost estimates at base scale: HTL decentralised**

Table 20 Detailed input data for decentralized HTL and upgrading at reference scale in 2030: 73 MW fuel output (2.3 PJ/y or 53 ktoe/y), 112 MW feedstock input (3.5 PJ/y or 84 ktoe/y).

Cost item	**Unit**	**Decentralized: HTL biocrude production**		**Decentralized: HTL oil upgrading**	
Host site		**NUTS-3**	**Pulp mill / biofuel plant**	**Oil refinery**	**Existing biofuel plant**
Input		Biomass	Biomass	Biocrude	Biocrude
Output		Biocrude	Biocrude	Biofuel	Biofuel
Production data					
Yield[1]	GJ_{output} / GJ_{input}	0.44	0.44	1.06	1.06
Electricity demand[2]	$GJ/GJ_{biocrude/biofuel}$	0.072	0.072	0.007	0.014
Electricity generation[2]	$GJ/GJ_{biocrude/biofuel}$	0.065	0.065	0	0
Net electricity demand[2]	$GJ/GJ_{biocrude/biofuel}$	0.007	0.007	0.007	0.014
Natural gas demand[3]	$GJ/GJ_{biocrude/biofuel}$	0	0	0	0.16
Hydrogen demand[3]	$GJ/GJ_{biocrude/biofuel}$			0.15	
Steam production[3]	$GJ/GJ_{biocrude/biofuel}$		0.10		
CAPEX[4]					
Feedstock handling	M€	0.85	0.42	0.00	0.00
Biomass conditioning	M€	5.14	5.14	0.00	0.00
HTL reactor	M€	9.77	9.77	0.00	0.00
Hydrotreater	M€	0.00	0.00	12.70	12.70
Hydrocracker	M€	0.00	0.00	4.70	4.70
Hydrogen plant	M€	0.00	0.00	0.00	5.09
Utilities	M€	6.19	6.19	0.00	1.03
Missing equipment (10%)	M€	2.20	2.15	1.74	2.35
Total purchased equipment cost (TPEC)	M€	**24.15**	**23.68**	**19.14**	**25.87**
Co-location strategy		Greenfield	Co-location	Retrofitting	Co-location
Lang factor[5]		5.39	4.98	4.51	4.98
Total capital investment (TCI)	M€	130	118	86	129
Specific capital costs	$€/kW_{biocrude/biofuel}$	1890	1710	1181	1763
Total annualised CAPEX[6]	$€/GJ_{biocrude/biofuel}$	**7.0**	**6.4**	**4.4**	**6.6**
OPEX					
Electricity[7]	$€/GJ_{biocrude/biofuel}$	0.25	0.25	0.25	0.51
Catalyst and chemicals[8]	$€/GJ_{biocrude/biofuel}$	0.31	0.31	0.34	0.34
Waste disposal[8]	$€/GJ_{biocrude/biofuel}$	1.65	1.65	0.00	0.00
Hydrogen[7]	$€/GJ_{biocrude/biofuel}$			4.37	
Natural gas[7]	$€/GJ_{biocrude/biofuel}$				2.65
Labor cost[9]	$€/GJ_{biocrude/biofuel}$	0.66	0.39	0.23	0.23
CAPEX-dependent OPEX[10]	$€/GJ_{biocrude/biofuel}$	6.11	5.53	3.82	5.70
Other[10]	$€/GJ_{biocrude/biofuel}$	0.49	0.45	0.50	0.52
Steam sales (credit)[7]	$€/GJ_{biocrude/biofuel}$		-1.85		
Total OPEX	$€/GJ_{biocrude/biofuel}$	**9.48**	**6.72**	**9.52**	**9.96**
CAPEX + OPEX (excl. feedstock)	$€/GJ_{biocrude/biofuel}$	**16.52**	**13.09**	**13.91**	**16.52**

1) Based on a biomass to biocrude yield of 0.247 kg/kg dry wood for a water catalyst at 300 ºC system (Tzanetis et al. 2017) and a biocrude to biofuel yield of 1.06 GJ/GJ (de Jong et al. 2017). The biocrude yield assumed in de Jong et al. (2017) was considered too optimistic (based on Goal case in Zhu et al (2014): 0.40 kg/kg dry wood).

2) Electricity consumption and generation are taken from de Jong et al. (2017). Steam and electricity are produced from anaerobic digestion gas and off-gases from the HTL reactor. For the centralized system at a refinery location with hydrogen supply and decentralized HTL conversion, off-gases are not used for hydrogen production, but are used to generate more electricity.
3) Based on de Jong et al (2017): hydrogen required from refinery sites for biocrude upgrading: 1.35 kg/GJ biocrude. Natural gas required for hydrogen production in distributed supply chains: 0.1649 GJ/kg hydrogen. In centralized supply chains (apart from refinery locations), hydrogen is produced from off-gases from the HTL conversion process.
4) Total purchased equipment costs were taken from de Jong et al. (2017) and adjusted from €$_{2015}$ to €$_{2023}$ using the CEPCI index (CE 2024).
5 The Lang factor reflects co-location/integration benefits (see Annex B.2).
6) Discount rate: 10%, plant lifetime: 20 years, annuity factor: 0.1175, load factor: 90%.
7) Calculated based on utility prices (Annex B.1).
8) Taken from de Jong et al. (2017), and adjusted from €$_{2015}$ to €$_{2023}$ using the Harmonised Index of Consumer Prices (HICP) (EUROSTAT 2024).
9) Labor requirement calculated according to Wessel's method (see de Jong et al. 2015) and average EU labor cost (32.50 €/h). Reduced labor costs at locations with co-location benefits (Annex B2).
10) Calculated similar to de Jong et al (2017): CAPEX-dependent OPEX (maintenance and repairs, operating supplies, local taxes, and insurance) are calculated as a factor equal to 10.2% of TCI. Others (distribution, marketing, patents, royalty fees) are calculated as 5.5% of total OPEX.

Table 21 Detailed input data for decentralized HTL and upgrading at reference scale in 2050: 73 MW fuel output (2.3 PJ/y or 53 ktoe/y), 112 MW feedstock input (3.5 PJ/y or 84 ktoe/y). The SMR unit is replaced with ex-situ green hydrogen supply.

Cost item	**Unit**	**Decentralized: HTL biocrude production**		**Decentralized: HTL oil upgrading**		
Host side		**NUTS-3**	**Pulp mill / biofuel plant**	**Existing biofuel plant**	**Oil refinery**	**Oil refinery (repurpose)**
Input		Biomass	Biomass	Biocrude	Biocrude	Biocrude
Output		Biocrude	Biocrude	Biofuel	Biofuel	Biofuel
Production data						
Yield[1]	$GJ_{biocrude/biofuel}/GJ_{biomass}$	0.60	0.60	1.10	1.10	1.10
Electricity demand	$GJ/GJ_{biocrude/biofuel}$	0.072	0.072	0.014	0.007	0.007
Electricity generation	$GJ/GJ_{biocrude/biofuel}$	0.065	0.065	0	0	0
Net electricity demand	$GJ/GJ_{biocrude/biofuel}$	0.007	0.007	0.014	0.007	0.007
Natural gas demand	$GJ/GJ_{biocrude/biofuel}$					
Hydrogen demand	$GJ/GJ_{biocrude/biofuel}$			0.15	0.15	0.15
Steam production	$GJ/GJ_{biocrude/biofuel}$		0.10			
CAPEX[2]						
Feedstock handling	M€	0.57	0.28	0.00	0.00	0.00
Biomass conditioning	M€	3.49	3.49	0.00	0.00	0.00
HTL reactor	M€	6.63	6.63	0.00	0.00	0.00
Hydrotreater	M€	0.00	0.00	8.62	8.62	4.31
Hydrocracker	M€	0.00	0.00	3.19	3.19	1.59
Hydrogen plant	M€	0.00	0.00	0.00	0.00	0.00
Utilities	M€	4.20	4.20	0.70	0.00	0.00
Missing equipment (10%)	M€	1.49	1.46	1.25	1.18	0.59
Total purchased equipment cost (TPEC)	M€	**16.39**	**16.07**	**13.76**	**12.99**	**6.49**
Co-location strategy		Greenfield	Co-location	Co-location	Retro-fitting	Re-purpose
Lang factor		5.39	4.98	4.98	4.51	3.85
Total capital investment (TCI)	M€	88	80	68	59	25
Specific capital costs	$€/kW_{biocrude/biofuel}$	1283	1161	937	801	343
Total annualised CAPEX	**$€/GJ_{biocrude/biofuel}$**	**4.8**	**4.3**	**3.5**	**3.0**	**1.3**

OPEX						
Electricity	€/GJ$_{biocrude/biofuel}$	0.25	0.25	0.51	0.25	0.25
Catalyst and chemicals	€/GJ$_{biocrude/biofuel}$	0.31	0.31	0.34	0.34	0.34
Waste disposal	€/GJ$_{biocrude/biofuel}$	1.65	1.65	0.00	0.00	0.00
Hydrogen	€/GJ$_{biocrude/biofuel}$			5.62	5.62	5.62
Natural gas	€/GJ$_{biocrude/biofuel}$					
Labor cost	€/GJ$_{biocrude/biofuel}$	0.66	0.39	0.23	0.23	0.23
CAPEX-dependent OPEX[2]	€/GJ$_{biocrude/biofuel}$	4.15	3.75	3.03	2.59	1.11
Other	€/GJ$_{biocrude/biofuel}$	0.39	0.35	0.54	0.50	0.42
Steam sales (credit)	€/GJ$_{biocrude/biofuel}$		-1.85			
Total OPEX	€/GJ$_{biocrude/biofuel}$	**7.40**	**4.85**	**10.27**	**9.54**	**7.97**
CAPEX + OPEX (excl. feedstock)	**€/GJ$_{biocrude/biofuel}$**	**12.18**	**9.17**	**13.76**	**12.52**	**9.25**

1) Based on a biomass-to-biocrude yield of 0.34.5 kg/kg dry wood for a Na_2CO_3(aq.) catalyst at 300 C system (Tzanetis et al. 2017) and a biocrude-to biofuel yield of 1.06 GJ/GJ (de Jong et al. 2017).
2) Based on a capital cost reduction of 32% from short- and long-term cost reductions (see section 5.4.4 of the main report).

B.4: CAPITAL COST ESTIMATES AT DIFFERENT SCALES

- **Gasification and Fischer-Tropsch (GFT)**

Figure 10 Gasification and Fischer-Tropsch (GFT) capital cost estimates at three different capacity levels for different host locations/integration levels, 2030.

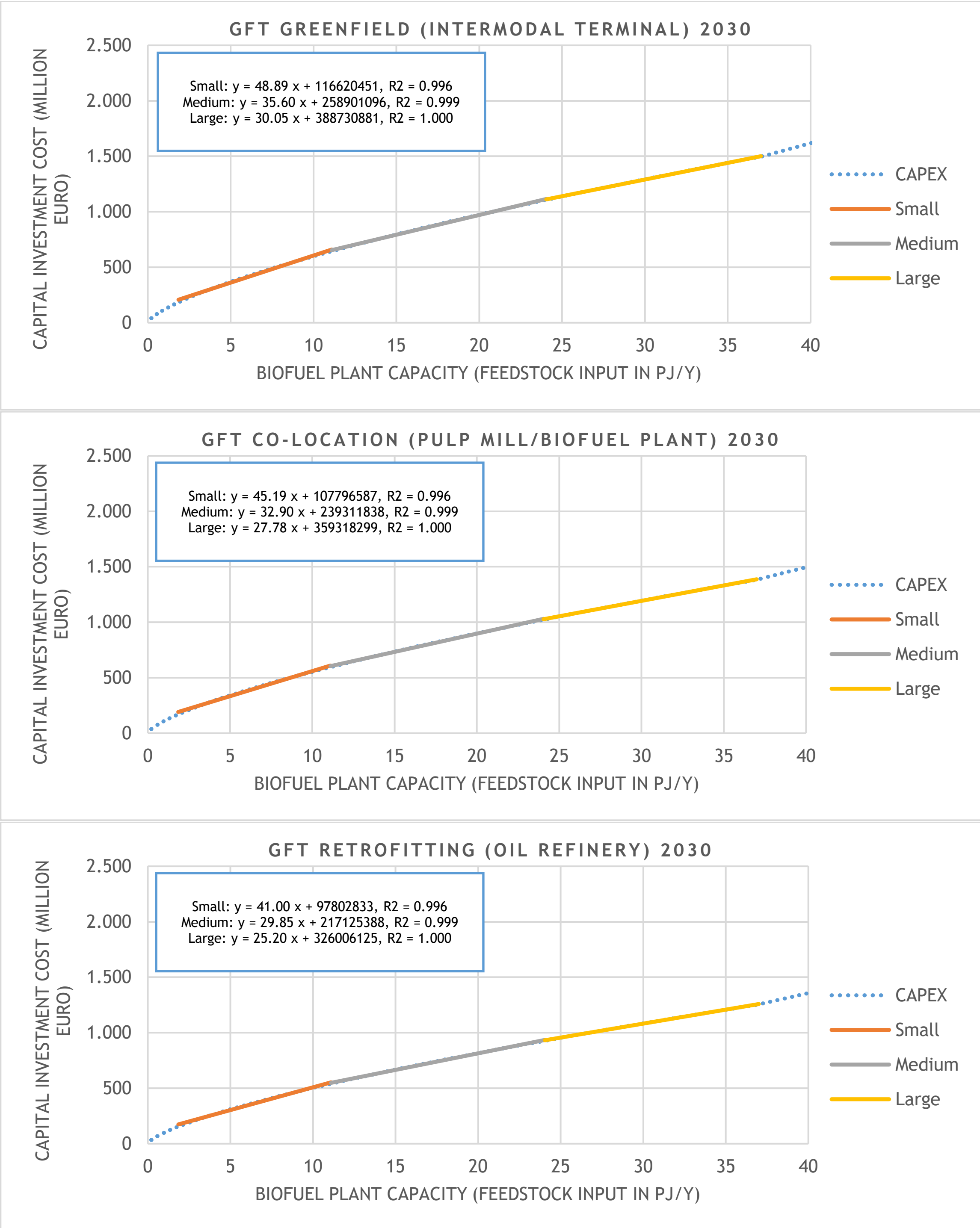
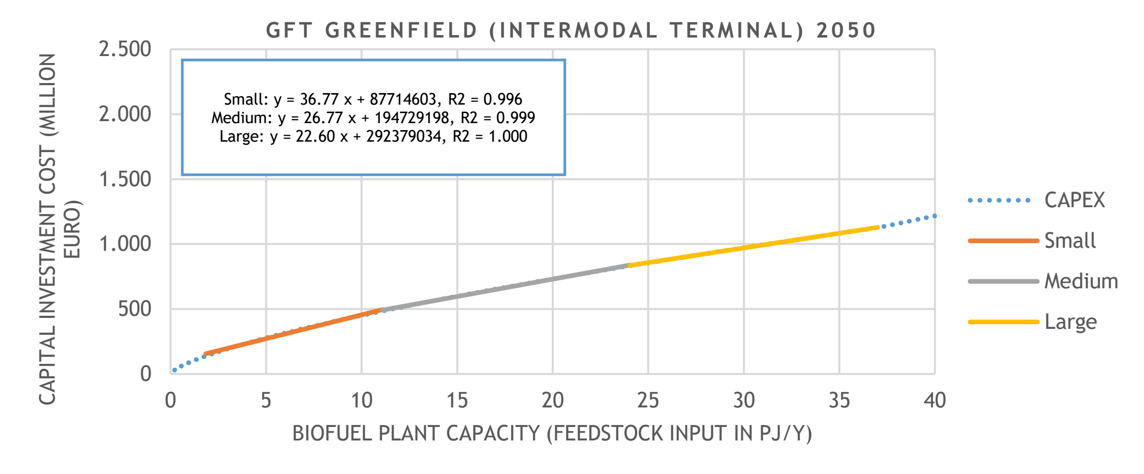
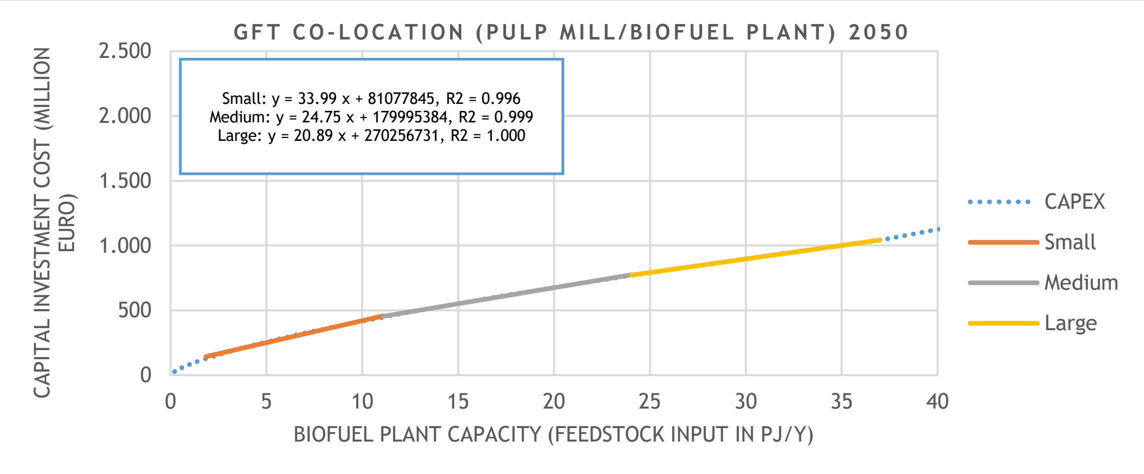
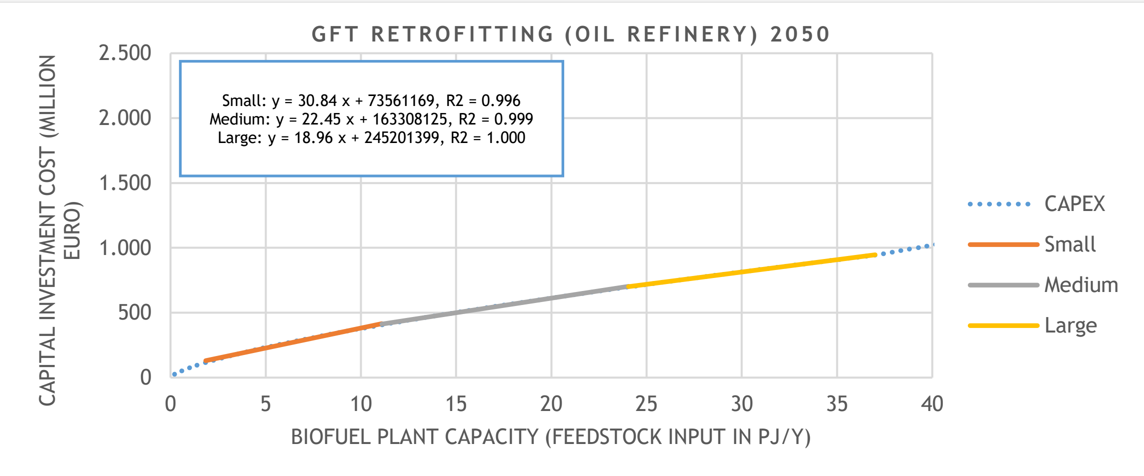


Figure 11 Gasification and Fischer-Tropsch (GFT) capital cost estimates at three different capacity levels for different host locations/integration levels, 2050.







- **HTL plus upgrading centralised (cs)**

Figure 12 HTL centralised (cs) capital cost estimates at three different capacity levels for different host locations/integration levels, 2030.

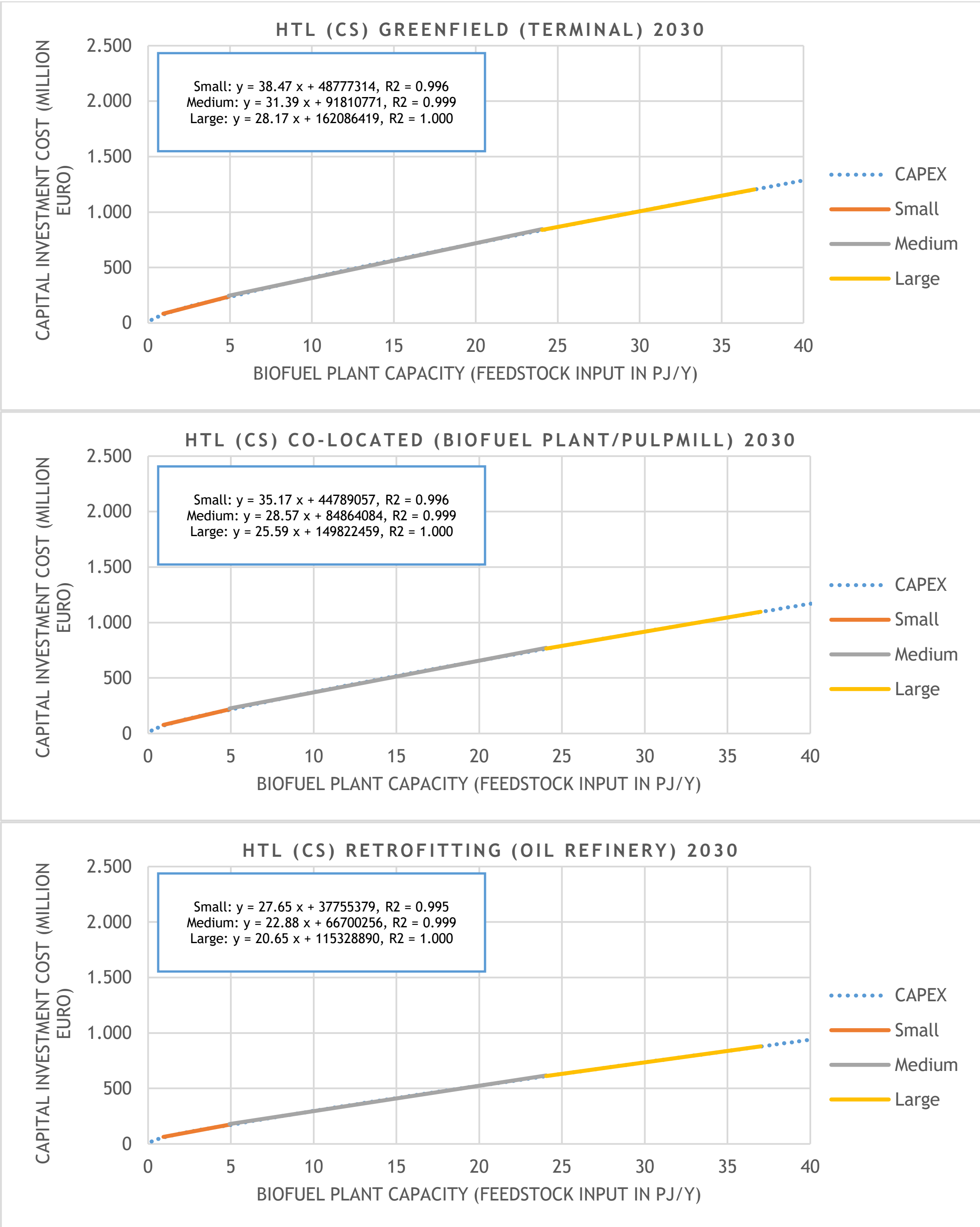
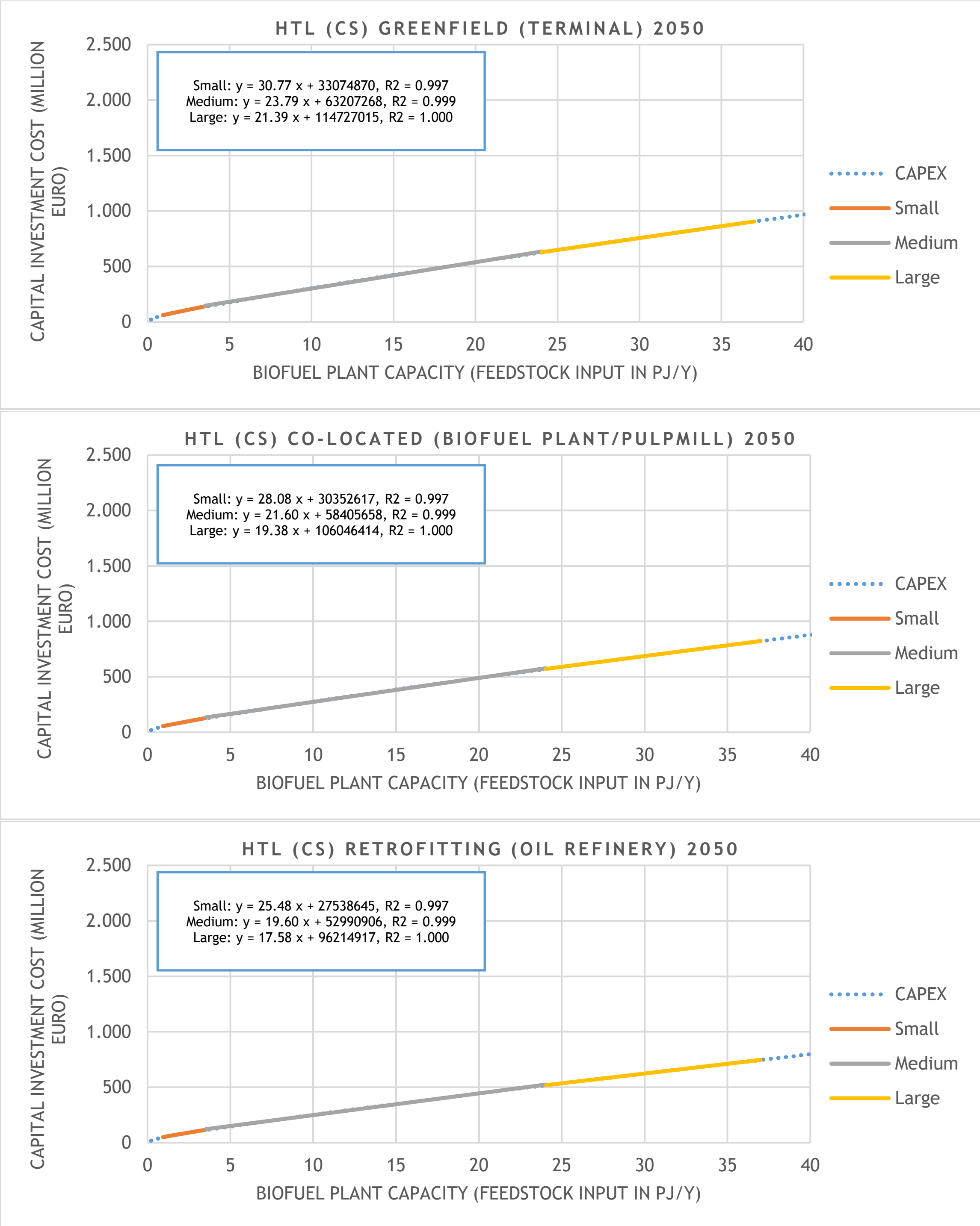
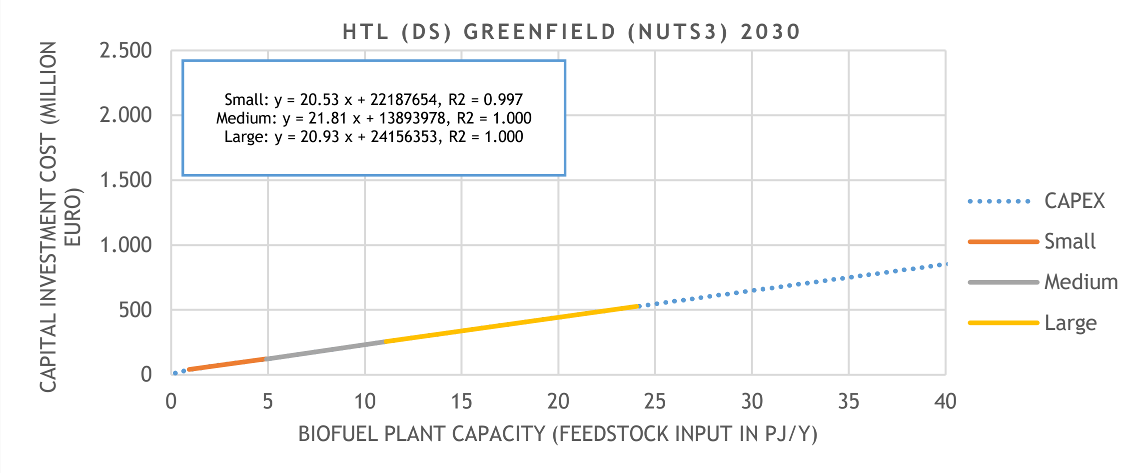


Figure 13 HTL centralised (cs) capital cost estimates at three different capacity levels for different host locations/integration levels, 2050.



- **HTL plus upgrading distributed (ds)**

Figure 14 HTL decentralised (ds) capital cost estimates at three different capacity levels for different host locations/integration levels, 2030.



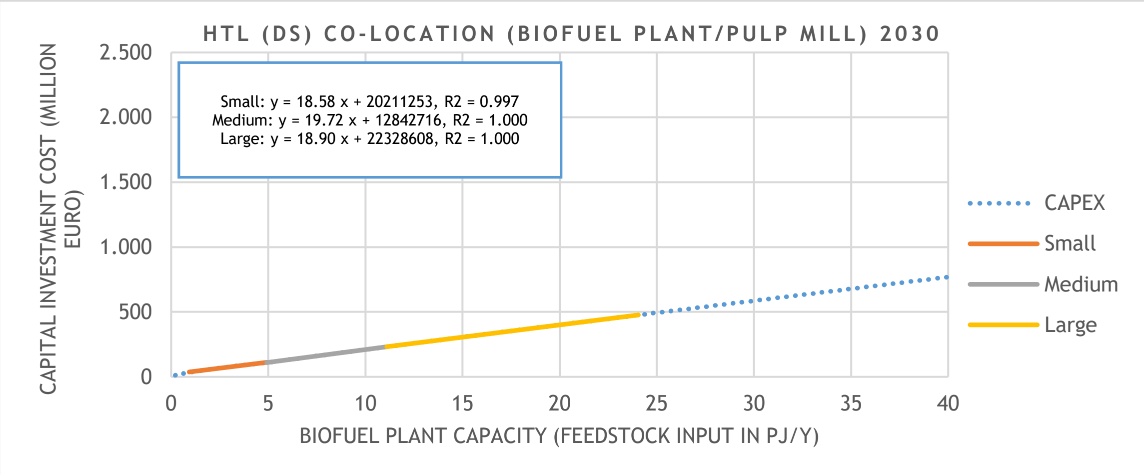
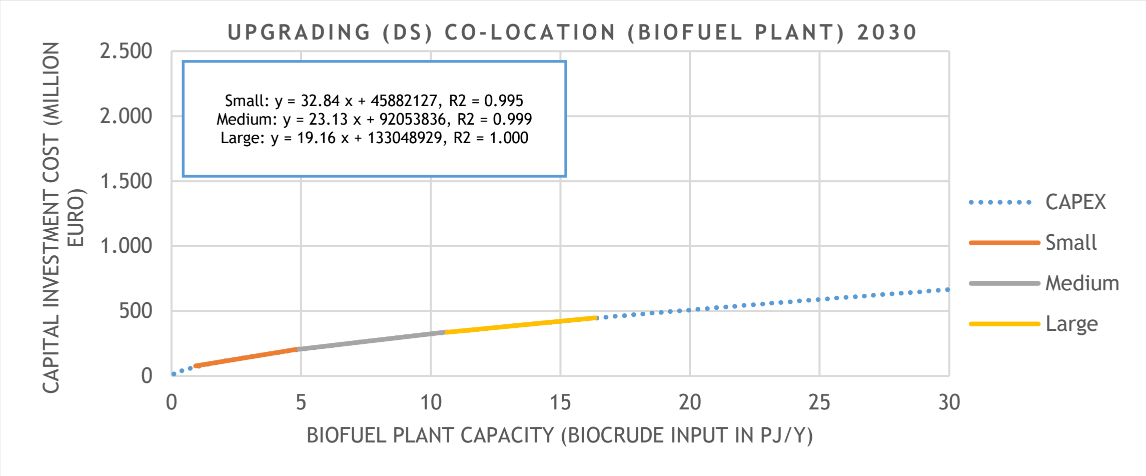


Figure 15 HTL upgrading decentralised (ds) capital cost estimates at three different capacity levels for different host locations/integration levels, 2030.



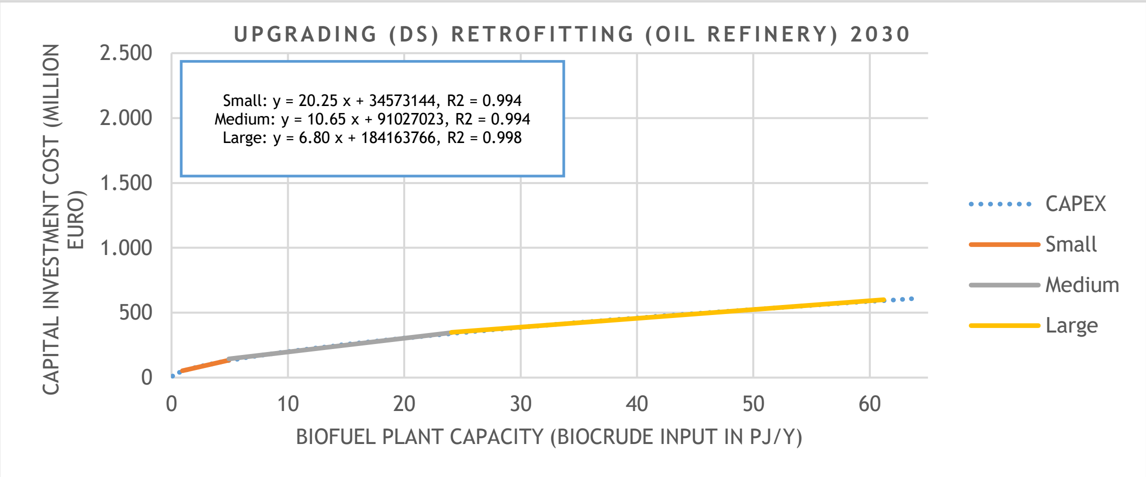
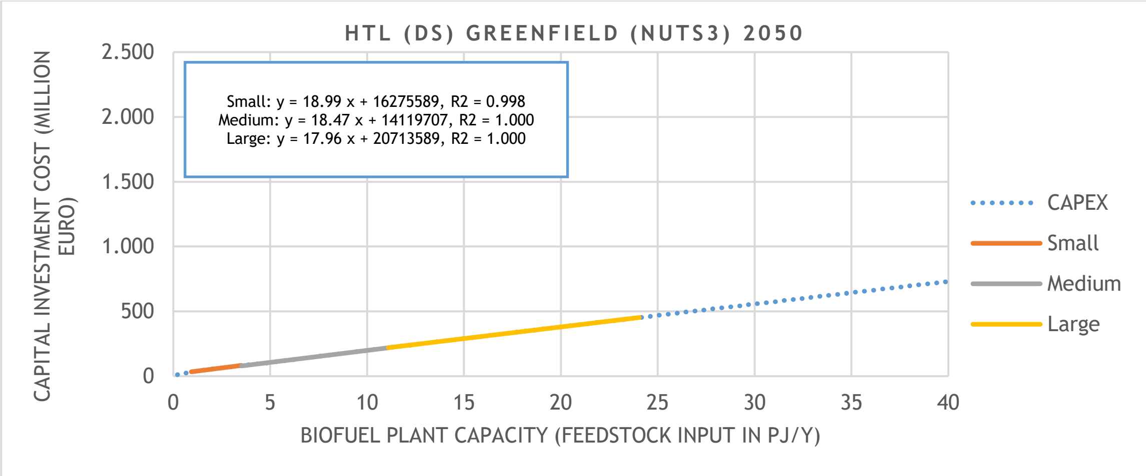


Figure 16 HTL decentralised (ds) capital cost estimates at three different capacity levels for different host locations/integration levels, 2050.



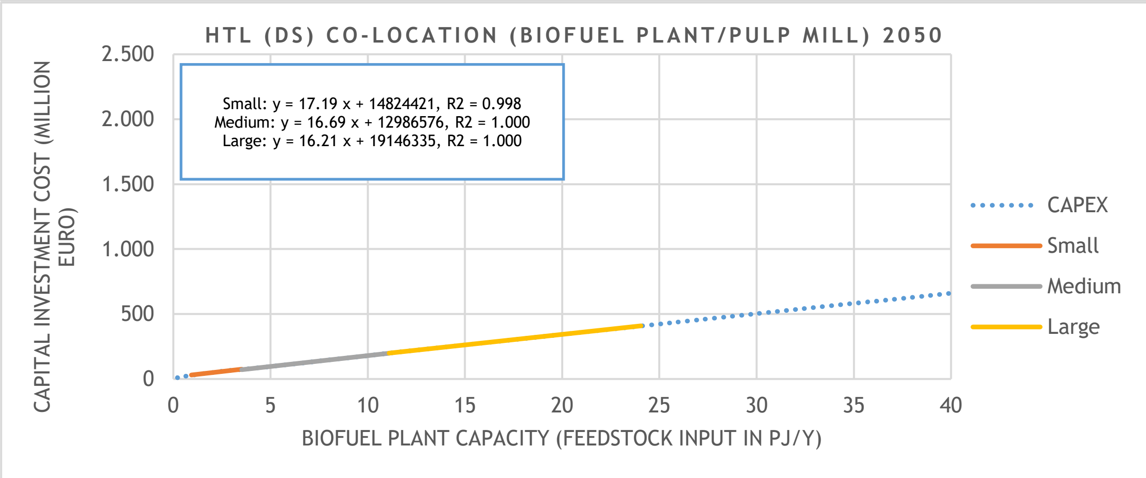
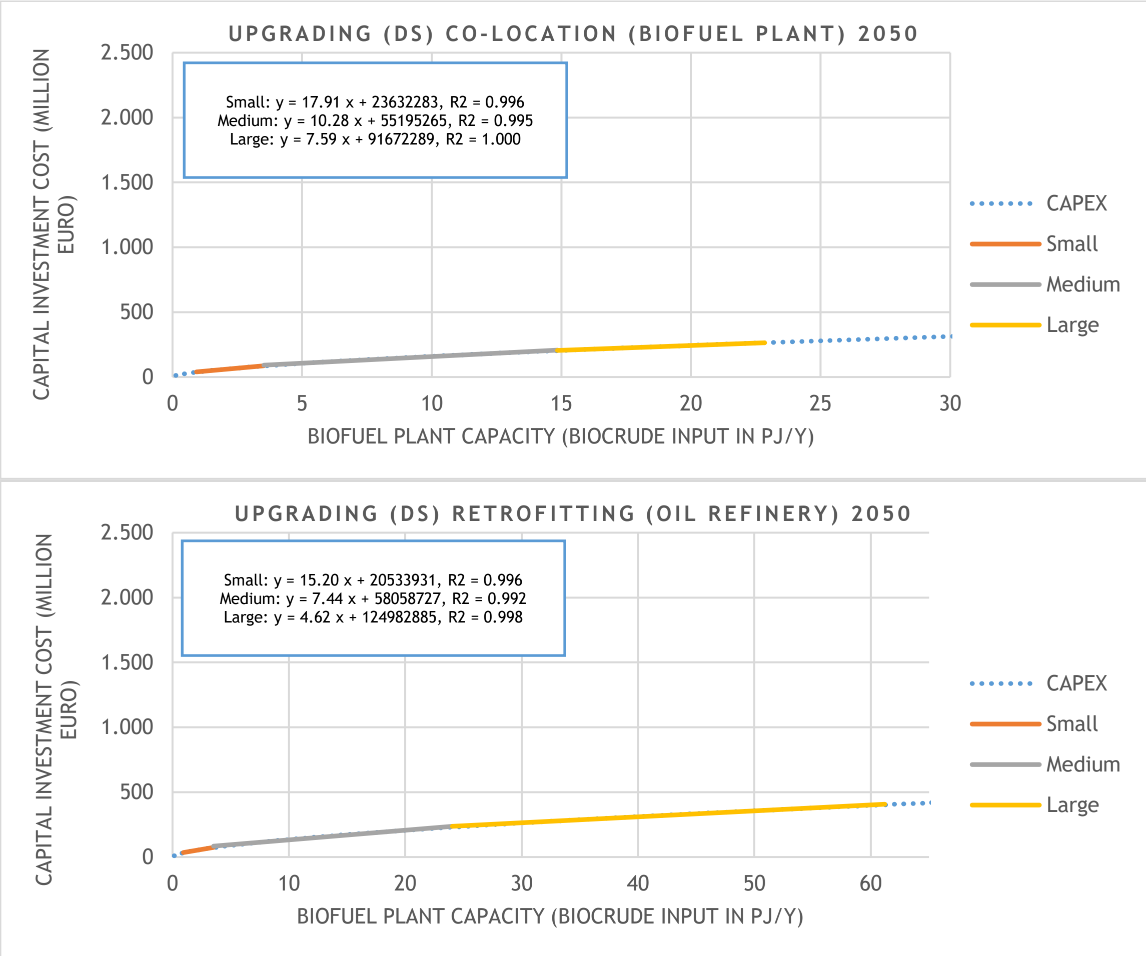


Figure 17 HTL upgrading decentralised (ds) capital cost estimates at three different capacity levels for different host locations/integration levels, 2050.



ANNEX C: TRANSPORT COSTS METHODOLOGY

The cost of biomass feedstock, biocrude and biofuel transport are calculated as a sum of three main cost components: time-related costs, distance-related costs and loading/unloading-related costs. These cost components are specific to mode *i* and country *j* and calculated as follows:

$$Total\ transport\ cost_{i,j} = Time\ related\ cost_{i,j} + Distance\ related\ cost_{i,j} + (Un)Loading\ cost_{i,j}$$

Most cost components are based on the study "*Cost Figures for Freight Transport*" (Meulen et al., 2023) which reports cost figures for freight transport for road, rail, inland waterways and maritime in the Netherlands. Although these cost figures are calculated exclusively for the Netherlands, they are detailed for different modes of transport and types of freight, including dry and wet bulk. To make these cost figures representative for Europe, fuel and labour costs were adjusted per country, as explained below.

- **Time-related costs**

Time-related costs factors are costs that are proportional to the time of travel (in € h^{-1}), but not to the distance. These include (Meulen et al., 2023):

- Fixed costs:
  - Asset depreciations or asset leases (mutually exclusive)
  - Insurance
  - Interest
  - Maintenance and repairs (x%)
- Mode-specific costs:
  - Usage of infrastructure and subsidy
  - Supporting services
  - Permits and certification
- Staff costs (on-board personnel):
  - Wages
  - Social security and pension contributions
  - Accommodation costs
- General operating costs:
  - Administration
  - Real estate and infrastructure
  - Wages including social charges for other personnel
  - IT and communications
  - Overhead

Time related costs are calculated in € t^{-1} based on the transport time and average payload per roundtrip.

$$Time\ related\ cost_{i,j} = \frac{(Fixed\ cost_i + General\ cost_i + Mode\ specific\ operation\ cost_i + Staff\ cost_{i,j}) \cdot Transport\ time_i}{Average\ payload\ (round\ trip)}$$

$$Transport\ time_i = \left(\frac{Distance_i}{Speed\ (average, effective\ hours)_i}\right) + (un)loading\ time_i$$

Fixed costs, general operating costs and mode specific operating costs are mode-specific. Staff costs are country specific:

$$Staff\ cost_i = Labor\ (FTEs)_i \cdot Labor\ cost_j$$

- **Distance related cost**

Variable distance related costs consist of (Meulen et al., 2023):

- Fuel / energy
- Bunkering
- Stores and supplies
- Maintenance and repairs (x%)

$$Distance\ related\ cost_{i,j} = \frac{(\text{Variable cost (excl.fuel and staff)}_i + \text{Fuel cost}_{i,j}) \cdot \text{Transport distance}_j}{Average\ payload\ (round\ trip)}$$

Non-fuel distance related costs were taken form Meulen et al. (2023). Fuel costs are calculated based on country-specific fuel prices and the mode specific fuel consumption:

$$Fuel/energy\ cost = Fuel\ consumption\ (av.) \cdot Fuel\ price$$

The diesel price was adjusted per country based on country-specific VAT and excise duty figures included in the transport model. Fuels used in inland waterways and maritime transport (MDO/IFO) were assumed to be the same for all countries.

- **Loading and unloading cost**

Loading and unloading costs include vehicle costs from Meulen et al (2023) and terminal handling costs based on Hoefnagels et al. (2014), adjusted to $€_{2023}$ with HICP (1.26). Terminal handling costs were assumed to be the same for dry and wet bulk.

- **Model parameters**

The mode-specific cost figures for inland transport are provided in Table 22. Most cost figures are based on Meulen et al. (2023), but fuel consumption and utilization rates were taken from JRC (Edwards et al., 2017) to allow for more consistent GHG calculations.

The total transport cost show ranges results from the variations in labour and fuel costs in individual countries.

Table 22 EU-average variable and fixed transport costs per vehicle type and transported freight (dry or wet bulk) for road, rail, and inland waterways. Main sources : Meulen et al. (2023), Edwards et al. (2017), Smeets et al. (2009).

Mode/network	Unit	Road		Rail (diesel)		Inland waterway				
Freight		Dry bulk	Wet bulk	Dry bulk	Wet bulk	Dry Bulk			Wet Bulk	
Type		Truck + trailer	Tractor + trailer	Charter train	Charter train	Small (II)	Middle (Iva)	Large (Va)	Middle (Iva)	Large (Va)
Labor (FTEs)	Person h^{-1}	1	1	2.5	2.5	1.0	1.3	1.7	1.4	2.2
Fuel type		Diesel	Diesel	Diesel	Diesel	MDO	MDO	MDO	MDO	MDO
Electricity consumption (av.)	kWh km^{-1}									
Fuel consumption (av.)[1]	l km^{-1}	0.31	0.31	9.8	9.8	2.9	7.1	12.7	6.9	11.6
Maximum load weight	t	27	29	2800	2800	540	1360	2700	1360	2700
Speed (average, effective hours)	km h^{-1}	22.9	41.7	49.7	49.7	5.4	6.4	7.6	6.6	7.5
Utilisation rate (transport efficiency)[1]		0.50	0.50	0.50	0.50	0.45	0.43	0.70	0.33	0.30
Average payload (roundtrip)	t	13.5	14.5	1400	1400	243	582	953	454	800
Fixed cost[2]	€ h^{-1}	9.0	11.6	405.4	356.9	6.7	19.6	54.0	60.4	84.5
General cost[2]	€ h^{-1}	10.2	12.0	144.5	135.5	2.7	3.7	5.2	3.7	3.6
Mode specific operation cost[3]	€ h^{-1}	0.6	0.6	214.9	203.7	1.3	2.9	4.2	2.8	3.7
Variable cost (excl. fuel and staff)[4]	€ km^{-1}	0.58	0.45	0.00	0.00	0.15	0.30	0.45	0.29	0.40
Rail tariffs (average)[4]	€ tkm^{-1}			0.09	0.09					
Total line-haul cost[5]	€ tkm^{-1}	0.251 (0.169 - 0.318)	0.161 (0.117 - 0.198)	0.116 (0.072 - 0.272)	0.115 (0.071 - 0.271)	0.044 (0.026 - 0.058)	0.030 (0.021 - 0.036)	0.029 (0.023 - 0.033)	0.052 (0.040 - 0.060)	0.041 (0.032 - 0.048)
Loading/unloading cost[6]	€ t^{-1}	1.25	1.45	0.43	0.39	0.06	0.06	0.08	0.10	0.11
Terminal handling & storage[6]	€ t^{-1}	2.50	2.50	3.90	3.90	1.50	1.50	1.50	1.50	1.50
Total (un)loading and terminal cost	€t^{-1}	3.75	3.95	4.33	4.29	1.56	1.56	1.58	1.60	1.61

1) Road and rail utilization rates and diesel consumption were taken from JRC (Edwards et al. 2017).

2) Fixed, general and mode-specific figures are from Panteia (Meulen et al. 2023), adjusted from $€_{2021}$ to $€_{2023}$ with HICP (1.14).

3) Variable cost figures are from Panteia (Meulen et al. 2023), but split in fuel and non-fuel variable cost.

4) Rail tariffs average EU: 0.09 €/t-km, range: 0.05 - 0.25 €/t-km.

5) Total line-haul cost calculated based on the following cost ranges for energy and labor in the EU27 in 2023. Diesel price (€/l) average EU: 1.73 (range: 1.54 - 2.07). MDO price (€/l): 0.90. Electricity price (€/kWh): 0.13. Labor cost (€/h) average EU: 32.5, (range: 8.2 - 50.7).

6) Loading and unloading costs include vehicle cost from Meulen et al (2023) and terminal costs based on Hoefnagels et al. (2014), adjusted to €2023 with HICP (1.26). Terminal costs were assumed to be similar for dry and wet bulk.

Table 23 Characteristics of maritime transport (Fritsche et al. 2019).

Parameter	Unit	Short sea
		Handysize
Ship characteristics		
Deadweight tonnes (DWT)	t	28000
Cargo Capacity	t	26000
Total displacement when under ballast	t	16600
Ballast	t	7000
Total displacement when fully loaded	t	36000
Hold volume for cargo	m^3	34667
Speed	km/h	27
Fuel consumption at full load	kg HFO /km	43.5
Fuel consumption when empty (at ballast)	kg HFO /km	33.6
Empty trip factor[1]		0.43

1) Distance empty/total distance.

Table 24 Financial parameters of maritime transport (Fritsche et al. 2019).

Parameter	Unit	Short sea			
		Handysize			
Financial parameters		Average	Range		
Daily rates	€ / day	5461	2651	-	42455
Bunker fuel cost (CST 380)	€/t	288	171	-	691
Port cost	€ / ship	13737	8495	-	19409
Harbour dues	€ / ship	14244	8828	-	129577
Towage	€ / ship	3753	2867	-	4376
Mooring	€ / ship	1058	855	-	4905
Pilotage	€ / ship	8926	4773	-	10128
Daily rates (one way)	€/(t-km)	0.001	0.000	-	0.005
Bunker fuel cost (CST 380)	€/(t-km)	0.001	0.000	-	0.002
Port cost	€/t_{wb}	0.610	0.377	-	0.861
Quality & safety management at port	€/t_{wb}	0.227	0.000	-	0.455
Documentation costs & agency fees	€/t_{wb}	0.273	0.091	-	0.455
Loading at export terminal	€/t_{wb}	5.91	2.73	-	9.09
Loaded weight determination	€/t_{wb}	0.182	0.091	-	0.273
Loaded quality determination	€/t_{wb}	0.091	0.091	-	0.091
Unloading at import terminal	€/t_{wb}	5.91	2.73	-	9.09

ANNEX D: BIOMASS DEMAND SCENARIOS

D.1: ADVANCED BIOFUELS SHARE PER COUNTRY

To derive the advanced biofuel share for each country, the activity per transport sector per country was used as projected and reported in the EU Reference Scenario 2020, and listed in the Table below.

Table 25 Advanced biofuels share for each country in the EU-27 + UK as calculated based on the transport activity projections reported in the EU Reference Scenario 2020 (EC, 2021).

Country	2030				2050			
	Road	Aviation	Maritime	Total Transport	Road	Aviation	Maritime	Total Transport
EU	100%	100%	100%	100%	100%	100%	100%	100%
Austria	3%	1%	0%	2%	3%	1%	0%	2%
Belgium	3%	3%	15%	4%	3%	3%	15%	5%
Bulgaria	1%	1%	0%	1%	1%	0%	0%	1%
Cyprus	0%	1%	1%	0%	0%	1%	1%	0%
Czech Rep	2%	1%	0%	2%	3%	1%	0%	2%
Germany	16%	18%	6%	15%	15%	17%	6%	13%
Denmark	1%	2%	2%	2%	1%	2%	2%	2%
Estonia	0%	0%	1%	0%	0%	0%	1%	0%
Greece	2%	2%	5%	2%	2%	3%	5%	3%
Spain	9%	12%	15%	10%	9%	12%	15%	11%
Finland	1%	1%	1%	1%	1%	1%	1%	1%
France	13%	12%	4%	12%	13%	11%	4%	11%
Croatia	1%	0%	0%	1%	1%	0%	0%	1%
Hungary	2%	0%	0%	1%	2%	0%	0%	1%
Ireland	1%	2%	1%	1%	1%	2%	1%	1%
Italy	11%	8%	6%	10%	10%	9%	6%	9%
Lithuania	1%	0%	0%	1%	1%	0%	0%	1%
Luxembourg	1%	1%	0%	1%	1%	1%	0%	0%
Latvia	0%	0%	1%	0%	0%	0%	1%	0%
Malta	0%	0%	5%	1%	0%	0%	5%	1%
Netherlands	3%	7%	25%	7%	2%	7%	26%	7%
Poland	7%	2%	1%	5%	8%	2%	1%	5%
Portugal	2%	2%	2%	2%	2%	2%	2%	2%
Romania	3%	1%	0%	2%	3%	1%	0%	2%
Sweden	2%	2%	5%	3%	2%	2%	6%	3%
Slovenia	1%	0%	0%	1%	1%	0%	0%	0%
Slovak Rep	1%	0%	0%	1%	1%	0%	0%	1%
UK*	13%	20%	5%	13%	16%	23%	5%	15%

* Since the UK was not included in the EU Reference 2020 scenario due to Brexit, the previous EU Reference 2016 scenario was used only for the UK

D.2: BIOENERGY SHARE PER COUNTRY (HEAT AND ELECTRICITY)

The share of bioenergy consumption per EU country was calculated using the datasets published in the EU Reference Scenario 2020. The data is summarised in Table 26.

Table 26 Percentage of bioenergy demand (non-transport energy) per country as calculated from the EU Reference Scenario 2020 (EC, 2021).

Country	EU Bioenergy Distribution%	
	2030	2050
AT	4%	4%
BE	2%	1%
BG	1%	1%
CY	0%	0%
CZ	3%	3%
DE	19%	17%
DK	3%	3%
EE	1%	1%
EL	1%	0%
ES	6%	8%
FI	6%	7%
FR	12%	13%
HR	1%	1%
HU	2%	2%
IE	1%	1%
IT	9%	8%
LT	1%	1%
LU	0%	0%
LV	1%	1%
MT	0%	0%
NL	1%	0%
PL	7%	9%
PT	2%	1%
RO	3%	4%
SE	7%	5%
SI	1%	1%
SK	1%	1%
UK[1]	9%	8%
sum	100%	100%

[1]Since the UK was not included in the EU Reference 2020 scenario due to Brexit; the previous EU Reference 2016 scenario was examined to identify which country's bioenergy profile most closely matches that of the UK. Italy was found to have the most similar bioenergy demand profile, hence the same bioenergy demand with Italy was assumed as a simplification.

D.3: BIOMASS DEMAND FOR NON-ENERGY USES

The percentage of the available biofeedstocks directed toward materials, biochemicals, and animal feed is presented in Table 27. These figures were derived from the Imperial College and Concawe study (ICL-Concawe, 2021).

Table 27 Percentage of biofeedstock availability projected to be used for materials, biochemicals and animal feed.

	2030			2050		
Feedstock	Low	Medium	High	Low	Medium	High
Straw*	11%	11%	10%	13%	12%	11%
Maize stover	20%	20%	20%	20%	20%	20%
Oil crop. Resid.	20%	20%	20%	20%	20%	20%
Prunnings	60%	40%	20%	60%	40%	20%
Energy crops	0%	0%	0%	0%	0%	0%
Stemwood	75%	70%	50%	75%	70%	50%
Primary forest resid.	60%	50%	40%	60%	50%	40%
Second. forest resid.	45%	40%	35%	45%	40%	35%
Biowaste	60%	50%	40%	65%	52%	46%

* The straw is the only feedstock for which a variable use ratio per country was reported. The EU total is included in the table.

ANNEX E: EXPERT INTERVIEWS AND CRITERIA FOR FUTURE ADVANCED BIOFUEL DEPLOYMENT

This section summarizes the findings of the interviews on the market rollout of advanced biofuels with a main focus on the development of Annex IX part A type biofuels. A detailed analysis of these interviews is provided in Rothenburger (2023). The insights are used to define the criteria for the supply chain modelling.

- **The role of advanced biofuels**

Advanced biofuels are expected to play a vital role in the energy transition. While road transport shifts towards electrification, the ReFuelEU Aviation (EU, 2023a)and FuelEU Maritime (EU, 2023b) initiatives will likely shape advanced biofuels and other renewables in these sectors. Aviation, with limited alternatives, is expected to heavily rely on advanced biofuels, facilitated by blending targets and GHG reduction goals. The shipping sector faces challenges, with alternatives like methanol, ammonia and hydrogen reducing reliance on advanced biofuels. Although long-term trends suggest that hydrogen and CO_2-based fuels may play an important role in transport, advanced biofuels have a clear role, especially in the period towards 2050. HEFA/HVO is the primary pathway today, but other options will likely emerge over time. Nevertheless, on the short term, advanced biofuels face economic challenges, leading to a likely market rollout only after 2030. The maturity level of these pathways is crucial for their deployment.

Long-term stable and effective policies, such as blending mandates, are required to create certainty for investors and consumers. Changes in ambition levels, uncertainties of future targets and changes in approved feedstock categories and fuel types that are eligible for support create risks and uncertainties. The short-term profit orientation of investors, uncertain policies and lack of mature technologies, have created a difficult playing field. Country-specific policies adapted to regional challenges and opportunities and with more ambitious and long-term, stable support, could provide a solution. At the same time, inconsistencies in policy implementation between member states also creates barriers to industries and investors that operate internationally. These include differences in sustainability criteria, calculation methods and differences in targets. Both carbon intensity reduction targets and renewable energy targets are applied in EU member states. Furthermore, national policies are also subject to changes leading to future market uncertainty. As an example, Sweden recently reduced its GHG reduction obligations for gasoline and diesel (Szumski, 2023).

- **Location factors of advanced biofuel development**

Reliable, sustainable and affordable feedstock supply chains are important for successful operation. They should enable year-round delivery of biomass at required specifications to commercial scale advanced biofuel refineries. Supply chains are already developed for first generation biofuels as part of agricultural commodities. Supply chains of waste-based biofuels are limited mainly to Annex IX part B type biofuels (e.g. used cooking oil). If biofuel plants are located in regions with abundant feedstock supply, short supply chains could be developed. It is therefore expected that the first advanced biofuel plants will be developed in biomass 'hot spot' areas such as forest rich regions in Northern Europe. However, the dependence on local, short feedstock supply chains also creates risks and challenges. Furthermore, access to feedstock supply is one of many factors that will determine future locations of advanced biofuel production.

Apart from access to feedstock supply, other important **regional accessibility factors** that were mentioned are: access to hydrogen and power supply, and access to (international) markets through blending facilities or terminals, and in the future also options to export CO_2 for utilization or storage (BECCUS). As a result, smaller-scale biorefineries or pre-treatment facilities could be strategically located near feedstock supply with final conversion or upgrading located in industrial areas with access to utilities and markets. Access to transport infrastructure (including road, rail, ports, terminals, depots and pipeline networks) and energy infrastructure (pipelines, power transmission lines, etc.) are therefore important. Because infrastructure is expensive, time consuming and complex to develop, access to existing infrastructure will be necessary in most cases.

Local, **site-specific factors** that were mentioned in the interviews considered the economic advantage of clustered activities or agglomeration economies. Existing chemical clusters and petrochemical areas could provide access to markets for products and by-products, co-location opportunities and access to utilities and energy and skilled labour. Transport costs could be reduced when terminals and other infrastructure could be shared with other industrial activities. At the same time, available land to develop new activities and infrastructure for dry bulk handling, apart from coal, is often lacking at these locations. Coal terminals could however provide an opportunity when coal is phased out as part of the energy transition. Other industrial plants or areas, including first generation biofuel production, wood processing and pulp & paper, could provide benefits for sharing infrastructure and other co-location strategies.

Despite that co-production strategies reduce the flexibility to locate new advanced biofuel production facilities compared to greenfield options, interviewees confirmed the relevance of co-location options. Retro-fitting was consistently ranked first while greenfield strategies were consistently ranked last as a valuable strategy for new plants by the interviewees:

1. Retro-fitting: changing parts of an existing facility/production line to co-produce advanced biofuels.

2. Repurposing: refurbishment of an existing (mothballed) facility to change its production to advanced biofuels.

2. Co-location: installing a new plant adjacent to an existing facility to make use of shared infrastructure.

3. Greenfield: building a new stand-alone facility at a new site, that can be strategically located in close proximity to biomass supply.

Finally, experts emphasize that there is no one-size-fits-all solution. Tailored, case-specific approaches are needed, recognizing that different situations require diverse solutions. Regional and local circumstances must be considered, and all available resources should be leveraged to address industry complexities.

- **Supply chain selection criteria and supply chain configurations**

Table 28 summarizes the criteria identified in the literature survey and expert interviews, the relevant supply chain strategies and method of operationalization in the supply chain modelling. The modelling approach to address these aspects is summarized below.

Table 28 Selection criteria for advanced biofuel supply chains, supply chain strategies and modelling approach.

	Feedstock	Transport	Pretreatment	Conversion/upgrading	Distribution/ end-use
Criteria (from expert interviews)	Feedstock delivered at specifications, all-year round, and affordable.	Available infrastructure • Road, rail, water, sea • Handling/ storage terminals	Close to feedstock supply	Access to utilities: • (Green) power • Hydrogen • Future: CO_2 network	Access to markets: • Road • Marine • Aviation • Other products
Supply chain strategies	Close to biomass rich areas. Feedstock diversification	• Intermodal transport • Transport of intermediates	Integration with existing industries • Pulp & paper, sawmills • Chemical parks/clusters • Oil refineries		Close to end-use markets / blending terminals
Modelling approach	Geographic mapping of biomass feedstock supply	GIS based intermodal transport network analysis	Supply chain modeling for different configurations • Centralized vs distributed supply chains • Integration strategies		Mapping of market access (blending terminal nodes)

ANNEX F: DETAILED RESULTS ADVANCED BIOFUEL SUPPLY CHAINS

This Annex provides further details of the advanced biofuel supply chain scenarios that complement the results provided in the main report (Chapter 9). These include:

- Annex F1: Biofuel production capacity and number of plants in the base and alternative feedstock scenarios.
- Annex F2: Detailed cost-supply curves and biomass use in the base and alternative feedstock scenarios.
- Annex F3: Biofuel production cost in the 2050 Repurpose Base and Alternative Feedstock scenarios.
- Annex F4: Distribution of biorefineries per country in the alternative feedstock scenarios.

F.1: BIOFUEL PRODUCTION CAPACITY AND NUMBER OF PLANTS

Table 29 Biofuel production capacity and number of plants per type and location in the Base scenarios.

Plant type	Location	2030		2050 LD		2050 HD		2050 RP	
		Capacity (Mtoe/y)	Number of plants	Capacity (Mtoe/y)	Number of plants	Capacity (Mtoe/y)	Number of plants	Capacity (Mtoe/y)	Number of plants
GFT	terminal	0.0	0	3.2	8	1.6	4	1.5	4
	pulp mill	0.0	0	1.2	3	0.0	0	0.8	2
	biofuel plant	0.0	0	2.4	6	0.0	0	0.8	2
	oil refinery	8.5	25	15.5	39	3.2	8	23.8	60
HTL (cs)	terminal	0.8	0	0.0	0	0	0	0.0	0
	pulp mill	0.0	0	0.0	0	0.0	0	0.0	0
	oil refinery	0.0	2	0.0	0	10.3	18	0.5	1
HTL (ds)	NUTS-3	0.0	0	2.3	10	22.5	100	1.1	4
	pulp mill	3.7	17	3.1	10	12.4	38	2.3	7
	biofuel plant	4.9	22	5.1	17	19.6	59	2.5	8
Upgrading (ds)	oil refinery	9.1	6	11.6	8	59.9	38	6.4	4
	biofuel plant	0.0	0	0.0	0	0.0	0	0.0	0
Total		**26.9**	**72**	**44.4**	**101**	**129.4**	**265**	**39.7**	**92**

Table 30 Biofuel production capacity and number of plants per type and location in the Alternative scenarios.

Plant type	Location	2030 (Low)		2030 (High)		2050 LD (Low)		2050 LD (High)		2050 HD (High)	
		Capacity (Mtoe/y)	Number of plants	Capacity (Mtoe/y)	Number of plants	Capacity (Mtoe/y)	Number of plants	Capacity (Mtoe/y)	Number of plants	Capacity (Mtoe/y)	Number of plants
GFT	terminal	0.0	0	0.0	0	2.9	9	2.8	7	7.2	18
	pulp mill	0.0	0	0.0	0	0.0	0	5.2	13	2.4	7
	biofuel plant	0.0	0	0.0	0	1.2	4	6.0	15	3.2	8
	oil refinery	8.8	26	10.8	32	12.2	31	17.5	44	23.9	60
HTL (cs)	terminal	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0
	pulp mill	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0
	oil refinery	0.0	0	0.0	0	0.4	1	0.0	0	2.9	5
HTL (ds)	NUTS-3	0.4	2	0.0	0	8.2	59	0.0	0	11.3	48
	pulp mill	3.7	16	3.4	14	3.3	18	0.4	2	10.0	29
	biofuel plant	4.9	22	3.7	16	3.9	21	1.8	6	14.9	45
Upgrading (ds)	biofuel plant	0.0	0	0.0	0	0.0	0	0.0	0	0.0	0
	oil refinery	9.5	7	7.5	5	17.1	19	2.4	3	39.8	26
Total		**27.4**	**73**	**25.4**	**67**	**49.3**	**162**	**36.1**	**90**	**115.6**	**246**

F.2: DETAILED COST SUPPLY CURVES AND BIOMASS USE

Base scenarios

Figure 18 Cost-supply curve of biomass delivered to advanced biofuel production plants and competing uses (E/H) per feedstock type (A) and end use (B). The difference between the feedstock cost (roadside) and the feedstock cost delivered is related to transport. The pie chart shows the shares of biomass use per type. Scenario: Base 2030.

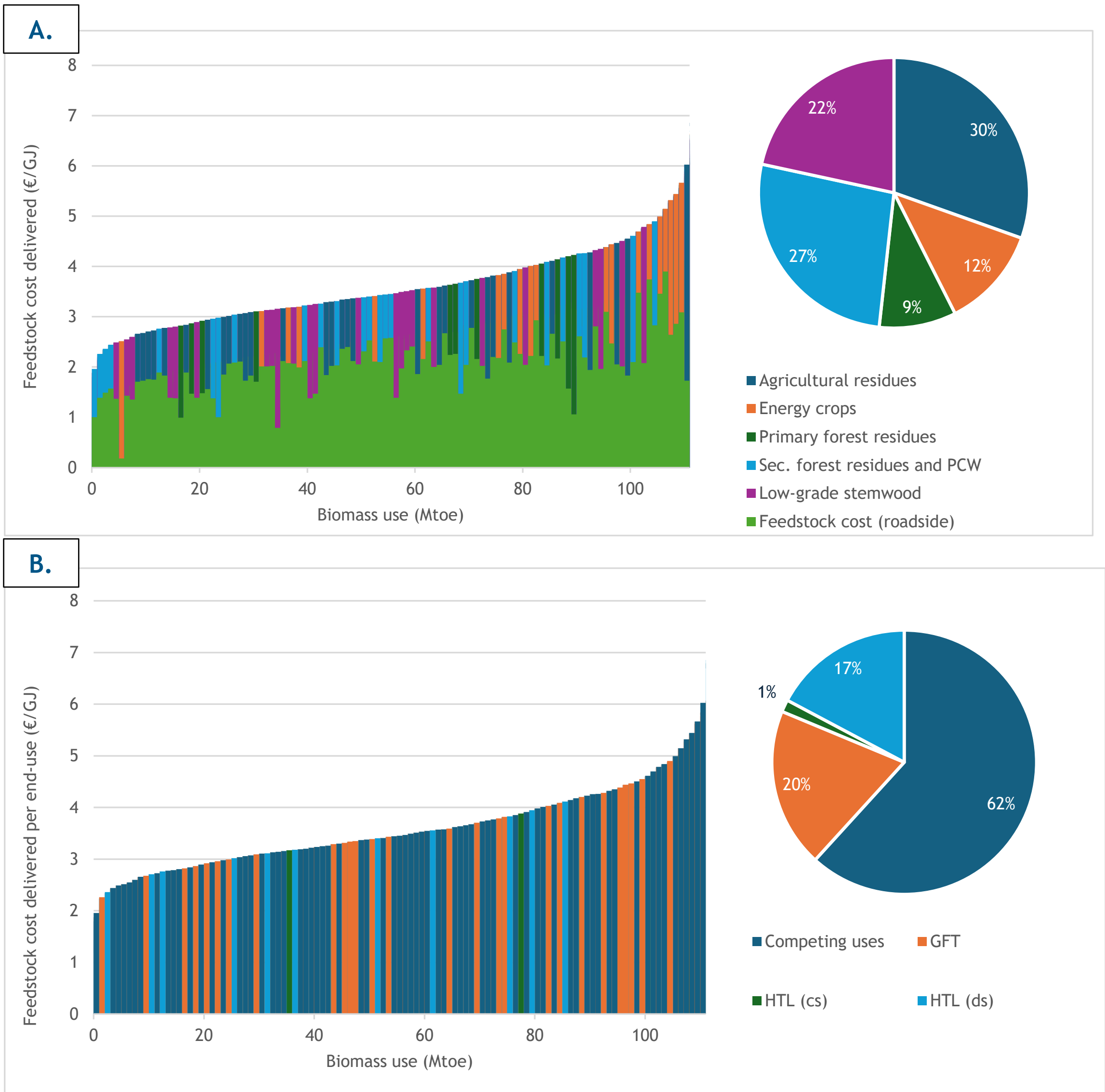


Figure 19 Cost-supply curve of biomass delivered to advanced biofuel production plants and competing uses (E/H) per feedstock type (A) and end use (B). The difference between the feedstock cost (roadside) and the feedstock cost delivered is related to transport. The pie chart shows the shares of biomass use per type. Base Scenario: 2050 Low Demand.

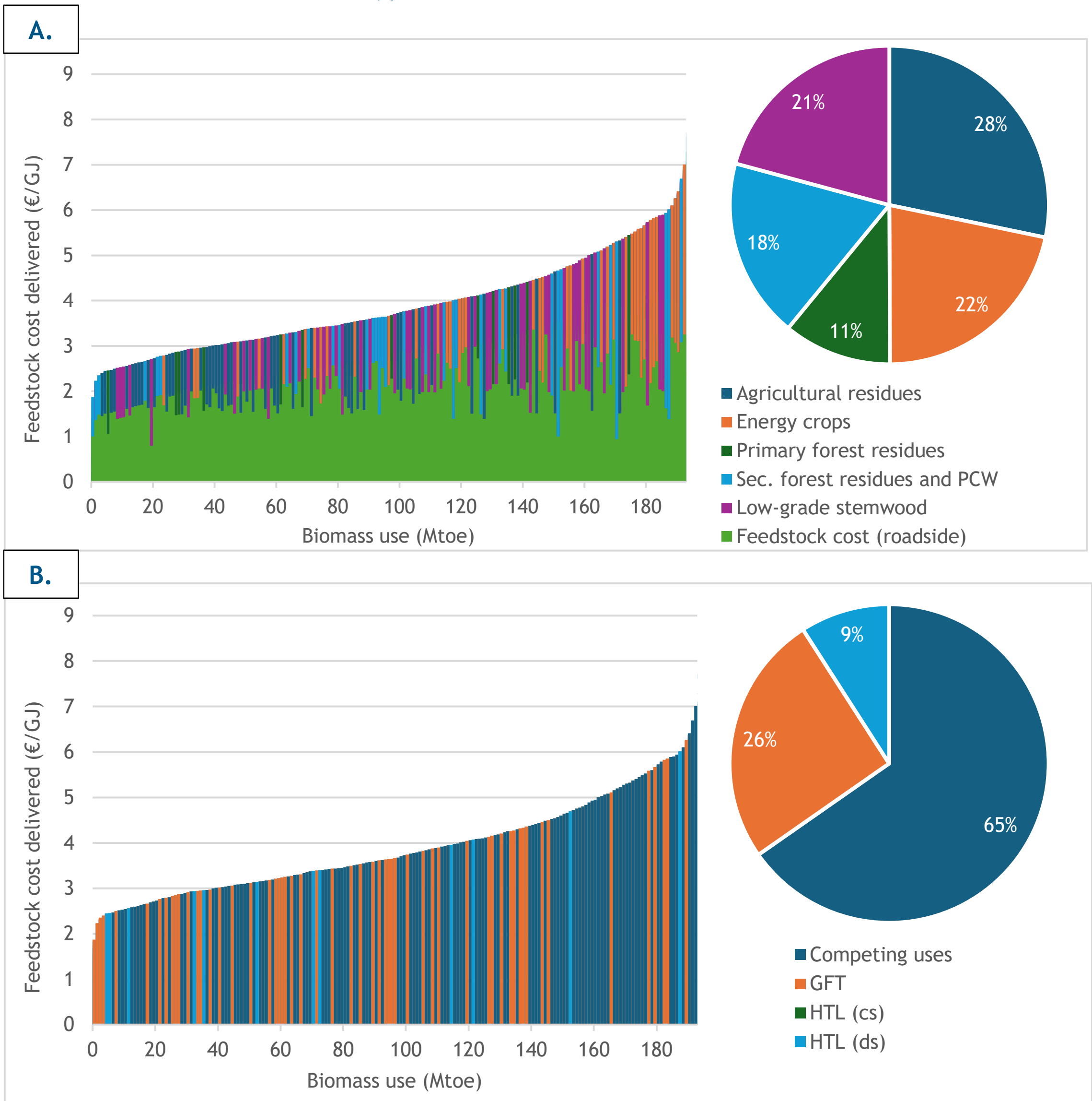
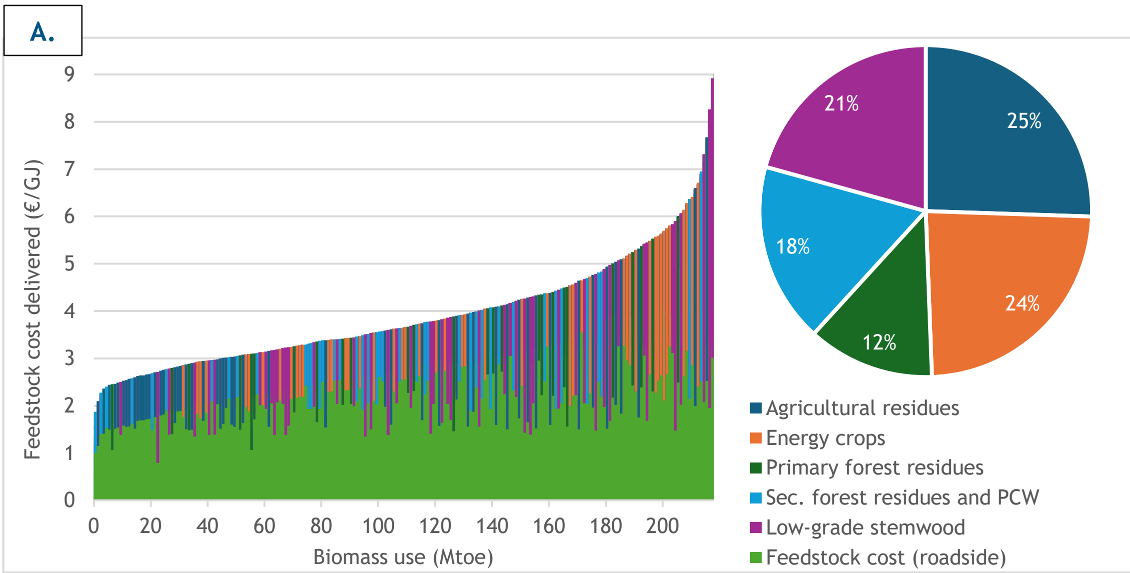


Figure 20 Cost-supply curve of biomass delivered to advanced biofuel production plants and competing uses (E/H) per feedstock type (A) and end use (B). The difference between the feedstock cost (roadside) and the feedstock cost delivered is related to transport. The pie chart shows the shares of biomass use per type. Base Scenario: 2050 High Demand.



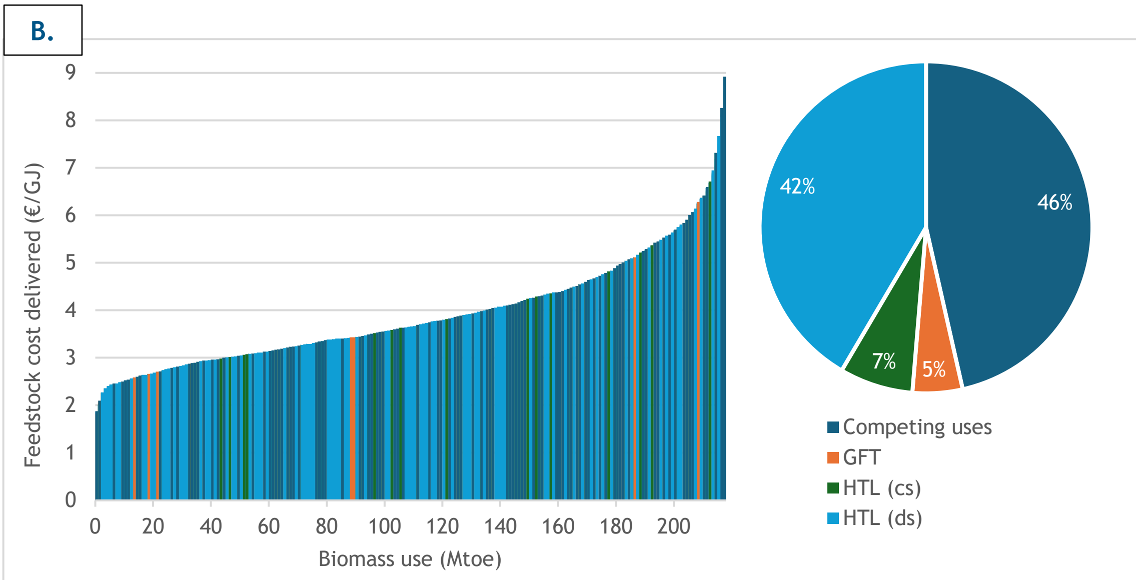
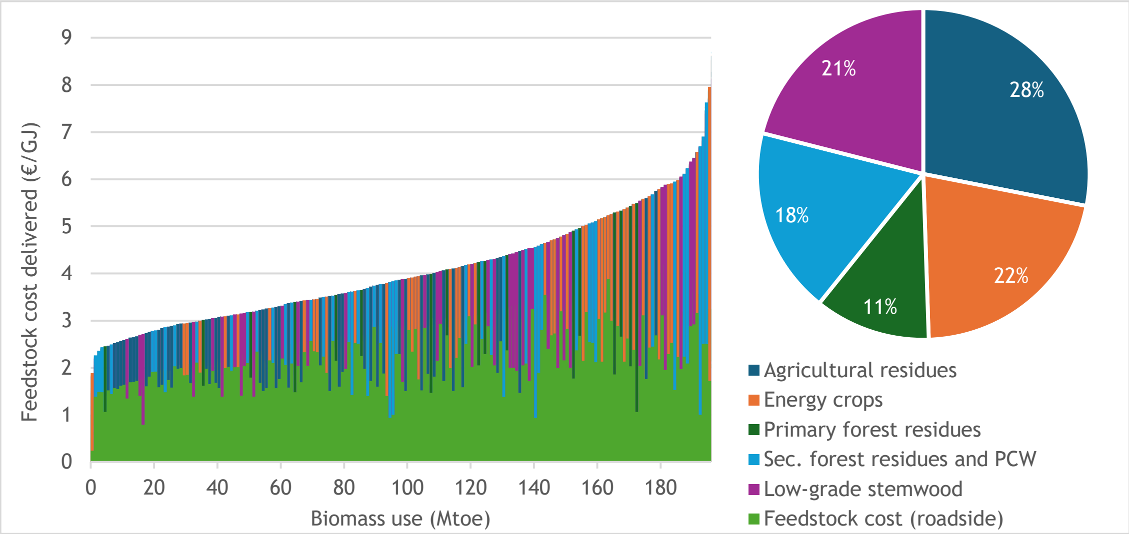
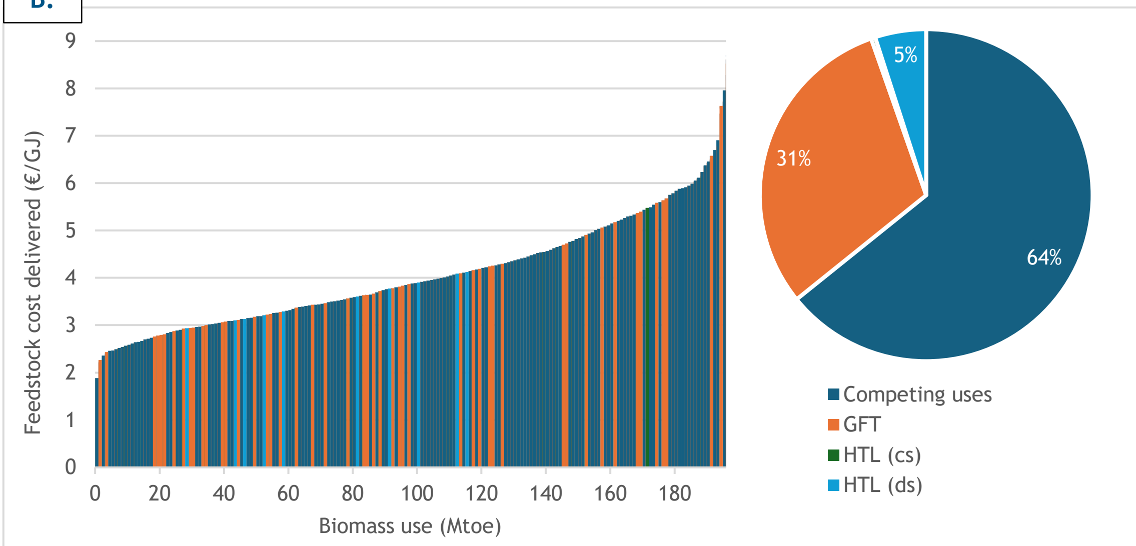


Figure 21 Cost-supply curve of biomass delivered to advanced biofuel production plants and competing uses (E/H) per feedstock type (A) and end use (B). The difference between the feedstock cost (roadside) and the feedstock cost delivered is related to transport. The pie chart shows the shares of biomass use per type. Base Scenario: Repurpose-2050

A.



B.



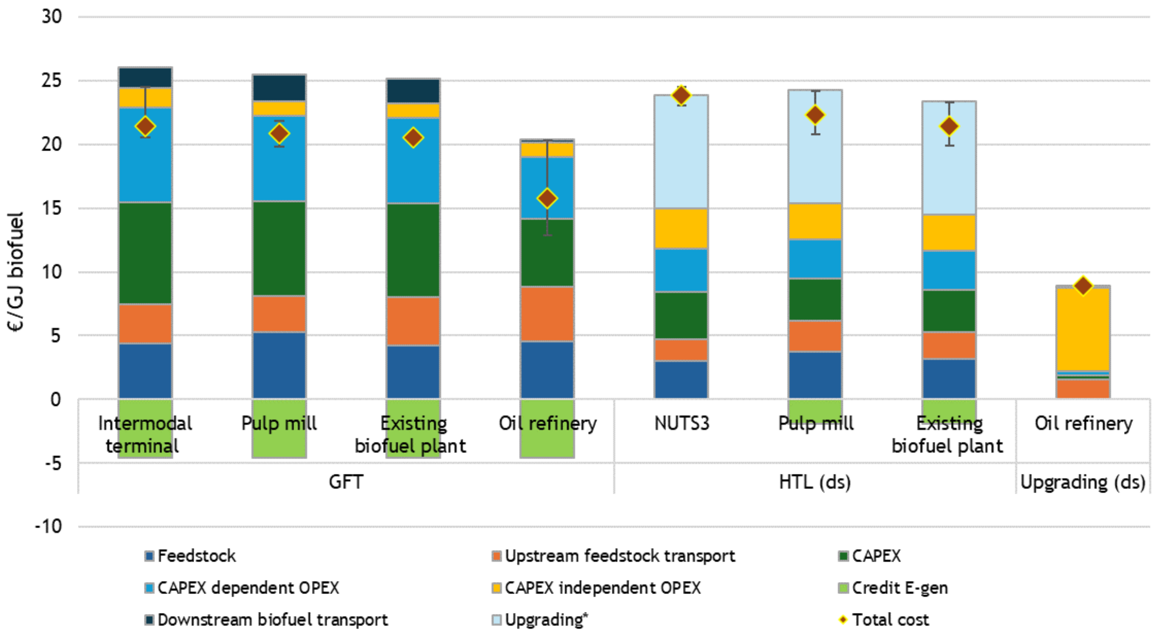
F.3: BIOFUEL PRODUCTION COSTS FOR THE 2050 REPURPOSE AND ALTERNATIVE FEEDSTOCK SCENARIOS

F.3.1: Base Scenarios

Repurpose -2050

All the other base scenarios are presented in the main report.

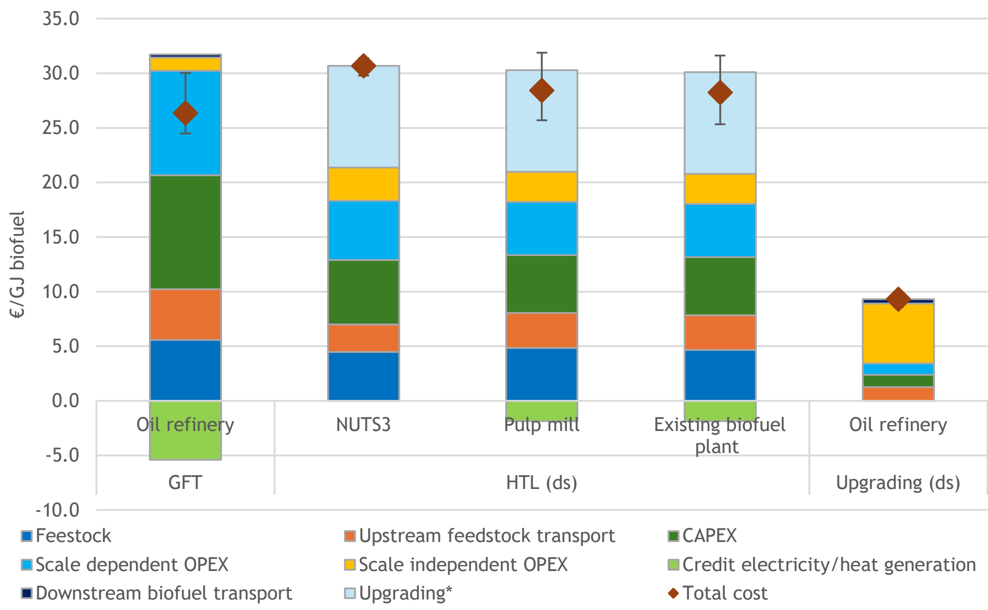
Figure 22 Breakdown of each pathway costs into the different components and average biofuel production cost per pathway/configuration. Scenario: 2050 Repurpose.



*) Average distributed upgrading and downstream fuel transport cost

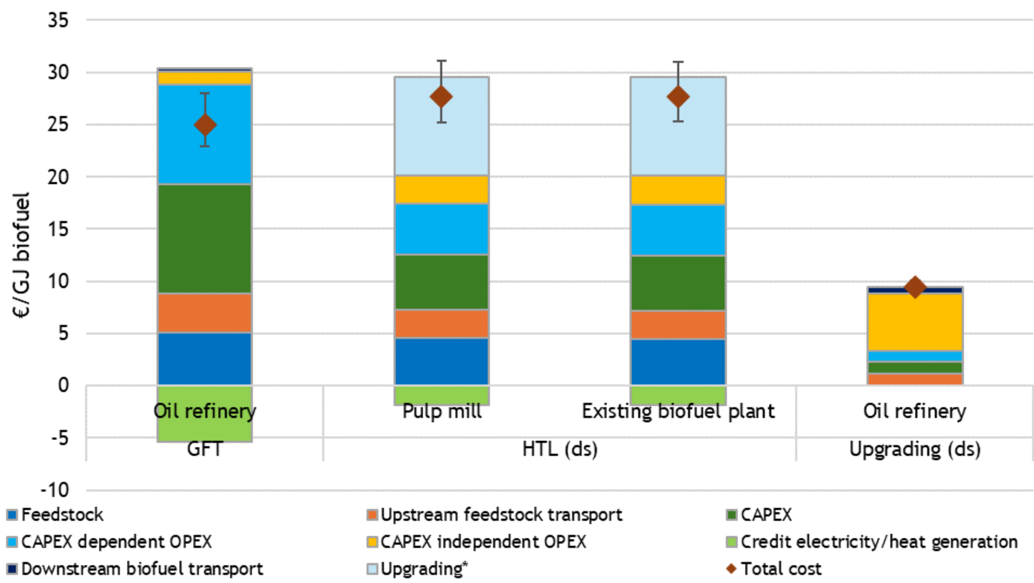
F.3.2: Alternative Scenarios

Figure 23 Breakdown of each pathway costs into the different components and average biofuel production cost per pathway/configuration. Scenario: 2030 (Low).



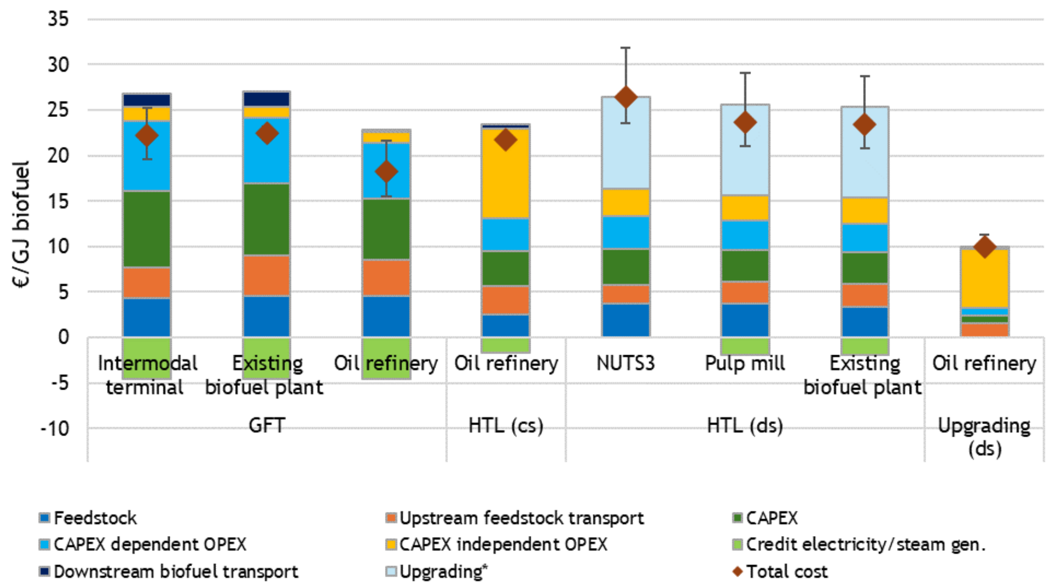
*) Average distributed upgrading and downstream fuel transport cost

Figure 24 Breakdown of each pathway costs into the different components and average biofuel production cost per pathway/configuration. Scenario: 2030 (High).



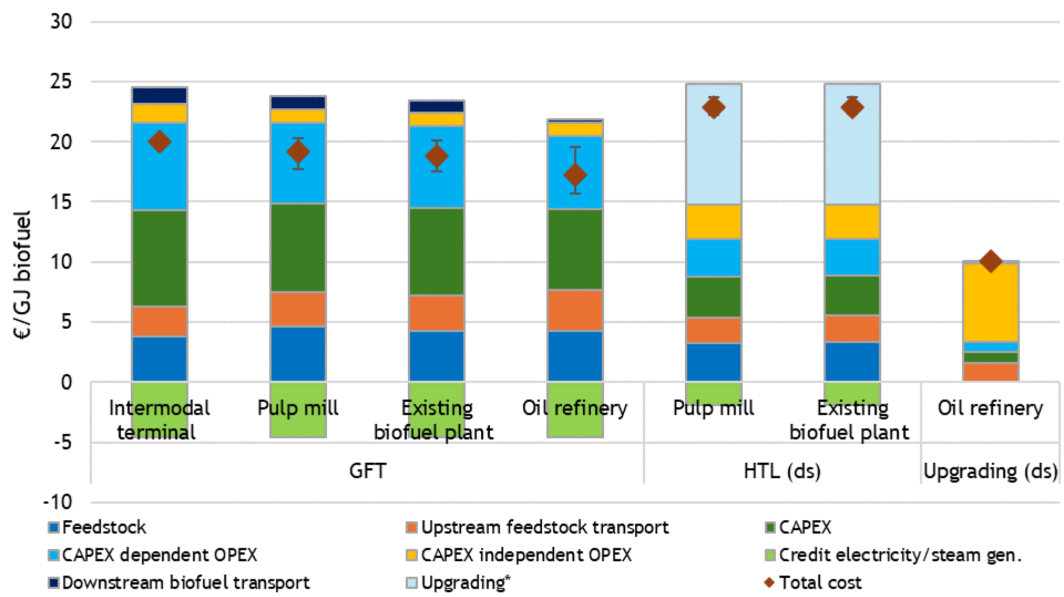
*) Average distributed upgrading and downstream fuel transport cost

Figure 25 Breakdown of each pathway costs into the different components and average biofuel production cost per pathway/configuration. Scenario: 2050 Low-Demand (Low).



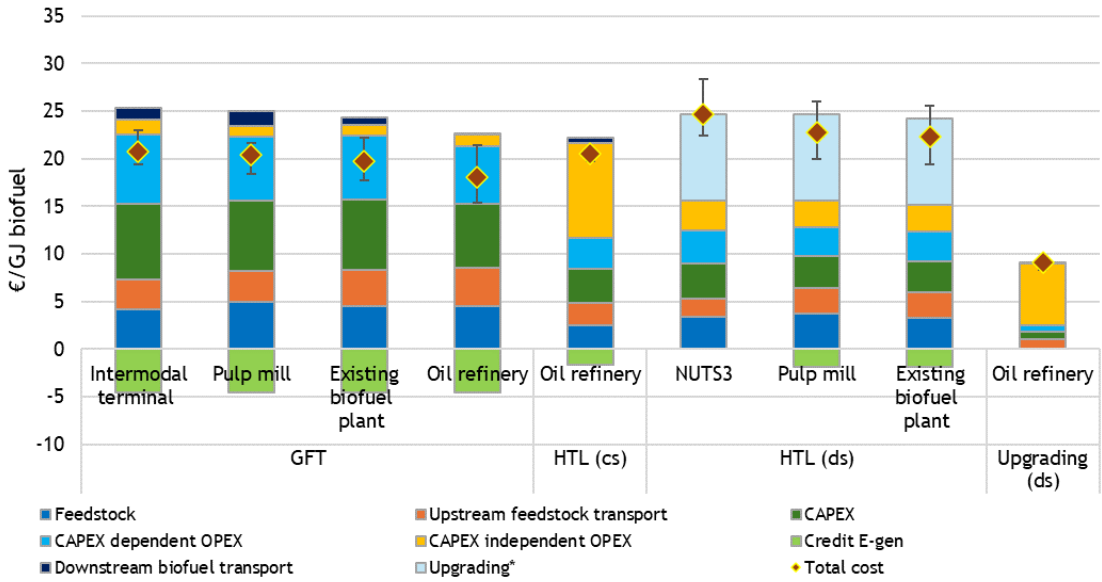
*) Average distributed upgrading and downstream fuel transport cost

Figure 26 Breakdown of each pathway costs into the different components and average biofuel production cost per pathway/configuration. Scenario: 2050 Low-Demand (High).



*) Average distributed upgrading and downstream fuel transport cost

Figure 27 Breakdown of each pathway costs into the different components and average biofuel production cost per pathway/configuration. Scenario: 2050 High-Demand (High).



*) Average distributed upgrading and downstream fuel transport cost

F.4: BIOREFINERIES DISTRIBUTION PER COUNTRY (ALTERNATIVE SCENARIOS)

Figure 28 Distribution of biocrude/biofuel production plants per country in the EU-27+UK. Scenario: 2030 (Low).

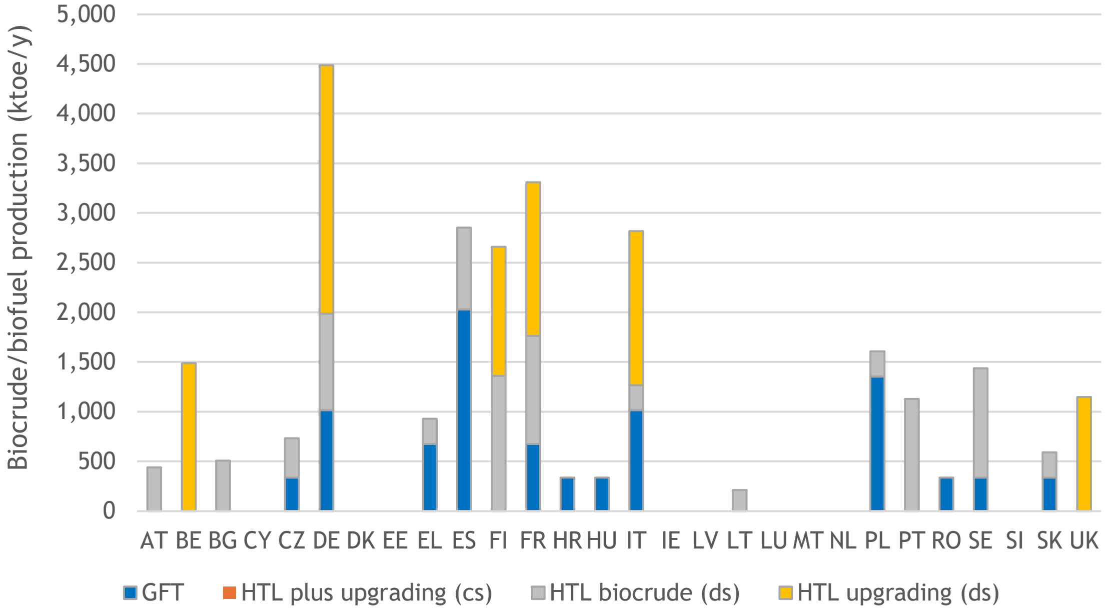


Figure 29 Distribution of biocrude/biofuel production plants per country in the EU-27+UK. Scenario: 2030 (High).

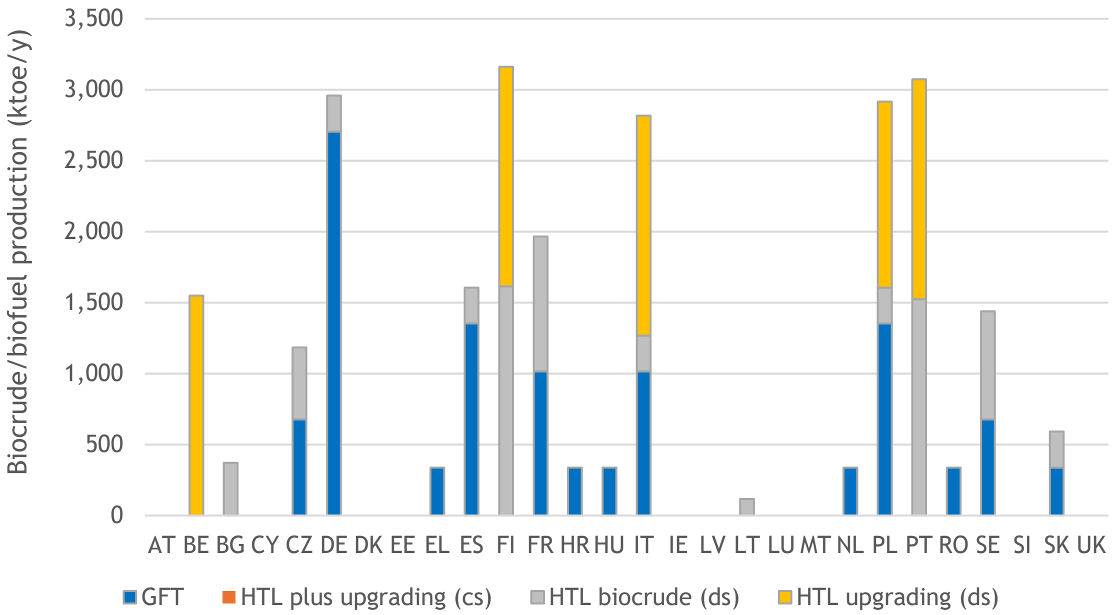


Figure 30 Distribution of biocrude/biofuel production plants per country in the EU-27+UK. Scenario: 2050 Low-Demand (Low).

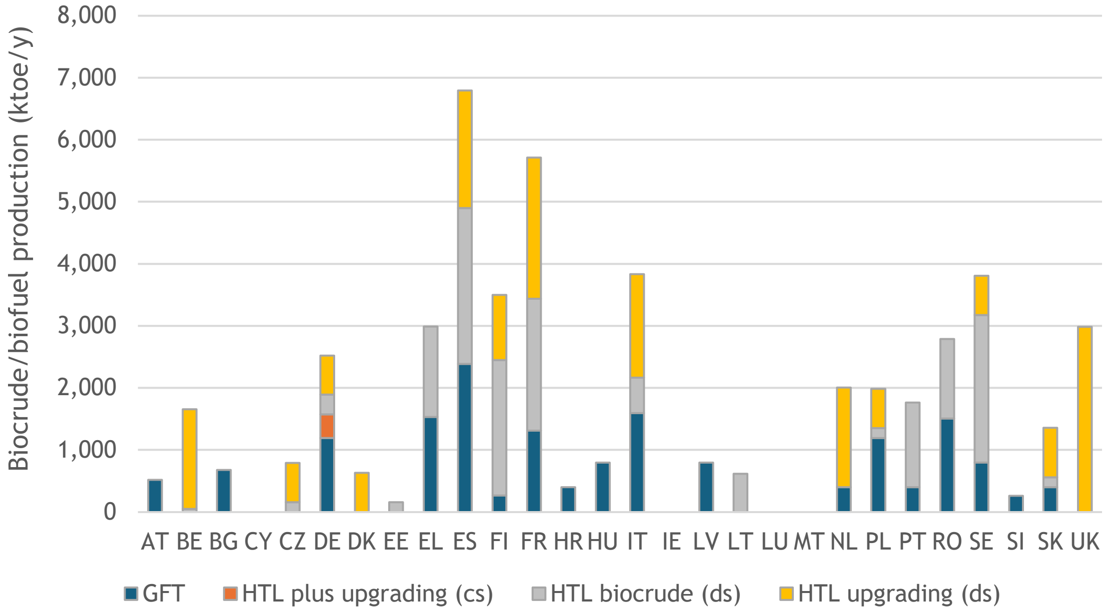


Figure 31 Distribution of biocrude/biofuel production plants per country in the EU-27+UK. Scenario: 2050 Low-Demand (High).

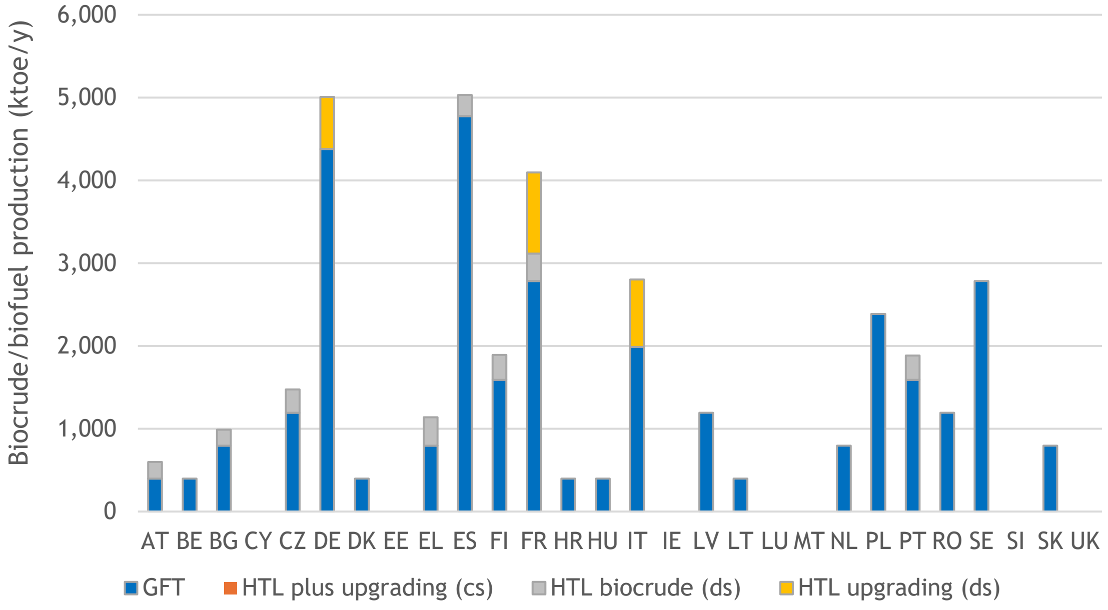
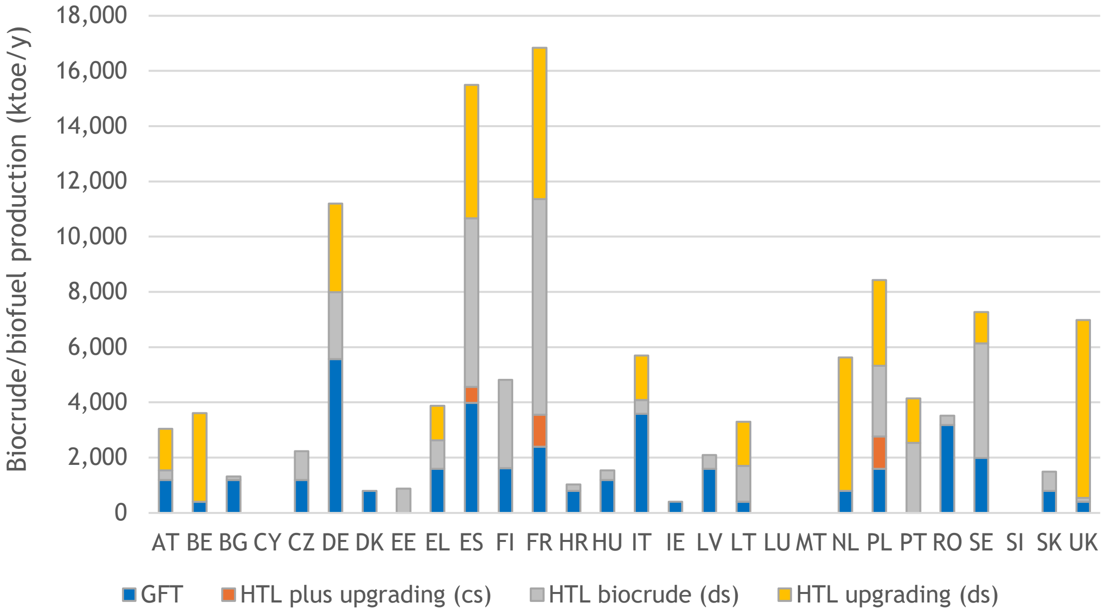


Figure 32 Distribution of biocrude/biofuel production plants per country in the EU-27+UK. Scenario: 2050 High-Demand (High).



F.5: BIOMASS, BIOCRUDE AND BIOFUEL INTRA-EU TRADE

Figure 33 Intra-EU country trade of biomass, biocrude, and biofuel trade in the Alternative feedstock scenarios. The % labels show the share of trade relative to the total demand of the respective flow (biomass, biocrude, biofuel).

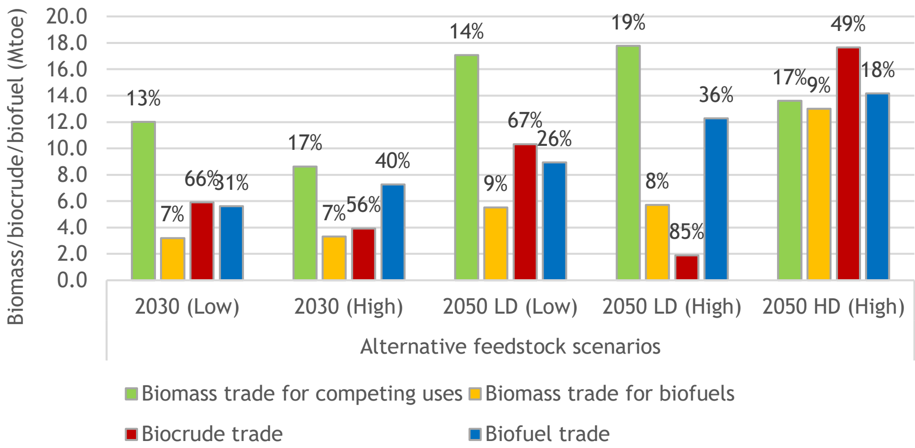


Table 31 Domestic biomass supply and trade (intra-EU) for all bioenergy uses (advanced biofuel, electricity, and heat) per country and only for advanced biofuels in the base scenarios (in ktoe/y). Domestic consumption = domestic supply + import – export.

Country	Domestic supply				Net import				Net export			
	2030	2050 LD	2050 HD	2050 RP	2030	2050 LD	2050 HD	2050 RP	2030	2050 LD	2050 HD	2050 RP
Domestic biomass supply and trade (for advanced biofuels and competing bioenergy uses)												
AT	2249	4985	5696	4755	490	3044	2343	2390	-476	-941	-861	-1174
BE	1147	1302	1141	1067	798	498	531	467	-120	-216	-389	-463
BG	2243	3413	3535	3413	0	27	285	27	-122	-205	-433	-247
CY	0	0	0	0	40	0	0	0	0	0	0	0
CZ	3800	4737	4809	5085	153	421	618	957	-555	-498	-425	-150
DE	16011	20298	19978	20864	3473	6606	4746	9231	-947	-1824	-2151	-1264
DK	1254	2042	2142	2146	1041	2179	2138	2960	-232	-104	-4	0
EE	452	700	2765	700	0	0	96	0	-326	-2007	-109	-2174
EL	1971	2651	6849	3535	61	0	0	0	-45	-1363	-1300	-635
ES	9735	20471	22373	18469	158	575	364	736	-146	-1448	-1065	-2459
FI	6983	9907	14079	9805	1178	2872	1883	2591	0	-427	0	-617
FR	12420	21155	24923	21046	366	1251	1041	1735	-2264	-4933	-3063	-5623
HR	1245	2102	2292	1600	276	883	1367	501	-399	-909	-781	-1350
HU	1848	2707	2923	2703	244	715	1152	719	-1119	-2047	-2059	-2133
IT	7747	13332	13410	13229	413	2783	1295	2002	-31	0	-444	-138
IE	373	775	780	896	1	226	143	988	-86	-59	-194	-54
LV	614	3612	4726	2722	69	73	171	79	-1429	-2231	-1117	-3120
LT	1125	2616	2448	1953	190	94	0	846	-403	-781	-981	-1399
LU	58	0	0	0	5	0	0	0	-34	-107	-107	-107
MT	0	0	0	0	0	0	0	0	0	0	0	0
NL	606	734	1041	806	262	150	683	962	-803	-493	-199	-434
PL	8692	14535	14909	13541	69	670	912	1089	-1844	-3120	-2746	-4113
PT	3801	4694	4919	4329	129	268	800	512	0	-205	-198	-641
RO	2847	6826	12102	8365	102	205	834	247	-132	-722	-689	-805
SE	7463	11704	16177	11667	351	41	653	0	-896	-2307	-1889	-3117
SI	340	613	388	687	36	86	175	12	-287	-1074	-1347	-943
SK	1035	2438	2208	1958	1129	1148	404	1319	-227	-955	-1391	-1641
UK	4127	5731	7732	6170	1891	4198	1362	4470	-1	-37	-55	-37
Total	**100183**	**164078**	**194342**	**161513**	**12925**	**29012**	**23995**	**34838**	**-12926**	**-29013**	**-23996**	**-34839**
Domestic biomass supply and trade for advanced biofuels												
AT	0	1412	2639	1300	0	1239	1072	468	-448	-604	-622	-604
BE	418	786	664	582	466	363	485	302	-1	-127	-178	-456
BG	1414	1767	2207	1767	0	0	267	0	-4	0	-181	-110
CY	0	0	0	0	0	0	0	0	0	0	0	0
CZ	2033	777	1935	1593	0	106	53	174	-135	-140	0	0
DE	4881	3732	5902	5889	1526	1835	1654	2870	-198	-1138	-1537	-479
DK	0	0	591	591	0	0	293	293	0	0	-4	0
EE	0	0	2202	0	0	0	96	0	0	0	0	0
EL	1971	2651	6849	3535	61	0	0	0	0	-624	-934	0
ES	5231	11234	14579	9239	158	34	289	187	0	-107	-263	-903
FI	3783	4065	8805	3683	0	0	146	0	0	0	0	-277
FR	4314	6109	12608	6039	198	247	441	692	-634	-2084	-1393	-3332
HR	608	910	1579	419	276	858	1101	465	-43	-44	-36	-212
HU	884	861	1950	884	0	23	82	0	-694	-998	-1025	-765
IT	2125	4813	5863	4445	18	1373	852	857	-18	0	-422	-123
IE	0	0	118	98	0	0	0	786	0	0	-71	0
LV	0	2651	4049	1767	0	0	16	0	-190	0	-47	-846
LT	384	1345	1370	612	190	25	0	846	0	0	-231	0
LU	0	0	0	0	0	0	0	0	-34	-67	-67	-44
MT	0	0	0	0	0	0	0	0	0	0	0	0
NL	0	734	1041	806	0	150	683	962	-622	-206	-19	-259
PL	4040	3811	6220	3179	69	298	673	355	-428	-25	-519	-715
PT	2729	3074	4023	2726	0	107	263	334	0	0	-151	0
RO	884	2651	8830	4122	0	0	582	110	0	-237	-55	-336
SE	3150	5214	11231	5137	0	0	344	0	0	0	-35	-77
SI	0	0	0	0	0	0	0	0	-273	-885	-981	-671
SK	698	1039	1149	854	760	729	0	605	0	-101	-708	-185
UK	0	0	1017	624	0	0	87	87	0	0	0	0
Total	**39546**	**59638**	**107422**	**59892**	**3721**	**7386**	**9479**	**10392**	**-3721**	**-7386**	**-9479**	**-10392**

Table 32 Domestic biomass supply and trade (intra-EU) for all bioenergy uses (advanced biofuel, electricity, and heat) per country and only for advanced biofuels in the alternative feedstock scenarios (in ktoe/y). Domestic consumption = domestic supply + import – export.

Country	Domestic supply					Net import					Net export				
	2030 (Low)	2030 (High)	2050 LD (Low)	2050 LD (High)	2050 HD (High)	2030 (Low)	2030 (High)	2050 LD (Low)	2050 LD (High)	2050 HD (High)	2030 (Low)	2030 (High)	2050 LD (Low)	2050 LD (High)	2050 HD (High)
Domestic biomass supply and trade (for advanced biofuels and competing bioenergy uses)															
AT	2798	1965	3690	4195	5463	931	774	1786	2402	2089	-554	-216	-576	-456	-1180
BE	843	984	545	1249	1118	219	77	63	285	290	-268	-451	-640	-428	-759
BG	1978	1669	2763	3762	4168	0	0	92	0	30	-194	-423	-285	-415	-438
CY	0	0	0	0	0	40	40	0	0	0	0	0	0	0	0
CZ	3371	4647	3489	6912	7215	324	190	215	485	598	-249	-500	-481	-313	-75
DE	14296	17597	15620	25528	27418	3635	3124	5304	5530	6143	-886	-1113	-1201	-1929	-2142
DK	1171	1365	1612	2733	2753	1124	930	1784	2373	2411	-101	-323	-68	-21	0
EE	452	452	829	700	2030	0	0	0	0	0	-721	0	-1269	-900	-1707
EL	2342	787	5832	2342	5258	0	97	0	0	0	-183	-8	-873	-122	-410
ES	11449	8414	16829	20680	27565	223	198	522	133	191	-137	-797	-1012	-670	-796
FI	5782	7277	8676	10827	13318	1674	749	2569	1923	2597	0	0	-267	-261	-299
FR	12079	12529	18377	22149	31812	419	546	998	636	1169	-2871	-1741	-3470	-3759	-2519
HR	1188	1321	1483	1833	2416	332	200	380	268	713	-479	-512	-806	-751	-1035
HU	1660	1816	2586	2831	3522	432	276	1223	591	1746	-1316	-1049	-1351	-2753	-2521
IT	8468	8894	10954	13630	14795	776	349	1523	718	1988	0	-46	-330	-39	-158
IE	373	373	615	721	947	1	1	190	280	741	-102	-77	-117	-85	0
LV	634	683	2516	3554	4885	50	0	83	131	321	-1599	-1086	-1416	-2158	-2237
LT	1063	1006	2103	2194	3772	153	0	0	30	348	-443	-134	-551	-737	-423
LU	46	63	0	0	0	17	0	0	0	0	-28	-42	-80	-155	-155
MT	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
NL	632	1416	327	893	847	236	336	557	874	921	-535	-285	-532	-626	-693
PL	8477	8761	10951	16398	18493	284	0	893	0	0	-2111	-2025	-2412	-3809	-4467
PT	3634	4224	4179	5180	5619	120	424	416	628	36	-39	0	-314	0	-33
RO	2836	2633	8727	6616	10489	113	316	285	415	664	-354	-184	-1014	-506	-1167
SE	7378	7975	10708	12113	16050	657	180	285	604	516	-981	-422	-1852	-1703	-1236
SI	351	149	828	640	501	24	227	309	59	61	-515	-181	-490	-311	-1065
SK	1151	814	1571	1886	2949	1013	1350	1041	1700	1431	-560	-320	-1139	-573	-1052
UK	3590	4464	5922	6506	7512	2428	1553	2068	3423	1606	-1	-1	-41	-10	-42
Total	**98042**	**102277**	**141734**	**176071**	**220915**	**15224**	**11937**	**22585**	**23487**	**26609**	**-15224**	**-11937**	**-22585**	**-23488**	**-26610**
Domestic biomass supply and trade for advanced biofuels															
AT	977	0	489	753	2591	13	0	660	466	635	-504	-176	-386	-456	-1029
BE	0	0	63	796	662	0	0	21	88	221	-2	-222	-557	-382	-610
BG	1149	840	1491	2090	2823	0	0	19	0	30	-39	-70	-120	0	-242
CY	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CZ	1733	2807	265	3011	4207	42	109	0	112	168	-27	-166	-26	0	0
DE	3674	6085	2605	7523	13616	1181	1559	1151	2198	2778	-332	-109	-622	-814	-1394
DK	0	0	0	709	1211	0	0	0	174	556	0	-61	0	0	0
EE	0	0	265	0	1466	0	0	0	0	0	0	0	0	0	-1065
EL	2342	787	5832	2342	5258	0	97	0	0	0	-87	0	-140	0	-203
ES	7016	3911	9442	11035	19814	153	198	41	0	73	0	-63	-205	-326	-370
FI	3078	3648	4230	4037	8030	0	0	3	0	875	0	0	0	0	-299
FR	3893	4634	6090	6416	19134	332	168	372	320	932	-861	-723	-1115	-1160	-1590
HR	551	684	522	616	1437	332	200	362	268	713	-34	-42	-111	0	-255
HU	836	884	1385	884	2086	48	0	382	0	1140	-516	-618	-593	-1119	-1386
IT	2998	3207	3794	4404	7733	227	19	694	15	1060	0	-19	-180	0	-132
IE	0	0	0	0	230	0	0	0	0	654	0	0	0	0	0
LV	0	0	1767	2651	4184	0	0	0	0	190	-153	0	0	-223	-292
LT	323	265	1025	853	2694	153	0	0	30	348	0	0	-27	0	0
LU	0	0	0	0	0	0	0	0	0	0	-28	-33	-21	-55	-83
MT	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
NL	0	830	327	893	847	0	53	557	874	921	0	-181	-253	-242	-353
PL	3952	4109	2615	5302	9565	158	0	302	0	0	0	-648	-11	-672	-1426
PT	2552	3384	3128	3701	4221	0	63	34	326	0	0	0	-41	0	-5
RO	884	884	5368	2651	7161	0	0	120	0	468	-96	0	-381	0	-660
SE	3372	3430	5699	5994	10957	0	61	38	192	355	0	0	-3	0	0
SI	0	0	433	0	0	0	0	141	0	0	-391	-180	-420	-268	-965
SK	894	674	530	1114	2033	564	784	619	653	884	-131	0	-303	0	-611
UK	0	0	0	0	1128	0	0	0	0	0	0	0	0	0	-31
Total	**40223**	**41062**	**57366**	**67775**	**133087**	**3203**	**3312**	**5516**	**5717**	**13001**	**-3203**	**-3312**	**-5516**	**-5717**	**-13001**

Table 33 Domestic supply and trade (intra-EU) of biocrude and advanced biofuels per country in the base scenarios (in ktoe/y). Domestic consumption = domestic supply + import – export.

Country	Domestic supply				Net import				Net export			
	2030	2050 LD	2050 HD	2050 RP	2030	2050 LD	2050 HD	2050 RP	2030	2050 LD	2050 HD	2050 RP
Domestic supply and trade of biocrude used for advanced biofuels												
AT	0	0	919	0	0	0	542	0	0	0	-1308	0
BE	0	159	689	0	0	1303	2234	0	0	0	0	0
BG	0	0	1326	0	0	0	136	0	-233	0	-159	0
CY	0	0	0	0	0	0	0	0	0	0	0	0
CZ	0	0	1193	0	0	0	269	0	-505	0	0	0
DE	1264	689	2413	0	1462	345	3344	0	0	0	0	0
DK	0	0	0	0	0	0	0	0	0	0	0	0
EE	0	0	0	0	0	0	0	0	0	0	-1379	0
EL	0	0	0	0	0	0	0	0	-117	0	-3049	0
ES	0	1670	6329	0	0	508	585	0	-427	-848	-1531	-1414
FI	1462	0	1462	0	0	0	0	0	-203	-848	-3908	-619
FR	955	840	4893	0	507	622	2062	0	-253	-853	-1345	-857
HR	0	0	0	0	0	0	0	0	0	0	-548	0
HU	0	0	0	0	0	0	0	0	0	0	-689	0
IT	0	0	1493	0	0	0	1430	0	-198	0	-415	0
IE	0	0	0	0	0	0	0	0	0	0	-71	0
LV	0	0	0	0	0	0	0	0	0	0	-848	0
LT	0	822	822	0	0	640	640	0	-253	0	0	-345
LU	0	0	0	0	0	0	0	0	0	0	0	0
MT	0	0	0	0	0	0	0	0	0	0	0	0
NL	0	0	689	0	1462	1462	3696	2923	0	0	-345	0
PL	0	0	1654	0	0	0	1269	0	-253	-345	-360	0
PT	914	0	1193	0	548	0	146	0	-287	-1379	-1379	-1306
RO	0	0	1462	0	0	0	0	0	0	0	-2595	0
SE	0	0	2757	0	0	0	0	0	-997	-2068	-4188	-961
SI	0	0	0	0	0	0	0	0	0	0	0	0
SK	0	0	0	0	0	0	1462	0	-253	0	-689	-345
UK	0	0	318	0	0	1462	6991	2923	0	0	0	0
Total	**4594**	**4180**	**29613**	**0**	**3978**	**6341**	**24806**	**5847**	**-3978**	**-6341**	**-24806**	**-5847**
Domestic supply and trade of advanced biofuels												
AT	0	398	1569	521	392	311	0	187	0	-795	-39	-274
BE	338	1836	3216	398	566	0	848	1438	0	-170	0	0
BG	174	316	699	316	0	0	0	0	-238	-480	-909	-480
CY	0	0	0	0	0	0	0	0	0	0	0	0
CZ	317	376	675	607	0	230	668	0	-21	-21	-933	-189
DE	2337	2826	7603	4103	372	1736	2496	458	-1906	-300	-876	-7
DK	0	0	583	398	280	522	573	125	0	0	0	0
EE	0	0	0	0	0	0	0	0	0	0	0	0
EL	495	970	981	995	0	25	1222	0	-182	-223	0	-596
ES	1494	3528	7854	3025	312	41	47	543	-198	-2050	-919	-156
FI	222	357	791	357	0	0	0	0	-1328	-836	-817	-836
FR	1577	2977	7904	2386	608	624	67	1214	-650	-222	-1310	0
HR	199	324	717	324	0	0	0	0	-139	-472	-264	-74
HU	241	398	398	398	0	74	647	74	-97	0	0	0
IT	715	2505	5549	2108	1258	862	1906	1260	0	-279	0	-279
IE	0	0	0	398	229	404	895	7	0	0	0	0
LV	0	0	0	0	0	0	0	0	0	-1193	-1193	-795
LT	0	437	968	398	234	0	0	40	0	-1171	-640	0
LU	0	0	0	0	0	0	0	0	0	0	0	0
MT	0	0	0	0	0	0	0	0	0	0	0	0
NL	1106	2006	4824	2536	153	530	790	0	-444	0	0	-1476
PL	1003	1526	3964	1502	0	264	0	288	-351	-65	-1399	-89
PT	339	124	1308	398	0	467	0	193	-1210	-274	-165	0
RO	338	632	1398	632	25	0	0	0	0	-561	-1403	-1273
SE	338	795	1943	935	145	140	128	0	0	0	-1090	-655
SI	0	0	0	0	0	0	0	0	0	0	0	0
SK	118	210	466	210	0	0	0	0	-221	-585	-1142	-187
UK	0	1608	8419	3529	2389	3464	2811	1543	0	0	0	-7
Total	**11352**	**24148**	**61830**	**26472**	**6962**	**9695**	**13098**	**7371**	**-6985**	**-9695**	**-13098**	**-7371**

Table 34 Domestic supply and trade (intra-EU) of biocrude and advanced biofuels per country in the alternative feedstock scenarios (in ktoe/y). Domestic consumption = domestic supply + import – export.

Country	Domestic supply					Net import					Net export				
	2030 (Low)	2030 (High)	2050 LD (Low)	2050 LD (High)	2050 HD (High)	2030 (Low)	2030 (High)	2050 LD (Low)	2050 LD (High)	2050 HD (High)	2030 (Low)	2030 (High)	2050 LD (Low)	2050 LD (High)	2050 HD (High)
Domestic supply and trade of biocrude used for advanced biofuels															
AT	0	0	0	0	344.655	0	0	0	0	1024.98	-435.43	0	0	-201.08	0
BE	0	0	50	0	0	1405	1462	1411	0	2923	0	0	0	0	0
BG	0	0	0	0	0	0	0	0	0	0	-505	-369	0	-193	-121
CY	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CZ	0	0	159	0	0	0	0	415	0	0	-392	-505	0	-283	-1034
DE	969	0	202	0	1603	1390	0	372	574	1314	0	-253	-116	0	-810
DK	0	0	0	0	0	0	0	574	0	0	0	0	0	0	0
EE	0	0	0	0	0	0	0	0	0	0	0	0	-159	0	-880
EL	0	0	0	0	1034	0	0	0	0	104	-253	0	-1460	-345	0
ES	0	0	1386	0	4226	0	0	338	0	159	-821	-253	-1123	-258	-1874
FI	1227	1462	955	0	0	0	0	0	0	0	-128	-144	-1228	-301	-3195
FR	641	0	1333	330	4857	820	0	735	563	125	-440	-946	-794	0	-2941
HR	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-230
HU	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-345
IT	253	253	522	0	504	1209	1209	997	739	958	0	0	-50	0	0
IE	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
LV	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-504
LT	0	0	0	0	1117	0	0	0	0	345	-210	-117	-615	0	-178
LU	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MT	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
NL	0	0	0	0	0	0	0	1462	0	4385	0	0	0	0	0
PL	0	253	0	0	2213	0	982	574	0	613	-253	0	-159	0	-345
PT	0	1182	0	0	1462	0	279	0	0	0	-1123	-334	-1367	-295	-1071
RO	0	0	0	0	0	0	0	0	0	0	0	0	-1283	0	-336
SE	0	0	574	0	1034	0	0	0	0	0	-1095	-758	-1808	0	-3102
SI	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
SK	0	0	0	0	0	0	0	727	0	0	-253	-253	-159	0	-689
UK	0	0	0	0	147	1083	0	2714	0	5700	0	0	0	0	0
Total	**3090**	**3150**	**5181**	**330**	**18541**	**5907**	**3932**	**10321**	**1876**	**17652**	**-5907**	**-3932**	**-10321**	**-1876**	**-17652**
Domestic supply and trade of advanced biofuels															
AT	0	0	0	398	1661	392	392	709	311	0	0	0	-517	0	-1038
BE	904	904	1608	398	3613	0	0	228	1438	690	-585	-645	0	0	0
BG	0	0	316	316	740	174	174	0	0	0	0	0	-364	-480	-453
CY	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CZ	317	317	376	607	1193	0	0	230	0	229	-21	-360	-255	-586	0
DE	2337	2268	2204	3728	7861	372	441	2358	834	2832	-1179	-440	0	-1278	-914
DK	0	0	522	398	795	280	280	0	125	429	0	0	-110	0	0
EE	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
EL	495	338	909	597	2321	0	156	86	398	12	-182	0	-621	-198	-522
ES	1638	1097	3158	3556	8143	192	733	411	13	223	-393	-257	-1123	-1216	-1241
FI	222	222	357	357	838	0	0	0	0	0	-1079	-1328	-961	-1233	-773
FR	1596	1015	3371	2476	7841	589	1169	229	1124	600	-631	0	-216	-1290	-1193
HR	199	199	324	324	759	0	0	0	0	0	-139	-139	-74	-74	-37
HU	241	241	398	398	692	0	0	74	74	414	-97	-97	-398	0	-501
IT	1833	1875	2852	2767	5187	139	98	515	600	2707	-731	-690	-409	-34	0
IE	0	0	0	0	398	229	229	404	404	550	0	0	0	0	0
LV	0	0	0	0	0	0	0	0	0	0	0	0	-795	-1193	-1591
LT	0	0	0	398	1025	234	234	437	40	0	0	0	0	0	-980
LU	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
MT	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
NL	0	338	1916	706	5619	1259	920	620	1830	325	0	0	-90	-90	0
PL	1003	1003	1502	1791	4197	0	0	288	0	0	-351	-1659	-323	-595	-1669
PT	0	339	398	591	1385	339	0	193	0	0	0	-1210	0	-1000	-223
RO	338	338	632	632	1481	25	25	0	0	0	0	0	-876	-561	-1701
SE	338	454	877	911	2193	145	30	58	24	0	0	-223	-550	-1873	-933
SI	0	0	0	0	0	0	0	0	0	0	0	0	-258	0	0
SK	118	118	210	210	398	0	0	0	0	96	-221	-221	-987	-585	-398
UK	1148	0	2986	0	6829	1241	2389	2086	5072	5061	0	0	0	0	0
Total	**12728**	**11068**	**24917**	**21556**	**65169**	**5610**	**7269**	**8926**	**12287**	**14166**	**-5610**	**-7269**	**-8926**	**-12287**	**-14166**

REFERENCES

Agronomic Crops Netwtok Ohio State University. (2017). *Nutrient Value of Wheat Straw*. https://agcrops.osu.edu/newsletter/corn-newsletter/nutrient-value-wheat-straw

Baranzelli, C., Jacobs-Crisioni, C., Batista e Silva, F., Perpiña Castillo, C., Barbosa, A., Arevalo Torres, J., & Lavalle, C. (2014). The Reference scenario in the LUISA platform–Updated configuration 2014. *Towards a Common Baseline Scenario for EC Impact Assessment Procedures. EUR, 27019.*

Brouwer, C., & Heibloem, M. (1986). Irrigation water management: irrigation water needs. *Training Manual*, *3*, 1–5.

Dees, M., Datta, P., Hohl, M., Fitzgerald, J., Verkerk, H., Zudin, S., Lindner, M., Forsell, N., Leduc, S., & Elbersen, B. S. (2017). *D1. 8 Atlas with regional cost supply biomass potentials for EU 28, Western Balkan Countries, Moldavia, Turkey and Ukraine: Issue: 1.1*. S2Biom.

Edwards, R., O'Connell, A., Padella, M., Mulligan, D., Giuntoli, J., Agostini, A., Koeble, R., Moro, A., & Marelli, L. (2017). Definition of input data to assess GHG default emissions from biofuels in EU legislation - Version 1c - July 2017. In *JRC Science for Policy Report EUR* (Vol. 28349). https://doi.org/10.2790/38802

EEA. (2020). *Corine Land Cover (CLC) 2018, Version 2020_20u1*. https://land.copernicus.eu/pan-european/corine-land-cover/clc2018?tab=metadata

EEA. (2023a). *Nationally designated areas (CDDA)*. https://www.eea.europa.eu/en/datahub/datahubitem-view/f60cec02-6494-4d08-b12d-17a37012cb28

EEA. (2023b). *Natura 2000 data - the European network of protected sites*. https://www.eea.europa.eu/en/datahub/datahubitem-view/6fc8ad2d-195d-40f4-bdec-576e7d1268e4

Elbersen, B., VAN VERZANDVOORT, M., BOOGAARD, S., MUCHER, S., CICARELLI, T., ELBERSEN, W., MANTEL, S., BAI, Z., MCAL-LUM, I., & Iqbal, Y. (2020). Deliverable 2.1 Definition and classification of marginal lands suitable for industrial crops in Europe. *EU Horizon*, 60.

Escobar, N., Ramírez-Sanz, C., Chueca, P., Moltó, E., & Sanjuán, N. (2017). Multiyear Life Cycle Assessment of switchgrass (Panicum virgatum L.) production in the Mediterranean region of Spain: A comparative case study. *Biomass and Bioenergy*, *107*, 74–85. https://doi.org/https://doi.org/10.1016/j.biombioe.2017.09.008

EU. (2023a). *REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on ensuring a level playing field for sustainable air transport (ReFuelEU Aviation)* . European Parliament and Council.

EU. (2023b). *REGULATION OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL on the use of renewable and low-carbon fuels in maritime transport, and amending Directive 2009/16/EC*. European parliament and Council.

European Commission. (2018). Directive (EU) 2018/2001 of the European Parliament and of the Council of 11 December 2018 on the promotion of the use of energy from renewable sources (recast). *Official Journal of the European Union*.

European Commission. (2023). *Weekly Oil Bulletin*. https://energy.ec.europa.eu/data-and-analysis/weekly-oil-bulletin_en

Eurostat. (2023a). *Agricultural land renting prices for one year by region*. https://ec.europa.eu/eurostat/databrowser/view/APRI_LRNT__custom_7019166/default/table

Eurostat. (2023b). *Labour cost levels*. https://ec.europa.eu/eurostat/databrowser/view/LC_LCI_LEV__custom_7132103/default/table

Eurostat. (2024). *Crop production in EU standard humidity*. https://ec.europa.eu/eurostat/databrowser/view/APRO_CPSH1__custom_9956092/default/table

Fazio, S., & Monti, A. (2011). Life cycle assessment of different bioenergy production systems including perennial and annual crops. *Biomass and Bioenergy*, *35*(12), 4868–4878.

Forte, A., Zucaro, A., Fagnano, M., Bastianoni, S., Basosi, R., & Fierro, A. (2015). LCA of Arundo donax L. lignocellulosic feedstock production under Mediterranean conditions. *Biomass and Bioenergy*, *73*, 32–47.

García-Condado, S., López-Lozano, R., Panarello, L., Cerrani, I., Nisini, L., Zucchini, A., Van der Velde, M., & Baruth, B. (2019). Assessing lignocellulosic biomass production from crop residues in the European Union: Modelling, analysis of the current scenario and drivers of interannual variability. *GCB Bioenergy*, *11*(6), 809–831.

Giuntoli, J., Agostini, A., Edwards, R., & Marelli, L. (2017). Solid and gaseous bioenergy pathways: input values and GHG emissions: calculated according to the methodology set in COM (2016) 767: Version 2. *European Commission, Joint Research Centre, Science and Policy Reports, Publications Office of the European Union, Luxembourg*.

González-García, S., Moreira, M. T., Feijoo, G., & Murphy, R. J. (2012). Comparative life cycle assessment of ethanol production from fast-growing wood crops (black locust, eucalyptus and poplar). *Biomass and Bioenergy*, *39*, 378–388.

Gordon, C., Cooper, C., Senior, C. A., Banks, H., Gregory, J. M., Johns, T. C., Mitchell, J. F. B., & Wood, R. A. (2000). The simulation of SST, sea ice extents and ocean heat transports in a version of the Hadley Centre coupled model without flux adjustments. *Climate Dynamics*, *16*, 147–168.

Järveoja, J., Laht, J., Maddison, M., Soosaar, K., Ostonen, I., & Mander, Ü. (2013). Mitigation of greenhouse gas emissions from an abandoned Baltic peat extraction area by growing reed canary grass: life-cycle assessment. *Regional Environmental Change*, *13*(4), 781–795. https://doi.org/10.1007/s10113-012-0355-9

Krzyżaniak, M., Stolarski, M. J., Szczukowski, S., & Tworkowski, J. (2016). Life cycle assessment of new willow cultivars grown as feedstock for integrated biorefineries. *BioEnergy Research*, *9*, 224-238.

KTBL. (2023). *MaKost database*. https://daten.ktbl.de/makost/#notLoggedInInfo?language=de-DE

Kuzma, S., Bierkens, M. F. P., Lakshman, S., Luo, T., Saccoccia, L., Sutanudjaja, E. H., & Van Beek, R. (2023). *Aqueduct 4.0: Updated Decision-Relevant Global Water Risk Indicators*.

Lammens, T., Vis, M., Berg, D. van den, Groot, H. de, Meulenbroek, B. van, Startisky, I., Annevelink, B., Elbersen, W., & Elbersen, B. (2016). *Bio2Match: a Tool for Matching Biomass and Conversion Technologies - S2Biom Deliverable D4.5*.

Lavalle, C., e Silva, F. B., Baranzelli, C., Jacobs-Crisioni, C., Vandecasteele, I., Barbosa, A. L., Maes, J., Zulian, G., Castillo, C. P., & Barranco, R. (2016). Land use and scenario modeling for integrated sustainability assessment. In *European landscape dynamics* (pp. 267–292). CRC Press.

Livingstone, D., Smyth, B. M., Lyons, G., Foley, A. M., Murray, S. T., & Johnston, C. (2022). Life cycle assessment of a short-rotation coppice willow riparian buffer strip for farm nutrient mitigation and renewable energy production. *Renewable and Sustainable Energy Reviews*, *158*, 112154. https://doi.org/https://doi.org/10.1016/j.rser.2022.112154

Mathanker, S. K., & Hansen, A. C. (2015). Impact of miscanthus yield on harvesting cost and fuel consumption. *Biomass and Bioenergy*, *81*, 162–166. https://doi.org/https://doi.org/10.1016/j.biombioe.2015.06.024

Meulen, S. V. D., Grijspaardt, T., Mars, W., Geest, W. V. D., Roest-Crollius, A., & Kiel, J. (2023). *Cost Figures for Freight Transport—Final Report. 2023*. https://www.kimnet.nl/binaries/kimnet/documenten/notities/2023/03/30/kostenkengetallen-voor-het-goederenvervoer/Cost+figures+for+freight+transport_def.pdf

Meys, R., Kätelhön, A., Bachmann, M., Winter, B., Zibunas, C., Suh, S., & Bardow, A. (2021). Achieving net-zero greenhouse gas emission plastics by a circular carbon economy. *Science*, *374*(6563), 71–76.

Monteith, J. L. (1965). Evaporation and environment. *Symposia of the Society for Experimental Biology*, *19*, 205–234.

Monti, A., Fazio, S., & Venturi, G. (2009). Cradle-to-farm gate life cycle assessment in perennial energy crops. *European Journal of Agronomy*, *31*(2), 77–84.

Panoutsou, C., & Maniatis, K. (2021a). Sustainable Biomass Availability in the EU, to 2050. *Concawe: Brussels, Belgium*.

Panoutsou, C., & Maniatis, K. (2021b). Sustainable Biomass Availability in the EU, to 2050. In *Concawe Report RED II Annex IX A/B*.

Perpiña Castillo, C., Lavalle, C., Baranzelli, C., & Mubareka, S. (2015). Modelling the spatial allocation of second-generation feedstock (lignocellulosic crops) in Europe. *International Journal of Geographical Information Science*, *29*(10), 1807–1825.

Ramirez-Almeyda, J., Elbersen, B., Monti, A., Staritsky, I., Panoutsou, C., Alexopoulou, E., Schrijver, R., & Elbersen, W. (2017). Assessing the potentials for nonfood crops. In *Modeling and optimization of biomass supply chains* (pp. 219–251). Elsevier.

Rees, J., Schmer, M., & Wortmann, C. (2017). *Corn Stover Removal: Nutrient Value of Stover and Impacts on Soil Properties*. https://cropwatch.unl.edu/2017/corn-stover-removal-nutrient-value-stover-and-impacts-soil-properties

Rettenmaier, N., Schmehl, M., Gartner, S., & Reinhardt, G. (2018). Final report on environmental assessment covering LCA & LC-EIA. *Seemla Project Reports, Supported by the EU's Horizon 2020 Programme under GA No. 691874*.

Schils, R., Olesen, J. E., Kersebaum, K.-C., Rijk, B., Oberforster, M., Kalyada, V., Khitrykau, M., Gobin, A., Kirchev, H., & Manolova, V. (2018). Cereal yield gaps across Europe. *European Journal of Agronomy*, *101*, 109–120.

Schmidt, T., Fernando, A. L., Monti, A., & Rettenmaier, N. (2015). Life Cycle Assessment of Bioenergy and Bio-Based Products from Perennial Grasses Cultivated on Marginal Land in the Mediterranean Region. *BioEnergy Research*, *8*(4), 1548–1561. https://doi.org/10.1007/s12155-015-9691-1

S&P. (2025). *Study on the potential evolution of Refining and Liquid Fuels production in Europe*.

Szumski, C. (2023, May 8). Sweden lowers fossil fuel reduction targets, risks 2030 climate goals. *EURACTIV*.

The World Bank. (2023). *The World Bank commodities data*. https://databank.worldbank.org/databases/commodity-price-data

Tian, X., Engel, B. A., Qian, H., Hua, E., Sun, S., & Wang, Y. (2021). Will reaching the maximum achievable yield potential meet future global food demand? *Journal of Cleaner Production*, *294*, 126285.

UK office for national statistics. (2023). *Labour costs and labour income, UK*. https://www.ons.gov.uk/economy/economicoutputandproductivity/productivitymeasures/datasets/labourcostsandlabourshare

Van Vuuren, D. P., Stehfest, E., den Elzen, M. G. J., Kram, T., van Vliet, J., Deetman, S., Isaac, M., Klein Goldewijk, K., Hof, A., & Mendoza Beltran, A. (2011). RCP2. 6: exploring the possibility to keep global mean temperature increase below 2 C. *Climatic Change*, *109*, 95–116.

Vera, I., Hoefnagels, R., Junginger, M., & van der Hilst, F. (2021). Supply potential of lignocellulosic energy crops grown on marginal land and greenhouse gas footprint of advanced biofuels—A spatially explicit assessment under the sustainability criteria of the Renewable Energy Directive Recast. *GCB Bioenergy*, *13*(9), 1425–1447.

Wagner, M., Mangold, A., Lask, J., Petig, E., Kiesel, A., & Lewandowski, I. (2019). Economic and environmental performance of miscanthus cultivated on marginal land for biogas production. *Gcb Bioenergy*, *11*(1), 34–49.

Warszawski, L., Frieler, K., Huber, V., Piontek, F., Serdeczny, O., & Schewe, J. (2014). The inter-sectoral impact model intercomparison project (ISI–MIP): project framework. *Proceedings of the National Academy of Sciences*, *111*(9), 3228–3232.