Imperial College London
Consultants

Sustainable biomass availability in the EU, to 2050

Ref: RED II Annex IX A/B

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EXECUTIVE SUMMARY

The aim of this report is to provide an estimation of the sustainable biomass potential availability in the European Union and the UK by 2030 and 2050 and to provide an evaluation of the advanced biofuel potential.

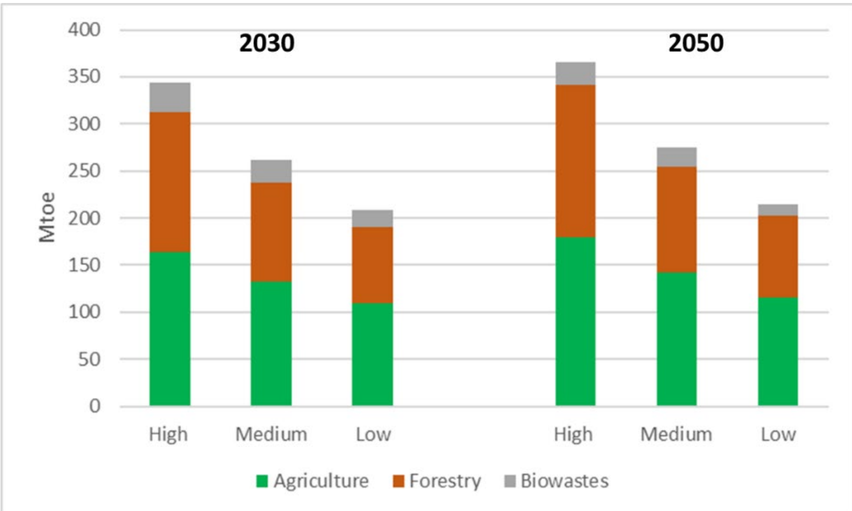
The work presented covers only domestic (EU27 & UK) feedstocks of agricultural, forest and waste origin included in Annex IX of RED II[1] (Part A and B). A short overview of the potential for imports and algae, based on other studies has been included as an Annex. Food and feed crops, and other sustainable feedstocks accepted by RED but not included in Annex IX, are not included in this study.

Three scenarios have been analysed: i) Low biomass mobilisation, ii) improved mobilisation in selected countries due to improvements in cropping and forest management practices and iii) enhanced availability through Research and Innovation (R&I) measures as well as improved mobilisation due to improvements in cropping and forest management practices.

The study analyses firstly the sustainable biomass availability for all markets and then estimates the amount that can be available for bioenergy after excluding the so far known demand from non-energy sectors.

Following, the study presents the status of the various technologies and value chains based on their maturity for market deployment and assesses the potential production of sustainable advanced biofuels for 2030 and 2050 on the basis of the biomass potentials calculated in in the previous part.

The maturity of the biomass conversion technologies in 2030 can be discussed with a certain degree of confidence however, for 2050 it is difficult to make assumptions on the status of the various biomass conversion technologies. Overall conservative assumptions have been taken into account.



Sustainable biomass availability (feedstocks mentioned in RED II Annex IX Part A and B) for bioenergy in 2030 and 2050 (in Mtoe) as estimated in this Imperial College London study.

Key facts for sustainable biomass availability in 2030 and 2050 are as follows:

- Sustainable biomass for all markets: 0.98 to 1.2 billion dry tonnes (392 to 498 Mtoe) can be available in 2030 and 1 to 1.3 billion tonnes (408 to 533 Mtoe) in 2050. From this, the estimated amount for bioenergy ranges from 520- 860 million dry tonnes (208-344 Mtoe) in 2030 and 539 -915 million dry tonnes (215-366 Mtoe) in

[1] https://ec.europa.eu/jrc/en/jec/renewable-energy-recast-2030-red-ii

2050. The reasons that potentials remain similar despite improvements in biomass mobilisation and increased research and innovation for higher yields are mostly related to:

- policies and regulations for the sustainable use of land and water resources, including a 30% reduction in agricultural land by 2050,
- improvements in forest management are slow due to the long growing cycles of forests that prohibit fast changes in growth of potentials, and
- increased awareness for waste reduction and strong regulations and requirements for recycling.

Key findings for future market deployment of biofuels are:

- In the 2050 timeframe it is assumed that sufficient quantities of renewable hydrogen will be available to be used in advanced biofuel thermochemical conversion technologies to increase the yield of advanced biofuels by converting the carbon in carbon monoxide and carbon dioxide to hydrocarbon fuel.
- For 2030 and 2050, the success of synthetic biofuels via the gasification technology, and especially for Fischer-Tropsch biofuels, is very critical because this value chain can offer the highest conversion yield to biofuel. When combined with renewable hydrogen, Fischer-Tropsch becomes the most productive route to convert lignocellulosic biomass to advanced biofuels with very high conversion yields.
- Hydrotreated lipids is and will remain the most developed value chain to produce hydrocarbon fuels, however, the long-term contribution of this value chain is hampered by the availability of lipids that meet the sustainability requirements of Annex IX of the Renewable Energy Directive.
- Cellulosic ethanol will play a key role in the near to medium term, but its significance will decrease with the exception of further converting it to hydrocarbon fuels.
- In the short to medium term coprocessing fast pyrolysis biooil in petroleum refineries can play a significant role if technical hurdles are solved. In the long term; and with the supply of renewable hydrogen; stand-alone fast pyrolysis and hydrothermal liquefaction biomass to biofuel plants can compete in the market.

The total estimated net biomass that can be used for biofuel production, including imports (49 Mtoe in 2030 and 56 Mtoe in 2050) and deducting the use of biomass for other non-transport (power, industry, service, agriculture and residential) related uses (130 Mtoe in 2030 and 170 Mtoe in 2050 according to the European Commission Impact Assessment[2]), has been estimated at **126-262 Mtoe for 2030** and **101 – 252 Mtoe for 2050** (note: the ranges correspond to the lowest and highest biomass availability scenarios).

This corresponds to advanced and waste-based biofuel production of **46 – 97 Mtoe for 2030** and **71 – 176 Mtoe for 2050**.

It is important to highlight that the biomass potential availability estimated in this study are based on very conservative assumptions. Furthermore, the potentials from algal biofuels plus other sustainable biomass feedstocks not included in RED II Annex IX have not been taken into consideration at all in the above calculations. Therefore, it can be concluded that the biomass potentials in 2030 and 2050 would most probably be higher than those estimated by this study.

However, to realise this potential, additional R&D would be required as well as the implementation of improved management strategies. Even if the potential is there, the supply chain would need to be developed to mobilise all these resources. This means that an enormous effort must be done in all Member States, as the maturity and reliability of several key biomass conversion technologies is still an issue and their progress towards market deployment is an important concern.

[2] Figure 77, Use of Bioenergy by sector and scenario, page 95, EC, Impact assessment, Stepping up Europe's 2030 climate ambition, SWD (2020) 176 Final, 17.9.2020

[1] INTRODUCTION

Context and the need for an updated view on potentials

Within the framework of the European Union low emissions strategy, Concawe is exploring a cross-sectorial Low Carbon Pathways (LCP) programme, identifying opportunities and challenges for different low-carbon technologies and feedstocks to achieve a significant reduction of the CO_2 emissions associated with both the manufacturing and use of refined products in Europe in the medium (2030) and longer-term (2050). Accessibility to sustainable low-carbon bio-feedstock is one of the key drivers to achieve an EU low-carbon economy by 2050:

- The European Commission's long-term strategic vision 'A Clean Planet for all' recognises the role of biofuels and biogas in the transport sector in all the scenarios.
- It is also a central piece in the 'Vision 2050' of the refining industry to ensure that the deployment of "low carbon fuels", and specifically the advanced biofuels, for the EU transport sector could be effectively realised with no availability constraints provided that the right framework conditions to leverage the full potential of the whole bioeconomy are put in place.

In this context, one of the key questions regarding the role of bio-feedstocks in transport sector is the potential availability of sustainable biomass (included in annex IX A and B of RED II) in EU and UK, and under which conditions and assumptions biomass availability can be improved and the biomass potential can be sustainably maximised by 2050 within safe planetary boundaries and without causing any other negative impacts (e.g. preserving high nature value areas, maintaining and improving biodiversity, reducing the use of arable land as well as the use of fertilisers and other chemical inputs).

How does the Imperial College London study capitalise on knowledge and experience from previous research and what 'new thinking' does the study introduce?

This study capitalises on knowledge and findings from relevant initiatives and studies that have addressed feedstocks across all EU Member States [3,4,5,6] with harmonised datasets and methodological approaches[7]. The analysis focuses in particular on the work conducted by JRC and DG RTD:

- JRC. 2015 (2019). ENSPRESO - an open data, EU-28 wide, transparent, and coherent database of wind, solar and biomass energy potentials.[8]

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[3] For the ones before 2020 the United Kingdom is included.

[4] Elbersen, B., Staritsky, I., Hengeveld, G., Jeurissen, L., Lesschen, J.P. & C.Panoutsou (2016) Outlook of spatial biomass value chains in EU28. Deliverable 2.3 of the Biomass Policies project http://iinas.org/tl_files/iinas/downloads/bio/biomasspolicies/Elbersen_et_al_2016_Outlook_of_spatial_biomass_value_chains_in_EU28_(D2.3_Biomass_Policies).pdf

[5] Dees, M., Elbersen, B., Fitzgerald, J., Vis, M., Anttila, P., Forsell, N., Ramirez-Almeyda, J., Glavonjic, B., Staritsky, I., Verkerk, H., Prinz, R., Leduc, S., Datta, P., Lindner, M., Zudin, S., Höhl, M., 2017b. Atlas with regional cost supply biomass potentials for EU 28, Western Balkan Countries, Moldavia, Turkey and Ukraine. Project Report. S2BIOM – a project funded under the European Union 7th Framework Programme for Research. https://www.s2biom.eu/images/Publications/D1.8_S2Biom_Atlas_of_regional_cost_supply_biomass_potential_Final.pdf

[6] BioSustain: Sustainable and optimal use of biomass for energy in the EU beyond 2020 – An Impact Assessment. https://ec.europa.eu/energy/sites/ener/files/documents/biosustain_report_final.pdf

[7] Panoutsou, C., Bauen, A., Böttcher, H., Alexopoulou, E., Fritsche, U., Uslu, A., … Maniatis, K. (2013). Biomass Futures: An integrated approach for estimating the future contribution of biomass value chains to the European energy system and inform future policy formation. Biofuels, Bioproducts and Biorefining, 7(2), 106– 114. https://doi.org/10.1002/bbb.1367

[8] ENSPRESO - an open data, EU-28 wide, transparent and coherent database of wind, solar and biomass energy potentials | EU Science Hub (europa.eu)

- DG RTD. 2017. Research and Innovation perspective of the mid- and long-term Potential for Advanced Biofuels in Europe[9] [10].

The work presented covers only domestic (EU27 & UK) feedstocks of agricultural, forest and waste origin included in Annex IX of RED II (Part A and B). A short overview of the potential for imports and algae, based on other studies has been included as an Annex. Food and feed crops, and other sustainable feedstocks accepted by RED but not included in Annex IX, are not included in this study (Table 1).

The Imperial College London study considers up-to-date assumptions, that are in line with the European Green Deal, for the sustainable increase of available European biomass acknowledging the biophysical restrictions of land resources and feedstocks as well as the adverse effects of climate change (e.g. desertification, reduced yields, land marginalisation, etc.). The study integrates the counterbalancing mechanisms of using new machinery, efficient crop management practices (seeding/ irrigation systems, crop rotation, cover crops, agroforestry and disease control in the field) as well as precision farming which will allow to monitor plants' development in the field and better target the needs as well as to ease farm management.

An Annex is included at the end of this report describing the methodologies used for the estimation of sustainable biomass availability.

This is Part I of the study (biomass availability estimation for all markets and the bioenergy). There is a Part II where we investigate the potential biofuel production and an excel file with the detailed data.

[9] Research and innovation perspective of the mid-and long-term potential for advanced biofuels in Europe - Publications Office of the EU (europa.eu)

[10] https://op.europa.eu/en/publication-detail/-/publication/448fdae2-00bc-11e8-b8f5-01aa75ed71a1

Table 1 Biomass feedstocks from Annex IX (Part A and B) considered in the Imperial College London study[11]

Annex IX Part A	Agricultural feedstocks	Forest feedstocks	Biowastes	Algae
(a) Algae if cultivated on land in ponds or photobioreactors				Overview based on recent studies
(b) Biomass fraction of mixed municipal waste, but not separated household waste subject to recycling targets under point (a) of Article 11(2) of Directive 2008/98/EC			Paper cardboard, Wood waste, Animal & mixed food waste, Vegetal waste, Municipal solid waste (MSW),	
(c) Biowaste as defined in point (4) of Article 3 of Directive 2008/98/EC from private households subject to separate collection as defined in point (11) of Article 3 of that Directive;			Paper cardboard, Wood waste, Animal & mixed food waste, Vegetal waste, Municipal solid waste (MSW)	
(d) Biomass fraction of industrial waste not fit for use in the food or feed chain, including material from retail and wholesale and the agro-food and fish and aquaculture industry, and excluding feedstocks listed in part B of this Annex	Secondary agricultural residues from agro-industries			
(e) Straw	Cereal straw, maize stover			
(f) Animal manure and sewage sludge	Solid and liquid manure from poultry, pigs, cattle		Sewage sludge	
(o) Biomass fraction of wastes and residues from forestry and forest-based industries, namely, bark, branches, pre- commercial thinnings, leaves, needles, treetops, saw dust, cutter shavings, black liquor, brown liquor, fibre sludge, lignin and tall oil;		Primary forest residues Secondary forest residues		
(p) Other non-food cellulosic material	Oilseed crop residues Agricultural prunnings			
(q) Other lignocellulosic material except saw logs and veneer logs		Fuelwood, Post-consumer wood		
Annex IX Part B				
(a) Used cooking oil			Used Cooking oil	
(b) Animal fats classified as categories 1 and 2 in accordance with Regulation (EC) No 1069/2009			Animal fats categories 1 and 2 are included in Animal & mixed food waste	

[11] Feedstocks from (g) to (o) [(g) Palm oil mill effluent and empty palm fruit bunches; (h) Tall oil pitch; (i) Crude glycerine; (j) Bagasse; (k) Grape marcs and wine lees; (l) Nut shells; (m) Husks; (n) Cobs cleaned of kernels of corn)] from Annex IX part A have not been included because there were no consistent statistical datasets available at the time of this study.

[2] DEVELOPING SCENARIOS FOR FUTURE BIOMASS AVAILABILITY

This section outlines the key assumptions for the scenarios examined in this study (no double counting has been taken into account in this study). All scenarios were formed under the following principles:

A. *Strong political will to deliver the **European Green Deal** targets & increased societal awareness that this is essential to achieve transition to zero carbon, zero pollution economy towards 2050.*

The target of emission cuts to at least 55% of 1990 levels by 2030 has been set[12] within the Green Deal and the European political system has reacted positively. The Next Generation EU scheme has contributed to align Member States around the Green Deal targets, and the management of the scheme is effective. To achieve carbon neutrality by 2050, the Agriculture, Food and Land Use sector (AFOLU) has been targeted with the goal to become carbon neutral by 2035[13]. This implies improvements in cropping and forest practices and reduction of arable land in favour of environmental benefits such as carbon storage, biodiversity, etc.

B. ***COVID-19** shifted attention and funding focus to the transition for zero carbon through **economic recovery** and **social resilience** and **welfare**.*

With the 2020 COVID-19 pandemic spreading rapidly, the focus on the European Green Deal diminished and attention shifted to economic recovery and social resilience. The Commission acted swiftly; the Recovery Package was widely accepted in July 2020[14] aiming to make fighting climate change central to Europe's economic recovery from the coronavirus pandemic. This study considers that the pandemic is not having a negative impact in the biomass deployment but a positive one, as an effective economic recovery can also stimulate the broadening of the biomass feedstock base which in turn will result in economic benefits for local producers[15] [16]. So the Imperial College London study considers the pandemic effects as an opportunity for local, sustainable biomass supply.

C. ***RED II and Annex IX** set the regulatory framework for advanced biofuels, bioliquids and biomass fuels*

Within the 14% target of renewables in transport sector, the Directive establishes a dedicated target for **advanced biofuels and biogas,** as those produced from feedstocks listed in Part A of Annex IX. The contribution of advanced biofuels as a share of final consumption of energy in the transport sector shall be at least 0.2 % in 2022, at least 1 % in 2025 and at least 3.5 % in 2030 (double counted). Part B of Annex IX also includes feedstocks for the production of biofuels and biogas for transport, the contribution of which towards the minimum share of 14% shall be limited and may be considered to be twice their energy content. These are: (a) Used cooking oil; (b) Animal fats classified as categories 1 and 2 in accordance with Regulation (EC) No 1069/2009.

This study will assess what is the role of biomass in meeting both the 2030 and the 2050 targets as set by REDII and the European Green Deal taking the respective ambitions announced by the aviation and maritime sectors into

[12] https://ec.europa.eu/clima/sites/clima/files/eu-climate-action/docs/com_2030_ctp_en.pdf

[13] https://ec.europa.eu/clima/sites/clima/files/eu-climate-action/docs/com_2030_ctp_en.pdf

[14] https://ec.europa.eu/info/strategy/recovery-plan-europe_en (retrieved 21.01.01)

[15] Panoutsou, C.; Chiaramonti, D. Socio-Economic Opportunities from Miscanthus Cultivation in Marginal Land for Bioenergy. Energies 2020, 13, 2741. https://doi.org/10.3390/en13112741

[16] L., Traverso; E., Mazzoli; C., Miller; G., Pulighe; C., Perelli; M. M., Morese; G., Branca. 2021. "Cost Benefit and Risk Analysis of Low iLUC Bioenergy Production in Europe Using Monte Carlo Simulation" Energies 14, no. 6: 1650. https://doi.org/10.3390/en14061650

consideration[17] [18] [19]. This study focused on feedstock listed in RED II Annex IX part A and B (Table 1 Biomass feedstocks from Annex IX (Part A and B) considered in the Imperial College London study).

In addition to the feedstocks in Part A and Part B of Annex IX the Commission is currently performing a study[20] for a longlist of feedstocks that are under consideration for inclusion in Annex IX, namely: Potato/beet pulp, Sugars (fructose, dextrose), Molasses, Vinasses, Spent grains, Whey permeate, Olive pomace, Raw methanol, Oil, beans and meals derived from rotation crops, Biomass from fallow land, Biomass from degraded / polluted land, Mixture meadow, Damaged crops, Animal residues (not fat, cat 2 and cat 3), Animal fats Cat 3, Municipal wastewater and derivatives (other than sludge), Soapstock and derivatives, Brown grease, Fatty acid distillates (FADs), Various oils from ethanol production, Distillers grain and solubles (DGS), Other biowaste.

From the above list the Imperial College London study considers biomass from degraded land only where lignocellulosic biomass crops can be grown. The study does not consider the other feedstocks due to lack of statistical timeseries of data that can form a dataset comparable to the ones used for all countries for agriculture, forestry and wastes. Food and feed crops and other feedstocks that are currently used in the EU for biofuel production and accepted by RED but not included in RED II Annex IX, have not been included in this study.

D. ***Low ILUC risk** concept*

The RED II Directive also introduces another concept: the Low-ILUC (Indirect Land Use Change) risk biofuels, bioliquids and biomass fuels, which will represent one of the main options to maintain current shares of renewables in transport and further develop the sustainable biofuels market potential in Europe from 2023 onwards, especially in sectors with limited short-term alternatives such as aviation, heavy duty road transport and maritime. The criteria for certification of low indirect land-use change-risk biofuels, bioliquids and biomass fuels have been outlined in the Commission Delegated Regulation (EU) 2019/807 of 13 March 2019[21] supplementing Directive (EU) 2018/2001. This Delegated Regulation defines low ILUC risk biofuels, bioliquids and biomass fuels as those 'that are produced under circumstances that avoid ILUC effects, by virtue of having been cultivated on unused[22], abandoned[23] or severely degraded[24] [25]land or emanating from crops which benefited from improved agricultural practices [26,27].

As of today, only palm oil has been identified as a high-ILUC feedstock. The Low-ILUC risk concept has first been developed to propose an alternative to use, in certain conditions, high-ILUC risk feedstocks to produce biofuels.

In addition, the REDII provides support for feedstock which has low indirect land-use change impacts when used for biofuels. The REDII Recitals says that this should be promoted for its contribution to the decarbonisation of the

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[17] European Union Aviation Safety Agency, EASA, European Aviation Environmental Report 2019

[18] ICAO/CORSIA. www.icao.int/environmental-protection/CORSIA/Pages/default.aspx

[19] https://safety4sea.com/eu-commission-to-propose-shipping-inclusion-in-ets-in-march/

[20] https://www.e4tech.com/resources/239-assessment-of-the-potential-for-new-feedstocks-for-the-production-of-advanced-biofuels-renewable-energy-directive-annex-ix.php

[21] https://eur-lex.europa.eu/legal-content/EN/TXT/PDF/?uri=CELEX:32019R0807

[22] 'unused land' means areas which, for a consecutive period of at least 5 years before the start of cultivation of the feedstock used for the production of biofuels, bioliquids and biomass fuels, were neither used for the cultivation of food and feed crops, other energy crops nor any substantial amount of fodder for grazing animals;

[23] 'abandoned land' means unused land, which was used in the past for the cultivation of food and feed crops but where the cultivation of food and feed crops was stopped due to biophysical or socioeconomic constraints;

[24] 'Severely degraded land' means land that, for a significant period of time, has either been significantly salinated or presented significantly low organic matter content and has been severely eroded.

[25] So far the definitions for marginal land are not clearly defined.

[26] https://ec.europa.eu/energy/sites/ener/files/documents/2_en_act_part1_v3.pdf

[27] https://ec.europa.eu/transparency/regdoc/rep/1/2019/EN/COM-2019-142-F1-EN-MAIN-PART-1.PDF

economy. This study includes the low ILUC risk concept to the scenario assumptions by addressing improved yields and exploitation of unused, abandoned or severely degraded land for biomass production.

E. Contribution of ***aquatic biomass***

Algae has been incuded taking into account the DG RTD study and a recent overview from JRC (see Annex I). This feedstock is not exhaustively evaluated as part of this study as it has been done with agriculture, forestry and biowastes.

F. Biomass for biobased products

Allocation of biomass raw materials to biobased products (bioplastics, biopharmaceuticals, construction materials, biochemicals, etc.) in this study has been performed by estimating the baseline sustainable potentials for all uses (i.e. bioenergy and biobased products and deducting the demand for each feedstock category and sector based on the projections of the CAPRI model[28] and statistics from JRC[29] . The remaining potential is then considered as available for all bioenergy applications (transport, heat, power, industry, agriculture, service and buildings).

G. Biodiversity

This study accounts for biodiversity risks as set in REDII. All three scenarios evaluated (explained below) increase in biomass availability without including biomass from:

- Conservation of land with significant biodiversity values (such as areas of High Nature Value, NATURA, etc.) which usually covers protected sites. The category assesses the risk of disturbing conservation land, including NATURA2000 and High Nature Value (HNV) farmland. In the potentials assessed in this study no such land is being considered as available for biomass feedstocks.
- Land management without negative effects on biodiversity: this study accounted for cultivation practices which are based on the following principles: use of domestic species and local varieties, avoiding monocultures and invasive species, preferring perennial crops and intercropping, use of methods causing low erosion and machinery use, low fertilizer and pesticide use and avoiding active irrigation.

H. Imports

Imported lignocellulosic biomass (pellets from agricultural residues, wood pellets and utilised cooking oil) for bioenergy has been addressed in this study (see Annex II) based on recent statistics and projections from recent relevant literature[30] [31] [32].

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[28] https://www.capri-model.org/dokuwiki/doku.php

[29] DataM - Home page - European Commission (europa.eu)

[30] Spöttle, et al (2013). Low ILUC potentials of wastes and residues for biofuels – Straw, forestry residues, UCO, corn cobs. Ecofys Netherlands B.V

[31] Biotrade2020(2016). See https://www.biotrade2020plus.eu/publications-reports.htm

[32] Ayla Uslu, Joost van Stralen & Larissa Pupo Nogueira. 2020. D6.2 RESfuels in transport sector. http://www.advancefuel.eu/contents/reports/d-62-deliverable-final-15may.pdf

SCENARIOS FOR THE ASSESSMENT OF SUSTAINABLE BIOMASS AVAILABILITY

Three scenarios have been analysed in the study: i) Low biomass mobilisation, ii) improved mobilisation in selected countries due to improvements in cropping and forest management practices and iii) enhanced availability through Research and Innovation (R&I) measures as well as improved mobilisation due to improvements in cropping and forest management practices.

SCENARIO 1: LOW MOBILISATION (LOW)

This scenario assumes low mobilisation of biomass for both 2030 and 2050. Key assumptions include:

- Farming and forest practices at 2020 levels.
- Small parts (25%) of unused, abandoned and degraded land are used for biomass crops.
- Emphasis is placed in residues and wastes for use in the energy and non-energy biobased sectors.

Biodiversity is included in the estimated potentials accounting for: i) conservation of land with significant biodiversity values (both direct and indirect), and ii) land management without negative effects on biodiversity.

SCENARIO 2: IMPROVED MOBILISATION IN SELECTED COUNTRIES (MEDIUM)

This scenario focuses on improved mobilisation which is the result of improvements in cropping and forest management practices. These take place in countries with high biomass availability (total estimated biomass potential ≥20 million tonnes per year) and in combination with either good institutional framework, established policies/ targets for bioenergy or advanced biofuels, strong infrastructure and strong innovation profiles (Germany, France, Sweden, Finland, Italy, United Kingdom, Austria, Spain) or in countries with low biomass supply costs (Poland, Romania, Czech Republic, Hungary, Bulgaria). Key assumptions include:

- Improved management practices in i) agriculture such as crop rotation, cover crops, agroforestry, etc. which can improve soil and increase biomass productivity and ii) forestry such as improved harvesting techniques, fertilisation (where possible), storage and transport optimisation, etc.
- Significant parts (50%) of unused, abandoned and degraded land are used for biomass crops.
- Emphasis remains on the use of residues and wastes in the energy and non-energy biobased sectors.

Biodiversity is included in the estimated potentials accounting for: i) conservation of land with significant biodiversity values (direct and indirect), and ii) land management without negative effects on biodiversity.

SCENARIO 3: ENHANCED AVAILABILITY THROUGH R&I & IMPROVED MOBILISATION (HIGH)

This scenario refers to all EU27 Member States and the United Kingdom and applies the highest rates for assumptions on increased mobilisation as well as increased improvements in management practices which can maximise the sustainable biomass availability across all feedstocks.

- Improved management practices in i) agriculture such as crop rotation, cover crops, agroforestry, etc. which can improve soil and increase biomass productivity and ii) forestry such as improved harvesting techniques, fertilisation (where possible), storage and transport optimisation, etc.
- Significant parts (75%) of unused, abandoned and degraded land are used for biomass crops.
- Improved research & innovation which results in higher yields; higher equipment efficiency for harvesting, crop species and varieties more resistant to climate change effects (such as high temperatures, prolonged dry periods, etc.)
- Emphasis remains on the use of residues and wastes in the energy and non-energy biobased sectors.

Biodiversity is included in the estimated potentials accounting for: i) conservation of land with significant biodiversity values (direct and indirect), and ii) land management without negative effects on biodiversity.

Table 2 Main assumptions for the three scenarios examined in the Imperial College London study describes the main assumptions for the three scenarios.

Table 2 Main assumptions for the three scenarios examined in the Imperial College London study

	Scenario 1 (Low)	Scenario 2 (Medium)	Scenario 3 (High)
Agriculture			
Removal rate of field residues	40%	45%	50%
Use of prunings	5%	20%	50%
Moderate yield increases in perennial lignocellulosic crops in unused, degraded and abandoned land	1%	1%	2%
Share of unused, degraded and abandoned land for dedicated crops, excluding biodiversity rich land and on land with high carbon stocks (Current share of unused, degraded and abandoned land for dedicated crops: There are no offical statistics- only at experimental and demonstration scale)	25%	50%	75%
Forestry			
Stem wood used for energy purposes[33] (Current stemwood for energy: 45%)	25%	30%	50%
Primary forestry residues availability for energy production	40%	50%	60%
Secondary forestry residues and post consumer wood availability for energy	55%	60%	65%
Wastes			
Biowaste used for energy production (Current collection for bioenergy: 40-45%)	60% in 2030 (65% in 2050) of biowaste is recycled and 40% in 2030 (35% in 2050) is separately collected and available for bioenergy	50% in 2030 (55% in 2050) of biowaste is recycled and 50% in 2030 (45% in 2050) is separately collected and available for Anaerobic Digestion	40% in 2030 (45% in 2050) of biowaste is recycled and 60% in 2030 (55% in 2050) is separately collected and available for Anaerobic Digestion

Table 3 compares the scenarios used in the JRC TIMES, DG RTD and this Imperial College London study.

[33] This concerns the fuelwood potential from roundwood and unused forest biomass currently unexploited. All material uses of stemwood were subtracted and only the stemwood currently used as fuelwood was incorporated in the potential.

Table 3 Key scenario assumptions for the Imperial College London, JRC TIMES and DG RTD studies

	Imperial College London	JRC TIMES	DG RTD	Comments on similarities/ differences
Agriculture				
Removal rate of field residues	40%; 45%; 50%	0-30%; 30%; 40%	20-50%	The removal rates across the studies are similar for the improved mobilisation scenario with a maximum of 40% - 50%
Removal rate of prunnings for energy	50%; 60%; 80%	10-20%; 40%; 60-90%	There is no indication of the % used	Agricultural prunnings are mostly used for energy purposes
Yield increases in perennial lignocellulosic crops in unused, degraded and abandoned land	1%; 1%; 2%	0.25; 0.5%; 1%	In the enhanced scenario, yield increase is 50% more than cereals	Yield increase rates are similar to al studies
Share of unused, degraded and abandoned land for dedicated crops[34]	25%; 50%; 75%	25%; 50%; 100%		Growing first generation crops and using arable land for bioenergy crops is included in JRC Times High Scenario (not in DG RTD). JRC TIMES in the high scenario (100%) is considered unrealistic in the context of the European Gren Deal.
Forestry				
Stem wood used for energy purposes	25%; 30%; 50%	45%; 48-58%; 55-77%	35%-50%	The % of stemwood for energy is similar with the exception of JRC TIMES in the high scenario (77%). The latter is considered unrealistic in the context of the European Gren Deal.
Primary forestry residues availability for energy production	40%; 50%; 60%	40-50%; 40-50%; 100%	35%-50%	The ratio of forest residues available for energy is similar with the exception of JRC TIMES in the high scenario (100%). The latter is considered unrealistic in the context of the European Gren Deal.
Secondary forest residues and post consumer wood	55%, 60%, 65%			
Wastes				
Biowaste used for energy production	See Table 2	50%; Base year; 80%	0%; 30HH[35]/15non HH%; 50HH/25non HH%	Ratios of biowaste used for energy production is similar with the exception of JRC TIMES in the high scenario (80%). The latter is considered unrealistic with the current planning of the Circular Economy[36].

[34] Current share of unused, degraded and abandoned land for dedicated crops is only at experimental and demonstration scale.

[35] HH: Household; non HH: non Household

[36] https://www.europarl.europa.eu/RegData/etudes/BRIE/2018/614766/EPRS_BRI(2018)614766_EN.pdf

[3] BIOMASS AVAILABILITY FOR ALL MARKETS IN THE EUROPEAN UNION AND THE UK IN 2030 AND 2050

This section provides an overview of the estimated sustainable biomass potential from agriculture, forestry and biowastes that can be available for all markets (energy and non-energy ones). The estimated figures for 2030 range from 0.98 to 1.2 billion dry tonnes (392 to 498 Mtoe). The respective numbers for 2050 remain similar and range from 1 to 1.3 billion tonnes (408 to 533 Mtoe).

The reasons that potentials remain unchanged between 2030 and 2050 despite improvements in biomass mobilisation and increased innovation for higher yields are mostly related to:

i) strong pressure for the sustainable use of land and water resources, including a 30% reduction in arable land by 2050,
ii) the fact that improvements in forest management are slow due to the long growing cycles of forests that prohibit fast changes in growth of potentials, and
iii) increased awareness for waste reduction and strong commitments for recycling.

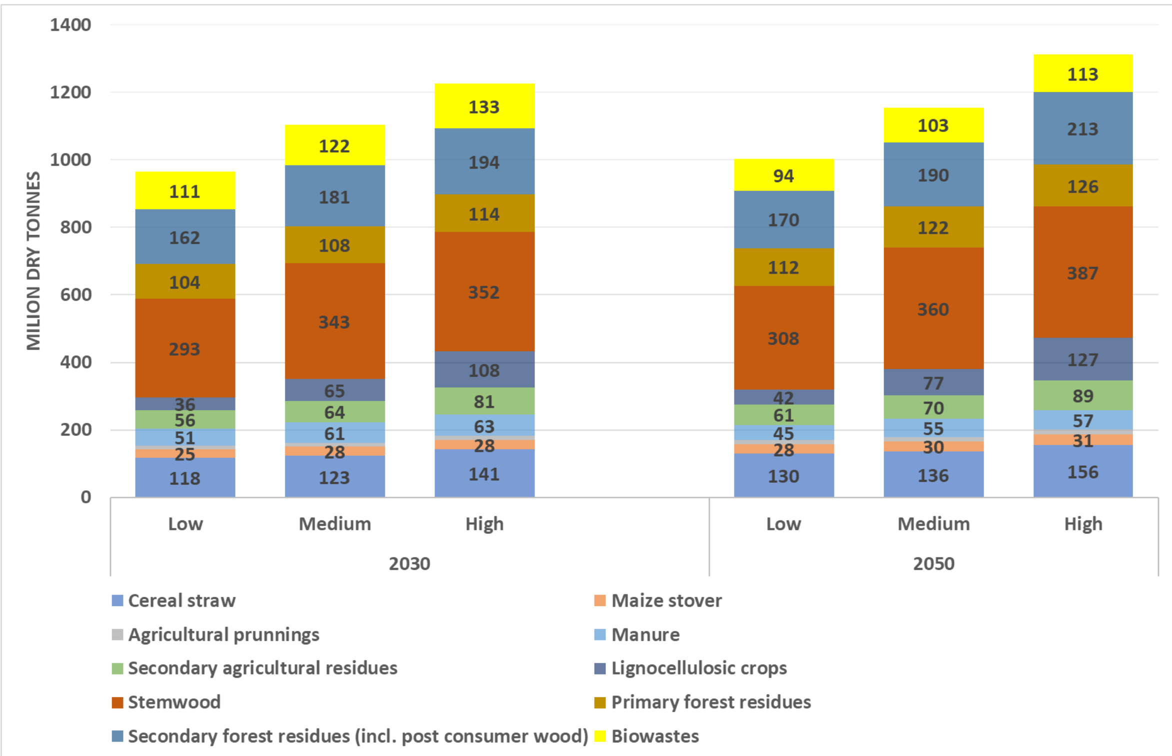

Figure 1 Estimated total sustainable biomass potentials (RED II Annex IX A and B) in 2030 and 2050 for all markets (in million dry tonnes)

Figures 1 and 2 provide an overview of the estimated total sustainable biomass potentials for all markets in 2030 and 2050. Table 4 presents the main opportunities and challenges for broadening the biomass feedstock base.

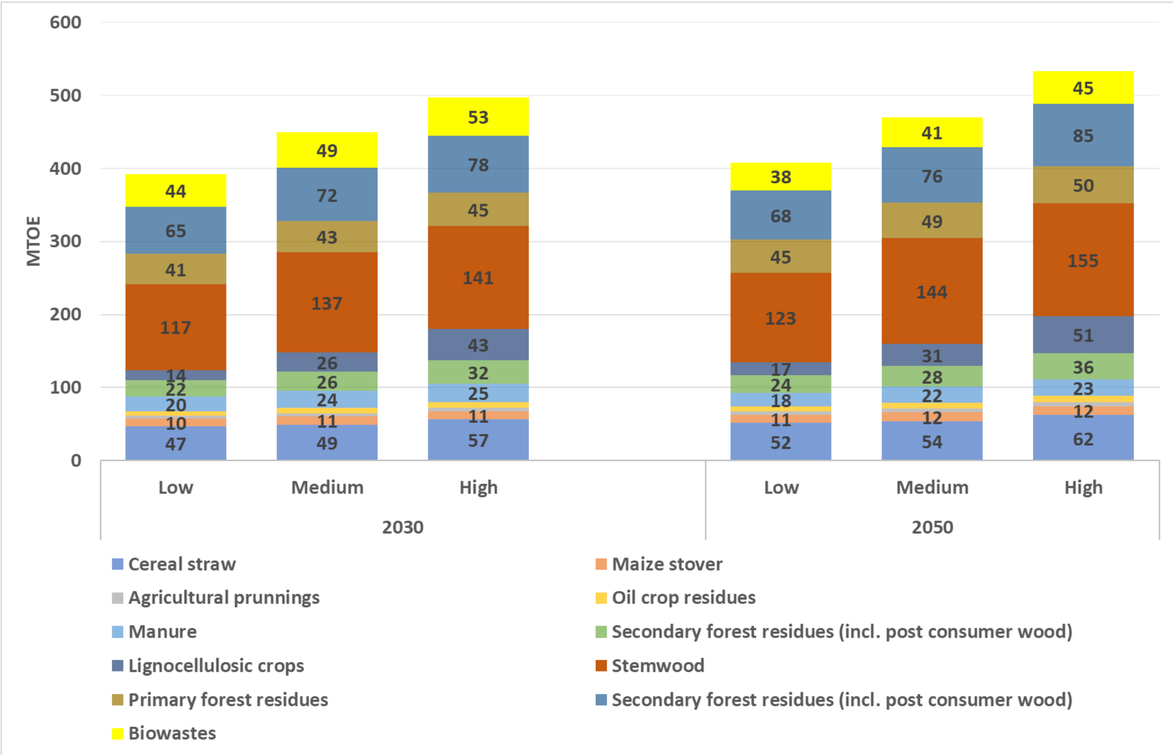

Figure 2 Estimated total sustainable biomass potentials (RED II Annex IX A and B) in 2030 and 2050 for all markets (in Mtoe)

Table 4 Opportunities and challenges for broadening biomass feedstocks

	Opportunities	Challenges
Agriculture	New machinery Efficient crop management practices Precision farming New varieties better adapted to local agroecological conditions. Improved knowledge through smart applications and increased numbers of young farmers and entrepreneurs	Pressure to develop agricultural land for environmental benefits such as carbon storage, biodiversity, etc., Land degradation from soil erosion, nutrient depletion and salinisation, etc.
Forestry	There is a large untapped potential of biomass from forestry. According to Lindner et al. [37] the biggest potentials can be found in Germany, Sweden, France, and Finland. In addition, especially in Southern and Western Europe forest utilization rates are low and in half of the EU countries less than two thirds of annual increment has been harvested [38] [39]. The potential could be further extended by developing technologies to access difficult terrains. Such terrains include steep slopes (especially in Central and Southern Europe) and peatlands (especially in Northern Europe). Digitalization and big data provide opportunities to radical innovations in biomass supply and logistics.	Climate change poses challenges to the whole European forestry. In Southern Europe droughts will be more common reducing growth and increasing risk for fires. In Northern Europe, on one hand, the increased temperatures will increase growth, but on the other hand the risk of natural damages will increase and the conditions for logging and transport deteriorate.
Biowastes	Increase awareness for biowastes collection among the public and especially in the young generation. Improve waste collection schemes across all Member States Use modern industrial separation technologies for maximising organic waste yield out of mixed waste streams.	Rising awareness for waste reduction and increase of recycling rates are expected to reduce biowaste availability at source.

[37] Lindner, M., Dees, M., Anttila, P., Verkerk, P., Fitzgerald, J., Datta, P., Glavonjic, B., Prinz, R. & Zudin, S. 2017. Assessing Lignocellulosic Biomass Potentials from Forests and Industry. In: Panoutsou, C. (ed.). Modelling and Optimization of Biomass Supply Chains: Top-Down and Bottom-up Assessment for Agricultural, Forest and Waste Feedstock. Academic Press. p. 127-167.

[38] FOREST EUROPE, 2015: State of Europe's Forests 2015.

[39] Improving practices for forest biomass supply and logistics. Perttu Anttila, Johanna Routa, Juha Laitila & Antti Asikainen (Luke); Rafaelle Spinelli (CNR). In ETIP Bioenergy. Opportunities and challenges for broadening biomass feedstock in Europe. November 2019 - Opportunities and Challenges for Broadening Biomass Feedstock in Europe (etipbioenergy.eu)

AGRICULTURE

This section presents the estimated biomass potentials from agriculture. It is based on data from statistics and information for all market projections to 2030[40] and 2050[32]. The main elements that form the background of the scenario assumptions in this study are:

Land use developments: Arable land in the European Union and the United Kingdom is expected to decline due to i) pressure to develop such land for environmental benefits such as carbon storage, biodiversity, etc., and ii) land degradation from soil erosion, nutrient depletion and salinisation, etc.

Yield increase: Adverse weather effects due to climate change (prolonged drought, changes in seasonal rainfall patterns, soil erosion, etc.) along with environmental pressures for reduced fertilisers and pesticides are expected to slow yield increases for arable crops. Decreases in arable crops will however be counterbalanced by using new machinery, efficient crop management practices (seeding/ irrigation systems in arable crops which result in field crop residues, crop rotation, cover crops, agroforestry and disease control in the field) as well as precision farming which will allow to monitor plants' development in the field and better target the needs as well as to ease farm management. In this study an average of 1% annual crop yield increase is applied in the estimated potentials.

Arable crops and field crop residues: The EU arable crop area is expected to gradually decline compared to the last decade, but thanks to a small growth in yield a slight production growth is expected[41]. Cereal production is expected to continue its growth by 2030 and then follow a stable trend to 2050, driven by feed demand (in particular for maize), good export prospects (in particular for wheat) and industrial uses for food gaining importance.

[40] OECD-FAO Aglink-Cosimo model. http://publications.jrc.ec.europa.eu/repository/bitstream/JRC92618/jrc92618%20online.pdf

[41] agricultural-outlook-2020-report_en.pdf (europa.eu)

The total estimated amount of biomass from agricultural field residues, secondary agricultural residues, manure and lignocellulosic perennial crops (woody and grasses) ranges from 311 to 452 million tonnes (124 to 181 Mtoe) for 2030 and 335 to 494 million tonnes (134 to 199 Mtoe) for 2050.

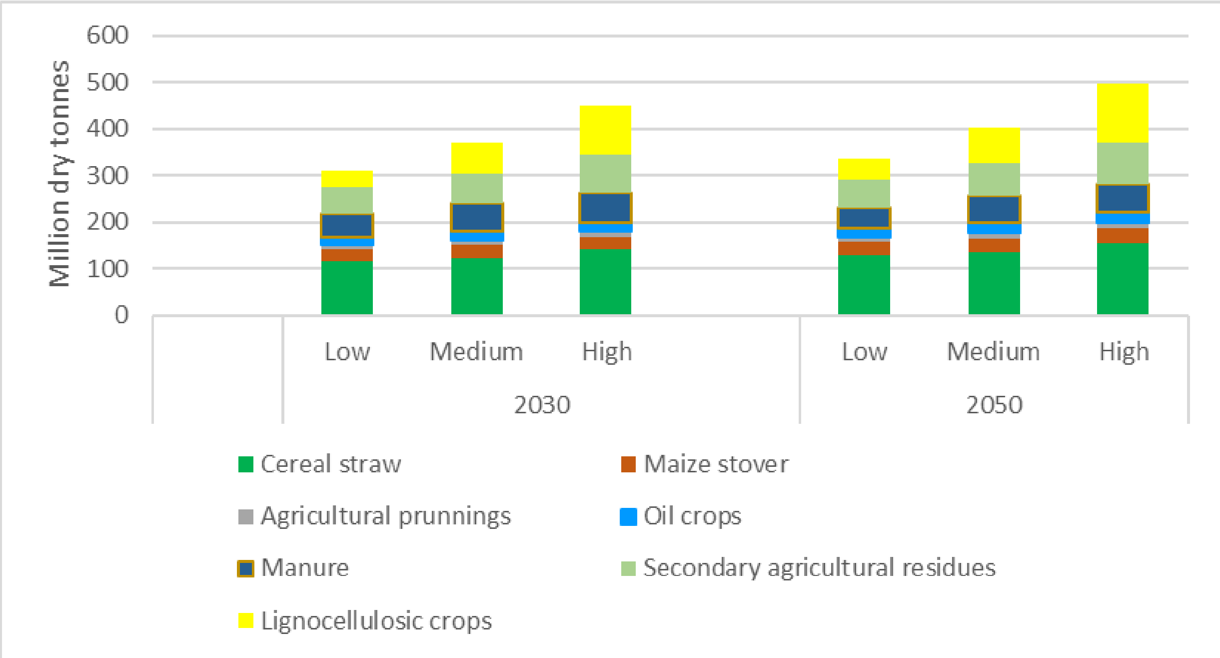

Figure 3 Estimated sustainable biomass potentials for all markets per feedstock type for 2030 and 2050 in million dry tonnes.

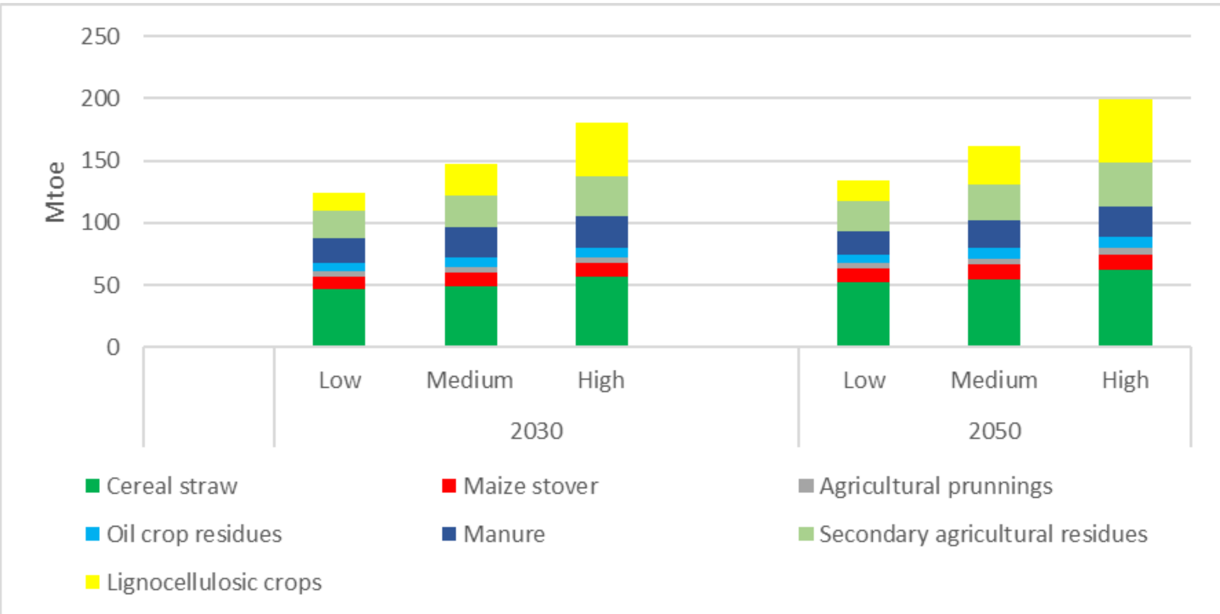

Figure 4 Estimated sustainable biomass potentials for all markets per feedstock type for 2030 and 2050 in Mtoe

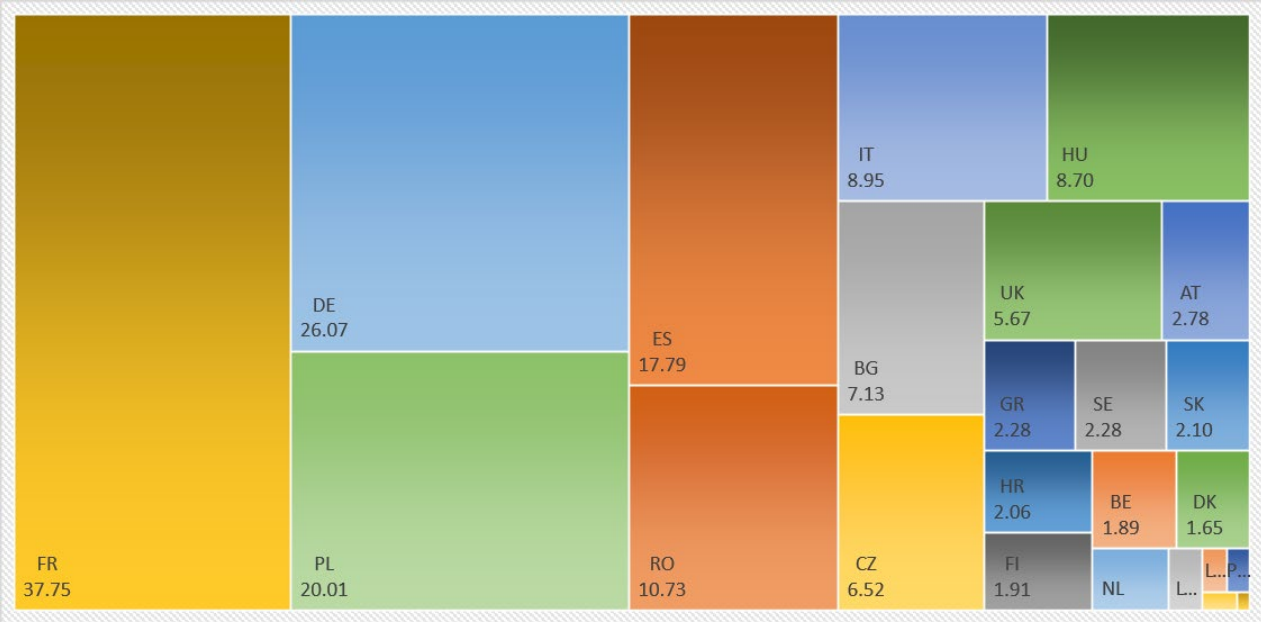

Figure 5 Geographic distribution of agricultural biomass from cereal straw, maize stover, oilseed crop field residues and agricultural prunnings in EU27 & UK (in million dry tonnes for 2030- Low mobilisation scenario). (See Annex X for country names)

Countries with high shares in the estimated potentials are France, Germany, Poland, Spain, Romania, and Italy followed by Hungary, Bulgaria, Czech Republic, and the UK.

Figure 6 shows the geographic distributions of cereal straw, maize stover, oil crop residues and agricultural prunnings.

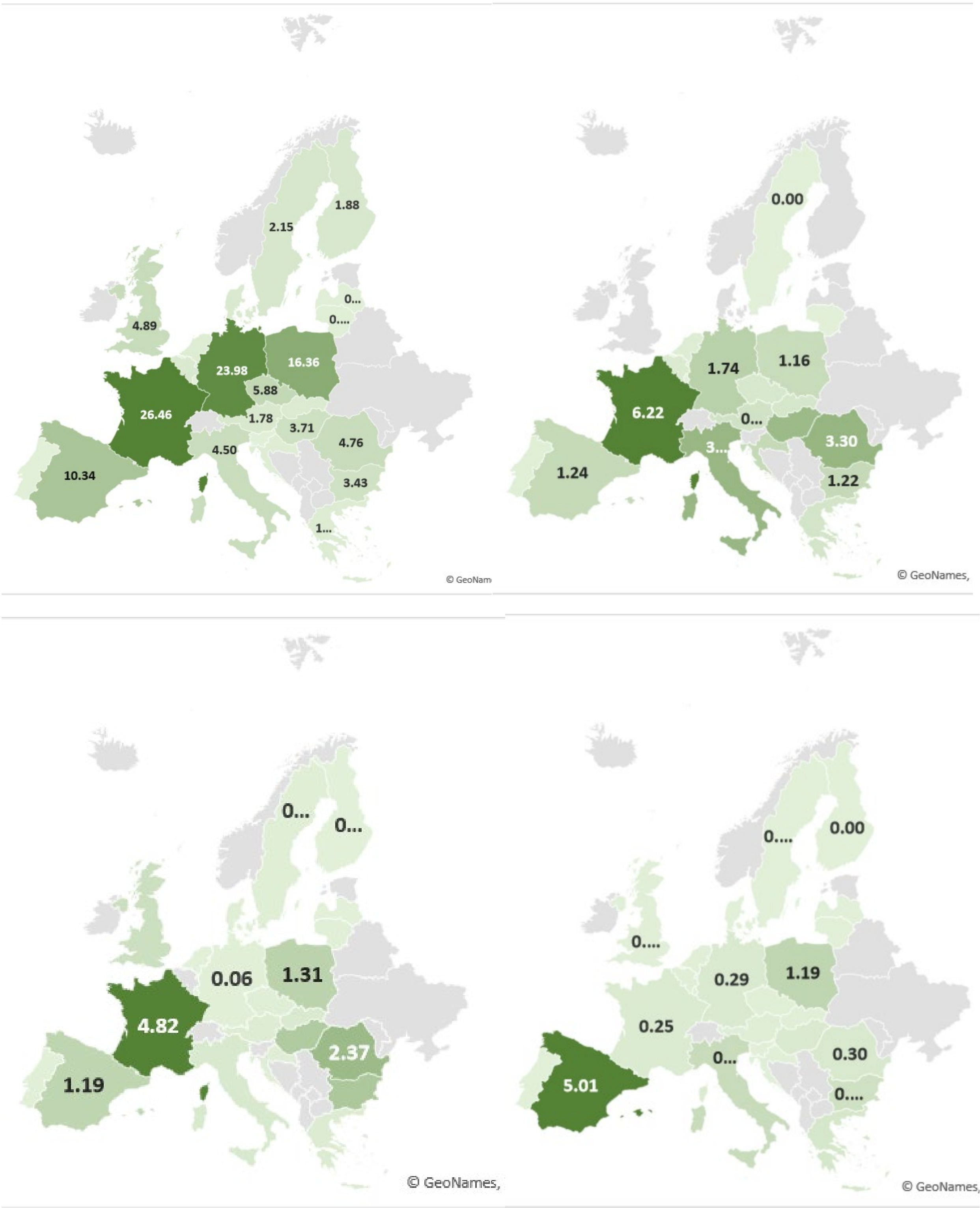

Figure 6 Geographic distributions (in million dry tonnes per year for the Low mobilisation scenario) of cereal straw (top left), maize stover (top right), oilseed crop field residues (bottom left) and agricultural prunnings (bottom right) in 2030.

FIELD CROP RESIDUES

Improvements in agricultural crop yields and in management practices are estimated to increase the biomass potential by 38% in 2050. This will be however counterbalanced with a projected decrease in agricultural area of 30%; therefore, this study considers an average 10% increase of field crop residues from 2030 to 2050. Table 5 Main assumptions for the estimation of agricultural field crop residues potential provides the main assumptions regarding crop and management practice improvements for 2030 and 2050.

Table 5 Main assumptions for the estimation of agricultural field crop residues potential

	Until 2030	Until 2050
Yield increases		
Crop yield improvements	9% (0.9% per year)[42]	18% (0.9% per year)
Management practice improvements	10% (1% per year)	20% (1% per year)
Land availability		
Reduction of arable land	-10%	-30%[43]

CEREAL STRAW

The estimated amount of cereal straw for 2030 in this study ranges from 118 to 141 million tonnes (47 to 57 Mtoe). The respective amount for 2050 ranges from 130 to 156 million tonnes (52 to 62 Mtoe).

MAIZE STOVER

Maize stover consists of the leaves, stalks and empty cobs of grain maize plants left in the field after harvest. Removal rates in this study range from 40 % in the Low Scenario to 50% in the High Scenario. The estimated amount of maize stover for 2030 in this study ranges from 25 to 28 million tonnes (10 to 11 Mtoe). The respective amount for 2050 ranges from 28 to 31 million tonnes (11 to 12 Mtoe).

OIL CROP RESIDUES

Field residues from oil crops include dried stalks of rapeseed, sunflower and soy which remain on the field after the harvest of the grains. The estimated amount of field residues from oilseed crops for 2030 in this study ranges from 16 to 19 million tonnes (6 to 8 Mtoe). The respective amount for 2050 ranges from 17 to 21 million tonnes (7 to 8 Mtoe).

[42] agricultural-outlook-2020-report_en.pdf (europa.eu)

[43] https://www.soilassociation.org/media/18074/iddri-study-tyfa.pdf?mod=article_inline

AGRICULTURAL PRUNNINGS

The prunnings and cuttings of fruit trees, vineyards, olives and nut trees are woody residues often left in the field (after cutting, mulching and chipping). They are the result of normal pruning management needed to maintain the orchards and enhance high production levels. The estimated amount of agricultural prunnings for 2030 in this study ranges from 10 to 12 million tonnes (4 to 5 Mtoe). The respective amount for 2050 increases by 20% and ranges from 12 to 15 million tonnes (5 to 6 Mtoe).

MANURE

The calculation of the manure potential was based on the work from the Biomass Policies project[44] which used the CAPRI livestock and land use patterns (for current and future situation) with the Miterra model. The model calculates per region and farm size group how much solid and wet manure is being produced in stables, as only that part of the manure can be collected. The manure availability is calculated for both liquid and solid manure and is only included in the potential if it is produced on farms with a size threshold above 200 Livestock Units (LU) in the low scenario and 100 LU in the high scenario. The farm size information is obtained from Eurostat Farm Structure Survey (FSS)[45] and developments in farm size from the past (from FSS, 2015) are extrapolated to the future for the situation at country level. Data on housing and grazing systems are derived from the Capri Coco database[46] and are based on national specific data sources. From these data estimates have been made on how many days the animals are inside and how much manure is produced during their stable period. The assumptions for liquid and solid manure are:

Low scenario

Liquid manure: all manure produced in stables at farms >200 LU can go into digestion for 2030. A 10% decrease is estimated for 2050 due to dietary changes (less meat products consumption) that results into lower animal raising.

Solid manure: 50% of the manure produced in stables on farms with >200 LU is included, the remaining 20% is expected to stay on the farm and used as fertiliser.

Medium Scenario

Liquid and solid manure: 20 % increase due to better collection of manure throughout the farms.

High Scenario

Liquid manure: all manure produced in stables at farms >100 LU can go into digestion.

Solid manure: 50% of the manure produced in stables on farms with >100 LU is included, the remaining 20% is expected to stay on the farm and used as fertiliser.

[44] Berien Elbersen, Igor Staritsky, Geerten Hengeveld, Leonne Jeurissen, Jan-Peter Lesschen & Calliope Panoutsou. (2016) Outlook of spatial biomass value chains in EU28. Deliverable 2.3 of the Biomass Policies project http://iinas.org/tl_files/iinas/downloads/bio/biomasspolicies/Elbersen_et_al_2016_Outlook_of_spatial_biomass_value_chains_in_EU28_(D2.3_Biomass_Policies).pdf

[45] https://ec.europa.eu/eurostat/statistics-explained/index.php/Glossary:Farm_structure_survey_(FSS)

[46] https://www.capri-model.org/docs/capri_documentation.pdf#search=%22COCO%22

The estimated amount of manure for 2030 in this study ranges from 51- 63 million dry tonnes (20 to 25 Mtoe). The respective amount for 2050 ranges from 45- 57 million dry tonnes (18 to 23 Mtoe). The slight reduction is due to projected reduction in animal raising towards 2050, due to dietary changes involving lower meat consumption.

For liquid manure cattle is most important in the north-western EU countries. Liquid pig manure availability is much more spread over Europe but is most dominant in the south of Spain and Northern Italy, in the north of Denmark, the Netherlands, Belgium, north-western Germany and Normandy.

For solid cattle manure France, UK, Czech Republic, Northern Italy, Ireland and several regions in Spain seem to be dominant. Solid pig manure potentials are mostly found in Denmark, Poland, Romania, Baltics, Normandy and Northern Spain. Poultry manure has a larger European spread, but is very important in Spain, most of Central East European countries, Northern Italy, France, Netherlands and Flanders. Sheep and goat manure is mostly a potential in Spain, France, Bulgaria and Romania, Ireland and UK.

SECONDARY RESIDUES FROM AGRO-INDUSTRIES

Secondary agricultural residues are produced in the (industrial) processing of agricultural crops into products and include olive pomace and pits, cotton gin trash, almond shells, peach pits, etc.

The estimated potential of secondary residues from agro-industries for all markets for 2030 in this study ranges from 56 to 81 million tonnes (22 to 32 Mtoe). The respective amount for 2050 ranges from 61 to 89 million tonnes (24 to 36 Mtoe).

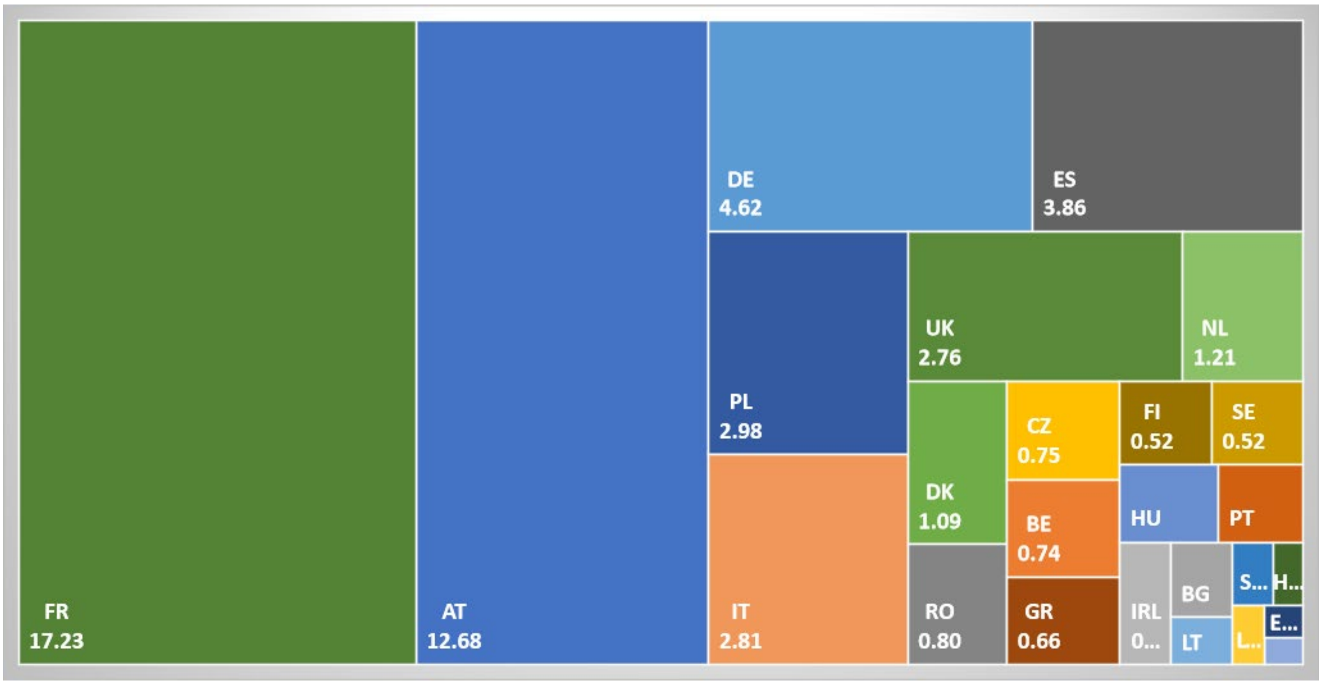

Figure 7 Regional distribution of estimated potentials for agro-industrial residues in 2030 (in million dry tonnes per year for the Low mobilisation scenario). Estimated total in the figure is 56 million dry tonnes. (See Annex X for country names)

France, Austria, Germany, Spain, Poland, Italy and UK have the largest shares in the estimated potentials across years and scenarios.

LIGNOCELLULOSIC CROPS

The lignocellulosic crop potential is estimated only in the unused, abandoned and degraded land, as shown in Figure 8. The estimated amount of lignocellulosic crops' potential for 2030 in this study ranges from 36 to 108 million tonnes (14 to 43 Mtoe). The respective amount for 2050 ranges from 42 to 127 million tonnes (17 to 51 Mtoe). The observed ranges are the result of using only 25% of the available marginal land in the Low Scenario (Scenario 1), 50% in the Medium Scenario (Scenario 2) and 75% in the High Scenario (Scenario 3). Table 6 Main assumptions for the estimation of lignocellulosic crops' potential in marginal lands in 2030 and 2050below provides the main assumptions regarding land availability and yields improvements for 2030 and 2050.

Table 6 Main assumptions for the estimation of lignocellulosic crops' potential in marginal lands in 2030 and 2050

	2020		2030		2050	
	Low quality	High quality	Low quality	High quality	Low quality	High quality
Land availability (marginal lands) (million ha)	13.7	4.6	14.5	5.5	14.5	5.5
Yields (t/ha)	6	8	6.6	8.8	7.8	10.4

Figure 8 Low (left)- and high (right)-quality land available for lignocellulosic crops in 2030 and 2050 (in 1,000 ha) shows the land (low quality left- high quality right) available for lignocellulosic biomass crops[47]

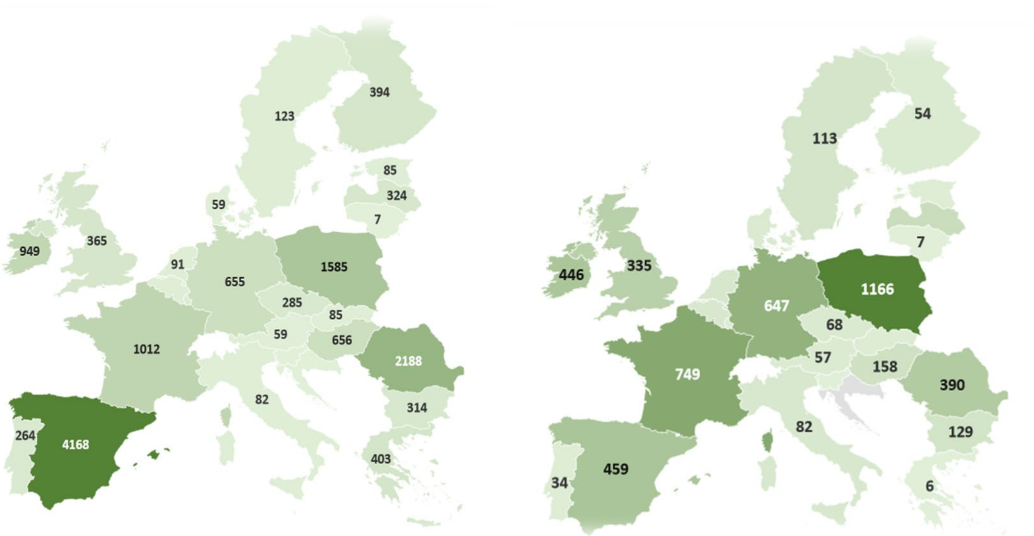

Figure 8 Low (left)- and high (right)-quality land available for lignocellulosic crops in 2030 and 2050 (in 1,000 ha)

The crop mix that has been examined in this study includes annual and perennial species. The latter are further categorised to perennial grasses and woody crops (Table 77).

[47] S2Biom Project Grant Agreement n°608622. C. Panoutsou et al., 2016. D8.2 Vision for 1 billion dry tonnes lignocellulosic biomass as a contribution to biobased economy by 2030 in Europe.
https://www.s2biom.eu/images/Publications/D8.1_S2Biom_Overview_report_of_current_status_of_biomass_in_Europe.pdf

Table 7 Lignocellulosic crops included in this study- structure of their supply chain, climatic and ecological profile[48]

Crop	Structure of the crop supply value chain				Climatic and ecological profile			
	Growth type	Establishment	Harvest	Yield (t/ha)	Soil type/ pH (min- max)	Input	Frost free days	Salt tolerance
Lignocellulosic crops								
Fiber sorghum	Annual	April/ May	Sept/ Oct	15–20	well drained (5.5–7.5)	Average	90	medium
Kenaf	Annual	May	Sept/ Oct	10–15	well drained (4.6–7.5)	Average		
Miscanthus	Perennial	Nov/ Jan	Nov/ Feb	10	variety of soils- well drained (4.5–8.0)	Average	120	
Switchgrass	Perennial	May	Nov/ Jan	8–10	variety- well drained	Low	120	medium
Cardoon	Perennial	Oct or Feb/ Mar	Jun/July	10–15	Low fertility	Low		high
Poplar	Perennial; Harvested every 6–15 years/(in very short rotations every 2–3 years)	April	Nov/ Dec	7–28	Low fertility	Average		
Willow	Perennial; Harvested on 3–4 years rotation	April	Nov/ Dec	10–30	variety of soils	Average		

[48] Panoutsou, C.; Alexopoulou, E. Costs and Profitability of Crops for Bioeconomy in the EU. Energies 2020, 13, 1222. https://doi.org/10.3390/en13051222

FORESTRY

There are three biomass feedstock types from forestry: i) stemwood (including roundwood[49]), ii) primary residues from thinnings & final fellings, stem and crown biomass from early thinnings, logging residues and stumps from final fellings, and iii) secondary residues from wood industries (sawmill and other wood processing). The primary forest exploitation is driven by the stemwood demand. There are several sustainability regulations for forest biomass removals which are usually managed through forest management plans coordinated by forest state and/or owner organisations. The common rule for sustainable forest management is that the long-term annual fellings[50] do not exceed the net annual increment[51]. This is subject to local climate, ecology and national forest management plans.

The total forest biomass potential in this study ranges from 558 to 659 million tonnes dry matter (223 to 264 Mtoe) for 2030 and from 590 to 726 million tonnes dry matter (236 to 291 Mtoe) for 2050. This potential comprises wood needed for all uses (i.e. construction, products, chemicals, energy, etc.).

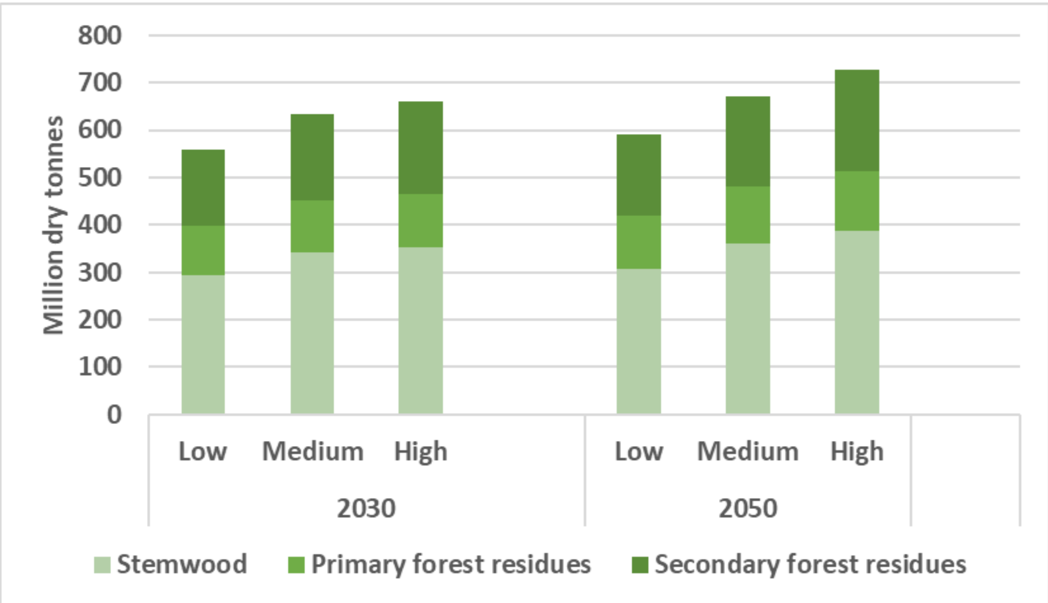

Figure 9 Estimated sustainable forest biomass potential for all markets per feedstock type for 2030 and 2050 (in million dry tonnes) per year.

[49] Roundwood: stemwood suitable for production of sawn-logs or pulp-logs, with top diameters fixed according to specific dimensional requirements in each country.

[50] This is the average annual volume of all standing trees, living or dead, measured overbark. It includes all trees with minimum diameter at breast height (d.d.h.) of 0.5 cm . that are felled during the given reference period, including the volume of trees or parts of trees that are not removed from the forest, other wooded land or other felling site. It includes silvicultural and pre-commercial thinnings and cleanings left in the forest, and natural losses that are recovered (harvested) (UNECE/FAO. 2000). https://www.eea.europa.eu/data-and-maps/indicators/forest-growing-stock-increment-and-fellings-3

[51] This is the average annual volume over the given reference period of gross increment minus the volume of natural losses on all trees with a minimum diameter of 0.5 cm d.b.h. (UNECE/FAO, 2000). https://www.eea.europa.eu/data-and-maps/indicators/forest-growing-stock-increment-and-fellings-3

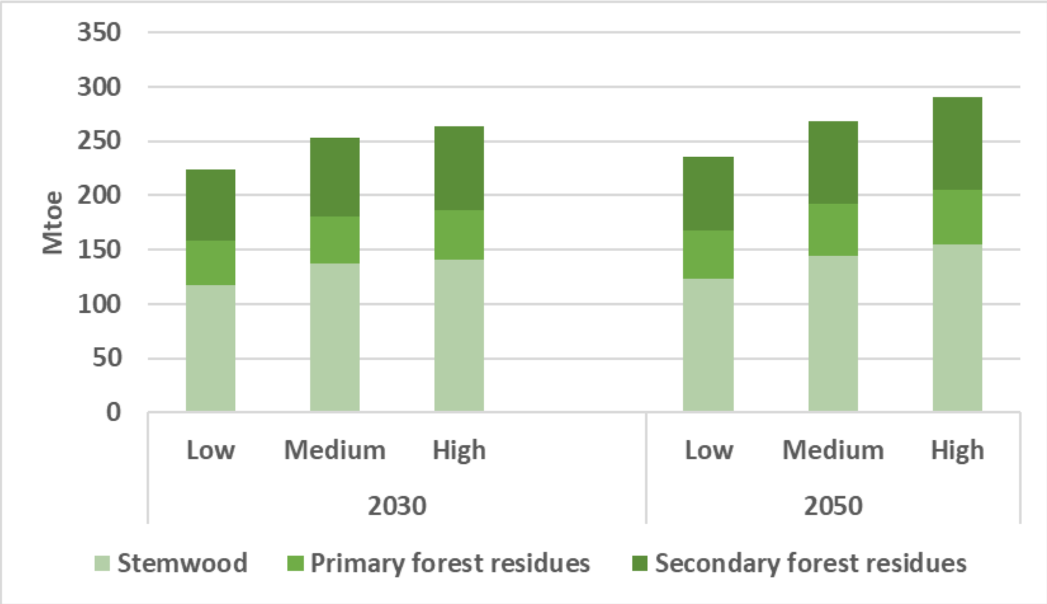

Figure 10 Estimated sustainable forest biomass potential for all markets per feedstock type for 2030 and 2050 (in Mtoe right) per year.

Countries with high shares in the estimated potentials are Sweden, Germany, UK, France, Finland, Poland, Austria, Italy, Romania, and Spain. Figure 11 shows the geographic distributions of stemwood, primary and secondary forest residues for Scenario 1: Low mobilisation in 2030.

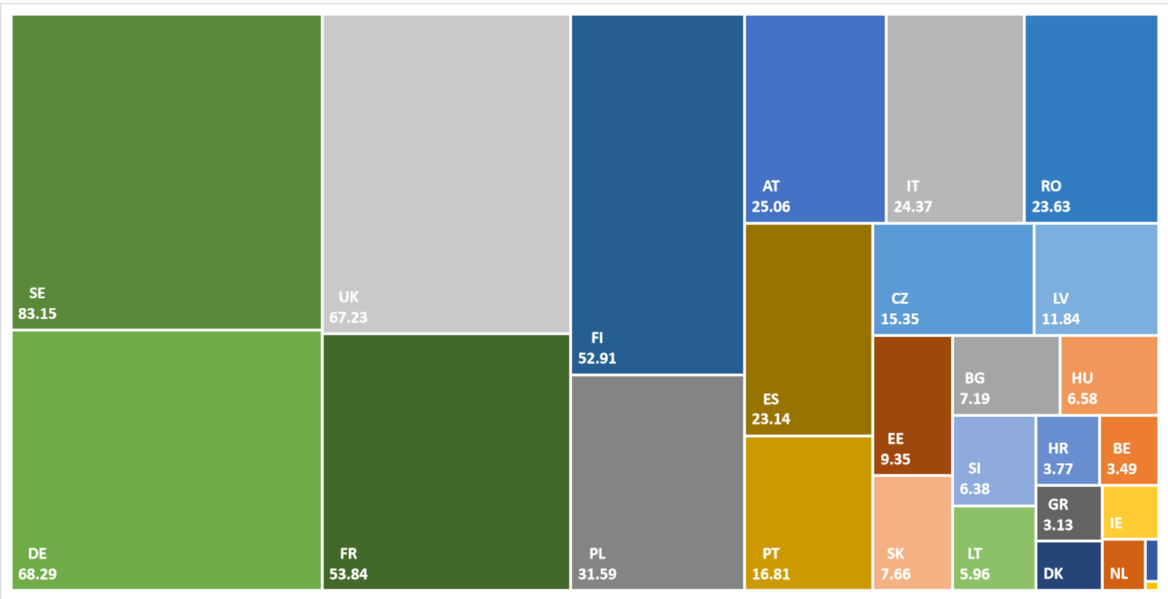

Figure 11 Regional distribution of estimated potentials for forest biomass for all markets (stemwood, primary, secondary and post-consumer wood) in 2030 for (in million dry tonnes per year for the Low mobilisation scenario). Estimated total in the figure is 558 million dry tonnes. (See Annex X for country names)

Countries that show large potentials because their stemwood harvest is significant are Sweden, Germany, UK, France, Finland, and Poland. There are also countries that have a relatively large residue potential while their stemwood harvest is not that large. For these countries, which include Italy, Slovakia, Bulgaria, and Slovenia, this can be explained by the particularly large potential of early thinnings which is independent of the stemwood harvest level itself. These countries have large shares of their forest that need (pre-commercial) thinning in a more coppicing system. The pre-commercial thinning activity will be the first step to bring their forests back into a more productive forest management system.

Given age structure of forests and current known material demand levels for wood one can expect that potentials are higher in Germany, Spain, Finland, France and Sweden. Some growth towards 2030 and 2050 is particularly expected in France and a couple of smaller countries Towards 2030 some increases in potential are also expected for Italy, Romania, and Hungary.

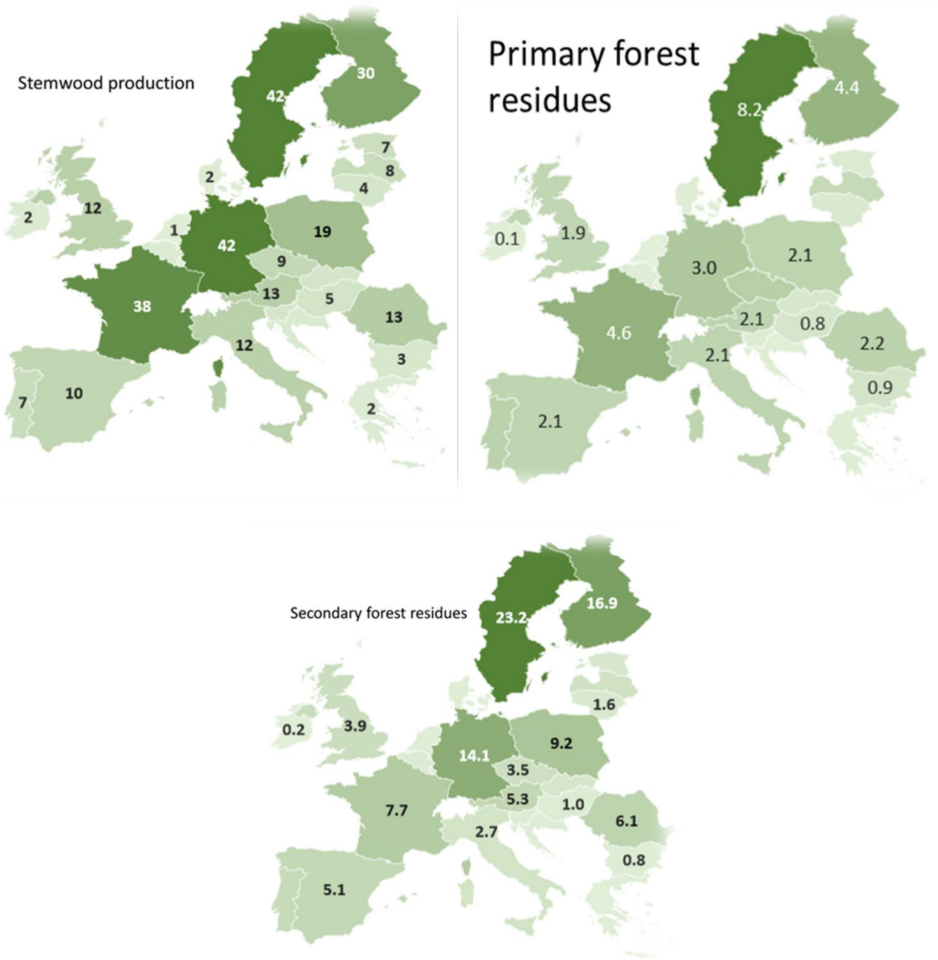

Figure 12 Geographic distribution of stemwood, primary and secondary forest residues (in million dry tonnes in Scenario 1: Low mobilisation in 2030)

STEMWOOD

Stemwood is the main product of forestry operations and can be defined as the part of tree stem from the felling cut to the tree- top with the branches removed, including bark.

In general, the estimated potential from stemwood (for all end use markets, including fuelwood for energy) presents only slight changes over time. This is mainly because the potential for each year is based on the average maximum harvest level that can be maintained throughout the next 50-year period. Therefore, within the examined scenarios the measures considered increased the potential availability of stemwood by less than 1% as compared to the low mobilisation scenario in 2050. This increase is mainly explained by an increase in biomass from thinnings (i.e. intermediate harvest).

The estimated potential for stemwood for all markets ranges from 293 to 352 million tonnes dry matter (117 to 141 Mtoe) for 2030 and from 308 to 387 million tonnes dry matter (123 to 155 Mtoe) for 2050. This potential comprises wood needed for all uses (i.e. products, chemicals, energy, etc.). The allocation of stemwood to other uses varies depending on the scenario considered as reported in Table 2.

PRIMARY FOREST RESIDUES

Primary forestry residues consist of:

- Stem and crown biomass from early pre-commercial thinnings which consists of (thin) stems, branches, bark and needles and leaves. Pre-commercial thinnings cover selective cuttings of young trees that have no value for the wood processing industry. Their removal is part of normal forest management and enhances the growth of the remaining trees.
- Logging residues from thinnings also including stem and crown biomass which consists of (thin) stems and branches, bark, needles and leaves.
- Logging residues from final fellings which is mostly branches, bark, needles and leaves.
- Stump extraction from final fellings which is the tree part below the felling cut so including tree roots.
- Stump extraction from thinnings which is also the part of the tree below the felling cut of the thinning tree.

The estimated potential for primary forest residues ranges from 104 to 114 million tonnes dry matter (41 to 45 Mtoe) for 2030 and from 112 to 126 million tonnes dry matter (45 to 50 Mtoe) for 2050. This potential comprises wood needed for all uses (i.e. products, chemicals, energy, etc.).

SECONDARY FOREST RESIDUES – POST CONSUMER WOOD

Secondary forestry residues assessed in this study include i) sawmill by-products (excluding saw dust), ii) saw dust from sawmills and iii) other forestry industry by-products.

The first two originate from the sawmill industries and are produced as a by-product during stemwood processing. They consist of bark, sawdust, slabs and chips originating from coniferous as well as non-coniferous stemwood. Most of these residues are already sold and used for material uses and in every large wood processing country the collection and trading are already well organised and structured.

Other forestry industry by-products derive from the processing of primary and further processed timber products, such as sawn wood, wood-based panels, joinery products, etc., into for instance window frames, furniture, doors etc. The by-products mainly consist of sawdust, shavings and off-cuts and their moisture content is often lower than that of sawmill by-products and amounts to 10-20% moisture. More than with the sawmill by-products, which are seen as a by-product, these biomass potentials are mostly considered as a waste stream. Their use is well organised though, much is already collected by waste-processing companies, and can often be collected for free or a small price. A large share of these residues are contaminated with paint, glue or other non woody materials and therefore only suitable to be used by waste processing companies. These waste companies also convert these contaminated residues into energy.

Post-consumer wood[52] includes all kinds of woody material that is available at the end of its use as a wood product, like packaging materials (e.g., pallets), demolition wood, timber from building sites, and used furniture. The quality of post-consumer wood depends on its former application, whether the material is painted, impregnated, or otherwise treated; whether it consists of sawn wood or panels; whether it is glued, nailed, or otherwise stuck together with other materials; if it is collected separately or integrally with other waste, etc. The quality of the post-consumer wood determines the possibilities to utilize it for material applications beyond combustion with energy application.

The estimated potential for secondary forest residues and post-consumer wood ranges from 162 to 194 million tonnes dry matter (65 to 78 Mtoe) for 2030 and from 170 to 213 million tonnes dry matter (68 to 85 Mtoe) for 2050. This potential comprises wood needed for all uses (i.e. products, chemicals, energy, etc.).

[52] Vis, M., Mantau, U., Allen, B., 2016. Study on the Optimised Cascading Use of Wood. Contract No. 394/PP/ENT/RCH/14/7689. Final report. Brussels, 337 pp. ,http://bookshop.europa.eu/ en/cascades-pbET0416305/

BIOWASTES IMPORTS FROM LIGNOCELLULOSIC BIOMASS AND UCO

Biowastes included in this study include paper and cardboard, wood waste, animal and mixed food waste (including animal fats), vegetal waste, municipal Solid Waste (MSW) and common sludges from households and economic sectors included in the Statistical Classification of Economic Activities in the European Community[53] (NACE). This study includes paper carboard, wood waste, animal fat cat 1 and cat 2, mixed food waste, vegetal waste, packaging, kitchen waste, and household equipment.

The estimated potential of biowastes for all uses for 2030 in this study ranges from 111 to 133 million tonnes (44 to 53 Mtoe). The respective amount for 2050 ranges from 94 to 113 million tonnes (38 to 45 Mtoe).

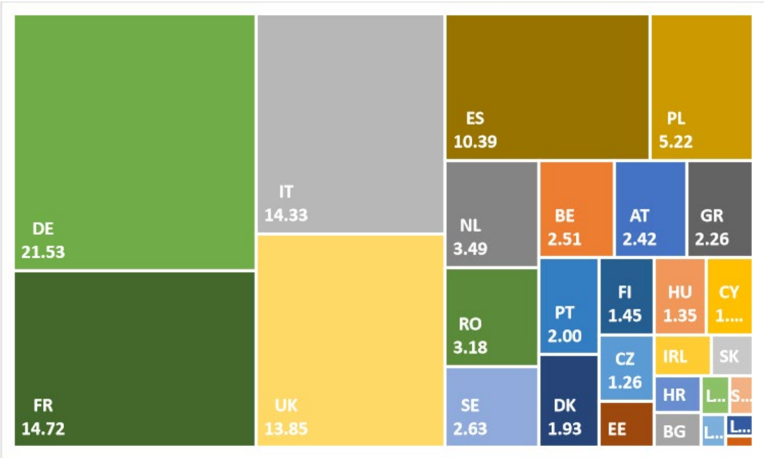

Figure 13 Regional distribution of estimated potentials for biowastes for all markets in 2030 for Scenario 1: Low mobilisation (in million dry tonnes). The estimated total in the figure is 111 million dry tonnes. (See Annex X for country names)

UK, Germany, France, Italy, Spain and Poland have the largest shares in the estimated potentials across years and scenarios.

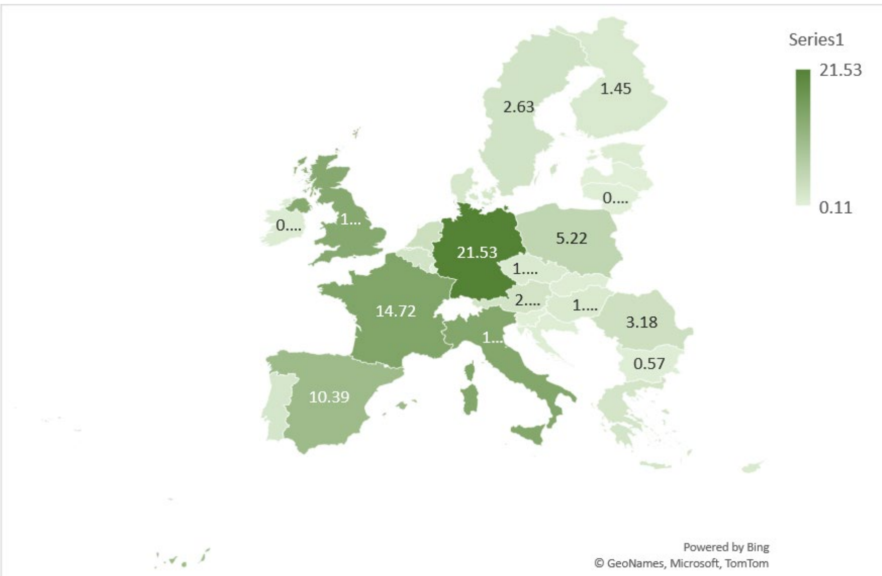

Figure 14 Geographic distribution of wastes for all markets in 2030 for Scenario 1: Low mobilisation (in million dry tonnes).

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[53] https://ec.europa.eu/eurostat/documents/3859598/5902521/KS-RA-07-015-EN.PDF

[4] BIOMASS AVAILABILITY EXCLUDING POTENTIAL DEMAND FOR NON ENERGY USES (BIOMASS FOR BIOENERGY)

This section presents the estimated biomass potentials for bioenergy (transport, heat and power) (excluding demand for non-energy uses (plastics, pharmaceuticals, etc.). Figures 15 and 16 present comparative estimates for biomass potentials (in Mtoe) for bioenergy in the Imperial College London, DG RTD and JRC TIMES studies based on feedstocks from Annex IX A & B (short-listed as detailed in Table 1). The potential longlist of feedstocks that are under consideration by the European Commission for inclusion in Annex IX is not included in the figures below.

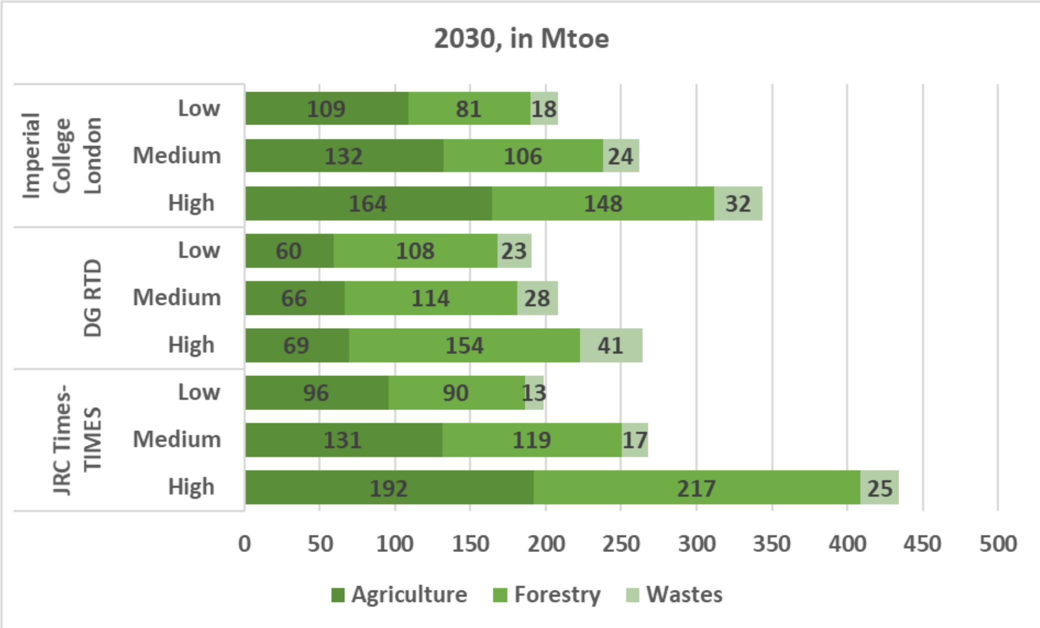

Figure 15 Comparative estimates for biomass potentials (in Mtoe) for bioenergy in the Imperial College London, DG RTD and JRC TIMES studies for 2030 (in Mtoe)

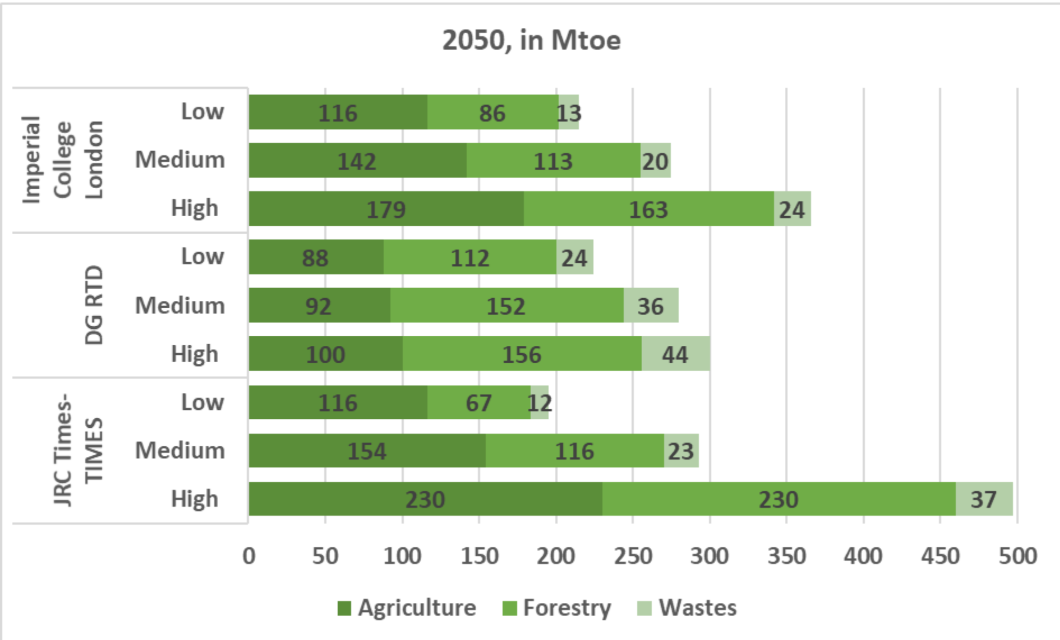

Figure 16 Comparative estimates for biomass potentials (in Mtoe) for bioenergy in the Imperial College London, DG RTD and JRC TIMES studies for 2050

Figures 17 and 18 present the estimated sustainable biomass potentials in the Imperial College London study that can be available for bioenergy in 2030 and 2050. (Please see Figures 1 and 2 for the total biomass potential across the whole economy).

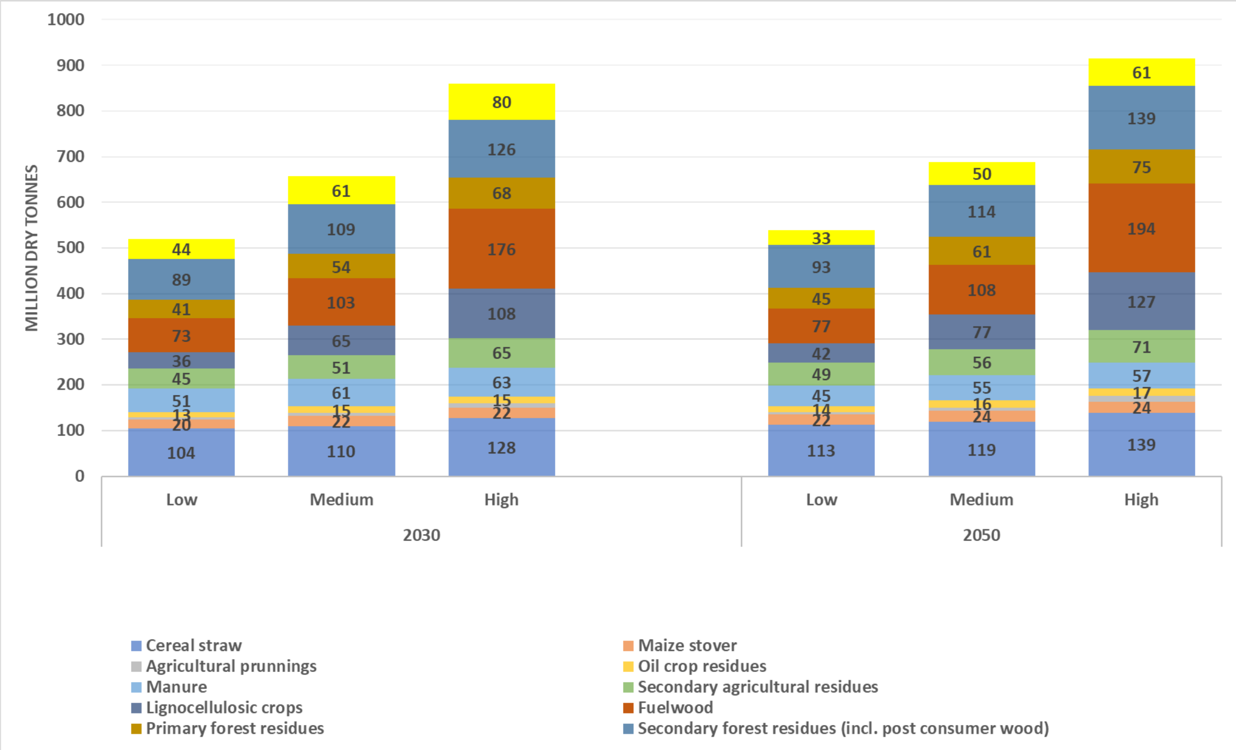

Figure 17 Estimated sustainable biomass potentials (RED II Annex IX A and B) that can be available for bioenergy in 2030 and 2050 (in million dry tonnes)

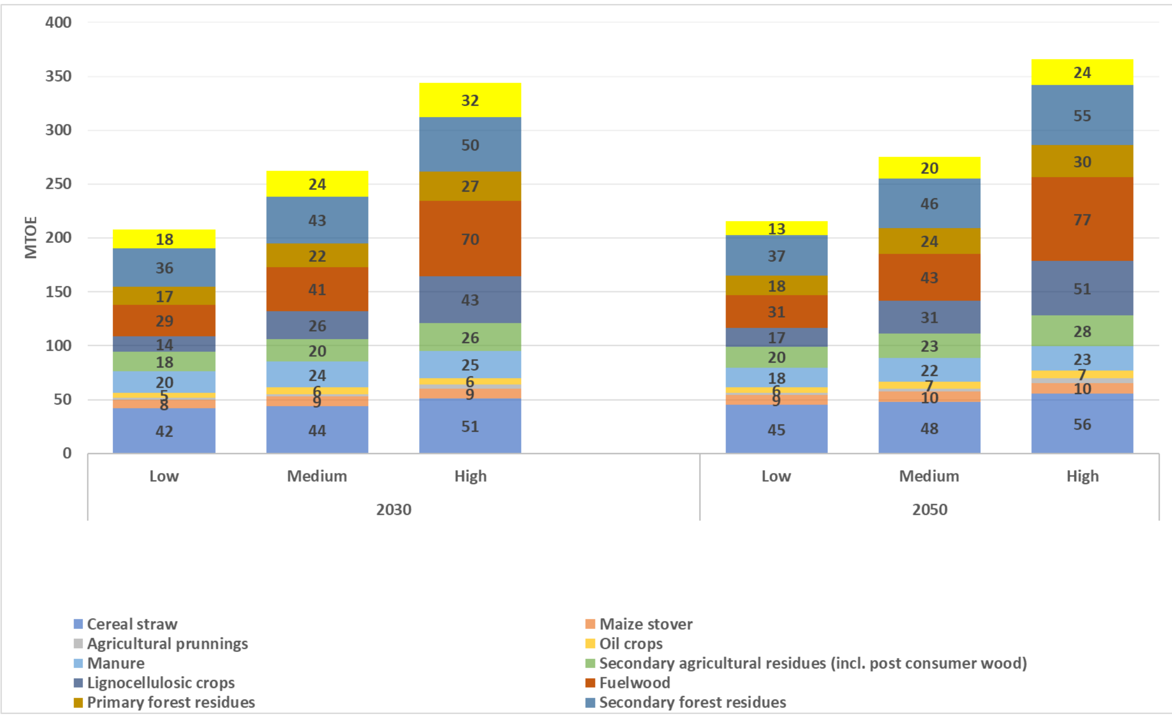

Figure 18 Estimated sustainable biomass potentials (RED II Annex IX A and B) that can be available for bioenergy in 2030 and 2050 (in Mtoe)

The estimated figures for 2030 range from 520- 860 million dry tonnes (208-344 Mtoe) for 2030. The respective numbers for 2050 remain similar and range from 539 -915 million dry tonnes (215-366 Mtoe).

The reasons that potentials remain unchanged despite improvements in biomass mobilisation and increased innovation for higher yields are mostly related to:

i) strong pressure for the sustainable use of land and water resources, including a 30% reduction in arable land by 2050,
ii) the fact that improvements in forest management are slow due to the long growing cycles of forests that prohibit fast changes in growth of potentials, and
iii) increased awareness for waste reduction and strong commitments for recycling.

The agricultural biomass feedstocks assessed in this study do not have any statistically reported competing uses for non-energy purposes, except cereal straw (which is being used for animal feed, animal bedding and mushroom growing). For cereal straw, the competing use was calculated based on livestock numbers and mushroom production levels. For cereal straw, the estimated potential in the previous section is reduced based on demand from non-energy uses that is projected by CAPRI[54] and statistics from JRC[55]. For maize and oil crop residues an average of 20% share is allocated to biobased markets both for 2030 and 2050.

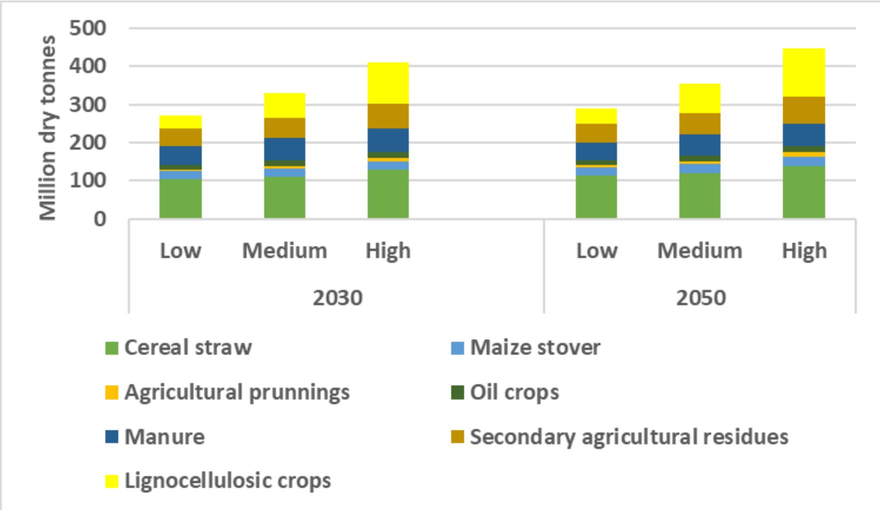

Figure 19 Estimated agricultural biomass potential for bioenergy - excluding the known demand for non-energy uses in million dry tonnes per year.

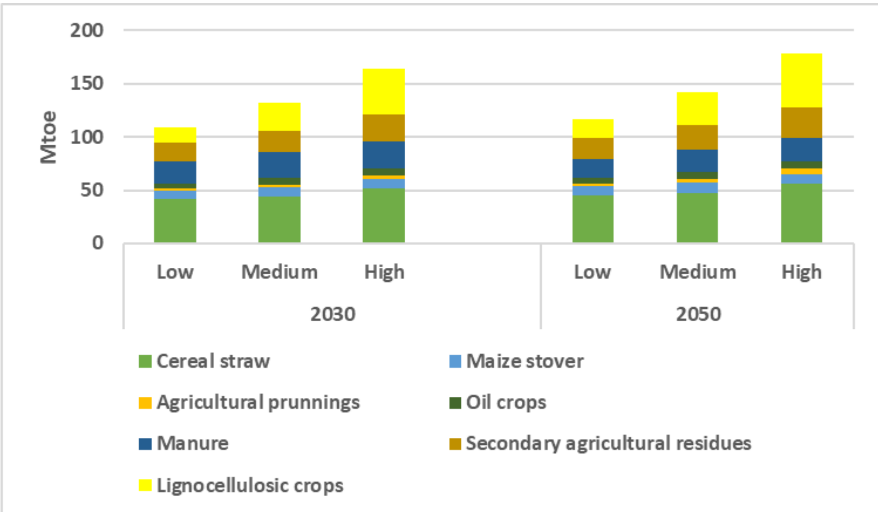

Figure 20 Estimated agricultural biomass potential for bioenergy - excluding the known demand for non-energy uses in Mtoe per year.

All the estimated quantities for manure are assumed to be available for bioenergy production. Following the reduction due to foreseen demand from non-energy uses the estimated biomass potential from agriculture ranges from 272 to 410 million tonnes (109 to 164 Mtoe) for 2030 and from 291 to 447 million tonnes (116 to 179 Mtoe) for 2050.

[54] https://www.capri-model.org/dokuwiki/doku.php

[55] DataM - Home page - European Commission (europa.eu)

FORESTRY

Current uses of stemwood are shared, almost equally between bio-based products and energy uses (fuelwood)[56]. The potential shown in this section concerns the fuelwood potential from stemwood and unused forest biomass currently unexploited. All material uses of stemwood were subtracted and only the stemwood currently used as fuelwood was incorporated in the potentials shown in Figures 21 and 22. Due to the increasing trends for sustainable use of stemwood, this study assumes 25% of stemwood being used for energy purposes as fuelwood in the Low scenario, 30% in the medium and 50% in the high scenario (Table 2).

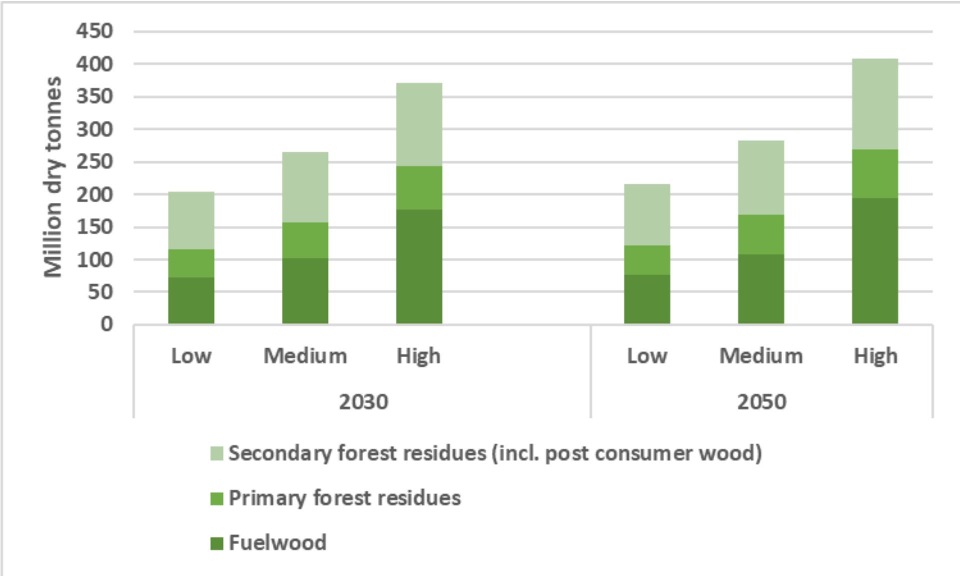

Figure 21 Estimated forest biomass potential for bioenergy - excluding the known demand for non-energy uses in million dry tonnes

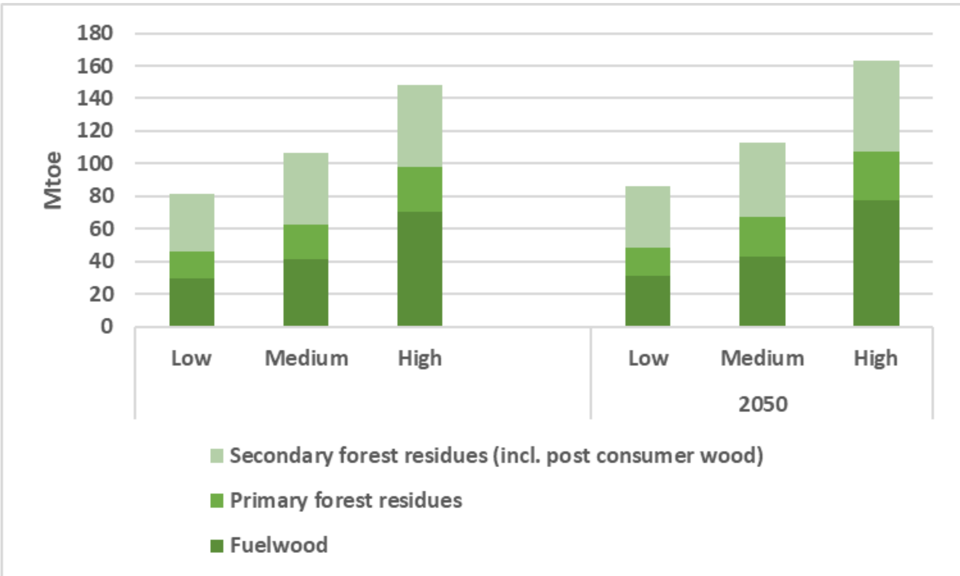

Figure 22 Estimated forest biomass potential for bioenergy - excluding the known demand for non-energy uses in Mtoe

The estimated biomass potential from forestry ranges from 204 to 370 million tonnes per year (81 to 148 Mtoe) for 2030 and from 215 to 408 million tonnes (86 to 163 Mtoe) for 2050.

[56] Camia, A., et. Al., 2021. The use of woody biomass for energy production in the EU. https://ec.europa.eu/jrc/en/publication/eur-scientific-and-technical-research-reports/use-woody-biomass-energy-production-eu . Table 4, page 47.

BIOWASTES

According to the Circular Economy Package[57] 55 % of municipal waste needs to be re-used and recycled by 2025, 60% by 2030, and 65% by 2035. The amount of municipal waste landfilled must be reduced to 10% or less of the total amount of municipal waste generated by 2035. This study applied the above rates to 2030 and to 2050 (the 65% announced for 2035) in the Low Scenario (Table 2). The estimated biomass potential from biowastes ranges from 44 to 80 million tonnes per year (18 to 32 Mtoe) for 2030 and from 33 to 61 million tonnes (13 to 24 Mtoe) for 2050.

This chapter includes estimates for Paper carboard, Wood waste, Animal fat cat 1 and cat 2, mixed food waste, Vegetal waste, packaging, kitchen waste, and household equipment.

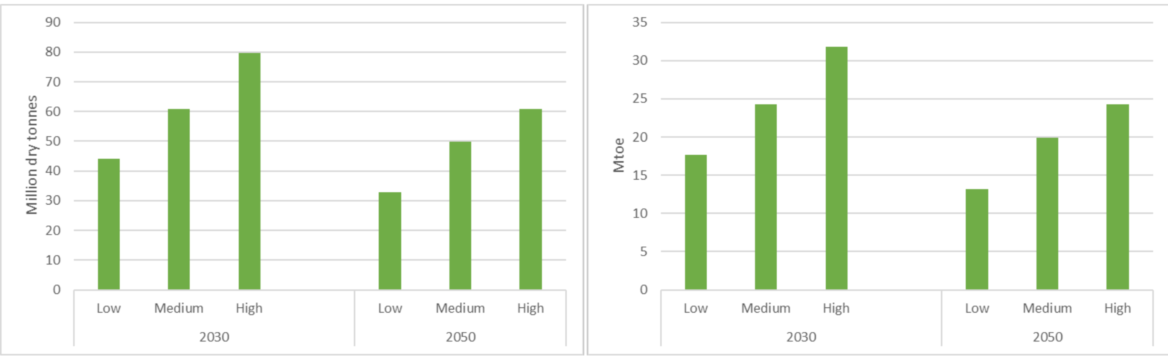

Figure 23 Estimated potential for biowastes for bioenergy - excluding the known demand for non-energy uses (left in million dry tonnes per year and right in Mtoe per year).presents the estimated potential for biowastes excluding the known demand for non-energy uses and Figure 24 Regional distribution and estimated biowastes potential for bioenergy - excluding the known demand for non-energy uses (in million dry tonnes, Scenario 1: Low mobilisation, for 2030) the regional distribution and estimated biowastes potential.

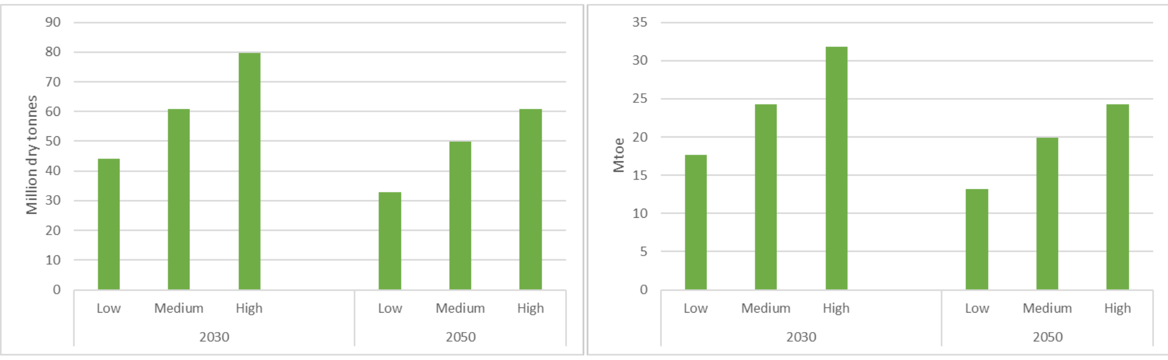

Figure 23 Estimated potential for biowastes for bioenergy - excluding the known demand for non-energy uses (left in million dry tonnes per year and right in Mtoe per year).

[57] Commission adopts ambitious new Circular Economy Package (europa.eu)

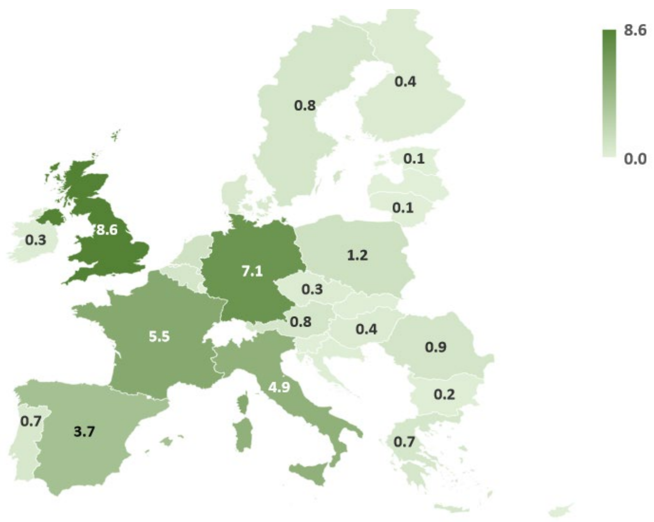

Figure 24 Regional distribution and estimated biowastes potential for bioenergy - excluding the known demand for non-energy uses (in million dry tonnes, Scenario 1: Low mobilisation, for 2030)

USED COOKING OIL FOR BIOENERGY

Between 2011 and 2016, the utilisation of UCO increased steadily, from 680,000 tonnes to 2.44M tonnes[58]. The prominent European users of UCO are Germany, Italy, the Netherlands, Spain and the UK.

The net imports of UCO and UCO based FAME biodiesel to the EU have significantly increased since 2014, with a large proportion of this UCO being sourced from China, Indonesia and Malaysia. In 2018, these three countries exported more than 500,000 tonnes of UCO to the EU[59]. Table 8 presents current volumes of cooking oil collection in the European Union, China and Japan.

Table 8 Used Cooking oil potential availability in EU, UK, China and Japan in 2016[60]

Country/ region	Annual quantity	Notes
EU27& UK	As of 2016, in all the EU countries combined, total UCO availability was approximately 1.7 million tonnes/yr, with 0.9 million tonnes/year in households and 0.8 million tonnes/yr in professional sector. Out of the total potential, 0.7 million tonnes/year were collected in 2016.	The recovery rate is 5.6% and 86% for households and professional sector respectively[61]. Some countries such as Belgium, Sweden, Austria and Netherlands have proven that household collection can be highly efficient.

[58] https://www.nnfcc.co.uk/files/mydocs/UCO%20Report.pdf

[59] https://www.ofimagazine.com/issues/ofi-september-october-2019

[60] B.H.H. Goh, C.T. Chong, Y. Ge, H.C. Ong, J.-H. Ng, B.o. Tian, et al. Progress in utilisation of waste cooking oil for sustainable biodiesel and biojet fuel production. Energy Convers Manag, 223 (2020), p. 113296, 10.1016/j.enconman.2020.113296

[61] EWABA. Greene Report (2016) Analysis of the current development of household UCO collection systems in the EU. https://theicct.org/sites/default/files/publications/Greenea%20Report%20Household%20UCO%20Collection%20in%20the%20EU_ICCT_20160629.pdf

China	5 million tonnes[62]	The government has offered recyclers various subsidies to encourage the collection and management of waste oils and push back illegal UCO recycling[63]. By regulating and incentivising the use of UCO as a source of clean power production such as biodiesel, the collection of UCO for restaurants becomes financially feasible[64].
Japan	0.1 to 0.5 million tonnes/year[65]	The increase in environmental awareness led to a cooperation between the communities and the government, thus UCO collection recovery has begun nationwide.

This study has estimated the potential availability for UCO in EU27 & UK following the assumptions below:

2030: Household collection rate: 15%; Professional collection rate: 90%

2050: Household collection rate: 45%; Professional collection rate: 90%

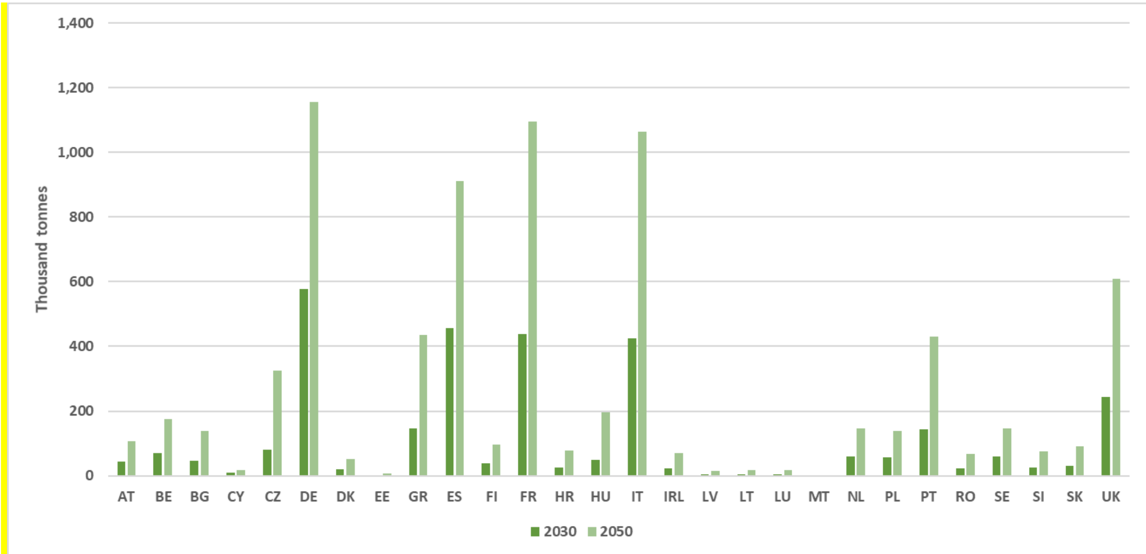

Figure 25 Estimated amounts of UCO for 2030 and 2050 (in thousand tonnes)

Figure 25 presents the estimated availability of UCO for 2030 and 2050 based on the assumptions described above. Further analysis is required to appreciate the efforts required to improve collectability and increase the scalability of future potential for UCO.

62 G. Chen, J. Liu, J. Yao, Y. Qi, B. Yan. Biodiesel production from waste cooking oil in a magnetically fluidized bed reactor using whole-cell biocatalysts. Energy Convers Manage, 138 (2017), pp. 556-564, 10.1016/j.enconman.2017.02.036

63 H. Zhang, L. Li, P. Zhou, J. Hou, Y. Qiu. Subsidy modes, waste cooking oil and biofuel: policy effectiveness and sustainable supply chains in China. Energy Policy, 65 (2014), pp. 270-274, 10.1016/j.enpol.2013.10.009

64 T. Liu, Y. Liu, S. Wu, J. Xue, Y. Wu, Y. Li, et al. Restaurants' behaviour, awareness, and willingness to submit waste cooking oil for biofuel production in Beijing. J Cleaner Prod, 204 (2018), pp. 636-642, 10.1016/j.jclepro.2018.09.056

65 M.R. Teixeira, R. Nogueira, L.M. Nunes. Quantitative assessment of the valorisation of used cooking oils in 23 countries. Waste Manage, 78 (2018), pp. 611-620, 10.1016/j.wasman.2018.06.039

WHAT IS REQUIRED FOR THE MOBILISATION OF SUSTAINABLE BIOMASS STREAMS?

This section builds on the findings from the Imperial College London study and the other ones consulted during this work and provides an overview of policy relevant recommendations for the mobilisation of domestic biomass feedstocks.

AGRICULTURAL BIOMASS

Currently straw is the largest agricultural biomass source in practically all EU countries. The main source of straw is cereals, but there are EU regions that also have large potentials of other stubbles such as grain maize stover in France, Romania, Hungary and Italy or rapeseed and sunflower stubbles in France and Germany.

All figures presented in section 4 of this report are net potentials for bioenergy so known competing uses from the non-energy biobased sectors have already been deducted and restrictions for sustainable removal levels have been applied.

In terms of geographic distribution among Member States, countries with large straw availability and limited competing use levels are Germany, France, Bulgaria, Czech Republic, Poland, Hungary and Romania.

Some relevant recommendations for the mobilisation of sustainable agricultural biomass could include among others:

- Introduce (where they are not existing) targeted national and/or regional rural development programmes focusing on shift to low-carbon economy.
- Ensure that budget from 'Greening Payments[66], which is one of the financing mechanisms of the Common Agricultural Policy, includes appropriate crop diversification activities matched to local ecosystems and practices which can lead to optimised biomass mobilisation, including sustainable harvesting of residues.
- Provide support in the form of grant or tax relief for improving existing wood trade centres to include other biomass forms, such as straw bales, prunnings, etc.
- Introduce new varieties with higher yields and good adaptation to local ecosystems and support research programmes on the selection and adaptation of varieties suitable to local ecosystems.
- Training of farmers and biomass suppliers on handling and delivering agricultural residues as well.
- Capacity building for improved quality handling and storage of field agricultural residues.
- Learn from Good Practices (e.g., Danish programme on straw for energy).

[66] https://ec.europa.eu/info/food-farming-fisheries/key-policies/common-agricultural-policy/income-support/greening_en

FOREST BIOMASS

Countries that show large forest biomass potentials because they have both already a large amount of wood going to fuelwood and a large residue potential because their stemwood harvest is significant are Germany, Sweden, Finland, France, Poland and Spain.

There are also countries that have a relatively large residue potential while their stemwood harvest is not that large. For these countries, which include Bulgaria, Italy, Slovenia and Slovakia, this can be explained by the particularly large potential of early thinnings which is independent of the stemwood harvest level itself. These countries have large shares of their forest that need (pre-commercial) thinning in a more coppicing system. The pre-commercial thinning activity will be the first step to bring their forests back into a more productive forest management system. An additional factor to low mobilisation is the high share of private forest owners with small forest holdings.

Given the age structure of forests and current known material demand levels for wood one can expect that potentials are the largest in Germany, Spain, Finland, France, and Sweden. Some growth towards 2020 and 2030 is expected in France and a couple of smaller countries, because of the age-structure of the standing forest. Some increases in potential are also expected for Italy, Romania, and Hungary.

In absolute terms the largest contribution to the EU wide potential through mobilisation of unused forest biomass is expected to come from France, Germany, Italy and Sweden. In these assessed potentials volume specific sustainability criteria for the extraction of residues are considered. However, such additional mobilisation can only take place if the market demand for this potential starts to increase, and landowners and land managers start to see this as a sufficient incentive to add new parcels into exploitation.

Currently the EU forest sector faces multiple and increasing demands with forest-based bioenergy accounting for almost 50% of total EU renewable energy consumption while in the same time wood is considered as an important source of raw material (construction material, green chemicals, viscose, bioplastics, etc.).

Some relevant recommendations for the mobilisation of sustainable forest biomass could include among others:

- Increased information provision policy towards private forest owners by means of capacity building and awareness campaigns at national and regional level.
- Encourage forest certification activities at national level: forest certification schemes and sustainable forest legislation are considered as key mechanisms to ensure sustainability in practices and biomass supply. National requirements could be better considered by national policy.

BIOWASTES

The availability of bio-waste is challenging mainly because it is not only found in separately collected kitchen and garden waste, but it is also part of integrally collected municipal waste[67].

The overall picture from this and other previous studies shows that the waste potential available per country does have a very strong relationship with the size of population or economy. At the same time smaller waste levels are observed in some countries than one would expect by the size of the population and economy. This is because some countries already have a very high recovery rate of waste. Examples of such countries are Austria, Belgium, Germany, Denmark, Estonia, Netherlands, Ireland, UK, Slovenia.

The countries with the largest household waste potentials are Germany, Spain, France, Italy, Romania and UK. The countries that have a large household waste potential in combination with low energy recovery, thus high disposal and incineration without energy recovery rate, are particularly Spain with 86%, Poland with 92%, Italy with 82%, Hungary with 86%, Greece with 100% and Slovakia with 88% disposal and incineration without energy recovery. France has a bit higher energy recovery of household waste but disposal and incineration without energy recovery is still at 66%.

Some relevant recommendations for the mobilisation of sustainable biomass from wastes could include among others:

- Refine terms and conditions in the Waste Directive and account for all potential uses and waste transportation issues.
- Introduce stimulating financial and regulatory measures to improve the collection rate of biowastes.
- Provide incentives for the collection of Used Cooking Oil from households.

[67] Martijn Vis. 2017. Assessing the potential from bio-waste and postconsumer wood. Pages 199- 218 In Modeling and Optimization of Biomass Supply Chains. DOI: http://dx.doi.org/10.1016/B978-0-12-812303-4.00008-2

[5] ADVANCED BIOFUEL PATHWAYS

This section starts with a brief description of the maturity of the various technologies and value chains that can convert biomass and waste streams to advanced biofuels[68]. The discussion is based on the development of the various technologies and the TRL they have reached by December 2020. The analysis is structured along three main vectors, those technologies already commercial, those that have reached First-of-a-kind (FOAK) status and those which are still at the development stage. Technologies still at lab scale, and those which are not expected to reach commercialisation by 2030 are only briefly discussed.

Annex VI summarises the state of the art of biomass conversion technologies to advanced biofuels.

Key messages are included in the box below.

Key Messages:

On average it takes about 2 to 2,5 years to build a First-of-a-Kind advanced biofuel plant from the moment that the financial package has been concluded.

It can take between 0,5 to 2 years to complete the commission of a First-of-a-Kind advanced biofuel plant once the construction has been completed.

Experience has shown that on average it takes about 10-20 year to bring a technology from the lab scale to First-of-a-Kind status for advanced biofuel technologies (see Annex VII).

There are several abandoned First-of-a-Kind plants around the world and in practically all cases this had nothing to do with the technology itself. Corporate commitment, strong financing and existing supportive legislation are of paramount importance and have to be co-current and mutually supportive.

The benchmarking of conversion technologies for advanced biofuels will start with a short review of the value chains, the classification of the conversion technologies being on the basis of their perceived TLR. There is more reliance on the actual status of the technologies in terms of lab scale, pilot scale, first-of-a-kind (FOAK) and commercial. Such an approach shows the actual physical status of "*steel in the ground*". By FOAK in this report it is understood to be a facility that has been constructed and includes all unit operations, from reception of the biomass[69] feedstock to the final product ready for shipment to the market. FOAKs provide the opportunity to the technology developer to test all technical systems and unit operations of a conversion technology and to carry out a reliable and detailed estimation of CAPEX & OPEX for a commercial facility. FOAKs also provide the opportunity to showcase the technology. However, most First-of-a-Kind plants still need to go under extensive optimisation which may entail significant extra investment by the technology provider. They rarely operate on a continuous basis but go through testing cycles to prove the reliability and flexibility of the technology.

In this analysis we consider a technology to have reached the FOAK status if the plant has been built, has been commissioned and has been operated successfully for at least 3 months at a scale which could considered commercially scalable. Also, a technology is considered to be in "FOAK in Deployment" if a technology developer has signed license agreement(s) with potential users. "FOAK in Development" denotes a technology for which a FOAK exists but there has been no confirmation for a license yet.

Conversion technologies based on known processes, for which sectors of the industry and especially refineries have years of experience, can move very fast from the lab to the commercial stage since they represent few technical risks and process unknowns. Such an example is the hydrotreatment of vegetable oils; hydrotreatment is a well understood process by the refining industry, and vegetable oils are "*similar*" to other refining streams.

[68] Technologies for food-based biofuels such as fatty acid methyl ester from vegetable oils, fats and lipids as well as ethanol from sugar and starches are considered out of scope of this analysis.
[69] The term biomass is understood to include all types of biogenic streams included biowaste from waste streams and municipal solid waste.

Figure 26 shows the six key value chains available to convert biomass to advanced biofuels[70]. In short, two of them, biomethane from anaerobic digestion and hydrotreatment of lipids are commercial, the cellulosic ethanol value chain has reached the FOAK status and is in the process of commercialisation while synthetic biofuels and paraffinic biofuels via gasification, pyrolysis and hydrothermal liquefaction are still in development towards a FOAK. These value chains are not exhaustive but they are the ones closest to market deployment.

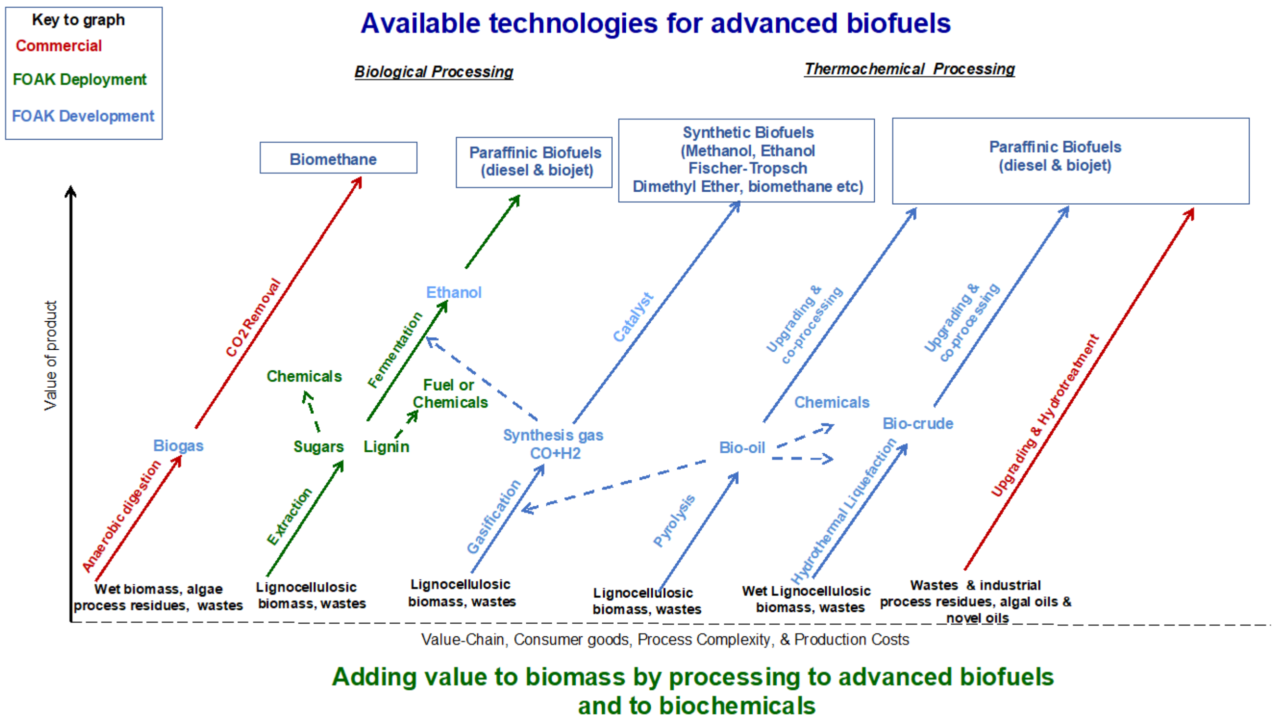

Figure 26: Simplified schematic for technologies and value chains for advanced biofuels[3]

Figure 27 shows the status of advanced biofuels technologies based on their TRL level as well as their status based on the technology development roadmap for all advanced biofuel conversion technologies, i.e. from *Research at Lab Scale*, to *Prototype at Pilot Plant*, to *Demonstration for Technoeconomic Viability* and finally *Commercialisation and Market Deployment*. Figure 27 also indicates some companies that have reached the last two stages and are either in market deployment or close to commercialisation.

Figure 28 shows the complexity but also the flexibility of the various biomass feedstocks or intermediates (such as fast pyrolysis oils) to be converted into advanced biofuels for the various markets via different biomass value chains. For example, lignocellulosic biomass, subject to the value chain and conversion technology, can be processed to produce alcohols (such as ethanol, methanol, butanol etc.), synthetic fuels (such as Fischer-Tropsch, bio DME, biomethane etc.) or fast pyrolysis oils that can subsequently co-processed in a refinery.

The commercially available conversion pathways for advanced biofuels are hydrotreatment to produce hydrotreated vegetable oils (HVO), and anaerobic/aerobic digestion to produce biogas that can be upgraded to biomethane. Cellulosic ethanol has progressed significantly and it is close to commercialisation.

[70] Maniatis K., adapted from Sub Group on Advanced Biofuels, Sustainable Transport Forum, Building up the Future, Final report, 2017, Ed. Maniatis K, Landälv I, Waldheim L, van den Heuvel E & Kalligeros S, European Commission, available at: https://ec.europa.eu/transparency/regexpert/index.cfm?do=groupDetail.groupDetailDoc&id=33288&no=1.

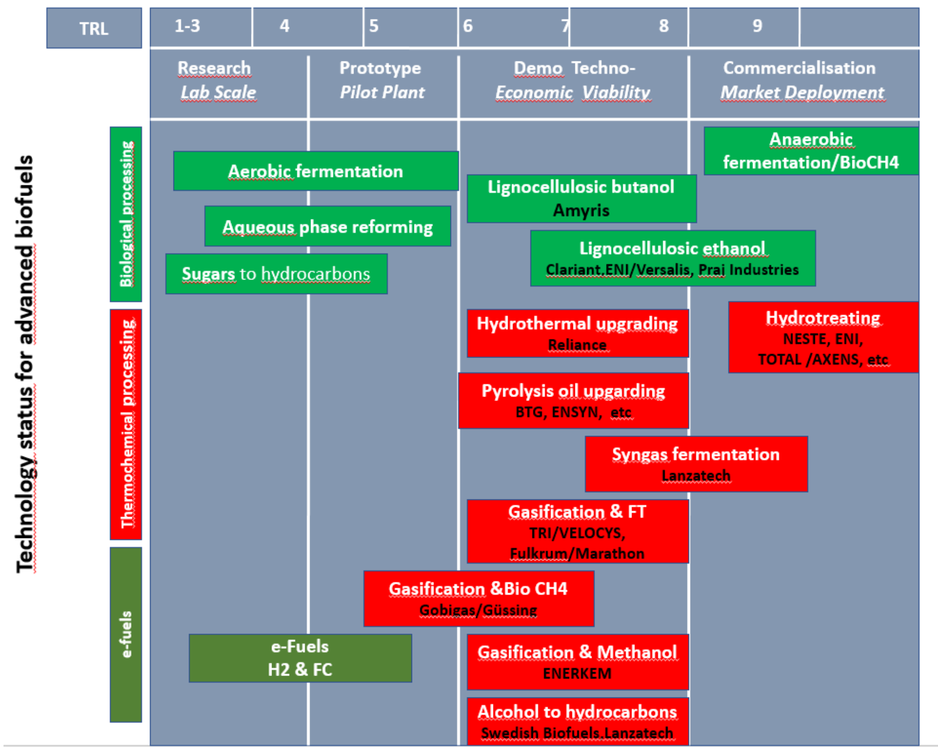

Figure 27: Status of advanced biofuels technologies based on their TRL level as well as their status based on the technology development roadmap

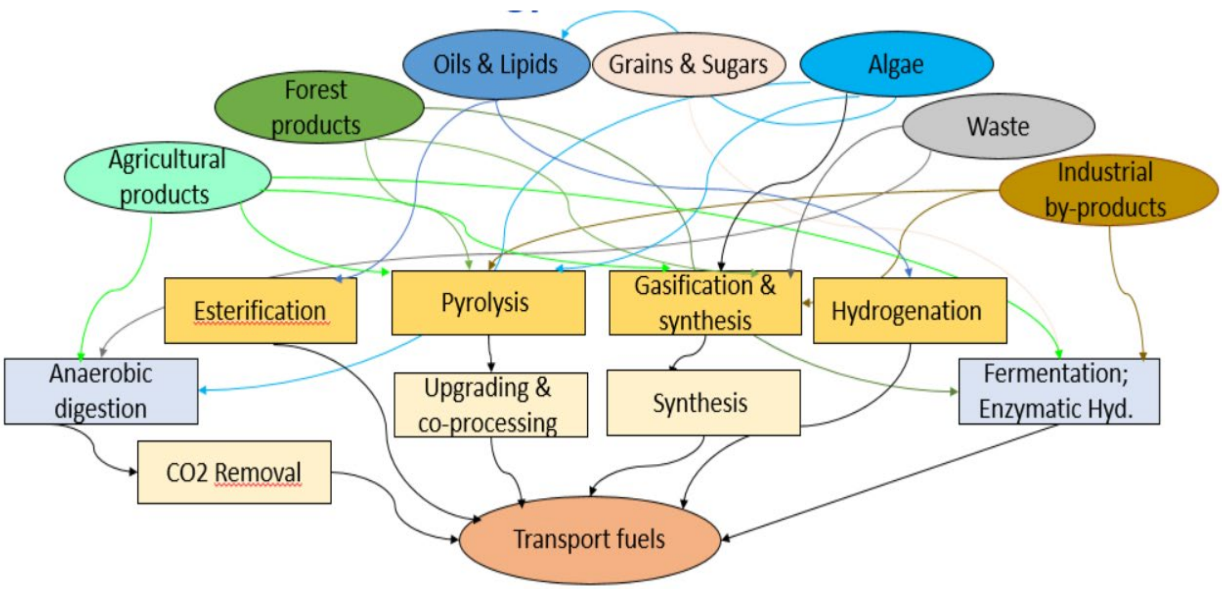

Figure 28: The complexity and flexibility of biomass value chains via conversion technologies and intermediate steps

Table 9: Outlook of the advanced biofuel pathways considered in this study

Raw material	Conversion pathway	Biofuel type	Status TRL (2020)	Fuel
Waste oils & fats, Used Cooking Oil (UCO), Veg. oils (through crop rotation, cover crops), liquid waste streams & effluents	Hydrotreatment including co-processing	Hydrotreated Vegetable Oil (HVO) / renewable diesel	Commercial	Drop-in blends with road diesel or neat HVO, Sustainable Aviation Fuels
MSW, sewage sludge, animal manures, agricultural residues, energy crops	Biogas or landfill production & removal of CO2	Biomethane		Captive fleets or injected in the gas grid
Lignocellulosic, agricultural residues, MSW, *solid* industrial waste streams/residues	Enzymatic hydrolysis & fermentation	Ethanol	TRL 8-9	Gasoline blends such as E5, E10 (drop-in), E20 (minor engine modifications), E85 flexi-fuel engines), ethanol with ignition improvers for diesel engines (ED95), or ethanol/butanol upgraded to biokerosene (ATJ)
	Gasification + fermentation	Ethanol	TRL 6-8	
Lignocellulosic solid agricultural residues, MSW, *liquid* industrial waste streams & effluents or intermediate energy carriers (torrified wood or pyrolysis oils)	Gasification + catalytic synthesis (including biomethane, methanol etc.)	Synthetic fuel	TRL 6-9	Drop-in blends with diesel, gasoline, Sustainable Aviation Fuels, bunker fuel or as pure biofuel e.g. bio-SNG, DME, methanol,
Lignocellulosic, MSW, waste streams	Pyrolysis or liquefaction (i.e. HTL) + Hydrotreatment	Hydrotreated bio-oil/biocrude	TRL 5-8	Neat or drop-in diesel, bunker fuel, gasoline, Sustainable Aviation Fuels; using the less processed HPO as fuel for maritime (less costly)
Pyrolysis oils or biocrudes from lignocellulosic, MSW, waste streams	Co-processing in existing petroleum refineries	Co-processed bio-oil/biocrude	TRL 5-7	Neat or drop-in diesel, bunker fuel, gasoline, Sustainable Aviation Fuels
CO_2 from RES systems and air (fermentation)	Reaction with RES H_2	e-fuel	TRL 5-7	Depends on fuel type, i.e. methanol or DME, ATJ

[6] MULTI CRITERIA ASSESSMENT OF POTENTIAL ALLOCATION

This section matches the different technological pathways to the biomass availability for 2030 and 2050 by using a matrix structure based on the Technological Readiness level of the feedstock- pathway combinations in these timeframes.

Table 10 presents the TRL scoring and Table 11 presents the assessment of feedstock Technological Readiness and availability for 2030 and 2050.

Within the three scoring groups of Table 10 Feedstock and conversion pathway Technological Readiness Level (TRL) scoring one or more of the relevant factors apply in the scoring results presented in Tables 12 and 13.

Table 10 Feedstock and conversion pathway Technological Readiness Level (TRL) scoring

TRL	Colour code	Relevant factors
TRL>8-9		**a) industrial production already available at commercial scale** **b) used at commercial scale for advanced biofuels** **c) high biomass availability**
TRL5-7		a) production available at demo scale b) recognized for its suitability for advanced biofuels c) medium biomass availability
TRL3-5		a) research to production development b) recognized end-use but still at the research level c) low biomass availability

Table 11 Feedstock Technological Readiness and availability for 2030 and 2050

Conversion pathway	Advanced Biofuel	Feedstock	2030	2050
Hydrotreatment	Hydrotreated Vegetable Oil (HVO) / renewable diesel	Waste oils and fats		
		Used Cooking Oil (UCO)		
Biogas or landfill production & removal of CO2	Biomethane	Biowaste[71]		
		Sewage sludge		
		Manure		
		Agricultural and forestry residues		
Enzymatic hydrolysis & fermentation	Ethanol (2030) Hydrocarbons (2050)	Biowaste		
		Solid industrial waste		
		Agricultural and forestry residues		
		Lignocellulosic crops		
Gasification + fermentation	Ethanol (2030) Hydrocarbons (2050)	Biowaste		
		Solid industrial waste		
		Agricultural and forestry residues		
		Lignocellulosic crops		
Gasification + catalytic synthesis	Synthetic fuel	Biowaste		
		Solid industrial waste		
		Agricultural and forestry residues		
		Lignocellulosic crops		
Pyrolysis or liquefaction (i.e. HTL) + Hydrotreatment	Hydrotreated bio-oil/biocrude	Biowaste		
		Solid industrial waste		
		Agricultural and forestry residues		
		Lignocellulosic crops		
Fast Pyrolysis & HTL Co-processing in existing petroleum refineries	Co-processed bio-oil/biocrude	Biowaste		
		Solid industrial waste		
		Agricultural and forestry residues		
		Lignocellulosic crops		

Note: Lignocellulosic crops are not expected to be deployed to any significant extend by 2030 and make a significant contribution.

Following the results from the feedstock Technological Readiness and availability were combined with the TRL of the conversion pathways in a value chain matrix for the Technological Readiness of the complete advanced biofuel value chain (see Table 12).

[71] Biowaste is what remains after the removal of recyclables (metals, glass, etc) from Municipal Solid Waste.

Table 12 Technological Readiness Level for advanced biofuel conversion pathways in 2030 and 2050

Conversion pathway	Advanced Biofuel	2030	2050
Hydrotreatment	Hydrotreated Vegetable Oil (HVO) / renewable diesel		
Biogas or landfill production & removal of CO2	Biomethane		
Enzymatic hydrolysis & fermentation	Ethanol (2030) Hydrocarbons (2050)		
Gasification + fermentation	Ethanol (2030) Hydrocarbons (2050)		
Gasification + catalytic synthesis	Synthetic fuel		
Pyrolysis or liquefaction (i.e. HTL) + Hydrotreatment	Hydrotreated bio-oil/biocrude		
Fast Pyrolysis & HTL Co-processing in existing petroleum refineries	Co-processed bio-oil/biocrude		

Table 13 Technological Readiness Level for advanced biofuel value chains in 2030 and 2050

Pathway	Fuel	Feedstock	2030	2050
Hydrotreatment	Hydrotreated Vegetable Oil (HVO) / renewable diesel	Waste oils and fats		
		Used Cooking Oil (UCO),		
Biogas or landfill production & removal of CO2	Biomethane	Biowaste		
		Sewage sludge		
		Manure (solid and liquid)		
		Agricultural residues (high moisture; sugarbeet leaves, etc.)		
Enzymatic hydrolysis & fermentation	Ethanol (2030) Hydrocarbons (2050)	Biowaste		
		Solid industrial waste (secondary agro and forest industries)		
		Agricultural residues (straw-like)		
		Lignocellulosic crops (grassy)		
Gasification + fermentation	Ethanol (2030) Hydrocarbons (2050)	Biowaste		
		Solid industrial waste (secondary agro and forest industries)		
		Agricultural (woody) & forestry residues		
		Lignocellulosic crops (woody)		
Gasification + catalytic synthesis	Synthetic fuel	Biowaste		
		Solid industrial waste (secondary agro and forest industries)		
		Agricultural (woody) & forestry residues		
		Lignocellulosic crops (woody)		
Pyrolysis or liquefaction (i.e. HTL) + Hydrotreatment *	Hydrotreated bio-oil/biocrude	Biowaste		
		Solid industrial waste (secondary agro and forest industries)		
		Agricultural (woody) & forestry residues		
		Lignocellulosic crops (woody)		
Fast Pyrolysis & HTL Co-processing in existing petroleum refineries	Co-processed bio-oil/biocrude	Biowaste		
		Solid industrial waste (secondary agro & forest industries)		
		Agricultural (woody) & forestry residues		
		Lignocellulosic crops (woody)		

***Note:** In further analysis, see Table 15, it is considered that by 2050 and with the availability of large quantities of renewable hydrogen stand-alone biorefineries of fast pyrolysis and HTL will be operating upgrading the biooil and biocrude respectively to biofuels with the renewable hydrogen. The feedstocks used are the same as in this table and they are not included herewith simply for clarity.

POTENTIAL ADVANCED BIOFUEL PRODUCTION BASED ON ESTIMATES OF AVAILABLE BIOMASS

This section provides an outlook of potential production of advanced biofuels by 2030 and 2050 based on the estimated available biomass for bioenergy applications estimated in this study. The assumptions used are summarized in Table 14.

Table 14 Assumptions used in the potential advanced biofuels production in 2030 and 2050

Assumption N°	Description
1	By 2050 there is abundance of renewable hydrogen (RH) that can also be used in advanced biofuel production.
2	Fischer-Tropsch (FT) is commercial by 2030. The drop-in characteristic of FT facilitates blending in various applications in addition to using FT neat in diesel engines.
3	Conversion yield for FT increases to 40% (mass) in 2050 with hybrid gasification + Renewable Hydrogen (RH). Using RH in the gasification process allows significant conversion of the carbon from carbon dioxide and carbon monoxide to fuel resulting in significant higher carbon conversion efficiencies.
4	Pyrolysis FCC-coprocessing is commercial by 2030.
5	Stand-alone fast pyrolysis with Renewable Hydrogen is commercial by 2050. Using RH to upgrade the bio-oil allows in-situ production of hydrocarbon fuels.
6	Hydrothermal liquefaction (HTL) is commercial by 2030 and is applied with the FCC coprocessing.
7	Stand-alone HTL with Renewable Hydrogen is commercial by 2050. Using RH to upgrade the bio-crude allows in-situ production of hydrocarbon fuels.
8	All biomethane produced in 2030 and 2050 is fed to the natural gas grid.
9	Conversion of biomass to hydrogen is not considered for simplification.
10	Conversion of biomass to methanol is not considered for simplification. There are no prospects at present to increase the oxygen content in the petrol EN228 standard. Methanol is considered by the shipping industry as a potential fuel but there are also several other alternatives for shipping.
11	Cellulosic ethanol is commercial by 2030.
12	Ethanol conversion to hydrocarbons is considered in 2050. Light duty vehicles are expected to be completely electrified by 2050. This will facilitate the utilisation of ethanol in aviation and other sectors.
13	For well-established commercial technologies such as hydrotreated vegetable oils (HVO) biomethane via anaerobic digestion and ethanol via gasification and fermentation, no improvement in conversion yield is foreseen in 2050

Annex VIII gives the biomass conversion yields used for 2030 and 2050 upon which the calculations for the estimated production of biofuels were based.

Table 15 compares the advanced biofuel production in 2030 and 2050 taking into account the total sustainable biomass for bioenergy. In Table 15 the ranges refer to the low and high biomass scenarios from section 4 above. In some value chains the availability of the feedstock is expected to decrease as has been analysed in the report and thus the corresponding advanced biofuel production decreases. Notable example is that of the biowaste the availability of which is expected to decrease for energy applications. The availability of biowaste in 2030 has been estimated 44-80 million tons decreasing to 33-61 million tons in 2050. On the other hand, the availability of Solid Industrial Waste is expected to increase from 133-191 million tons in 2030 to 142-210 million tons in 2050. These changes in feedstock availability may be modulated by an expected increase in the conversion yield expected in 2050 due to the learning curve and optimization improvements. For example, although the biowaste availability is decreased from 44 – 80 million tons per year in 2030 to 33-61 million tons per year in 2050 the production in synthetic biofuels via gasification (Fischer-Tropsh) is expected to increase from 9.2 – 16.8 Mtoe in 2030 to 13.2- 24.4 Mtoe in 2050 when renewable hydrogen (RH) is used in the process.

Other notable variations concern the utilisation of agricultural residues such as straw and corn stover. For the 2030 time frame their utilisation is considered only in the cellulosic ethanol value chain while their utilisation in thermochemical conversion is not pursued due to their physical properties (such as low bulk density) that complicates their handling and processing (e.g. feeding into the conversion reactor) in gasification and pyrolysis plants. However, if there will be significant demand for drop-in fuels it is expected that the industry and technology developers will be able to develop reliable technologies to use such fuels in thermochemical processing facilities. Thus, in Table 7 such feedstock is not considered for 2030 for the gasification and pyrolysis conversion technologies while it is taken into account for 2050.

For the 2030 time frame it is considered that pyrolysis technologies have reached the commercialization stage for co-processing in refineries; however, in 2050 it is considered that pyrolysis conversion technologies (fast pyrolysis and hydrothermal liquefaction (HTL) can operate on stand-alone mode with the supply of renewable hydrogen (RH) to upgrade the biooil and biocrude to hydrocarbon fuels. In this study it is assumed that there will be significant quantities of RH available by 2050 which could also be used in biofuels production. This is a justified assumption given the penetration of renewable electricity at present and that expected by 2050 as predicted by several studies[72][73][74]. The use of RH will increase the conversion efficiency of fast pyrolysis to 24% and of HTL to 28% in stand-alone operation mode (see Annex VIII).

For the 2050 timeframe it is assumed that all lignocellulosic biomass will be used in Fischer-Tropsch plants with RH since this is the value chain that provides the maximum conversion efficiency to biofuels and maximizes the use of natural resources.

The supply of RH can make a significant difference in the gasification Fischer-Tropsch value chain by converting the carbon of the CO_2 and CO gas components to biofuel. This study considers that there will be sufficient renewable hydrogen to increase the Fischer-Tropsch conversion efficiency to 40% (see Annex VIII).

The hydrogen requirements have been estimated at 0.065 kg H_2/kg biomass in the Fischer-Tropsch process (see Annex VIII for further explanations). The total lignocellulosic biomass predicted in Section 4 of this study ranges from 392 to 623 million tonnes based on the low and high biomass scenarios (see the projected feedstock for 'Gasification+catalytic synthesis+RH" in Table 40). Thus, the hydrogen consumption to achieve the 40% yield in Fischer-Tropsch is estimated at 25.5 – 40.5 million tonnes.

GTM Focus (see footnote 70) predicts that by 2050 the global hydrogen production will be 540 Mt of which about 85 Mt will be used in transport (or 16%). In 2050, 211 Mt per annum of low carbon hydrogen will be produced. This will consist by about 155 Mt of green hydrogen, 45 Mt of blue hydrogen and 11 Mt of "other" types of hydrogen.

According to IEA (see footnote 71) 528 Mt of hydrogen will be produced globally in 2050, around 25% is produced within industrial facilities (including refineries), and the remainder is merchant hydrogen (hydrogen produced by one company to sell to others). 62% will be electrolysis based while 38% will be fossil based with CCUS. Almost 40% of the low-carbon hydrogen used in 2050 is used in transport in the form of hydrogen-based fuels. This amounts to 206 Mt which include ammonia (56 Mt or 10.6%), synthetic fuels (44 Mt or 8.3%) and hydrogen (106 Mt or 20%).

The Energy Transitions Commission (ETC) estimates that by 2050, 500-800 Mt of hydrogen (of which 85% green hydrogen and 15% blue hydrogen) would be needed to achieve net zero economy (see footnote 72). About 290 Mt of hydrogen will be used for transport applications in the form of hydrogen-based fuels. This corresponds to 44% of the low-carbon hydrogen, which include ammonia (88 Mt or 11 %), synthetic liquids (56 Mt or 7%) and hydrogen (146 Mt or 18% [75]).

All three of the above reports estimate the global needs for hydrogen above 500 Mt while ETC predicts even higher needs at 800 Mt. GTM Focus allocates the smallest quantities of hydrogen to transport applications while the predictions of IEA and ETC are very similar.

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72 gtm focus – Wood Mackenzie, The next five years in green hydrogen, 23/03/2021.

73 IEA, Net Zero by 2050, A road map for the global energy sector, 2021.

74 Energy Transitions Commission, Making the hydrogen economy possible: accelerating clean hydrogen in an electrified economy, April 2021.

75 The 146 Mt for hydrogen is interpolated from Exhibit C of footnote 7.

In all three reports the assumptions used are numerous and the predictions made can be considered debatable and contentious; however, it is clear that if the *net zero target* is to be achieved by the global economy massive quantities of hydrogen have to be produced while the majority of it should be renewable or coupled to CCUS. At the same time the allocation of hydrogen to the transport sector is recognized by all reports while this allocation is based on certain assumptions boundary conditions by the studies. GTM Focus has the statement "*The range of outcomes is enormous; no opinion on the long-term outlook is "right"*" on the slide Global hydrogen production by end use 2010 – 2050; and this is a very true statement. It is now practically impossible to predict how the various markets and sectors will develop in the next 30 years thus.

Therefore, the requirement for 25.5 – 40.5 million tonnes renewable hydrogen to achieve the 40% yield in the Fischer-Tropsch value chain in this study is not unreasonable. Furthermore, the refineries will be generating significant quantities of hydrogen themselves and thus it can be used preferentially in situ for Fischer-Tropsch synthesis.

Finally, the eventual production of blue and grey hydrogen from natural gas and coal respectively has not been taken into account in these estimates.

Table 15 Potential advanced biofuels production in 2030 and 2050 (taking into account the total sustainable biomass for bioenergy estimated in section 4 of this study)

Pathway	Fuel	Feedstock	Estimated advanced biofuel quantity 2030 (million tons)	Estimated advanced biofuel quantity 2050 (million tons)	2030 Estimated advanced biofuel quantity (Mtoe)	2050 Estimated advanced biofuel quantity (Mtoe)	2050 Estimated advanced biofuel quantity (Mtoe) +RH
Hydrotreatment	Hydrotreated Vegetable Oil (HVO) / renewable diesel	Waste oils and fats	1.9	1.9	1.9	1.9	
		Used Cooking Oil (UCO)	2.6	6.5	2.6	6.5	
Biogas or landfill production & removal of CO2	Biomethane	Biowaste	0.8 - 1.4	0.6 - 1.0	0.9 - 1.6	0.7 - 1.2	
		Sewage sludge	0.1- 0.2	0.1- 0.2	0.1 - 0.2	0.1 - 0.2	
		Manure (solid and liquid)	1.0 -1.1	0.9 -1.0	1.1 - 1.3	1.0 - 1.2	
		Agricultural residues (high moisture; sugarbeet leaves, etc.)	0.1	0.1	0.1	0.1	
Enzymatic hydrolysis & fermentation	Ethanol (2030) Hydrocarbons (2050)	Biowaste	10.6 - 19.2	5.1 - 9.4	6.8 - 9.3	5.1 - 9.4	
		Solid industrial waste (secondary agro & forest industries)	31.9 - 45.8	21.9 - 32.3	20.4 -29.3	21.9 - 32.3	
		Agricultural residues (straw-like)	32.9 - 39.6	20.9 - 24.0	21.0 - 25.3	20.9 - 24.0	
		Lignocellulosic crops (grassy)	8.6 - 25.9	6.5 - 19.6	5.5 - 16.6	6.5 - 19.6	
Gasification + fermentation	Ethanol (2030) Hydrocarbons (2050)	Biowaste	11.9 - 21.6	5.2 - 8.2	7.6 - 13.8	5.2 - 8.2	
		Solid industrial waste (secondary agro &forest industries)	35.9 - 51.6	22.6 - 27.0	22.9 - 33.0	22.6 - 27.0	
		Agricultural (woody) & forestry residues	1.4 - 1.9	0.9- 1.0	0.9 - 1.2	0.9- 1.0	
		Lignocellulosic crops (woody)	9.7 - 29.2	6.2 - 18.9	6.2 - 18.7	6.2 - 18.9	N/A

Pathway	Fuel	Feedstock	Estimated advanced biofuel quantity 2030 (million tons)	Estimated advanced biofuel quantity 2050 (million tons)	2030 Estimated advanced biofuel quantity (Mtoe)	2050 Estimated advanced biofuel quantity (Mtoe)	2050 Estimated advanced biofuel quantity (Mtoe) +RH
Gasification + catalytic synthesis	Synthetic fuel	Biowaste	9.2 -16.8	13.2 - 24.4	9.2 -16.8	7.6 - 14.0	13.2 - 24.4
		Solid industrial waste (secondary agro & forest industries)	27.9 - 40.1	56.8 - 84	27.9 - 40.1	32.7 - 48.3	56.8 - 84.0
		Agricultural residues (straw-like)	N/A	54.4 - 62.4	0	31.3 - 35.9	54.4 - 62.4
		Agricultural (woody) & forestry residues	1.0 - 1.5	2.4 - 3.2	1.0 - 1.5	1.4 - 1.8	2.4 - 3.2
		Lignocellulosic crops (woody)	7.6 - 22.7	16.8 - 50.8	7.6 - 22.7	9.7 - 29.2	16.8 - 50.8
Fast Pyrolysis & HTL Co-processing in existing petroleum refineries	Co-processed bio-oil/biocrude	Biowaste	4.8 - 8.8	4.0 - 7.3	4.8 - 8.8	4.0 - 7.3	
		Solid industrial waste (secondary agro & forest industries)	14.6 - 21.0	17.0 - 25.2	14.6 - 21.0	17.0 - 25.2	
		Agricultural residues (straw-like)	N/A	16.3 - 18.7	0	16.3 - 18.7	
		Agricultural (woody) & forestry residues	0.6 - 0.8	0.7 - 1.0	0.6 - 0.8	0.7 - 1.0	
		Lignocellulosic crops (woody)	4.0 - 11.9	5.0 - 15.2	4.0 - 11.9	5.0 - 15.2	N/A
Pyrolysis stand-alone + RH	Hydrocarbon fuels	Biowaste		7.9 - 14.6			7.9 - 14.6
		Solid industrial waste (secondary agro & forest industries)		34.1 - 50.4			34.1 - 50.4
		Agricultural residues (straw-like)		32.6 - 37.4			32.6 - 37.4
		Agricultural (woody) & forestry residues		1.4 - 1.9			1.4 - 1.9
		Lignocellulosic crops (woody)		10.1 - 30.5			10.1 - 30.5
HTL stand-alone + RH	Hydrocarbon fuels	Biowaste		9.2 - 17.1			9.2 - 17.1
		Solid industrial waste (secondary agro & forest industries)		39.8 - 58.8			39.8 - 58.8
		Agricultural residues (straw-like)		38.1 - 43.7			38.1 - 43.7
		Agricultural (woody) & forestry residues		1.7 - 2.2			1.7 - 2.2
		Lignocellulosic crops (woody)	N/A	11.8 - 35.6	N/A	N/A	11.8 - 35.6

Table 16 summarises the potential advanced biofuel quantity per value chain for 2030 and 2050. **The biofuel quantities should not be added together for a total since the same biomass feedstock is used in different value chains**. Overall the biofuel quantity is increasing between 2030 and 2050 with the exception of biomethane which remains practically the same.

Table 16 Estimated advanced biofuel production per value chain in 2030 and 2050 (taking into account the total sustainable biomass for bioenergy estimated in section 4 of the study)

Advanced Biofuel	2030 Estimated advanced biofuel quantity (Mtoe)	2050 Estimated advanced biofuel quantity (Mtoe)
Hydrotreated Vegetable Oil /renewable diesel	4.5	8.4
Biomethane	2.2 – 3.2	1.9 – 2.7
Ethanol from Enzymatic hydrolysis & fermentation	53.7 – 80.5	N/A
Hydrocarbons from Enzymatic hydrolysis & fermentation	N/A	54.4 - 85.3
Gasification/Fermentation ethanol (GFE)	37.6 - 66.7	N/A
GFE Hydrocarbons	N/A	34.9 - 55.1
Fischer-Tropsch from Gasification + catalytic synthesis	45.7– 81.1	82.7 - 129.2
Fischer-Tropsch from Gasification + catalytic synthesis & RH	N/A	143.6– 224.8
Fast Pyrolysis & HTL Co-processing in existing petroleum refineries	24.0 - 42.5	43.0- 67.4
Pyrolysis stand-alone & RH	N/A	86.1 - 134.8
HTL stand-alone & RH	N/A	100.6 - 157.4

Table 17 summarises the potential advanced biofuel quantity per feedstock for 2030 and 2050 by selectively choosing the value chain and conversion technology that results to the highest production of biofuel, considering the increase of yields due to renewable hydrogen as a high technology scenario (in terms of technology development for renewable hydrogen and gasification processing). The total estimated biofuel production amounts to 78 – 129 Mtoe in 2030 and 160 – 255 Mtoe in 2050. The ranges refer to the low and high biomass scenarios.

When considering liquid biofuels only the total estimated biofuel production amounts to 77 - 128 Mtoe in 2030 and 159 – 252 Mtoe in 2050.

Table 17 is indicative since it takes into consideration the total sustainable biomass for bioenergy for conversion to advanced biofuels while no allocation for other applications (bio-power, industry, services, agriculture and buildings) is considered.

Table 17 High Technology Scenario: Potential advanced biofuel quantity per feedstock for 2030 and 2050, taking into account the maximum yields per pathway and the total sustainable biomass for bioenergy)

Biofuel	Feedstock	2030 Estimated advanced biofuel quantity (Mtoe)	2050 Estimated advanced biofuel quantity (Mtoe)
Hydrotreated Vegetable Oil /renewable diesel	Waste oils and fats	1.9	1.9
	Used Cooking Oil (UCO)	2.6	6.5
Biomethane	Sewage sludge	0.1 - 0.2	1.0 - 1.2
	Manure (solid and liquid)	1.1 - 1.3	0.4 - 0.4
	Agricultural residues (high moisture; sugar beet leaves, etc.)	0.1	0.1
Ethanol and hydrocarbons from Enzymatic hydrolysis & fermentation	Agricultural residues (straw-like)	21.0 - 25.3	N/A
	Lignocellulosic crops (grassy)	5.5 - 16.6	6.5 - 19.6
Fischer-Tropsch from Gasification + catalytic synthesis	Biowaste	9.2 -16.8	13.2 - 24.4
	Solid industrial waste (secondary agro and forest industries)	27.9 - 40.1	56.8 - 84.0
	Agricultural residues (straw-like)	N/A	54.4 - 62.4
	Agricultural (woody) & forestry residues	1 - 1.5	2.4 - 3.2
	Lignocellulosic crops (woody)	7.6 - 22.7	16.8 - 50.8
Total		**78.0 – 129.1**	**160.0 – 254.5**
Total Liquid advanced biofuel taking into account the total sustainable biomass for bioenergy		**76.7 - 127.5**	**158.5 – 252.8**
Average conversion yield on energy basis		**37%**	**70%**
Average conversion yield on dry mass basis		**15%**	**29%**

A LOOK INTO DEMAND BASED ON AVAILABILITY – TRAJECTORIES BASED ON THE EUROPEAN COMMISSION SCENARIOS

It must be taken into account that from the total sustainable biomass for bioenergy, there would be some potential use for power, industry, services & agriculture and residential heat demand in 2030 and 2050, which will decrease the availability of feedstock for advanced biofuel production. No allocation to transport has been done in this study in the absence of an economic model. Figure 29 shows the use of bioenergy estimated by the European Commission in the recently published Impact Assessment[76] (about 130 Mtoe for 2030 and 170 Mtoe for 2050).

[76] Figure 77, Use of Bioenergy by sector and scenario, page 95, EC, Impact assessment, Stepping up Europe's 2030 climate ambition, SWD (2020) 176 Final, 17.9.2020

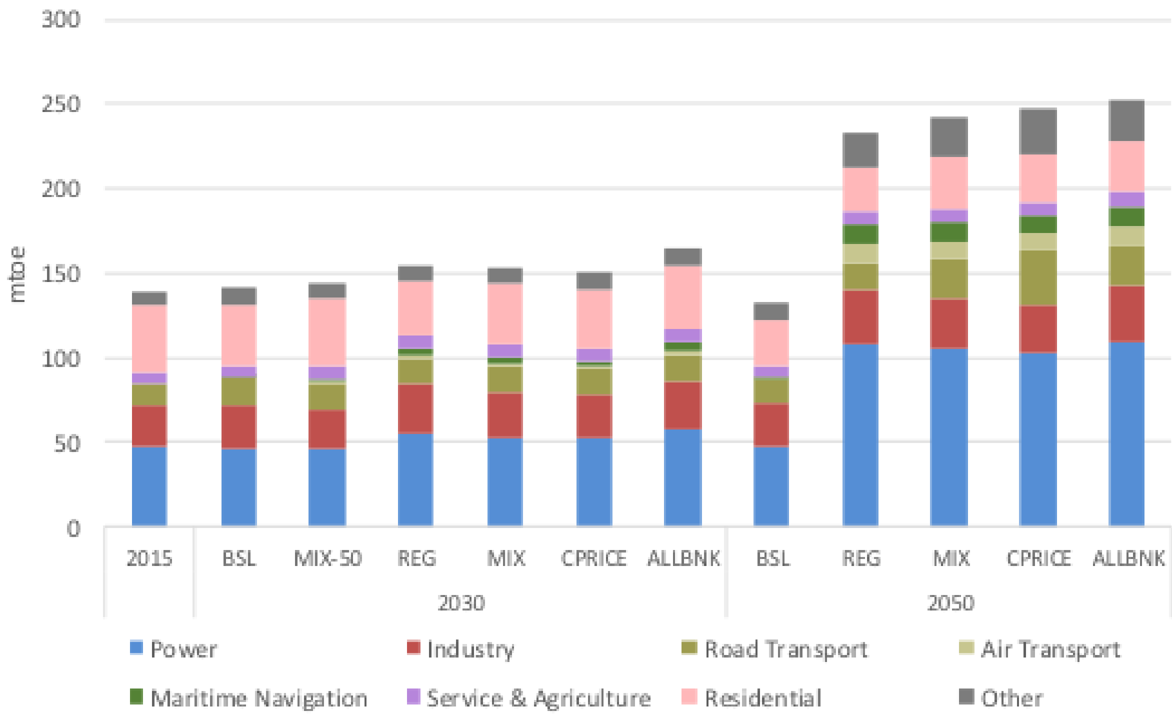

Figure 29 Use of bioenergy estimated by the PRIMES model in the Impact Assessment from the EU Commission

Table 18 Comparison of biomass available for biofuels among this study including imports and PRIMES allocation to other non-transport sectors (Mtoe) and total estimated biomass for biofuel

	2030	2050
Estimated biomass for bioenergy (this study)	208-344	215-366
Estimated biomass imports (this study, see Annex 2)	48	56
Estimated biomass for advanced biofuels (*): balance of biomass for biofuel accounting the demand for other uses estimated by PRIMES (EU Commission)	78 – 214	45 – 196
Total estimated biomass left for biofuels in transport (with imports)	**126 - 262**	**101 - 252**

(*) Estimated biomass for advanced biofuels if the power, industry, services & agriculture and residential heat demand biomass allocation estimated by PRIMES is taken into account.

The total estimated net biomass that can be used for biofuel production, including imports (49 Mtoe in 2030 and 56 Mtoe in 2050) and deducting the use of biomass for other non-transport (power, industry, service, agriculture and residential) related uses (130 Mtoe in 2030 and 170 Mtoe in 2050 according to the European Commission Impact Assessment[77]), has been estimated at **126-262 Mtoe for 2030** and **101 – 252 Mtoe for 2050** (note: the ranges correspond to the lowest and highest biomass availability scenarios). The following table 20 summarises the potential sustainable availability for the production of advanced and waste/based biofuels as defined in the first part of the study (including the combination of the range in terms of low/high availability with the high technology conversion scenario, with and without all the bioenergy sectors and imports considered).

[77] Figure 77, Use of Bioenergy by sector and scenario, page 95, EC, Impact assessment, Stepping up Europe's 2030 climate ambition, SWD (2020) 176 Final, 17.9.2020

Table 19 Summary table –Biofuels potential availability

	Potential biofuels availability 1 (All bioenergy)		Potential biofuels availability 2 (Allocation to transport based on PRIMES)	
2030	**Potential advanced and waste-based biofuels (EU domestic production)(1)**	**Potential advanced and waste-based biofuel (EU + imports) (1)**	**Potential advanced and waste-based biofuel adjusted according to PRIMES allocation to non-transport sector (EU domestic production)**	**Total Potential advanced and waste-based biofuel (EU + imports)**
	76.7 - 127.5	**94.5-145.3**	**28.9 – 79.2**	**46.7 – 97.0**
2050	**Potential advanced and waste/based biofuels (this study) (1)**	**Potential advanced biofuel estimated due to imports (this study)**	**Potential advanced biofuel adjusted according to PRIMES allocation to non-transport sector**	**Total Potential advanced biofuel (EU + imports)**
	158.5 – 252.8	**197.7-292**	**31.5 – 137.2(2)**	**70.7 – 176.4**

(1) Potential advanced biofuels taking into account that all the bioenergy estimated in the low and high scenarios of this report were allocated to advanced biofuels for transport sector. The ranges include the low and the high biomass availability scenarios, taking into account the maximum conversion yields for the different pathways per type of feedstock (High Technology Scenario).

(2) The potential for advanced biofuels by the estimated balance of biomass for biofuel is an approximate estimation of the estimated biomass for advanced biofuels considering the same average conversion efficiency as in this study.

Note: In this study no imports of biofuels in the EU have been considered. Only imports of biomass in the EU have been considered.

Based on the above tables Annex IX provides a sensitivity analysis constructed on several assumptions that may affect the value chains to be used in the future.

It is important to highlight that the biomass potentials availability estimated in this study are based on very conservative assumptions, as explained in sections 1-4. Furthermore, the potentials from algal biofuels plus other sustainable biomass feedstocks not included in RED II Annex IX have not been taken into consideration at all in the above calculations. Therefore, it can be concluded that the biomass potentials in 2030 and 2050 would most probably be higher than those estimated by this study.

To realise this potential, additional R&D would be required as well as the implementation of improvement management strategies. Even if the potential is there, the supply chain would need to be developed to mobilise all these resources.

ANNEXES

I. ALGAE

Both micro-algae and macro-algae are considered as a potential feedstock for biofuel production in the overall biorefinery concept. Theoretical calculations show attractive potential for future algae-based biofuels, with high productivity per unit land area (in areas where no other agricultural-based crops could be cultivated), but cost reduction and scale-up are critical challenges up to now.

Data on the amount of algae biomass produced in Europe is reported under different EU level collection frameworks for catch and aquaculture statistics. This data is based on Member States and European Economic Area (EEA) member countries submissions[78] and centralized in Eurostat fisheries statistics and the European Commission's Joint Research Centre (JRC).

Figure 32 presents the location of algae plants in Europe.

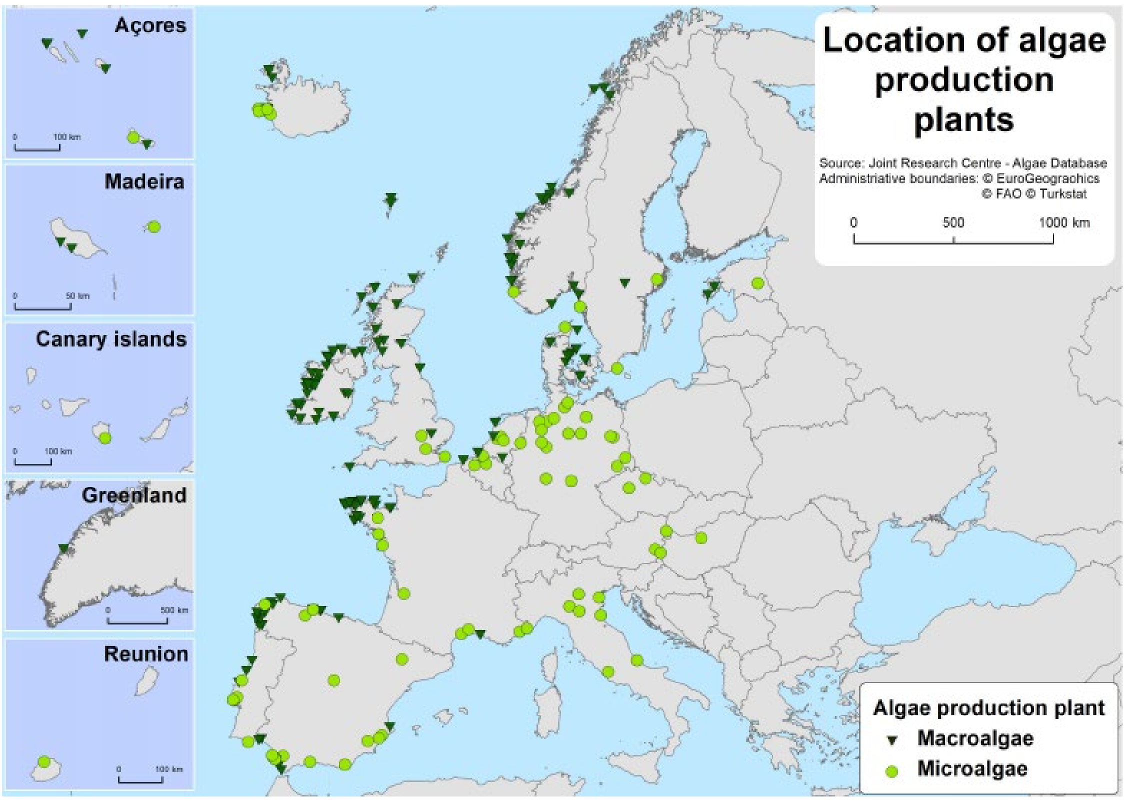

Figure 30 Location of algae plants in Europe (source: JRC[79])

Currently, algae biomass is directed primarily for food and food-related applications including the extraction of high-value products for food supplements and nutraceuticals.

[78] EU 2019/909 (2019). Commission Implementing Decision (EU) 2019/909 of 18 February 2019 Establishing the List of Mandatory Research Surveys and Thresholds for the Purposes of the Multiannual Union Programme for the Collection and Management of data in the Fisheries and Aquaculture Sectors. Available online at: http://dcf.mir.gdynia.pl/wp-content/uploads/2019/10/COM_Impl-Decision_2019-909_EU-MAP_surveys-thresholds.pdf

[79] https://knowledge4policy.ec.europa.eu/visualisation/bioeconomy-differentcountriesen#algaeprodplants

According to the results of a recent JRC study[80], the European algae sector amounts to 225 macroalgae (67%) and microalgae (33%) producing companies. Spain, France and Ireland support the largest number of macro- and microalgae companies followed by Norway, the United Kingdom, Germany and Portugal (Figure 32 Location of algae plants in Europe (source: JRC). The same study reports that there are several constraints, that still limit the sector expansion, the primary ones being, but not limited to, the small market size for algae commodities in Europe, the variability in the annual biomass supply, the current state of technological development in the production and processing of biomass.

According to the available statistics used in this JRC study, algae biomass production was increasing worldwide and reached 32.67 Million tonnes [Fresh weight (FW)] in 2016 from which 0.57% of the volume was produced in Europe (including EU 27 + United Kingdom + Iceland + Norway) (Araújo et al., 2019a based on data from FAO). At the global level, algae biomass is mostly supplied by aquaculture (96.5% in 2016) while in Europe harvesting from wild stocks contributed to 98% of the total algae production volume in the same period[81, 82]. The analysis acknowledges that there are significant knowledge gaps exist with this data. All studies also acknowledge that no wildly harvested macroalgae should be used for biofuel production due to sustainability constraints.

Due to the uncertainty about the development of both macro and micro-algae for the bioenergy sector, this report does not attempt to make any projections about the future use of algae for advanced biofuel production; highlighting that more research and development would be needed in this area.

[80] Frontiers | Current Status of the Algae Production Industry in Europe: An Emerging Sector of the Blue Bioeconomy | Marine Science (frontiersin.org)

[81] Araújo, R., Lusser, M., Sanchez Lopez, J., and Avraamides, M. (2019a). Brief on Algae Biomass Production. Luxembourg: Publications Office of the European Union.

[82] Araújo, R., Sanchez Lopez, J., Landa, L., and Lusser, M. (2019b). Report on the community of practice workshop: algae production in Europe: status, challenges and future developments. ARES 2019:3524950.

II. BIOMASS IMPORTS

The main sources of imported biomass pellets and wood chips (from forestry residues and industry residues, and roundwood from dedicated short rotation plantations) are Brazil (BRA), east Canada (CA), north west Russia (RU) and south east United States of America (US).

Europe is so far the largest pellet consumer in the world with 27 million tonnes of pellets being consumed annually. In 2018, the EU28 saw a significant growth of around 2 million tonnes with the industrial use of pellets being led by the UK. With a production volume of 20,1 million tonnes (16,9 million for the EU28), Europe solely supplies 74% of its pellet use (65% for EU28).

There are two significant regions who are net importers of pellets in the world, namely, the EU28 and Asia. The figure below confirms this current hegemony of the EU28 regarding its pellet consumption and in stark comparison Asia is continuing to grow at a rapid rate, becoming the driving force of the pellet market development alongside Europe.

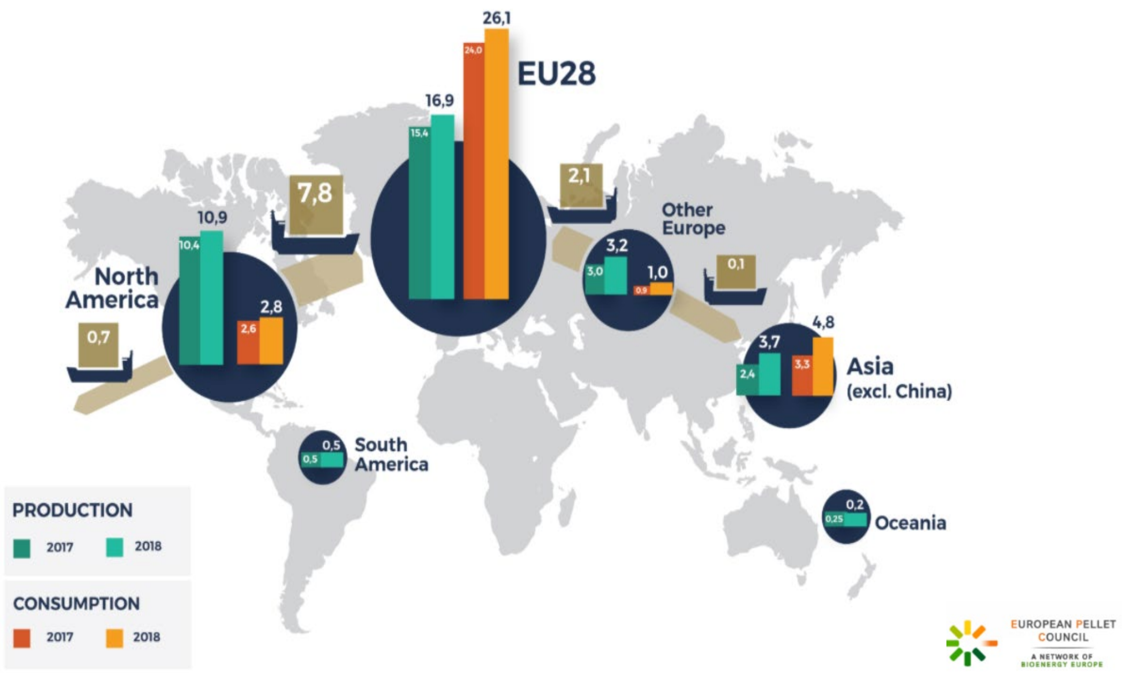

Figure 31 World pellet map & trade-flows[83] (2018, in million tonnes)

[83] https://epc.bioenergyeurope.org/about-pellets/pellets-statistics/world-pellet-map/

Key figures for the pellet market are as follows:

- In 2018, global production of wood pellets was 35 Million tonnes (actual weight, not dry matter).
- Wood pellet imports to EU from the USA and Canada were 3.7 Mtoe in 2015, 4.5 Mtoe in 2016 and 5.0 Mtoe in 2017.
- Pellet costs range between 7 and 11.5 €/GJ while wood chip costs range between 5.5 and 10 €/GJ.
- The United States was the largest producer and exporter of wood pellets in 2018 with actual US production of 7.3 Mt (actual weight). US exports of wood pellets in 2018 were 5.4 million tonnes. Most of the exports went to Europe – primarily to the United Kingdom, although exports increased significantly to Denmark, Italy and the Netherlands.
- Russia had annual production capacity of 3.6 Mt (actual weight) in 2018, although Russian plants were operating at only a 50% load factor. Russian exports rose 30% for the second year running and totalled 1.5 Mt in 2018.

Several studies have estimated the potential of biomass imports for all bioenergy markets.

Figure 34 provides an overview of the respective estimates for the years between 2020 and 2050. Imports of wood pellets and agricultural residues are based on the BioTrade project[84]. Import potential of biomass for bioenergy are derived from the Biomass Policies project. The estimated UCO potential has been derived from Spöttle et al (2013) [85].

Costs and sustainability are critical factors that impact both the quantities and the quality of imported biomass.

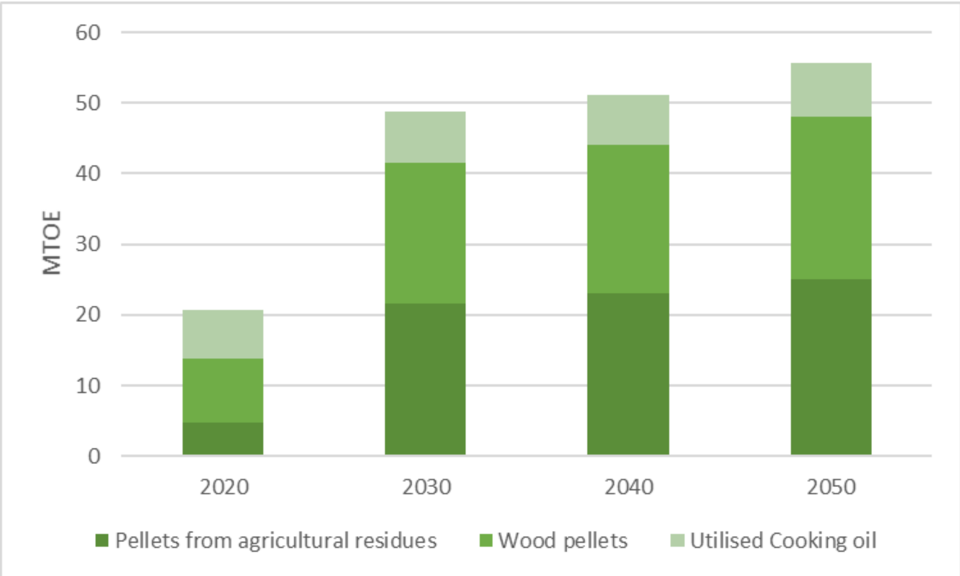

Figure 32 Biomass import potential (Mtoe) for the years between 2020 and 2050 (*Sources: BioTrade2020 project; Biomass Policies project and Spöttle et al (2013)*)

The reported potential for imports ranges from 49 to 56 Mtoe for 2030 and 2050 respectively, which can on average provide additional biomass feedstock in the range of 16-30% of the estimated domestic potential in this study.

[84] Biotrade2020(2016). See https://www.biotrade2020plus.eu/publications-reports.html

[85] Spöttle, et al (2013). Low ILUC potentials of wastes and residues for biofuels – Straw, forestry residues, UCO, corn cobs. Ecofys Netherlands B.V.

PRIMARY FIELD RESIDUES

DEFINITION

Primary agricultural residues are produced on field following crop harvesting (field residues) and regular tree pruning activities (arboricultural residues).

Field crops are producing two types of field residues, i.e. fresh or dry residues. Green field crop residues, such as sugarbeet are left in the field in fresh, succulent condition. These residues have high moisture content and are usually rotting in the field while occasionally some of them are used for animal feeding. Dry field residues derive from field crops, cultivated in various European regions, and they may come from small grain cereals (wheat, barley, oat, rye, and rice), maize, oil crops (sunflower, rapeseed, etc.), etc. These residues are incorporated into the soil, burned in the field or collected and used for various purposes.

Arboricultural residues are the prunnings of grapes and trees such as apple trees, olive oil trees, pear trees etc., as well as from final disposal of old trees or from removal of whole grape or tree plantations for cleaning fields to be given to other more productive crops. Table 21 provides an overview of the biomass categories included in primary agricultural residues.

Table 20 Overview of biomass categories included in primary agricultural residues

Category	Residue type	Crop origin	Definition
Dry field	Straw/ stubbles	Cereals	Dried stalks of cereals (including rice), rapeseed and sunflower which are separated from the grains during the harvest. Available on field.
		Oil- crops: Rapeseed/ sunflower	
		Rice	
		Grain maize (stover)	Stover consists of leaves, stalks and bare cobs from grain maize plants left in the field after harvest
Green field		Sugarbeet leaves & tops	Sugarbeet leaves and tops are the harvest residues separated from the main crop, during harvest. Available on field.
Dry arboricultural	Pruning/ cutting	Apple, pear & apricot pruning	The prunings and cuttings of fruit trees, vineyards, olives and nut trees are woody residues produced after cutting, mulching and chipping activities. They are the result of normal pruning management needed to maintain the orchards and improve their productivity. Available on field.
		Cherries	
		Vineyards	
		Olives	
		Citrus	
		Nut trees	

Current uses for primary agricultural residues include soil incorporation for maintenance of soil organic matter[86], animal bedding and feeding as well as horticultural activities such as mushroom, flower bulbs and strawberry

[86] The EC Soil Framework Directive52 defines SOM as "*the organic fraction of the soil, excluding undecayed plant and animal residues, their partial decomposition products, and the soil biomass*". SOM consists of between 50 and 58% carbon (C) and hydrogen (H), oxygen (O), nitrogen (N), phosphorous (P) and sulphur (S). http://eur-lex.europa.eu/legal-content/ES/TXT/PDF/?uri=CELEX:52006PC0232&from=EN

production. Emerging uses include renewable energy, advanced biofuels and bio-based materials. Table 22 Current and emerging (in bold) uses for primary agricultural residuesprovides an overview of current uses for primary agricultural residues. Renewable energy from primary agricultural residues is referred here as emerging and includes the high efficiency boilers and innovative CHP applications. It does not refer to old stoves and boilers with low efficiencies which use prunnings. However, these traditional uses still exist and occur mostly in rural mountainous regions across Europe.

Table 21 Current and emerging (in bold) uses for primary agricultural residues

	Straw			***Grain maize***	***Sugarbeet leaves & tops***	***Prunings***			
	cereals	*Oil-crops*	*rice*			*Fruit trees*	*Nut trees*	*Olives*	*Vineyards*
Residue incorporation to the soil to preserve soil quality and improve soil carbon	√	√	√	√	√				
Animal bedding	√	√	√						
Animal feed	√	√	√						
Mushroom production	√	√	√						
Frost protection	√	√	√						
Strawberry/ lower bulbs production	√	√	√						
Paper& pulp	√	√	√						
Building materials	√	√	√			√	√	√	√
Energy, fuels	√	√	√	√	√	√	√	√	√

DATA SOURCES

Data on area and yields of the main straw delivering crops can be derived from national and European wide agricultural statistical sources (see Table 23).

Average crop yield data are available at national level and it is recommended to use annual averages across a five to ten-year period to capture the respective weather and climatic variations.

Table 22 Overview of data sources providing information on area and yields and can be used as input for calculation of potentials from primary agricultural residues

Data source	Spatial coverage	Spatial resolution	Description/relevance
FADN	EU-28	Regional (Nuts2/3)	Farm accountancy data
EUROSTAT/FSS	EU-28 + Norway, Switzerland, Croatia	Regional (Nuts2/3)	Data on areas under cultivation per crop
Eurostat annual crop statistics	EU-28	National and for some items regional (NUTS1/2)	Crop statistics are collected on areas under cultivation (expressed in 1,000 hectares), the quantity harvested (expressed in 1,000 tonnes) and the yield (expressed in 100kg/ha).
IACS/LPIS	EU28	Parcel size	Land use per parcel to be aggregated to any regional levels. Disclosure rules make access to these data difficult in some countries.

FARM ACCOUNTANCY DATA NETWORK (FADN)

The Farm Accountancy Data Network (FADN) is an annual survey carried out by all Member States of the European Union. FADN data are collected every year from a sample of the agricultural holdings which are selected based on sampling plans established at the level of each region in a given country. The methodology applied aims to provide representative data along three dimensions: region, economic size and type of farming.

FADN represents the only source of harmonised microeconomic data (farm level) that are obtained using the same methodologies across all countries. Respective aggregated data can be found in the Standard Results database (http://ec.europa.eu/agriculture/rica/diffusion_en.cfm).

Currently, the annual FADN sample covers approximately 80.000 holdings. They represent a population of about 5 million farms in the Member States, which cover approximately 90% of the total utilized agricultural area (UAA) and account for about 90% of the total agricultural production of the Union.

The stratification of the FADN sample is done using the information of the Farm Structure Survey (FSS) on distribution of the total EU farm population over size and (sectoral) type. The survey however does not cover all the agricultural holdings in the Union but only those which due to their size could be considered commercial. This implies that often part time farms and smaller extensive farms particularly occurring in Southern and CEEC are under-represented.

The FADN data are available at individual farm level per FADN region. However, the accessibility to the individual farm data are restricted to FADN Liaison Agencies and permission to use the data needs to be obtained from DG-Agri. Data are only available at the FADN region level (See Figure 35). Publication of the data in reports requires a minimal representation of the figure by more than 15 farms.

Figure 33 FADN regions

EUROSTAT STATISTICAL DATA SOURCES (FSS, CROP SURVEY AND SAPM)

The main EU wide statistical source of information on agricultural land use is the Farm Structural Survey (FSS) and the crop survey.

FSS provides EU wide harmonised data for agricultural holdings in the EU including:

- Number of agricultural holdings
- Land use and area (crops)
- Main crops, area, yield, total production
- Farm Labour Force (including age, gender and relationship to the holder)
- Economic size of the holdings
- Type of activity
- Other gainful activity on the farm
- System of farming
- Machinery
- Organic farming

The frequency of data collection for FSS is every two years. This implies that the Member States are obliged to deliver the standard data every two years which can be based on a sample of farms but every 10 years a full scope survey is carried out in the form of an agricultural census. The most recent census took place in 2010 in all EU Member States.

The survey data can only be derived in aggregated format at different geographic levels (Member States, regions, and for basic surveys also district level). The data can also be arranged by size class, area status, legal status of the holding, objective zone and farm type.

In addition to the FSS there is also **Survey on agricultural production methods (SAPM)** which was carried out for the first time in 2010 to collect data at farm level on agri-environmental measures. European Union (EU) Member States could choose whether to carry out the SAPM as a sample survey or as an exhaustive survey. Data were collected on tillage methods, soil conservation, landscape features, animal grazing, animal housing, manure application, manure storage and treatment facilities and irrigation. Regarding irrigation, Member States were asked to provide estimation (possibly by means of models) of the volume of water used for irrigation on the agricultural holding.

The Member States collected information from individual agricultural holdings and, observing rules of confidentiality, data were transmitted to Eurostat. The results of the SAPM are linked at the level of individual agricultural holdings to the data obtained from the Farm structure survey (FSS) in 2010[87].

The basic unit underlying the SAPM is the agricultural holding: a technical-economic unit, under single management, engaged in agricultural production. The SAPM covers all agricultural holdings with a utilised agricultural area (UAA) of at least one hectare (ha) and those holdings with a UAA of less than 1 ha where their market production exceeds certain natural thresholds.

Crop statistics refer to annual data on area, production harvested and yield for cereals and for other main field crops (mainly dried pulses, root crops, fodder and industrial crops); humidity of the harvested crop (humidity content in %) and agricultural land use. For some products regional figures (NUTS 1 or 2) are available too. The data refer to areas under cultivation (expressed in 1 000 hectares), the quantity harvested (expressed in 1,000 tonnes) and the yield (expressed in 100kg/ha). The information concerns more than 100 crop products.

The earliest data are available from 1955 for cereals and from the early 1960's for fruits and vegetables. However, most Member States have started to send in data in the 1970's and 1980's. The statistical system has progressively improved

[87] The legal basis for the SAPM is Regulation 1166/2008 of 19 November 2008 on farm structure surveys and the Survey on agricultural production methods, which repealed Council Regulation 571/88.

and enlarged. The current Regulation (EC) No 543/2009 entered into force in January 2010. It simplified the data collection and reduced the number of crop sub-classes. At present Eurostat receives and publishes harmonised statistical data from 28 Member States broken down in:

- 17 categories and subcategories for cereals;
- 30 categories and subcategories for other main crops (mainly Dried pulses, Root crops and Industrial crops);
- 40 categories and subcategories for vegetables;
- 41 categories and subcategories for fruits;
- 18 categories and subcategories for UAA (Utilised Agricultural Area).

The main data sources are administrative records, surveys and expert estimates. National Statistical Institutes or Ministries of Agriculture are responsible for the national data collection in accordance with EC Regulations. Eurostat is responsible for drawing the EU aggregations. For further information see: http://ec.europa.eu/eurostat/cache/metadata/en/apro_cpp_esms.htm#meta_update1418757870727

METHODOLOGY

The methodology described in this section addresses the theoretical, technical and sustainable potentials for primary agricultural residues in Europe[88]. Figure 36 Methodology for assessing the potentials from primary agricultural residuesprovides an overview of the methodological steps and the main assumptions in the calculation flows.

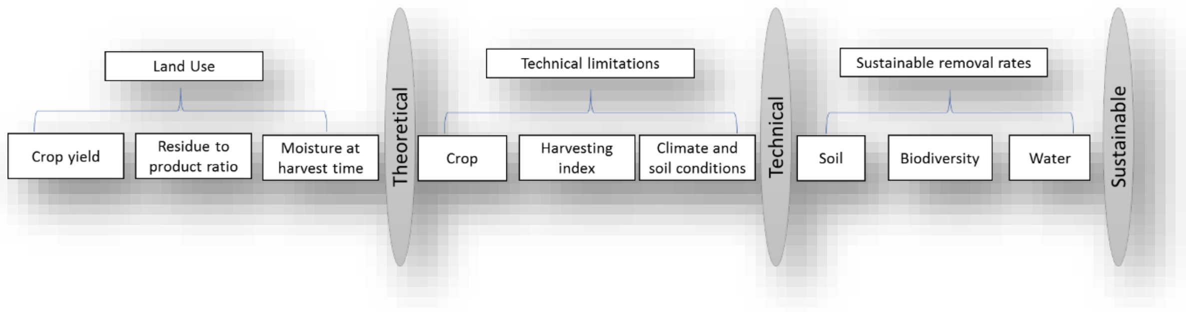

Figure 34 Methodology for assessing the potentials from primary agricultural residues

Theoretical Potential: The total quantity of residues that can be produced annually from a specific crop. Theoretical Potential is the quantity grown or disposed, constrained only by land and crop growth related factors.

For the theoretical potential, the calculation of the residue-to-yield factor is applied to the main product yield to estimate the above ground biomass production per crop with the following formula:

$$\text{Theoretical residue yield}(i) = \text{Area}\ (i) * \text{Yield}\ (i) * \text{Residue ratio}\ (i) * \text{Dry matter content}\ (i)$$

Where:

Theoretical residue yield(i) = above ground biomass of crop i
Area (i) = Crop area of crop i
Yield (i) = Yield level of the main product of crop i
Residue ratio (i) =Residue-to- main crop ratio for crop i
Dry matter content (i) = Dry matter content of crop i

It is worth noting here that estimating the theoretical residue yield per hectare depends strongly on local practices. However, to facilitate work in top down biomass potential assessments, default values for the residue ratios can be found in relevant literature.

A set of representative values for residue yield ratios and dry matter content (%) are presented in Table 24 Residue yield ratios as reported in selected studies for the under study primary agricultural residuesand 25.

[88] C. Panoutsou, C. Perakis, B. Elbersen, T. Zheliezna, I. Staritsky. Assessing Potentials for Agricultural Residues. Modelling and Optimization of Biomass Supply Chains. Elsevier (2017), pp. 169-197, 10.1016/B978-0-12-812303-4.00007-0

Table 23 Residue yield ratios as reported in selected studies for the under study primary agricultural residues (highlighted in yellow the ratios used in this study)

	Straw			Grain maize	Sugarbeet leaves & tops	Prunnings			
Study (country/ ies)	*Cereals*	*Oil-crops*	*Rice*			*Fruit trees*	*Nut trees*	*Olives*	*Vineyards*
Panoutsou (EU)	1.0	1.8	0.8		0.70	0.35	0.35	1.3	0.5
Scarlat (EU)	0.8	2.0	0.8						
Synenergy (W. Balkans, UA, MD)	1.0	1.5	1.2	1.5		0.30	0.30	1.0	0.25
Geletukha (UA)	1.0	2.0	1.0		0.75	0.30	0.30		0.25
World Bank (W. Balkans)	1.0	1.5		1.4		0.35	0.3	0.50	0.40

Table 24 Dry matter content as reported in selected studies for the under study primary agricultural residues (highlighted in yellow the ratios used in this study)

	Straw			Grain maize	Sugarbeet leaves & tops	Prunnings			
Study (country/ ies)	*cereals*	*Oil-crops*	*rice*			*Fruit trees*	*Nut trees*	*Olives*	*Vineyards*
Panoutsou (EU)	75	60	75	60	50	80	80	80	80
Scarlat (EU)	85	60	75	70					
Synenergy (W. Balkans, UA, MD)	85	85	85	85	55	85	85	85	85
Geletukha (UA)	80	75	80	65	45	80	80	80	80
World Bank (W. Balkans)	85	85		80		80	80	80	80

Small grain cereals and oilseed crops are harvested during the summer period and therefore moisture content of crop residues is low (15% on average).

Maize is an exception, since it is harvested from second half of September to late November and therefore moisture content will depend on the cultivated hybrid as well as on weather conditions and whether they are suitable for on-field drying. Thus, moisture content of maize stover at harvest time will vary from less than 15% to over 50%. Nevertheless, if properly stored, moisture content of maize stover usually drops below 20% after a few months (4-5 months).

Technical Potential: This considers technical limitations related to the crop physiology, the harvest/ collect index and the prevailing climate and soil conditions in each region. There are several factors that limit the amount of primary field residues that can be recovered from the fields. These include the harvesting equipment, the crop type, growth pattern and variety, the harvest index (related to the growth and crop management practices) as well as losses from lodging (crops flattened by wind or rain). Thus, calculation of technical potential considers these factors and is lower than the theoretical one.

Technical potential = Theoretical residue yield (i) * technical availability factor

A set of representative values for technical availability is presented in Table 26 Technical availability factors (%).

Table 25 Technical availability factors (%) (highlighted in yellow the ratios used in this study)

	Straw			Grain maize	Sugarbeet leaves & tops	Prunings			
Study (country/ ies)	*cereals*	*Oil-crops*	*rice*			*Fruit trees*	*Nut trees*	*Olives*	*Vineyards*
Panoutsou (EU)	50	70	50	45	45	85	85	65	70
Scarlat (EU)									
Synenergy[89] (W. Balkans, UA, MD)	40	40	40	60	60	90	90	60	70
Geletukha[90] (UA)	40	40	40	50	60				
World Bank (W. Balkans) [91]	40	40		50		85	85	85	75

Sustainable potential: The term “sustainable potential” is used to describe the amount of primary agricultural residues that can be removed from the land without adversely affecting the soil quality, causing negative impacts to biodiversity and water in each region. Consequently, the sustainable potential is lower than the technical one.

Regarding to soil quality, appropriate accounting of residue removals from the field has to consider the following: removal of nutrients available in the harvested residues, impact on Soil Organic Matter (SOM), Soil Organic Carbon (SOC) and effects on reduction or elimination of wind erosion and soil compaction protection cover. These should be considered to preserve soil fertility and productivity whilst in the same time allow for residue exploitation in the various markets.

Sustainable potential = Technical residue yield (i) * sustainable removal rates

A set of representative values for sustainable removal rates is presented in Table 27 Sustainable removal rates.

Table 26 Sustainable removal rates (%) (highlighted in yellow the ratios used in this study)

	Straw			Grain maize	Sugarbeet leaves & tops	Prunnings			
Study (country/ ies)	*cereals*	*Oil-crops*	*rice*			*Fruit trees*	*Nut trees*	*Olives*	*Vineyards*
Panoutsou (EU)	35	45	35	50	55	85	85	85	75
Scarlat (EU)	40		40	45	50				
Synenergy (W. Balkans, UA, MD)	55	55	55	55		80	80	80	80
Geletukha (UA)	30	40	30	40					
World Bank (W. Balkans)	40	45	45	50		90	90	90	90

[89] World Bank, 2015. Sector study on biomass-based heating in the Western Balkans.

[90] Geletukha, G.G., Zheliezna, T.A., Kucheruk, P.P., Oleynik, Y.M., Tryboi, O.V., 2015. Bioenergy in Ukraine: State of the art and prospects for development. Part 1 Indus. Heat Eng. 37 (2), 68.

[91] World Bank, 2016. Glavonjic, B., Perakis, Ch., Stojadinovic, D. Sector study on biomassbased heating in the Western Balkans. Task 1 report. Analysis of the biomass supply potential.

SECONDARY RESIDUES FROM AGRO-INDUSTRIES

Secondary agricultural residues are produced in the (industrial) processing of agricultural crops into products.

DEFINITIONS

There are several types of secondary agricultural processing residues, such as olive pomace and pits, cotton gin trash, almond shells, peach pits, etc.

An overview is presented in Table 28 while detailed information is provided in the following section, including their currently known uses.

Table 27 Overview of residue categories included in secondary agricultural residues

Category	Residue type	Crop origin	Definition
Secondary residues using agricultural products	Olive pits	Olive trees	Olive pits are separated from the rest of the olives when these are processed for making olive oil or when processed to tale olives
	Fruit pulp, kernels, husks, etc.	Fruit trees, vineyards, arable crops	Agro-industries process primary agricultural products into final products through pealing, crushing, drying, etc. and this results in many vegetal residues (e.g. soya and rape cake, seed husks, etc.).

Currently known uses for secondary agricultural residues include fertilisers, animal feed and compost . Emerging used include renewable energy and biobased chemicals and materials.

Renewable energy from secondary agricultural residues is referred here as emerging and includes the high efficiency boilers and innovative CHP applications which produce process heat and electricity within the respective agro-industries. It does not refer to old type boilers with low efficiencies which use the secondary residues with low efficiencies. However, these traditional uses still exist and occur mostly in rural regions across Europe. Table 29 provides the currently known and emerging uses for secondary agricultural residues.

Table 28 Currently known and emerging uses for secondary agricultural residues

	Olive pomace & pits	*Cotton gin residues*	*Cereal bran*	*Rice husks*	*Oil crop residues*	*Pressed grapes*	*Fruit juice dregs*	*Sugarbeet industries*	*Potato industry residues*
Fertilisers						√			
Animal feed		√	√	√	√		√	√	
Compost		√	√		√	√	√	√	√
Energy	√								
Biobased chemicals & materials	√	√	√			√	√	√	√

METHODOLOGY

This section presents the methodology and indicators used in this study for each of the secondary residues included in this chapter.

OLIVE POMACE AND PITS

Olive pits are a by-product from the olive oil industry. Calculation of the secondary residues from this source can be based on the total area of oil olives and the respective average yield per hectare of olive pits or the residue/main product ratio.

*Area * olive pit yield per hectare*

Suggestion for ratios:

*Italy (Del Blasi, 1997): 0.3 tonne dry matter/ha/year of olive pits

or

*Area * olives' yield per hectare * residue to-main product ratio*

*Portugal (Diaz & Azevedo, 2004): 0.07 dry matter residue/main product ratio

*Greece (Nikolaou et al., 2002): 0.21 wet mass residue/main product ratio (wet assuming 30% moisture)

COTTON GIN RESIDUES

The process of cotton ginning produces a by-product composed of bur and stem fragments, immature cottonseed, lint, leaf fragments, and dirt. So-called "cotton gin waste" or trash. These are residues from the cotton ginning factories.

Calculation of the secondary residues from this source can be done based on the total area (hectares) of cotton and the average per hectare yield of the main product and then apply a residue/main product ratio.

*Area * per hectare yield of cotton * residue to-main product ratio*

*Greece (Nikolaou et al., 2000): 0.1 wet mass residue/main product ratio (wet assuming 13% moisture)

CEREAL BRAN

These are residues from the flour mills. In wheat processing 20% to 25% wheat is left unused (Kent et al., 1994). Wheat bran represents roughly 50% of these quantities and about 10 to 19% of the kernel, depending on the variety and milling process (Ash, 1992; WMC, 2008; Prikhodko et al., 2009; Hassan et al., 2008). So the residue to yield factor used is 10% of cereals processed.

Calculation of the secondary residues from this source can be done based on the total area (hectares) of cereals used for flour production and the average per hectare yield of the main product and then apply a residue/main product ratio.

*Area * per hectare yield of cereal * residue to-main product ratio*

*Portugal (Diaz & Azevedo, 2004): for rye 0.3 wet mass residue/main product ratio (wet assuming 12.5% moisture). For wheat flower the ratio is 0.19 (13 % moisture) and for maize flower the ratio is 0.2 (18% moisture)

RICE HUSK

These are residues from the rice mills. Rice husk is approximately 20% of the processed rice, with average moisture content of 10% (Nikolaou, 2000).

Calculation of the secondary residues from this source can be done based on the total area (hectares) of rice and the average per hectare yield of the main product and then apply a residue/main product ratio.

*Area * per hectare yield of rice * residue to-main product ratio*

*Greece (Nikolaou et al., 2002): 0.16 wet mass residue/main product ratio (wet assuming 10% moisture)

OIL CROP RESIDUES (SOY, SUNFLOWER AND RAPE SEED)

These are residues from seed oil processing factories.

Calculation of the secondary residues from this source can be done based on the total area (hectares) of rice and the average per hectare yield of the main product and then apply a residue/main product ratio.

*Area * per hectare yield of oil seeds * residue to-main product ratio*

*Portugal (Diaz & Azevedo, 2004): for sunflower 0.6 wet mass residue/main product ratio (wet assuming 10% moisture). For rape and soy the ratio is 0.8 (13% moisture).

NUT PEELINGS (WALNUT, ALMOND, HAZELNUT)

These are secondary residues from the peeling plant for nuts.

Calculation of the secondary residues from this source can be done based on the total area (hectares) of nut trees and the average per hectare yield of the main product and then apply a residue/main product ratio.

*Area * per hectare yield of nuts * residue to-main product ratio*

*Greece (Nikolaou et al., 2002): 0.95-1.5 wet mass residue/main product ratio (wet assuming 5%-8% moisture)

PRESSED GRAPES DREGS

These are secondary residues from the vine industry. Of the processed grapes 4.6% consists of dregs and 1.5% of stalks (FABbiogas, Italian country report[92]).

Calculation of the secondary residues from this source can be done based on the total area (hectares) of vineyards and the average per hectare yield of the main product and then apply a residue/main product ratio.

*Area * per hectare yield of grapes * residue to-main product ratio*

*Portugal (Diaz & Azevedo, 2004): 0.19 wet mass residue/main product ratio (wet assuming 80% moisture)

FRUIT JUICE DREGS (ORANGES AND OTHER CITRUS TREES)

The secondary residues from the juice industry.

Calculation of the secondary residues from this source can be done based on the total area (hectares) of citrus (going to fruit juice production!) and the average per hectare yield of the main product and then apply a residue/main product ratio.

*Area * per hectare yield of citrus fruits * residue to-main product ratio*

*Portugal (Diaz & Azevedo, 2004): 0.56 wet mass residue/main product ratio (wet assuming 80% moisture)

SUGAR BEET INDUSTRY RESIDUES (PULP & MOLASSES)

[92] http://www.fabbiogas.eu/fileadmin/user_upload/Download/National_Report-Italy-english.pdf

Residues from the sugar mill. About 45% of the sugarbeet ends up as pulp in the sugar mill process.

Calculation of the secondary residues from this source can be done according to the total area (hectares) of sugarbeet and the average per hectare yield of the main product and then apply a residue/main product ratio.

POTATO INDUSTRY RESIDUES

Residues from the potato processing industry.

Calculation of the secondary residues from this source can be done based on the total area (hectares) of potatoes converted to starch and feed the average per hectare yield of the main product and then apply a residue/main product ratio. Main residues concern potato peels and press fibre. About 15% of the processed potatoes (towards chips, crisps and starch) consists of peels.

The extraction of starch from starch potatoes into potato flour delivers press fibre which is estimated to amount to 15% of the input (e.g. 150 kg/ton potato input). The press fibre consists for 83.5% of moisture (Elbersen et al., 2011).

IV: ASSESSMENT OF FOREST BIOMASS

The information in this section is based on: *Deliverable 2.2. Guidelines for data collection to estimate and monitor technical and sustainable biomass supply by B. Elbersen, I. Staritsky, G. Hengeveld, J. P. Lesschen (DLO-Alterra) & C. Panoutsou (Imperial College London)*

For the assessment of biomass potentials from forestry one needs basic statistical data which come from forest inventories[93]. Before analysing these types of data and the methods to assess forest potentials it is important to understand the basic forest production system and the different products that can be harvested from forestry.

At the highest level three different biomass feedstock groups are derived from forestry: stemwood (including roundwood[94]), primary residues and secondary residues from forest industries. The primary forest exploitation is driven by the stemwood demand. Stemwood is the main product and can be defined as the part of tree stem from the felling cut to the tree top with the branches removed, including bark. It can be classified in:

1. High quality stemwood for materials (e.g. for furniture, building materials)

2. Pulpwood stemwood (demand for it is mostly for conventional uses in paper, cardboard and plywood industries)

With the production of the stemwood many residue products are also available which can be (partly) removed from the forests and which cover: wood available from (pre-commercial) thinnings and the primary residues associated with the harvested stemwood.

These primary forestry residues consist of the following categories:

1) Stem and crown biomass from early pre-commercial thinnings which consists of (thin) stems, branches, bark and needles and leaves. Pre-commercial thinnings cover selective cuttings of young trees that have no value for the wood processing industry. Their removal is part of normal forest management and enhances the growth of the remaining trees.
2) Logging residues from thinnings also including stem and crown biomass which consists of (thin) stems and branches, bark, needles and leaves.
3) Logging residues from final fellings which is mostly branches, bark, needles and leaves
4) Stump extraction from final fellings which is the tree part below the felling cut so including tree roots
5) Stump extraction from thinnings which is also the part of the tree below the felling cut of the thinning tree

As to the removal of forest biomass there are several sustainability restrictions which are usually managed through forest management plans coordinated by forest state and/or owner organisations.

The <u>common rule for sustainable forest management</u> is that the <u>long-term annual fellings do not exceed the net annual increment</u>.

For the assessment of forest potential the focus should be on the 'forest available for wood supply' (FAWS) which is defined by FAO (1999) as 'forest where any legal, economic or specific environmental restrictions do not have a significant impact on the supply of wood'. This definition therefore covers forests where harvest is taking place but could also include forests with no harvest. In many regions in Europe forest harvesting does not reach the net annual increment since in a share part of the forests there is no harvesting taking place, even though there are no legal nor environmental restrictions to do so. In these parts of the forests there is still additional harvest possible of:

1. Additional harvestable stemwood: stemwood which could be harvested without harming future harvests.

[93] http://enfin.info/

[94] Roundwood: stemwood suitable for production of sawn logs or pulp logs, with top diameters fixed according to specific dimensional requirements in each country.

2. Additional residues: the primary residues associated with the additional harvestable stemwood.

For estimating the potential from forests for bioenergy and bio-material generation the guidelines presented here will focus on identifying the availability of primary and secondary forest biomass. The conventional stemwood uses for higher quality products in existing conventional material production processes (e.g. pulp and paper, furniture and building materials) should be subtracted for as far as possible from this potential.

The approaches presented here will be largely following the BEE Methods handbook (Vis et al., 2010) where an extensive overview and explanation is given of the methodologies to assess forest biomass potentials.

The stemwood considered as available for bioenergy and biofuels in the study concerns the fuelwood potential from roundwood and unused forest biomass currently unexploited. All material uses of stemwood were subtracted and only the stemwood currently used as fuelwood was incorporated in the potential, further capped to 25% (Low scenario), 30% (Medium scenario) and 50% (High scenario).

METHODS FOR ASSESSING THE PRIMARY FOREST BIOMASS POTENTIAL

STEMWOOD

The most basic assessment of the theoretical stemwood potential requires data on the minimum annual increment and the wood removals. Calculation of the theoretical stemwood potential for additional uses in energy and bioeconomy uses is then presented underneath (BEE Methods handbook, Vis et al., 2010, p.31):

$$THP\_SW_{x,y} = NAI_{x,y} \times (1-Hl_{x,y}) - SWrem_{x,y} \times (1+Bf)$$

Where:

$THP\_SW_{x,y}$ = Theoretical stemwood potential for additional uses (energy and bioeconomy uses) in country x in year y

$NAI_{x,y}$ = net annual increment of stemwood in country x in year y

$Hl_{x,y}$ = harvest losses in country x in year y

$SWrem_{x,y}$ = stemwood removals in country x in year y

Bf = bark fraction (0-1), which needs to be subtracted in case the stemwood removal data are reported underbark

Input data for making this calculation are easily available from national, Eurostat and FAO statistics, but are generally more challenging to get at detailed regional resolution. The data sources for this data are presented and discussed in BEE Methods handbook (Vis et al., 2010, p.32). As for the harvest losses (HL) it is suggested to use a default value of 0.08 (=8%) for coniferous and of 0.10 for the broadleaved species.

To assess the technical-sustainable stemwood potential for energy and other biobased uses the theoretical potential needs to be further reduced for different technical and sustainable reduction criteria. These technical criteria refer to soil fertility, technical limitations on the accessibility of the forest for example for slope and distance to forest roads. Sustainability criteria are related to biodiversity (e.g. no or limited exploitation of forest biomass in protected areas), soil and water protection areas, risks for soil compaction.

All these additional reduction criteria are critical to make a more realistic technical and sustainable potential estimate and these are best to be obtained through a spatially explicit methodology using overlays of the forest areas with the areas imposing the reduction factors in order to derive realistic reduction shares. The reason spatially explicit assessment approaches need to be followed is because these reduction factors are simply not available from statistical data sources. What is possible however that average overlay results are used provided externally specifying the share of forest area covered by e.g. protected areas or the share of forests located on steep slopes.

PRIMARY FORESTRY RESIDUES

The assessment of the theoretical biomass potential for logging residues that is related to this additional theoretical stemwood potential as discussed above becomes more complicated. The logging residue potential depends on the maximum allowable volume of final fellings and the species composition. It is the former type of information which is more challenging to obtain, specifically in relation to the species composition of the stemwood harvest in time. One can therefore only assume a similar species composition for every harvest year unless more specific species composition data are available from the forest inventory.

The calculation for the theoretical logging residues potential (at maximum utilisation rate, so assuming all residues are available for bioenergy and bioeconomy uses), the BEE study (Vis et al., 2010, p 37-38) proposes the following formula:

$THP\_LR_{x,y} = \sum_{i=1}^{n}(IRWrem_{i,x,y} / (1\text{-}HL_{x,y}) * BEF_{i,x,y}) + \sum_{i=1}^{n}(THP\_SW_{i,x,y} / (1\text{-}HL_{x,y}) * BEF_{i,x,y})$

Where:

i	= tree species/tree species group
$THP\_LR_{i,x,y}$	= theoretical potential for logging residues at a maximum utilisation rate in country x in year y
$IRWrem_{i,x,y}$	= industrial roundwood removals for i-tree species in country x in year y
$THP\_SW_{i,x,y}$	= theoretical stemwood potential for i-tree species for energy and wider bioeconomy uses in country x in year y
$Hl_{x,y}$	= harvest losses (ie share of stem tops and small trees; 0-1) in country x in year y
$BEF_{i,x,y}$	= crown biomass expansion factor for i-tree species in country x in year y (the factors usually range between 0.1-0.5 for mature stands and do not include the stemwood itself)

The share of different species in the total growing stock and the species specific crown biomass expansion factors (BEF) are often difficult to obtain. If no data are available IPCC default values will need to be used which are generally considerably less accurate.

The technical potential for forest residues is calculated simply by relating the BEF to the technical stemwood potential instead of to the theoretical one. So in formula by changing it to:

$\mathbf{TCP\_TLR_{x,y}} = \sum_{i=1}^{n}(IRWrem_{i,x,y} / (1\text{-}HL_{x,y}) * BEF_{i,x,y}) + \sum_{i=1}^{n}(\boldsymbol{TCP}\_SW_{i,x,y} / (1\text{-}HL_{x,y}) * BEF_{i,x,y})$

Where:

$THP\_TLR_{i,x,y}$	= Technical potential for total logging residues in country x in year y
$TCP\_SW_{i,x,y}$	= technical stemwood potential for energy and other biobased products use for i-tree species in country x in year y

This implies that the reduction factors for the calculation of the technical (and possibly sustainable) potential have been subtracted as discussed above. The challenge here is that for calculation of total technical stemwood potential only a distinction can be made in coniferous and broadleaved species, while for the calculation of residues account needs to be taken of species specific stemwood production levels since residue potential levels are strongly dependent on the species types.

STUMP BIOMASS POTENTIAL

Stump technical potential is calculated in a similar way as for primary residues again based on what is suggested in the BEE methods handbook (Vis et al., 2010). It is a factor dependent on the tree species. Every tree has a maximum stump biomass expansion factor.

$THP\_S_{x,y} = NAI_{x,y} \times BEFS_{i,x,y}$

Where:

$THP\_S_{x,y}$	= Theoretical potential of stumps for additional uses (energy and bioeconomy uses) in country x in year y
$NAI_{x,y}$	= net annual increment of stemwood in country x in year y
$BEFS_{i,x,y}$	= stump biomass expansion factor for i-tree species (factor ranges between 0.14-0.23 and sdoes not include the stemwood

For the technical potential it is necessary to apply the different technical and sustainable reduction factors.

The formula for calculating the technical stump potential is then:

$TCP\_S_{x,y}$ = $RS * THP\_S_{x,y} * RFc1_{x,y} * RFc2_{x,y} * RFc3_{x,y} * ... * RFcn_{x,y} *....$

Where:

$TCP\_S_{x,y}$ = Technical potential of stumps for additional uses (energy and bioeconomy uses) in country x in year y

$RFc1,2,3,.._{x,y}$ = reduction factors for different constraining criteria 1, 2, .. in a country and a year.

For stumps it is likely however that the sustainable reduction factors are large as the risks for adverse effects on especially biodiversity are large. In many countries stump extraction is not even allowed according to sustainable forest management practices. Only in Sweden, Finland and UK it is normal practice.

SECONDARY FORESTRY BIOMASS

There are four secondary forestry residues categories (**Error! Reference source not found.**:

1) Sawmill by-products (excluding saw dust)
2) Saw dust from sawmills
3) Other forestry industry by-products
4) Black liquor

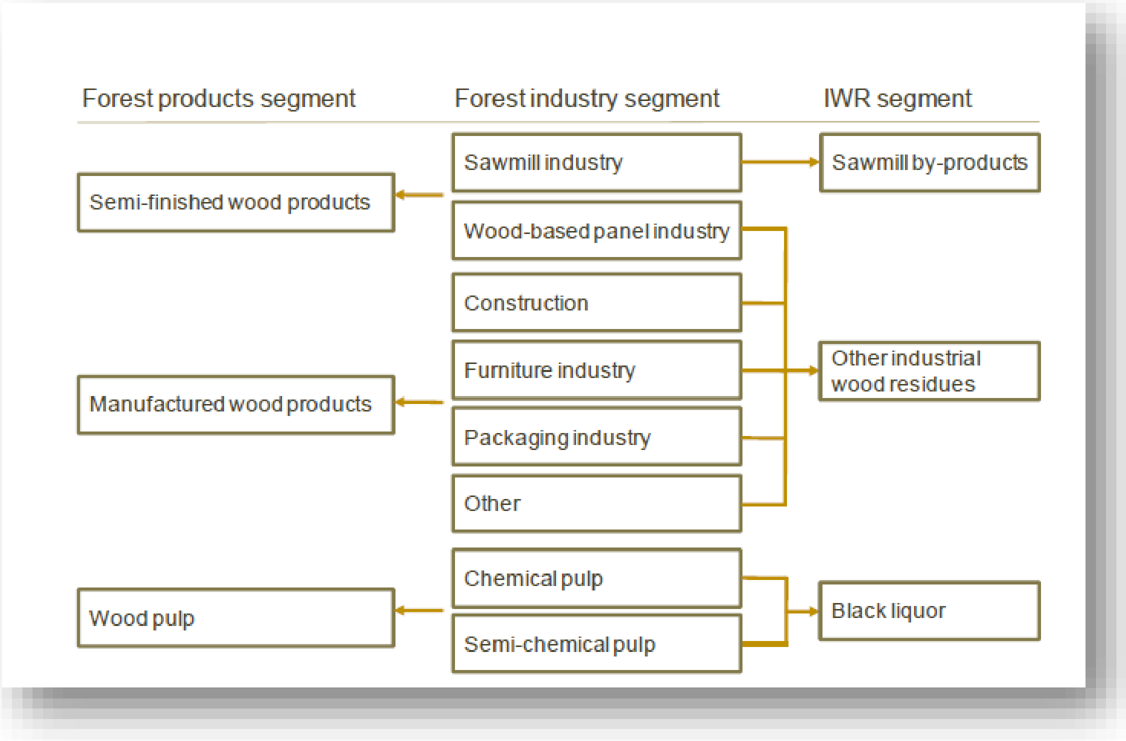

Figure 35 Diagram of forest industries producing secondary residues[95] (Source: Saal, U (2010) in EUwood Methodology report, 2010)

SAWMILL BY-PRODUCTS

The sawdust and the other residues originating from the sawmill industries are produced as a by-product during the processing of stemwood. The stemwood processing steps and resulting residues are well described in the Ecofys report (Spöttle et al, 2013, p 54-55) and in the EU wood methodology report by Saal, U (2010). It is as follows: When stemwood arrives at the sawmill, it is first debarked and the stemwood log ends are trimmed resulting in two types of residues, bark and slabs, which can be collected, and the slabs can be further chipped. After this the stemwood logs are sawn, dried, planed and smoothed taking off the unwanted pieces. This all results in different types of residues:

- **Bark**
- **Sawdust** is generated when the stemwood logs are cut into planks. The amount of sawdust produced depends on the type of sawing machines used which can vary according to the thickness of the blades. Thicker blades creat more sawdust. If prices are high for sawdust, mills may decide to produce more sawdust until the prices drop again.

[95] IWR: Industrial Wood Residues

- **Slabs, edgings and trimmings** where slabs are the long-rounded sides of the log that are sawn off and can be kept intact or further chipped. Edgings and trimmings are produced.
- during edging of boards. Non-coniferous sawmills produce relatively more slabs than coniferous sawmills as the value of the residue wood is higher (than if it were chipped) and can be potentially used for other purposes.
- **Chips** are made from the edgings and trimming residues of the planks that are generated during the sawmilling process.

Situation for coniferous species

Sawmills size class	Max. annual capacity [m³ log input]	Share of total cuttings [%]	SBP assortments Dust [%]	Slabs [%]	Chips [%]
x-small sawmill	< 1,000	1.39	33.20	61.70	5.20
small sawmills I	1,000 - 2,500	3.97	34.27	57.23	8.51
small sawmills II	2,500 - 5,000	2.86	33.42	54.82	11.76
small sawmills III	5,000 - 10,000	7.52	33.85	28.84	37.31
medium size sawmills I	10,000 - 20,000	6.07	35.50	8.88	55.62
medium size sawmills II	20,000 - 50,000	7.56	38.73	1.82	59.46
large sawmills I	50,000 - 100,000	9.16	33.43	0.10	66.47
large sawmills II	100,000 - 500,000	34.38	35.20	0.40	64.40
x-large sawmills	> 500,000	27.09	31.40	1.00	67.60
Total		**100.00**	**34.33**	**23.87**	**41.81**

Situation for non-coniferous species

Sawmills size class	Max. annual capacity [m³ log input]	Share of total cuttings [%]	SBP assortments Dust [%]	Slabs [%]	Chips [%]
x-small sawmill	< 200	0.10	36.62	58.18	5.19
small sawmills I	200 - 500	1.64	36.81	57.67	5.60
small sawmills II	500 - 1000	1.15	35.40	48.61	15.98
small sawmills III	1000 - 2500	6.67	31.16	49.73	19.16
medium size sawmills I	2500 - 5000	7.38	30.47	51.80	17.80
medium size sawmills II	5000 - 10000	21.09	28.70	53.08	18.31
large sawmills I	10000 - 20000	29.98	39.86	39.86	20.30
large sawmills II	20000 - 50,000	15.70	27.38	36.03	36.59
x-large sawmills	> 50,000	16.29	24.30	36.00	39.70
Total		**100.00**	**32.30**	**47.89**	**19.85**

Figure 36 Size distribution and types of residues produced as % of total residue volumes in German sawmills (Source: Mantau and Hick (2008)

The recovery rate describes the ratio of roundwood input – and sawnwood output of a considered unit. This ratio is determined by the tree species, sawmill size and technology applied, in addition at country level this average ratio depends on the country's sawmill size structure. The ratio between sawnwood and by-products is therefore variable. Hence, comprehensive data for each country are necessary to estimate the sawmill by-products volumes. However, the availability of data for all EU countries is limited, although some data are available on annual sawnwood production separated into coniferous and non-coniferous sawnwood. Country specific data on recovery rates, sawmill sizes and sawmill size structures are partly available. In the whole of Europe a rough figure can be assumed to be 50/50 which means that 50% of the processed wood results in a main product and 50% into a by-product. As indicated this ratio can be very different as in Dutch sawmills it amounts to 53/47 for coniferous sawnwood and 51/49 for non-coniferous sawnwood and in Germany it is 60/40 for coniferous sawnwood and 65/35 for non-coniferous sawnwood.

Much more detailed data on the share of different types of residues per sawmill can be identified per country but are not always published. For Germany Mantau and Hick (2008) made an extensive inventory. Such inventories are scarce and not available for many countries.

Therefore, in the EU wood study (Saal, U, 2010) an extensive assessment was done of the availability of sawmill by-products and since there is no better study published since then, it is logical to take this as the best example and data source. This is also the reason why the EUwood approach was used in the EFOSOS II study and the approach was also extended to further non-EU countries there.

In the following a summary is given of this EUwood approach. This approach can be up-dated and applied for the area of interest using more specific information if available.

The first step in EUwood was an analysis of the size distribution of sawmills in individual countries. Based on this, the countries sawmill sector was categorized according to three possible structural types (See **Error! Reference source not found.**):

Type A is characterised by mostly large and very large (>500,000 m³) sawmills.

Type B is characterised by large but not very large mills, there are no very large sawmills.

Type C is characterised by medium and small sawmills only. There are no extra-large mills; however, large mills have an important share of annual cutting.

Coniferous sawmill size structure type			Non-coniferous sawmill size structure type		
A	**B**	**C**	**A**	**B**	**C**
Austria	Denmark	Bulgaria	Austria	Romania	Bulgaria
Czech Rep.	Finland	Greece	Germany	Estonia	Finland
Germany	Latvia	Ireland	Slovakia	Netherlands	Hungary

Source: EUwood

Figure 37 Distribution of (selection of) countries according to sawmill size structure (Source: Saal, 2010 in EUwood Final report)

Secondly, the secondary residue volume was calculated. In EUwood an inventory was done of the relative recovery rates to be used as the starting point for the further distribution over types of residues. The recovery ranges used in EUwood were derived from different studies but the main source was from Fonseca (2010) who identified recovery rates for each country. The recovery rate ranges were then grouped into three ranges to match to the Type A, B and C countries (Table 30 Recovery rate per group of country classified according to size structure of sawmill industry (Source: Saal, 2010 in EUwood Final report)).

Table 29 Recovery rate per group of country classified according to size structure of sawmill industry (Source: Saal, 2010 in EUwood Final report)

Type	Coniferous	Non-coniferous
A	49-54%	40-50%
B	55-59%	51-55%
C	60-65%	56-66%

Based on the recovery rates the total secondary residue volume can be calculated. The statistical figures from FAOSTAT on the production data of coniferous and non-coniferous sawnwood were used as input[96] for the EUwood (and EFSOS II) study. For up-dated calculations these FAOSTAT data can be downloaded as these are publicly available and regularly up-dated.

Calculation of the total volume of the sawmill by-products is calculated in EUwood in 2 steps:

TAC = $SW_{produced}$ /$RR_{assigned}$

Where:

TAC = total annual cutting volume going to the sawmill industry,

SW = sawnwood,

RR=recovery rate. This rate is country specific and depends on the size structure of the sawmill industry (see Table 18)

SBP = TAC / ((100%-RRassigned) – losses%)

Where:

SBP = Sawmill by-products – total volume

TAC = total annual cutting volume,

Losses% = This rate is an average share of 0.7% (coniferous) respectively 1.6% (non-coniferous) for losses. This is subtracted from the total cutting volume. Losses are considered as unrecovered volumes, which do not account for sawmill by-products or produced sawnwood (e.g. due to losses during transport).

Third the total sawmill by-product volume is further sub-divided in residues types according to the segments of residue products belonging to the sawmill country typology in A, B and C types as explained above (**Error! Reference source not found.**).

Coniferous				Non-coniferous			
Type	Dust	Slabs	Chips	Type	Dust	Slabs	Chips
A	33.32	4.53	62.15	A	31.66	43.40	24.97
B	35.26.	4.93	59.82	B	32.12	48.84	19.09
C	35.05	11.49	53.48	C	32.97	52.12	14.96
Source: EUwood							

Figure 38 Segmentation (%) in residue types per group of country classified according to size structure of sawmill industry (Source: Saal, 2010 in EUwood Final report)

[96] See http://www.factfish.com/statistic/sawnwood%2C%20non-coniferous%2C%20production%20volume

V: ASSESSMENT OF BIOMASS FROM WASTE

The information in this section is based on: *Deliverable 2.2. Guidelines for data collection to estimate and monitor technical and sustainable biomass supply by B. Elbersen, I. Staritsky, G. Hengeveld, J. P. Lesschen (DLO-Alterra) & C. Panoutsou (Imperial College London)*

The waste potentials can best be assessed using Eurostat or national waste generation and waste treatment data as input. Eurostat data can be downloaded directly from the Eurostat website[97]. Since 2004 data on waste generation and treatment are collected per EU member state[98]. Because this data is collected according to fixed categories (European Waste Classification for statistical purposes) which are based on the waste sources, it is logical that the potentials assessed are also ordered accordingly. At the highest level a distinction is made between waste from households (HH) and waste from business activities (NACE classification). For a detailed classification of the Eurostat waste data see Table 31.

In order to calculate waste potentials the following steps are proposed:

1) First identify the total waste generation per category of waste
2) Then identify the waste treatment categories
3) Calculate the waste treatment factors to identify which part is already going to alternative useful uses (e.g. compost, backfilling etc.) and which part of the waste is available for further conversion into energy or other bioeconomy uses. So the part already going to energy is also perceived to be available as part of the potential.

The total waste generation reported by Eurostat is only the basis for assessing the biomass potential. The waste assessment can be done for the years for which data are available. A distinction is made between data used to determine the total waste generation and data to determine the current waste treatments. The latter figures determine the final potential.

97 http://epp.eurostat.ec.europa.eu/portal/page/portal/environment/data/database

98 Regulation on waste statistics (EC) No. 2150/2002, amended by Commission Regulation (EU) No. 849/2010, prescribe that data on the generation and treatment of waste is collected from the Member States.

Table 30 Waste categories selected from Eurostat for assessing the waste potentials

Household (HH)/ economic sectors (NACE)	Waste type	Definition	NACE code-waste statistics	Explanation
HH	Paper	See underneath NACE 'Paper and cardboard wastes'	EP_HH.W072	Paper
HH	Wood waste	Separately collected wood wastes from households.	EP_HH.W075	Wood waste
HH	Animal and mixed food	See underneath NACE 'animal and mixed food waste'	EP_HH.W091	Animal and mixed food
HH	Vegetal waste	See underneath NACE 'vegetal waste'	EP_HH.W092	Vegetal waste
HH	Municipal Solid Waste (MSW)	Household and similar wastes are mixed municipal waste, bulky waste, street-cleaning waste like packaging, kitchen waste, and household equipment except separately collected fractions. They originate mainly from households but can also be generated by all sectors in canteens and offices as consumption residues.	EP_HH.W101	Municipal Solid Waste (MSW)
HH	Common sludges	See underneath NACE 'common sludges'	EP_HH.W11	Common sludges
NACE	Paper and cardboard wastes	These wastes are paper and cardboard from sorting and separate sorting by businesses and households. This category includes fibre, filler and coating rejects from pulp, paper and cardboard production. These wastes are largely generated by three activities: separate collection, mechanical treatment of waste and pulp, and paper and cardboard production and processing. All paper and cardboard wastes are non-hazardous.	W072.TOTAL	Total paper
			W072.C17_C18	Paper from manufacture of paper and paper products; printing and reproduction of recorded media
			W072.TOT_excl_above	Paper from other economic sectors
NACE	Wood waste	These wastes are wooden packaging, sawdust, shavings, cuttings, waste bark, cork and wood from the production of pulp and paper; wood from the construction and demolition of buildings; and separately collected wood waste. They mainly originate from wood processing, the pulp and paper industry and the demolition of buildings but can occur in all sectors in lower quantities due to wooden packaging. For some countries this category is corrected (e.g. PO, SK, ...) because this category overlaps with the forest potential category 'secondary forestry residues' particularly with the sub-category 'Other forestry industry by-products'. Wood wastes are hazardous when containing hazardous substances like mercury or tar-based wood preservatives, which makes it	W075.TOTAL	Total wood
			W075.C16	Wood from manufacture of wood and of products of wood and cork, except furniture
			W075.TOT_excl_above	Wood from other economic sectors

		only suitable for incineration and not recycling.		
Household (HH)/ economic sectors (NACE)	**Waste type**	**Definition**	**NACE code- waste statistics**	**Explanation**
NACE	Animal and mixed food	These wastes are animal and mixed wastes from food preparation and products, including sludges from washing and cleaning; separately collected biodegradable kitchen and canteen waste, and edible oils and fats. They originate from food preparation and production (agriculture and manufacture of food and food products) and from separate collection. Animal and mixed waste of food preparation and products are non-hazardous.	W091.TOTAL	Total animal and mixed food
			W091.A	AnMixfood from Agriculture, forestry and fishing
			W091.C10-C12	AnMixfood from Manufacture of food products; beverages and tobacco products
			W091.E	AnMixfood from companies in water collection, treatment and supply; sewerage; remediation activities and other waste management services.
			W091.G-U_X_G4677	AnMixfood from all services (except wholesale of waste and scrap)
			W091.TOTAL-4 above	AnMixFood other
NACE	Vegetal waste	These wastes are vegetal wastes from food preparation and products, including sludges from washing and cleaning, materials unsuitable for consumption and green wastes. They originate from food and beverage production, and from agriculture, horticulture and forestry. Vegetal wastes are non-hazardous.	W092.TOTAL	Total vegetal waste
			W092.A	Vegetal waste from agriculture, forestry and fishing
			W092.C10-C12	Vegetal waste from Manufacture of food products; beverages and tobacco products
			W092.E	Vegetal waste from companies in water collection, treatment and supply; sewerage; remediation activities and other waste management services
			W092.G-U_X_G4677	Vegetal waste from all services (except wholesale of waste and scrap)
NACE	Used fats & oils (UFO)	Used animal fats and vegetal oils.	NOT reported separately in Eurostat	This category is included in the Eurostat waste category 'Animal and mixed waste'.

Household (HH)/ economic sectors (NACE)	Waste type	Definition	NACE code- waste statistics	Explanation
NACE	Municipal Solid Waste (MSW)	See MSW from HH above.	W101.TOTAL	Total MSW
NACE	Common sludges	These are waste water treatment sludges from municipal sewerage water and organic sludges from food preparation and processing. They mainly originate from households and industrial branches with organic waste water (mainly pulp and paper as well as food preparation and processing). They can also occur in waste water treatment plants or in the anaerobic treatment of waste. All common sludges are non-hazardous. Comparability can be problematic between countries using different statistical units as they will not assign the waste to the same economic sector.	W11.TOTAL	Total common sludges
			W11.C	Common sludges from all manufacture manufacturing companies
			W11.E	Common sludges from Water collection, treatment and supply; sewerage; remediation activities and other waste management services

To assess which part of the waste is already recovered for other useful uses and which part can really be seen as potential data on waste generation and waste treatment need to be combined. The waste treatment data are reported in Eurostat according to the following categories:

1) Waste going to recovery/treatment: NO POTENTIAL/Competing
2) Incineration with energy recovery: POTENTIAL (already going to energy)
3) Incineration without energy recovery: POTENTIAL (scenario specific)
4) Disposal on or into land (landfill): POTENTIAL (scenario specific)
5) Other disposal NO POTENTIAL/Competing

The treatment figures can be applied to the total waste generation figures as percentages and not as absolute figures as the absolute figures never add up to the total of the waste generation figures. The treatment data is specified at regional level (NUTS1) per type of waste category, while the waste generation data are only available at national level.

In addition for certain types of waste streams such as for paper and cardboard, use fats and oils and municipal solid waste (MSW) additional data sources were consulted to make better interpretation of their current and future generation levels and recycling rates.

Future waste potentials

For extrapolations of waste potentials into the future it is best to calculate waste per head ratios by dividing total waste generation by number of inhabitants. Existing population development projections (e.g. such as from Eurostat, FAO and OECD) can then be used to extrapolate the waste generation data into the future. Assumptions need to be made however in relation to how waste treatment and recycling rates develop. A very useful study used for the calculation of current and future MSW potentials is the ARCADIS (2009), Assessment of the options to improve the management of bio-waste in the EU. Study for DG-ENV.

VI STATE OF THE ART IN BIOMASS CONVERSION TECHNOLOGIES TO ADVANCED BIOFUELS

This Annex aims at providing the reader with a short description of advanced biofuels technologies, technology developers and plants at demonstration or commercial level. There are numerous technologies, value chains and possible applications making this area a challenging one. Some of the value chains are ready to be commercialized and few are actually commercial. Others are at *first-of-a-kind* (FOAK) plant level while there are few that still have to reach the FOAK level before market deployment can be considered.

Since all use various types of biomass resources, have different production capacities and produce different types of biofuels for different applications; it is impossible to identify or propose winners and this has never been the aim of this report.

This Annex is not exhaustive as new facilities and projects are announced regularly. Furthermore, several recent publications[99,100,101,102,103] have addressed the state of the art of biomass conversion to advanced biofuels so this Appendix aims to highlight some of the examples available to investors. The objective is to discuss the various value chains that are expected to be commercial in the near future or by 2030. Technologies, value chains and processes that are still in the early research or pilot phase and are not expected to be in the market by 2030 are not addressed.

The structure followed in this Annex is to start with the description of the technologies and the various value chains that are commercial to be followed by those that are at large demonstration scale. Where appropriate non-European technologies are also presented. The analysis below follows Figures 26 and 27 above in the main part of this study.

BIOLOGICAL CONVERSION

The key biological conversion process routes for advanced biofuels are the production of biomethane via upgrading biogas produced from anaerobic digestion and cellulosic ethanol. A recent development is fermentation of synthesis gas produced from thermal biomass gasification. In this process the synthesis gas is cooled and then is fed to bacteria which convert it to ethanol.

BIOMETHANE VIA BIOGAS UPGRADING

A generalized pathway of this value chain is given in Figure 41. After the anaerobic digestion step the carbon dioxide is removed via various technologies and the biomethane can either be liquified or compressed subject to the downstream application. Most commonly biomethane is injected into the natural gas grid.

There are more than 17,000 biogas plants in the EU and the majority of them are decentralized CHP facilities. About 400 of them produce biomethane with the majority of such plants in Germany, Sweden and the UK. The biomethane is mainly injected into the natural gas grid and in few cases it is used in captive fleets where centralized filling stations

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[99] Ingvar Landälv, "Technology Status and Reliability of the value chains", Sub Group on Advanced Biofuels, edited: K. Maniatis, L. Waldheim, E. van den Heuvel & S. Kalligeros, February 2017, available at : https://op.europa.eu/en/publication-detail/-/publication/f1c977d1-67a4-11e8-ab9c-01aa75ed71a1/language-en .

[100] Technology Status and Reliability of the value chains, 2018 Update by ART Fuels Forum, , edited: I.Landälv, L. Waldheim, K. Maniatis, http://artfuelsforum.wpengine.com/wp-content/uploads/2019/04/ART-Fuels-Forum-SGAB-Biofuels-Technology-report-2018-update.pdf.

[101] The Role of Renewable Transport Fuels in Decarbonising Road Transport, Production Technologies and Costs, AMF ANNEX 58 & IEA Bioenergy Task 41 Project 10, Ed. D. Baconsky; November 2020, available at: https://www.ieabioenergy.com/blog/publications/new-publication-the-role-of-renewable-transport-fuels-in-decarbonizing-road-transport/.

[102] IEA Bioenergy Task 39, The Potential and Challenges of Drop-in Biofuels, Report T39-T1 July 2014, S. Karatzos eta al, available at: https://task39.sites.olt.ubc.ca/files/2014/01/Task-39-Drop-in-Biofuels-Report-FINAL-2-Oct-2014-ecopy.pdf.

[103] Danish Energy Agency & Energinet, Technology Data - Renewable Fuels, 2020 update, available at: https://ens.dk/sites/ens.dk/files/Analyser/technology_data_for_renewable_fuels.pdf.

are available. It is not possible to select any plant to show as an example in this study since this might imply preferential treatment of the technology provider.

Upgrading biogas to biomethane has become a widely used technology beyond Europe and several technology providers operate in countries like the USA, India, China etc.

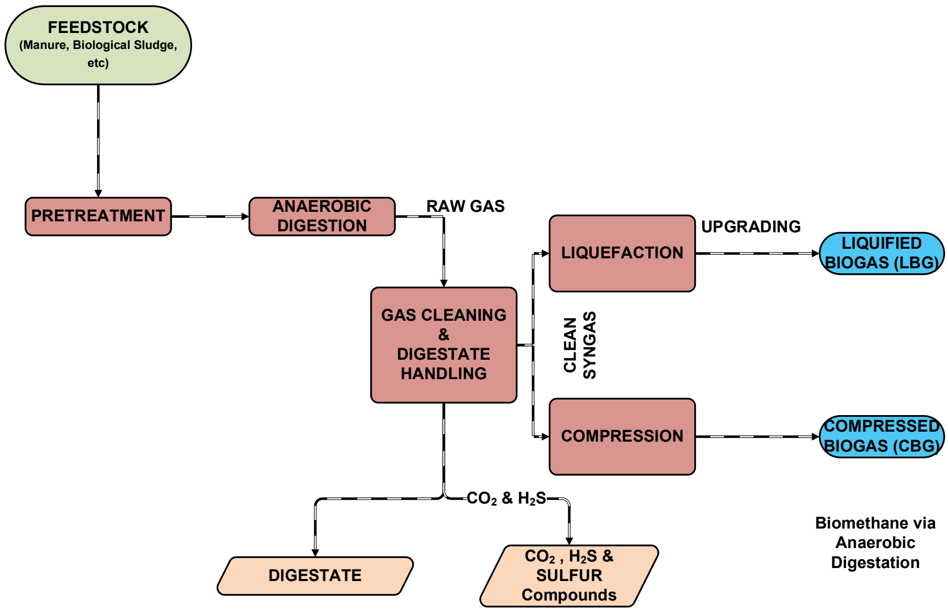

Figure 39 Simplified process flow diagram for biomethane from anaerobic digestion[104]

NOTE: All simplified process flow diagrams of this section have been taken with permission from footnote 12.

CELLULOSIC ETHANOL

A generalized pathway of this value chain is given in Figure 42. The cellulosic ethanol technology has progressed significantly the last decade and several FOAKs have been built and tested. The technology is ready for commercialization and few technology providers have signed licensing agreements in the EU and elsewhere and plants are under construction expected to be taken into operation in 2021. The key innovation in this value chain has been related to the development of enzymes and yeasts able to extract the sugars and convert them to ethanol.

The first large FOAK plant was built by Biochemtex (now Versalis of ENI) and this was followed by several other in the US and Europe. The DuPont, Abengoa and DSM/POET FOAKs in the US have all been abandoned or used for other purposes as well as the INBICON plant in Denmark. Table 32 shows some active technology developers and the status of their technology. Photos 1 to 5 show snapshots of some of the plants of the technology providers. There are other companies that have developed cellulosic ethanol technologies in an effort to maximise the use of sustainable carbon resources of their operations such as Borregard and AustroCel Hallein; however, these are not actively pursuing the commercialization of their technology for green field operations starting from biomass feedstocks since their technology is part of a wider biorefinery. Such developments are considered a niche opportunity for advanced biofuels and thus they are not discussed further.

Valmet has been successful in developing a robust front-end BioTrac technology for the pretreatment of the feedstock and its technology is being used by Clariant, and Praj Industries[105].

[104] ART Fuels Forum, R Singh, S Kalligeros & J Uppal, Advanced Biofuels in India: A comparative analysis between India and the EU for cooperation and investment, October 2018.
[105] Booklet on Biomass Conversion Technologies, EUBCE, Ed. by K Maniatis, available at: https://www.eubce.com/wp-ontent/uploads/2021/05/Booklet-on-Biomass-Conversion-Technologies_April-2021.pdf.

Clariant has been commercializing its technology with a plant under construction in Podari, Romania and several other under development in Eastern Europe and China (see footnote 103).

Chempolis was successful to have formed a joint venture with Fortum and Numaligarh Refinery Ltd to construct a biorefinery in the state of Assam in Northeast India using locally grown bamboo.

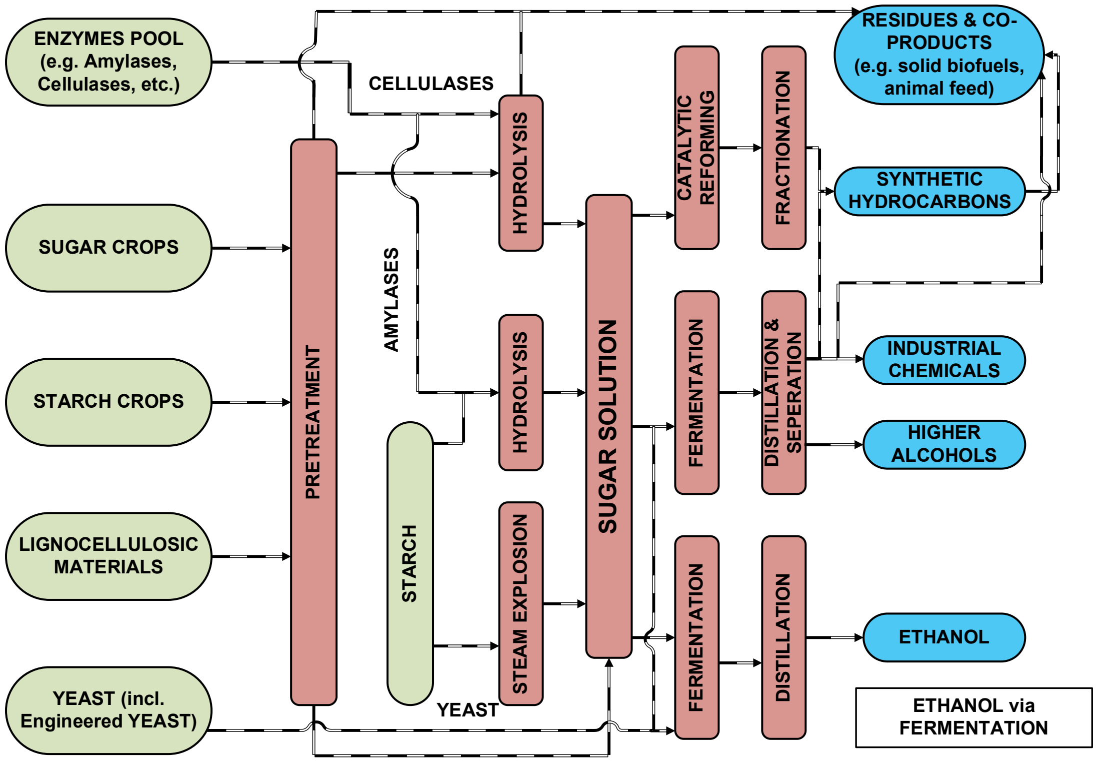

Figure 40 Ethanol, higher alcohols, industrial chemicals & hydrocarbons via sugar extraction from biomass and fermentation[12]

Table 31 Technology developers for cellulosic ethanol

N°	Technology Developer	Plant/Location	Production Capacity t/yr	In operation since	TRL
1	VERSALIS (BIOCHEMTEX)	Crescentino, Italy	40,000	2013	9
2	CLARIANT	Straubing, Germany	900	2012	8
		Romania	50,000	2021	9
3	PRAJ INDUSTRIES	Pune, India, several			9
4	CHEMPOLIS	Assam, India	48,000	2021?	9
6	ST1, Cellunolix®	Kajaani, Finland	7,200	2016	8
		Undecided, Finland	36,000	2020?	8
7	IFP Futurol	Pomacle, France	75	2011	5
		Bucy-le-Long, France	7,500	2016	8

Praj Industries has developed its own FOAK plant in Pune India based on bagasse and other agricultural residues. Based on successful trials and due diligence of this technology by Indian oil companies, Praj has entered into MOU to build 4 cellulosic ethanol plants with Indian state oil companies using rice straw as feedstock. Praj is cooperating with Sekab to upgrade and commercialise the cellulosic ethanol technology for softwood residues (see footnote 103).

ST1 was the first to build a demonstration plant for cellulosic ethanol from sawdust in Kajaani, Finland based on its Cellunolix® technology. ST1 has completed environmental impact assessments for three new plants to be built in the Nordic countries. Each of the three plants would be five times the size of the Kajaani demonstration plant. Their raw material would consist of sawdust and other wood residues. The plants are planned in Pietarsaari on the west coast of Finland, in Kajaani and in Norway.

AXENS, in cooperation with IFP Energies Nouvelles (IFPEN) and other companies has developed the Futurol project with a pilot plant built at Pomacle, France. This has been followed by the construction and commissioning of the industrial biomass pre-treatment prototype, installed at the Tereos sugar plant in Bucy le Long, in the Aisne area of northern France. Axens has sold a licence of a 55 kt/y cellulosic ethanol plant to INA.

Photo 1 The Biochemtex/Versalis plant at Cresentino, IT

Photo 2 Clariant's development plant at Starubing, DE

Photo 3 The Praj Indian Oil Corporation plant in Panipat,

Photo 4The ST1 plant in Kajaani, FI Haryana

Photo 5 The FUTUROL pilot plant at Pomacle, FR

GASIFICATION FOLLOWED BY FERMENTATION

Biomass gasification followed by fermentation has been developed by Lanzatech as an adaptation of its waste gases fermentation to ethanol technology. The main project under development is the EC funded project at ArcelorMittal in Gent (Photo 6). The project will use biomass as a feed in the steel mill in order for the ethanol to be legally classified as bioethanol and sold in the EU market. A smaller project is under development at the Mangalore Refinery and Petrochemicals Limited (MRPL), a leading Indian Refining company based in Mangalore. MRPL is planning to install the bioethanol facility in the State of Karnataka, India.

Lanzatech has several other projects for waste fossil gases but these are out of scope of this study (see footnote 103).

Table 32 Technology developers for gasification and fermentation

N°	Technology Developer/Plant	Plant/Location	Production Capacity tones/yr	In operation since	TRL
1	Lanzatech	Gent ArcelorMittal	62,000 ethanol	2021?	9
		MRPL, India biowaste	16,000 ethanol	N/A	9

Photo 6 The Lanzatech plant at Gent, Belgium

GASIFICATION AND SYNTHESIS TO FISCHER-TROPSCH

Biomass gasification has received significant RD&D support as it offers high efficiencies and the potential to produce biofuels via the synthesis gas (CO+H2) route over dedicated catalysts. Figure 43 shows a generalized process flowsheet for the production of synthetic fuels and chemicals.

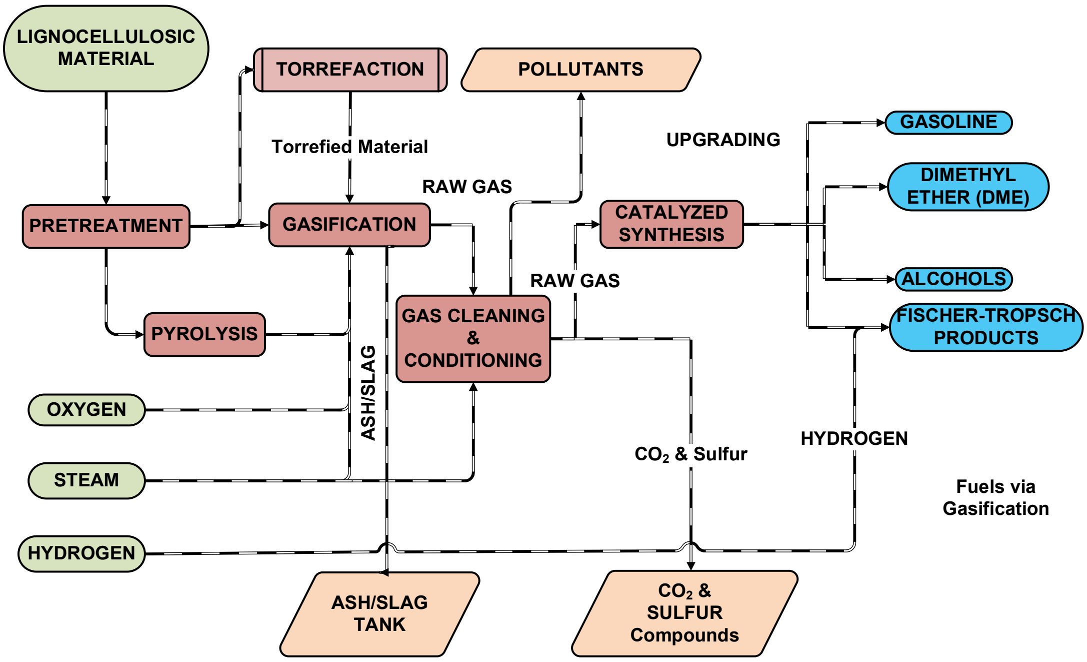

Figure 41 Fuels, industrial chemicals & hydrocarbons via biomass gasification and syntheis[12]

The main type of reactor used is bubbling or circulating fluidized bed gasifiers, which is versatile type of reactor and can tolerate feedstock in a certain size range. Entrained-flow gasifiers operate with fine biomass (size <1mm) at temperatures in the range of 1000-1500°C which is normally above the melting point of the ash of the feedstock and thus low alkali metal eutectics and tars are avoided. Entrained bed gasifiers can easily operate with liquids. Air, oxygen and/or steam can be used as the oxidizing feed.

Significant efforts have been undertaken in the past with large scale demonstration projects such as the Vernamo (IGCC for CHP), CHOREN (Fischer-Tropsh) and the GOBIGAS (biomethane); however these had to be abandoned.

Table 34 lists some of the technology providers while Photos 7 to 8 show snapshots of the Enerkem and TRI plants respectively.

Enerkem has been successful in commercializing its technology for ethanol and methanol from biowaste. Its first plant was built in Edmonton for ethanol production and this was followed by a second in Varennes[106] for methanol. Enerkem is leading a consortium of world-leading companies and the Port of Rotterdam to build Europe's first advanced waste-to-chemicals facility in Rotterdam. The planned facility will convert up to 360,000 tons of waste into 220,000 tons (270 million litres) of biomethanol. A similar facility has recently been announced to be built in Tarragona[107]. Enerkem at present concentrates to ethanol and methanol production with no announcement yet for Fischer-Tropsch.

Velocys is developing two commercial sustainable aviation fuel projects, one from biomass in Natchez, Mississippi, USA, and one from biowaste in Immingham, UK[13]. Both use the ThermoChem Recovery International (TRI) gasification

[106] Enerkem Press Release, 08/12/2020, https://enerkem.com/newsroom/releases/?communique_id=122575.
[107] Enerkem Press Release, 27/04/2021, https://enerkem.com/news-release/repsol-to-join-enerkem-and-agbar-to-build-a-waste-to-chemicals-plant-in-tarragona/.

system and the same syngas cleaning and product upgrading technologies (see footnote 103). The TRI gasification system is a two-stage technology that utilizes an indirectly-heated, medium-temperature, deep fluidized bed steam reformer with a smaller higher temperature, fluidized bed second stage to generate a reliable syngas stream. TRI is also constructing another plant for sustainable aviation fuel at Reno Nevada.

Table 33: Technology developers for synthetic fuels via gasification

N°	Technology Developer/Plant	Plant/Location	Production Capacity tones/yr	In operation since	TRL
1	Enerkem	Edmonton, CA biowaste	30,000 ethanol	2021?	9
		Varennes, CA biowaste	100,000 ethanol	2023?	9
		Rotterdam, NL biowaste	220,000 methanol	2023?	9
		Tarragona, SP biowaste	220,000 methanol	2024?	9
2	Velocys/TRI	Altalto Immingham biowaste	37,000 SAF	2023?	8
		Natchez, Mississippi biomass	75,000 SAF	2024?	8
3	TRI	Reno, US biowaste	32,000 SAF	2022?	9

Photo 7 The ENERKEM plant at Edmonton, Alberta, Canada

Photo 8 The TRI plant under construction at Reno Nevada, USA

FAST PYROLYSIS

The fast pyrolysis technology has also progressed well and offers the benefits of a liquid fuel with concomitant advantages of easy storage and transport as well as comparable power generation efficiencies at the smaller scales of operation that are likely to be realised from bio-energy systems as compared with fossil fueled systems. However, the upgrading of pyrolysis oils to biofuels is still considered very expensive and at present the technology developers are moving towards co-processing pyrolysis oils in petroleum refineries. Figure 44 shows a generalized process flowsheet for the production of synthetic fuels and chemicals from biomass fast pyrolysis.

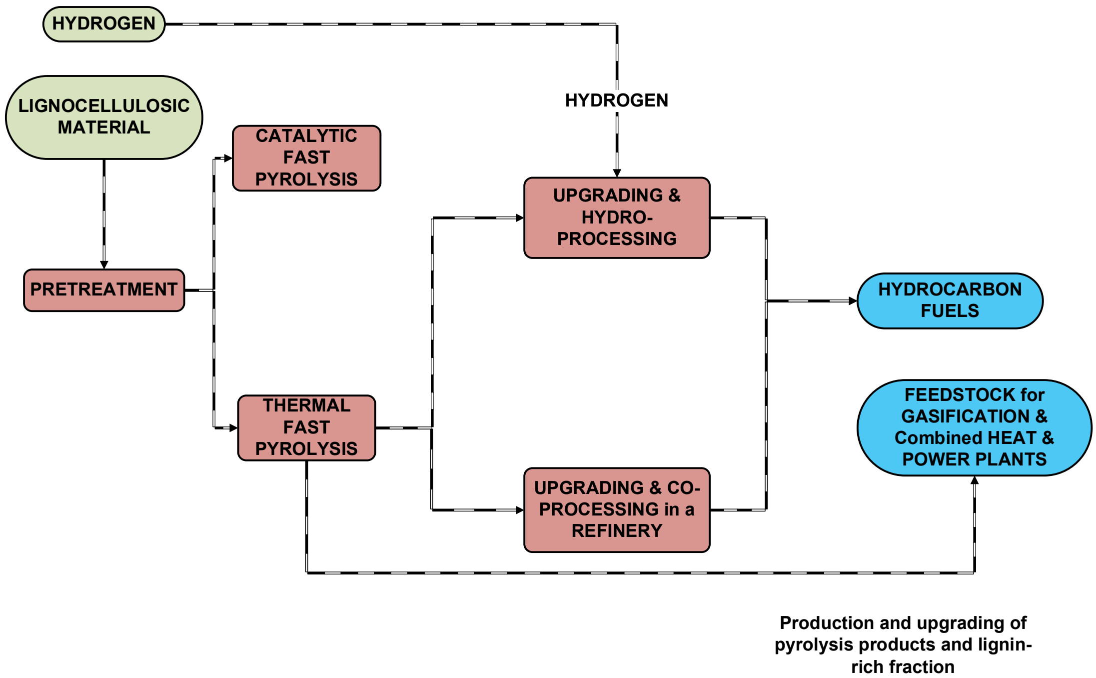

Figure 44 Simplified process flow diagram for pyrolysis. Process flowsheet also shows upgrading to hydrocarbon fuels or co-processing in a refinery.

Fast pyrolysis has been developed over several years in the EU by few companies which have provided for continuity in the development of the technology mainly in the Netherlands and Finland. Initial work focused on producing a fuel oil for power and heat applications and few commercial facilities are operational at present in the EU with good prospects for further commercialisation. The focus recently has turned in co-processing bio-oil in existing refineries aiming at reducing downstream processing costs in upgrading the bio-oil into a transport fuel. Upgrading the biooil directly by hydrogen is still considered relative too expensive and it is at low TRL.

Table 35 shows the technology developers for advanced biofuels via fast pyrolysis in the EU. The plants have been operating with the purpose to supply the bio-oil for CHP applications in commercial facilities; however, serious efforts are being undertaken into upgrading the bio-oil into advanced biofuels via coprocessing. Photos 9-11 show some of the plants of the technology developers.

Fortum[108] integrated a fast pyrolysis unit in the Joensuu CHP plant in 2013. Bio-oil is produced from forest residues, wood from first thinnings and other wood biomass, such as forest industry by-products, sourced locally from the Joensuu region. The Joensuu bio-oil plant's annual production of 50,000 tones corresponds to the heating needs of more than 10,000 households. In 2018 it was announced that Valmet and Fortum have entered into a joint development with Preem to continue the development work of fast pyrolysis for advanced biofuels[109].

[108] Fortum Press Release, 29/11/2013, https://www.fortum.com/media/2013/11/fortums-bio-oil-plant-commissioned-joensuu-first-its-kind-world .
[109] Bioenergy International, 10/04/2018, available at: https://bioenergyinternational.com/biofuels-oils/valmet-fortum-announce-bio-oil-collaboration-preem.

Table 34 Technology developers for fast pyrolysis

N°	Technology Developer/Plant	Plant/Location	Production Capacity tones/y	In operation since	TRL
1	Fortum	Joensuu, Finland	50,000	2013	9
2	Biomass Technology Group, (BTG)	EMPYRO Hengelo, NL	24,000	2015	9
		Green Fuel Nordic, FI	24,000	2020	
		Pyrocell SE	24,000	2021	
3	ENSYN	1. Rhinlander, Wiconsin	N/A		9
		2. Renfrew, Ontario	20,000		
		3. Cote Nord, Quebec	50,000	2022	

BTG has developed a Rotating Cone Reactor technology that is rather compact. BTG started the commercial operation of the EC funded Empyro plant in 2015. The complete production of biooil is sold to a dairy products factory, Friesland Campina, in Borculo, The Netherlands. The biooil replaces natural gas achieving an up to 90% GHG reduction. A sister plant was taken into operation in 2020 at Green Fuel Nordic and a third, Pyrocell project, is under construction by a joint venture of Setra Group and Preem (see footnote 103). BTG has also been investing significant resources in coprocessing biooil in petroleum refineries[110].

Photo 9 Fortum's Joensuu plant in Finland

Photo 10 BTG's plant at Green FuelNordic, Lieksa, Finland

ENSYN developed the Rapid Thermal Processing (RTP) technology converting non-food biomass from the forest and agricultural sectors to biooil. The biooil produced by the ENSYN plants is used mainly in heating applications. ENSYN initiated commercial operations in the food industry in 1989, producing food flavouring ingredients for Red Arrow Products Company LLC, of Wisconsin; in 2015 the company was acquired by the Kerry Group. ENSYN has formed a joint venture with Honeywell UOP called Envergent. One task for the new company is to develop a process which makes it possible to combine fast pyrolysis of biomass feedstocks with upgrading of the product to a degree

[110] BTG Presentation, BioFIT webinar, 24/03/2021,available at: https://www.biofit-h2020.eu/news-and-events/Concawe-bdi-and-btg-bioliquids-at-6th-biofit-meeting-24-march-2021/BTG-Bioliquids_BioFIT_AdvancedBiofuelsfromFPBO_web.pdf.

which makes it possible to combine pyrolysis technology with crude oil refining in existing oil refineries. The most recent plant is the Côte-Nord plant located at a sawmill. The plant aims to export the biooil to the US market for heating applications.

Photo 11 ENSYN's plant in Renfrew, Canada

HYDROTHERMAL LIQUEFACTION

Hydrothermal liquefaction is a process similar to fast pyrolysis with the main difference being that it is applicable for converting wet biomass (such as algae) into crude-like oil under moderate temperature and high pressure. A catalyst is often used to facilitate the conversion process. The biocrude needs upgrading before it can be used as a transport fuel.

There are several efforts to develop the technology in the EU and elsewhere and work is ongoing. However, the most advanced technology provider is Reliance/CRI in India (see Photo 12). Table 36 shows the technology developer for HTL.

Table 35 Technology developers for HTL

N°	Technology Developer/Plant	Plant/Location	Production Capacity MW	In operation since	TRL
1	CRI/SHELL/IH2	Bangalore, India	5 ton per day input	2017	8

The IH2 technology is a catalytic thermochemical process that converts biomass directly to high purity hydrocarbon fuels and/or blend stocks with an energy content recovery of about 70% in all configurations. The process uses catalytic hydropyrolysis, i.e. pyrolysis in the presence of a high concentration of hydrogen, in a pressurized fluidized bed. This technology can produce gasoline (petrol), civil jet fuel grade and diesel.

While the IH2 technology concept was developed by the Chicago-based Gas Technology Institute (GTI) for conversion of municipal and agriculture waste into liquid transport fuel, the worldwide license rights for the new technology were acquired by CRI Catalyst Company[111], a subsidiary of Royal Dutch Shell. The minimum commercially viable scale of this technology is expected to be from 500 to 1000 TPD of biomass. A 500 TPD plant will produce about 200 TPD of renewable ‘drop in advanced biofuel.

Photo 12 Photo of the CRI/SHELL demonstration plant in Bangalore, India

[111] See https://www.cricatalyst.com/.

The hydrotreating process is very flexible allowing the conversion of waste streams into drop-in fuels of relative low cost. HVO is easily blended into regular diesel in any proportion, with no adverse impact on fuel quality or engines and it is therefore the preferred biofuel for existing diesel engines either for trucks or passenger cars. From an economic point of view, FAME is cheapest but cannot be blended at higher levels. The best quality of HVO can be used in aviation as bio-kerosene, however this requires some additional processing. The main limitation for the HVO capacity is to source raw materials (vegetable oils, grease, tallow and UCO etc.) from sources that are acceptable from a sustainability perspective on the market where they are sold.

Figure 45 shows the simplified process flow diagram for HVO production. A key element in the process is the supply of hydrogen, which is needed for the hydrotreating process. HVO plants can be either standalone green-field or they can be integrated in existing refineries. Integration in existing refineries has the advantages that several services such as utilities, ancillaries are readily available while in general the permitting and licensing procedures are greatly simplified resulting in relative fast revamping compared to a green field**.** In the EU there is tendency to retrofit existing refineries in HVO refineries as has been the case with ENI, TotalEnergies, and other, see Table 37.

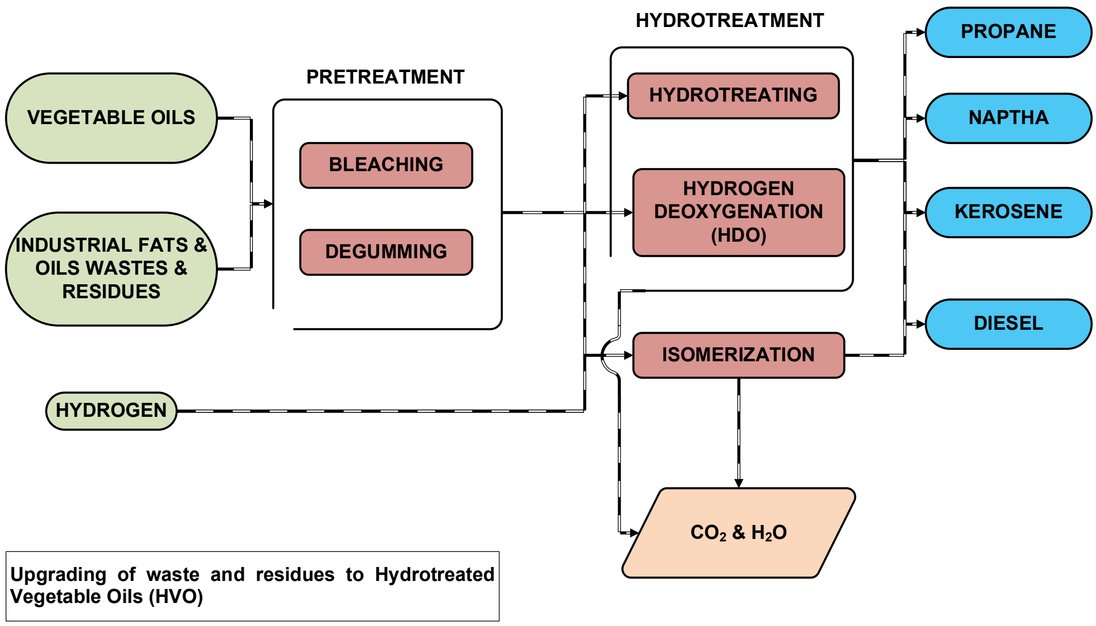

Figure 42 HVO Simplified process flow diagram showing the variety of hydrocarbon fuels that can be produced

NESTE, being the first company world-wide to produce this drop-in fuel on a commercial basis, has built plants worldwide. Other European refineries are reconverting existing oil refineries into HVO biorefineries. The problem this market and value chain faces in the EU is the fact that large scale commercial refineries need large volumes of vegetable oils or waste lipid streams and the most common feedstock is palm oil which faces political and stakeholders' opposition in the EU. However, all European HVO producers have to use sustainable feedstock in their operations in the near future to comply as biofuel in the EU.

ENI has converted its Venice and Sicily refineries to HVO production. The Venice plant will be producing 420,000 tonnes/y in 2024 while the Sicily refinery aims to use feedstock not in competition with the food chain. Today ENI has a total processing capacity of 1.1 million tonnes per year with the goal of doubling its total capacity by 2024, reaching 5–6 million tonnes by 2050.

UPM's Lappeenranta Biorefinery has been the first commercial-scale biorefinery to produce renewable wood-based HVO and naphtha. The biorefinery is located next door to the UPM Kaukas pulp and paper mill, using the crude tall oil residue of Kaukas pulp production. UPM plans to build a new multi-feedstock biorefinery either at Kotka, Finland or Rotterdam of a capacity of 500,000 tonnes/y. UPM is currently also working on innovative feedstock options such as Brassica carinata in Uruguay.

Table 36: Technology developers for HVO

N°	Technology Developer	Plant/Location	Production Capacity tones/yr	In operation since	TRL
1	NESTE	Porvoo 1, Finland	200,000	2007	9
		Porvoo 2, Finland	200,000	2009	9
		Singapore	1,300,000	2010	9
		Rotterdam, Netherlands	1,200,000	2011	9
2	ENI	Venice, Italy	360,000	2014	9
		Gela, Sicily, IT	700,000	2019	9
3	UPM	Lappeenranta, Finland	130,000	2015	9
4	TotalEnergies	La Mede, France	500,000	2019	9
5	Preem	Gothenburg, Sweden	210,000	2021	9
		Lysekil Sweden	750,000	2024?	9

TotalEnegies reconverted its Mede refinery to a HVO biorefinery with a capacity of 500,000 tonnes/y based on several feedstocks. The plant has been designed to process any kind of oil.

Co-processing vegetable oils together with fossil feeds has attracted attention recently. As the refinery processes are complex and units interlinked, co-processing bio-feeds in integrated refinery lines results in fractionation of bio-components in multiple products streams. Preem's plant in Gothenburg has its capacity recently increased producing for the first time 100% renewable fuels[112]. Preem has also announced reconverting the Lysekil refinery to operate with renewable feedstocks (such as tall oil, tallow, and other renewable feedstocks) with a capacity of about 750,000 tonnes/y as of 2024[113].

There are also other developments at smaller capacities in Europe such as those in Spain of CEPSA's three refineries (Huelva-La Rabida, Algeciras–San Roque and Tenerife), REPSOL four refineries (La Coruña, Tarragona, Bilbao and Cartagena) as well as the BP refinery in Castellon all of which are capable of co-producing HVO. In Portugal GALP has a co-processing capacity of 47,000 tones/yr at its Sines refinery.

Furthermore, there are several other HVO plants in the US, China and elsewhere but there is little scope of including them in this study.

Although it may appear that once the feedstock is secured it is relative easy to build an HVO plant or reconvert an existing refinery to a HVO one; the reality is much more complex since the new types of residue streams used require additional pre-treatment steps before they can be used in the refinery and the overall investments are relative high.

Photos 13 to 17 show some of the HVO plants in Europe.

[112] Preem Press Release, 21/01/2021, https://www.preem.com/in-english/press/.

[113] Preem Press Release, 11/11/2020, https://www.preem.com/in-english/press/.

Photo 13 NESTE's HVO plant in Rotterdam

Photo 14 ENI's Green Refinery plant in Venice

Photo 15 UPM's Lappeenranta biorefinery plant

Photo 16 Total's biorefinery at La Mede

Photo 17 Preemraff in Gothenburg

VII: AVERAGE TIME TO BRING A TECHNOLOGY FROM THE LAB SCALE TO FOAK AND COMMERCIAL STATUS

New innovative biomass conversion technologies are complex systems of design and engineering work and have to go through several steps such as kinetic modelling, lab bench scale plants, lab pilot plants, stand-alone pilot plants, small scale demonstration plants, FOAK stage and finally commercial scale. In addition, a significant part of the modelling and the design work has to be repeated for different types of biomass such as straw, bagasse and softwood. Scaling up from lab-scale plant to demonstration and FOAK requires significant investments and a dedicated team of scientists, engineers and experts to work on it. Once such a team has been built it is of paramount importance to be kept together otherwise if dismantled for one reason or the other a large amount of knowledge is lost.

Even when a technology has reached the commercial stage continuous development and optimisation work needs to be sustained to further reduce the capital and operating costs in order to make the technology competitive with existing fossil fuel alternatives and/or other competing technologies (eg. gasification vs fast pyrolysis) using the same biomass feedstock.

Figure 46 shows the time taken for the Biomass Technology Group (BTG) to start from the basic technology research in 2005 to reach the commercial deployment stage in 2020.

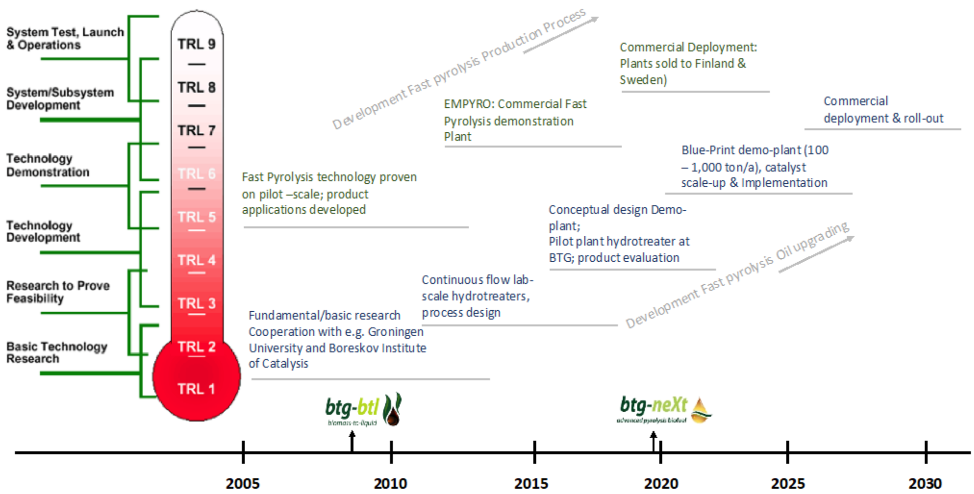

Figure 46 Technology development from basic research to commercialisation for BTG's fast pyrolysis process (courtesy Mr René Venendaal, CEO BTG)

Figure 47 shows the time taken for ENERKEM to develop its gasification technology to commercial applications.

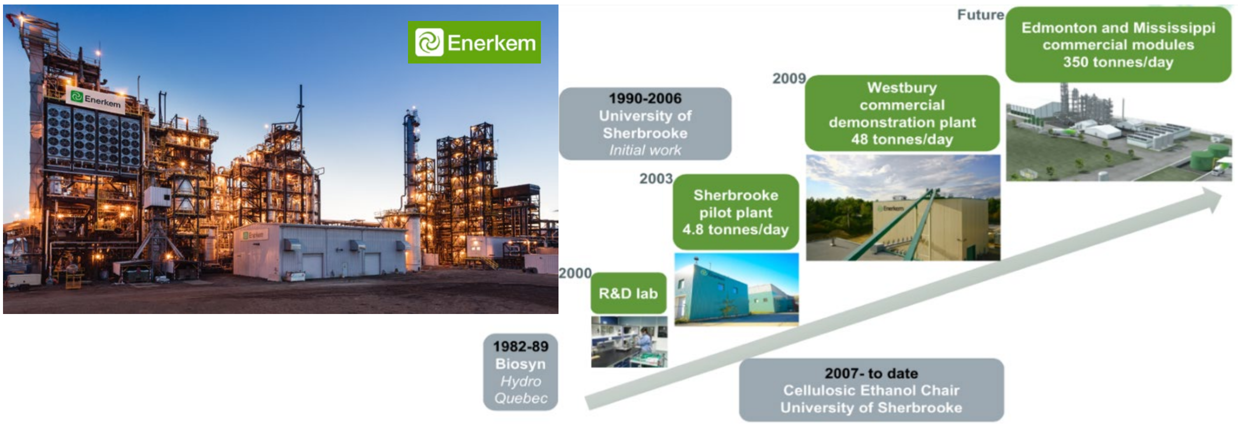

Figure 43: Technology development from basic research to commercialisation for ENERKEM's gasification process

Figure 48 shows the time taken for AXENS to develop its Futurol cellulosic ethanol technology to commercial applications with its various partners.

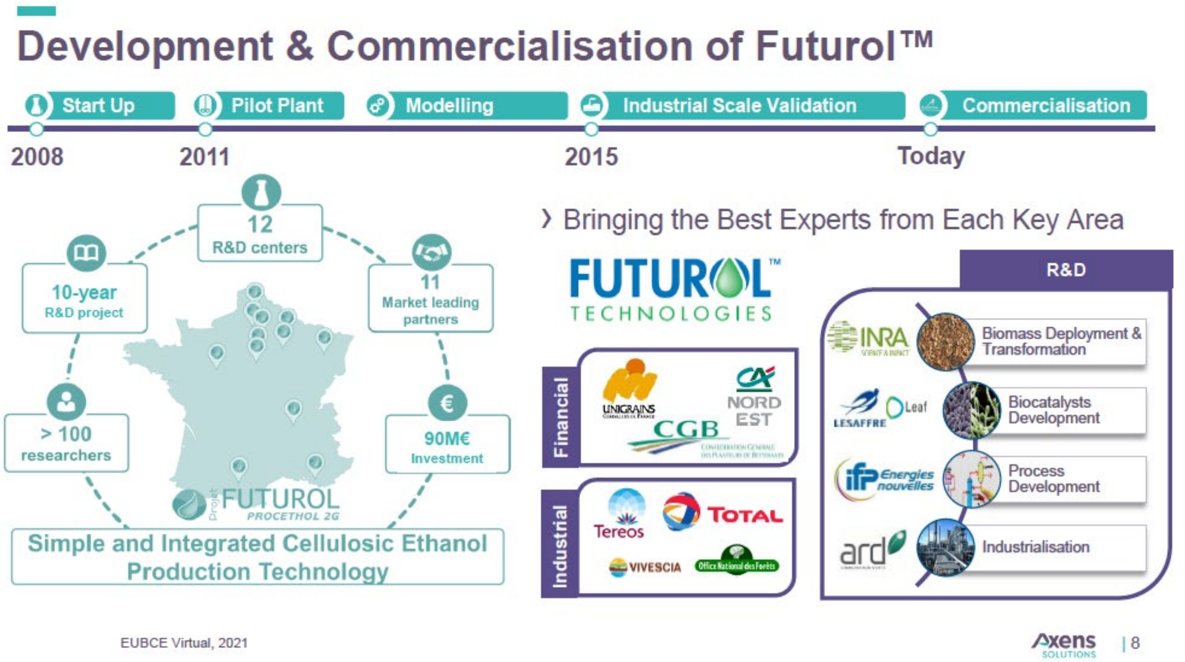

Figure 48 Technology development from basic research to commercialisation for AXENS's Futurol process[13]

Figure 49 shows the time taken for Lanzatech to commercially scale up its technology for sustainable aviation fuel.

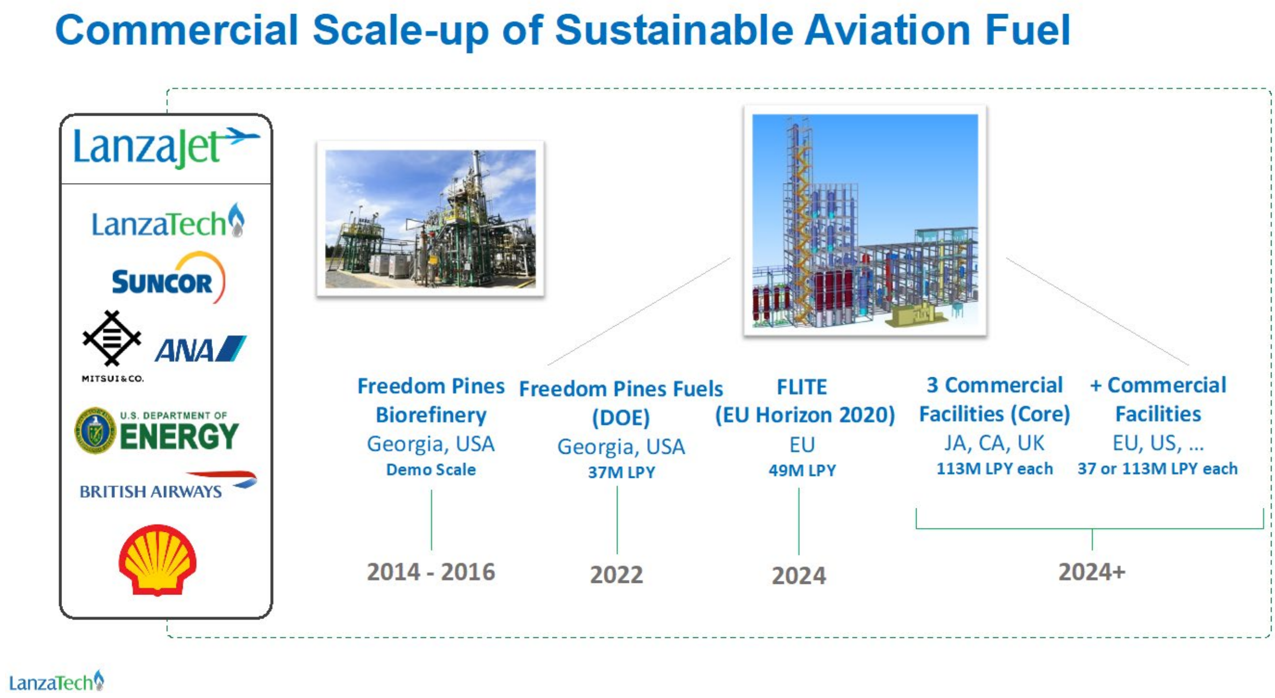

Figure 49 Time taken for commercialising Lanzatech's technology for SAF[114]

The above figures indicate that for both thermochemical and biological conversion technologies it takes several years to develop a technology from the early lab scale work to FOAK status and a commercial technology. This doesn't imply that with significant and continuous finance and appropriate and supporting legislation the development time can't be reduced; however, it is important to understand the development time for new biomass conversion technologies take several steps and a long time.

[114] J Holmgren, Presentation at EUBCE 2021.

VIII: ADVANCED BIOFUEL PATHWAYS PROJECTED BIOFUEL PRODUCTION CONVERSION YIELDS

Technology developers rarely publish actual data on biomass conversion yields to biofuels and scientific papers from academia rarely have access to performance data from large scale demonstration and commercial plants. The biomass conversion yields to biofuels used in this report have been derived from three key publications on the state of the art on biofuels production:

1. I. Landälv, L. Waldheim & K. Maniatis, editors, Technology status and reliability of the value chains, ART Fuels Forum, update of the Sub Group on Advanced Biofuels 2017 Report, 2018 Update, available at: http://artfuelsforum.wpengine.com/wp-content/uploads/2019/04/ART-Fuels-Forum-SGAB-Biofuels-Technology-report-2018-update.pdf.
2. IEA Bioenergy, A. Brown et al, Advanced Biofuels – Potential for Cost Reduction, available at: https://www.ieabioenergy.com/wp-content/uploads/2020/02/T41_CostReductionBiofuels-11_02_19-final.pdf.
3. Danish Energy Agency & Energinet, Technology Data - Renewable Fuels, 2020 update, available at: https://ens.dk/sites/ens.dk/files/Analyser/technology_data_for_renewable_fuels.pdf.

Furthermore, the data were discussed extensively with Mr Lars Waldheim, consultant on biomass conversion technologies and co-author of the first two reports mentioned above. His contribution is highly appreciated.

The biomass conversion yields to biofuels used in this work are given below in Table 38 for 2030 and 2050. Whenever other references were also taken into consideration these are listed in the Table.

Table 37 Biomass conversion yields to biofuels

Biofuel	Biomass feedstock	Yield in 2030, % or Nm^3/t	Yield in 2050, % or Nm^3/t	Yield in 2050 with renewable H_2 or additional conversion, %	Comments	Ref.
Hydrotreated Vegetable Oil (HVO) / renewable diesel	Animal fats, UCO	85	85	85 (no change since this is complete hydrogenation)	No increase in yield is foreseen by 2050 since this is the maximum yield possible.	1
Biomethane from Biogas or landfill production & removal of CO_2	biowaste, sludge, manures and agricultural residues	24 Nm^3/t	24 Nm^3/t	It is possible to use RH to convert the CO_2 (after separation of the CH_4 to biofuel), however, this isn't taken into consideration in this study for simplicity.	No increase in yields is foreseen by 2050 since this is a well-established industrial technology. There are several conversion yields in the literature for the various residues and waste streams. In this study the report by the Swedish waste association was taken as reference, (see Table 12 page 59) for waste streams. For grasses and crops data provided by Arthur Wellinger were taken as reference. It was decided to take an average value of 24 Nm^3/t for all biomass waste streams to simplify the calculations.	2
Ethanol from Enzymatic hydrolysis & fermentation	Various as per Table 7 of Part II	24	28	55*	Conversion yield is expected to increase to 28% in 2050 due to technology development,	N/A

					improvements in enzymes and yeast and progressing on the learning curve Ethanol conversion to hydrocarbons is expected in 2050.	
Ethanol from Gasification & fermentation	Various as per Table 7 of Part II	27	27	55*	No increase in yields is foreseen by 2050 since this is a biological process. Ethanol conversion to hydrocarbons is expected in 2050.	N/A
FT from Gasification + catalytic synthesis & RH	Various as per Table 7 of Part II	21	24	40	Conversion is expected to increase to 24% in 2050 due to progressing on the learning curve. With the availability of renewable hydrogen the conversion is expected to increase to 40%.	3,4
Fast Pyrolysis Co-processing and stand alone	Various as per Table 7 of Part II	11	12	24$	A slight increase in yields is foreseen by 2050 in coprocessing mode due to optimisation. With the availability of renewable hydrogen the conversion is expected to increase to 24% in stand-alone mode.	5
HTL coprocessing and stand alone	Various as per Table 7 of Part II	11	12	28$	A slight increase in yields is foreseen by 2050 in coprocessing mode due to optimisation. With the availability of renewable hydrogen the conversion is expected to increase to 28% in stand-alone mode.	6

FT = Fischer-Tropsch

RH = Renewable hydrogen

HTL = Hydrothermal Liquefaction

*: The yield is not related to hydrogen addition but to the reaction: $nC_2H_5OH = C_{2n}H_{4n}+nH_2O$, $C_{2n}H_{4n} +2H_2=C_{2n}H_{4n+2}$. This corresponds to n*30/(n*46)=30/46 =0.65. However, the conversion doesn't produce 100% hydrocarbons due to the production of soot and other lighter hydrocarbons which reduce the final yield to 0.55.

$: The FCC coprocessing technology is very different to the hydrogenation. It is also possible to produce a significant fraction of hydrogen from char and by-products; however, since this is very early stages of development it hasn't been considered in this study.

References:

4. The Potential and Challenges of Drop-in Biofuels, IEA Bioenergy Task 39, July 2014, available at: https://task39.sites.olt.ubc.ca/files/2014/01/Task-39-Drop-in-Biofuels-Report-FINAL-2-Oct-2014-ecopy.pdf
5. Avfall Sverige, Rapport: U2014:02, Styrmedel för biogasproducktion, 2014, (in Swedish).
6. I. Hannula Hydrogen enhancement potential of synthetic biofuels manufacture in the European context: A techno-economic assessment, Energy, Vol 104, 01/06/2016, available at: https://doi.org/10.1016/j.energy.2016.03.119
7. M. Hillestad et al, Improving carbon efficiency and profitability of the biomass to liquid process with hydrogen from renewable power, Fuel, Volume 234, 15 December 2018, Pages 1431-1451, available at: https://doi.org/10.1016/j.fuel.2018.08.004
8. A. de Rezende Pinho et al, Fast pyrolysis oil from pinewood chips co-processing with vacuum gas oil in an FCC unit for second generation fuel production, Fuel 188 (2017) 462-473, Elsevier, available at: http://dx.doi.org/10.1016/j.fuel.2016.10.032.
9. E.M. Lozano, H. Pedersenl & A. Rosendah, Integration of hydrothermal liquefaction and carbon capture and storage for the production of advanced liquid biofuels with negative CO2 emissions, Applied Energy, Vol 279, 01/12/2020, available at: https://doi.org/10.1016/j.apenergy.2020.115753.

Hilestad et al (see reference 4 above) conclude that "*By adding hydrogen, produced from renewable electric power, to the BtL process, the carbon efficiency can be increased from 38% to more than 90%. The increased carbon efficiency is possible because the water gas shift reaction is avoided and instead a reversed water gas shift is introduced to convert CO_2 to CO.*"

Tables 39 and 40 show the potential production of advanced biofuels by 2030 and 2050 respectively by combining the conversion pathway with the feedstocks for all the bioenergy sector (no allocation among bioenergy sectors) and the yields of each conversion technology.

The tables should not be seen or used in an additive manner as the same biomass source can be used for various value chains and conversion technologies. For example, lignocellulosic biomass can be used either in production of cellulosic ethanol or in the production of Fischer-Tropsch while biowaste can be used in anaerobic digestion to produce biomethane (via biogas upgrading) or it can be used in gasification & fermentation for the production of ethanol.

SIMPLIFIED ESTIMATION OF RENEWABLE HYDROGEN REQUIREMENTS FOR FISCHER-TROPSCH

This section provides for a ball park estimation of the use of hydrogen in Fischer-Tropsch conversion for the increase of carbon conversion to biofuel[115].

21% conversion efficiency

For a biofuel yield of 0.21 kg biofuel/kg dry biomass, this corresponds to 0.18 kg C/kg dry biomass.

Alkenes hydrocarbons are $C_xH_{(2x+2)}$. For x in the range of 8-20 which is good for fuels the approximation of C_xH_{2x}, is used. This corresponds to a hydrocarbon weight of 14 for x=1 and a carbon weight of 12/14 which multiplied by the yield of 0.21 results to 0.18. The error is 2/114 or < 2 % at x=8 and 2/282 or <1 % at x=20.

Dry biomass typically has 0.48 kgC/kg dry biomass, thus a conversion of 0.18 kg C/kg dry biomass represents 38 % of the carbon.

If all carbon ended up in hydrocarbon liquids it would be 0.56 kgC/kg biomass.

40% conversion efficiency

For a biofuel yield of 0.40 kg/kg dry biomass, this corresponds to 0.34 kg C/kg biomass; or 71 % of the biomass C.

Therefore in order to get to 0.40 kg biofuel/kg biomass, external renewable hydrogen can be used to convert 0.34-0.18 kg C/kg biomass= 0.16 kg C/kg biomass.

The H2 consumed then depends on how much is CO, (consuming 2 H2 on a kmol basis) and how much is CO2, (consuming 3 H2 on a kmol basis). The amount of CO available in the gas would be more or less the CO converted in the water gas shift to produce hydrogen to get to the ideal 2:1 H2/CO ratio in the first place (case of yield 0.2) . This would typically be one third of the CO in the syngas before shift as this has typically H2/CO =1:1, so 0.18/ (2/3)=0.27 kg/C as CO.

This means that 0.27-0.18=0.09 kg C could come from CO, and thus 0.07 from CO2 to reach 0.16 kg C.

Hydrogen consumption would then be =0.09/12*2*2+0.07/12*3*2=0.03+0.035=0.065 kgH_2/kg biomass.

115 Data provided by Mr Lars Waldheim, Waldheim Consulting, lars.waldheim@waldheim-consulting.se

Table 38 Projected biofuel quantity production for 2030 assuming all the sustainable biomass for bioenergy taking into account European feedstocks listed in Annex IX A and B of RED II/2018.

Pathway	Fuel	Feedstock	Projected feedstock (million tonnes)	Conversion yield to fuels mass % or as specified	Estimated advanced biofuel quantity (million tonnes)	Estimated advanced biofuel quantity (Mtoe)
Hydrotreatment	HVO	Animal fats	2.2	85	1.87	1.87
		Used Cooking Oil (UCO),	3.1	85	2.6	2.6
Biogas or landfill production & removal of CO2	Biomethane	Biowaste	44-80	24 Nm3/ton feed	0.8 - 1.4	0.9 - 1.6
		Sewage sludge	6 to 9	24 Nm3/ton feed	0.1- 0.2	0.1 - 0.2
		Manure (solid and liquid)	56-62	24 Nm3/ton feed	1.0 -1.1	1.1 - 1.3
		Agricultural residues (high moisture; sugarbeet leaves, etc.)	2.5	41.4 Nm3/ton feed	0.1	0.1
Enzymatic hydrolysis & fermentation	Ethanol	Biowaste	44-80	24	10.6 - 19.2	6.8 - 9.3
		Solid industrial waste (secondary agro & forest industries)	133-191	24	31.9 - 45.8	20.4 -29.3
		Agricultural residues (straw-like)	137-165	24	32.9 - 39.6	21.0 - 25.3
		Lignocellulosic crops (grassy)	36-108	24	8.6 - 25.9	5.5 - 16.6
Gasification + fermentation	Ethanol	Biowaste	44-80	27	11.9 - 21.6	7.6 - 13.8
		Solid industrial waste (secondary agro & forest industries)	133-191	27	35.9 - 51.6	22.9 -33.0
		Agricultural (woody) & forestry residues	5 to 7	27	1.4 - 1.9	0.9 - 1.2
		Lignocellulosic crops (woody)	36-108	27	9.7 - 29.2	6.2 - 18.7
Gasification + catalytic synthesis	Synthetic fuel	Biowaste	44-80	21	9.2 -16.8	9.2 -16.8
		Solid industrial waste (secondary agro & forest industries)	133-191	21	27.9 - 40.1	27.9 - 40.1
		Agricultural (woody) & forestry residues	5 to 7	21	1.0 - 1.5	1.0 - 1.5
		Lignocellulosic crops (woody)	36-108	21	7.6 - 22.7	7.6 - 22.7
Fast Pyrolysis & HTL Co-processing in existing petroleum refineries	Co-processed bio-oil/biocrude	Biowaste	44-80	11	4.8 - 8.8	4.8 - 8.8
		Solid industrial waste (secondary agro & forest industries)	133-191	11	14.6 - 21.0	14.6 - 21.0
		Agricultural (woody) & forestry residues	5 to 7	11	0.6 - 0.8	0.6 - 0.8
		Lignocellulosic crops (woody)	36-108	11	4.0 - 11.9	4.0 - 11.9

Table 39 Projected biofuel quantity production for 2050 assuming all the sustainable biomass for bioenergy taking into account European feedstocks listed in Annex IX A and B of RED II/2018.

Pathway	Fuel	Feedstock	Projected feedstock (million tonnes)	Conversion yield to fuels mass % or as specified	Estimated advanced biofuel quantity (million tonnes)	Estimated advanced biofuel quantity (Mtoe)
Hydrotreatment	HVO	Animal fats	2.2	85	1.9	1.9
		Used Cooking Oil (UCO)	7.7	85	6.5	6.5
Biogas or landfill production & removal of CO2	Biomethane	Biowaste	33-61	24 Nm3/ton feed	0.6 - 1.0	0.7 - 1.2
		Sewage sludge	6 to 8	24 Nm3/ton feed	0.1- 0.2	0.1 - 0.2
		Manure	50-60	24 Nm3/ton feed	0.9 -1.0	1.0 - 1.2
		Agricultural residues (high moisture; sugarbeet leaves, etc.)	2.5	41,4 Nm3/ton feed	0.1	0.1
Enzymatic hydrolysis & fermentation	Ethanol to Hydrocarbons	Biowaste	33-61	15.4	5.1 - 9.4	5.1 - 9.4
		Solid industrial waste (secondary agro & forest industries)	142-210	15.4	21.9 - 32.3	21.9 - 32.3
		Agricultural residues (straw-like)	136-156	15.4	20.9 - 24.0	20.9 - 24.0
		Lignocellulosic crops (grassy)	42-127	15.4	6.5 - 19.6	6.5 - 19.6
Gasification + fermentation	Ethanol to Hydrocarbons	Biowaste	33-61	14.85	4.9 – 9.1	4.9 – 9.1
		Solid industrial waste (secondary agro and forest industries)	142-210	14.85	21.1 – 31.2	21.1 – 31.2
		Agricultural (woody) & forestry residues	6 to 8	14.85	0.9- 1.2	0.9- 1.2
		Lignocellulosic crops (woody)	42-127	14.85	6.2 - 18.9	6.2 - 18.9
Gasification + catalytic synthesis + RH	Synthetic fuel	Biowaste	33-61	40	13.2 - 24.4	13.2 - 24.4
		Solid industrial waste (secondary agro & forest industries)	142-210	40	56.8 - 84	56.8 - 84
		Agricultural residues (straw-like)	136-156	40	54.4 - 62.4	54.4 - 62.4
		Agricultural (woody) & forestry residues	6 to 8	40	2.4 - 3.2	2.4 - 3.2
		Lignocellulosic crops (woody)	42-127	40	16.8 - 50.8	16.8 - 50.8

Co-processing in existing petroleum refineries	Co-processed bio-oil/biocrude	Biowaste	33-61	12	4.0 - 7.3	4.0 - 7.3
		Solid industrial waste (secondary agro & forest industries)	142-210	12	17.0 - 25.2	17.0 - 25.2
		Agricultural residues (straw-like)	136-156	12	16.3 - 18.7	16.3 - 18.7
		Agricultural (woody) & forestry residues	6 to 8	12	0.7 - 1.0	0.7 - 1.0
		Lignocellulosic crops (woody)	42-127	12	5.0 - 15.2	5.0 - 15.2
Pyrolysis stand-alone + RH	Hydrocarbon fuels	Biowaste	33-61	24	7.9 - 14.6	7.9 - 14.6
		Solid industrial waste (secondary agro & forest industries)	142-210	24	34.1 - 50.4	34.1 - 50.4
		Agricultural residues (straw-like)	136-156	24	32.6 - 37.4	32.6 - 37.4
		Agricultural (woody) & forestry residues	6 to 8	24	1.4 - 1.9	1.4 - 1.9
		Lignocellulosic crops (woody)	42-127	24	10.1 - 30.5	10.1 - 30.5
HTL stand-alone + RH	Hydrocarbon fuels	Biowaste	33-61	28	9.2 - 17.1	9.2 - 17.1
		Solid industrial waste (secondary agro & forest industries)	142-210	28	39.8 - 58.8	39.8 - 58.8
		Agricultural residues (straw-like)	136-156	28	38.1 - 43.7	38.1 - 43.7
		Agricultural (woody) & forestry residues	6 to 8	28	1.7 - 2.2	1.7 - 2.2
		Lignocellulosic crops (woody)	42-127	28	11.8 - 35.6	11.8 - 35.6

IX: SENSITIVITY ANALYSIS BASED ON TECHNOLOGY DEVELOPMENT

This section carries out a sensitivity analysis based on several assumptions that may affect the value chains to be used in the future. This section doesn't aim to predict winning or losing value chains since there is no way to be able to foresee how the future legislation will develop in the EU.

Actually, the EU legislation on biofuels, renewable fuels and low carbon fuels has been changing every few years and the RED II Directive is under revision even before it was possible to be adopted by National legislations. This has created insecurity for the investors to finance biorefineries and facilitate the deployment of advanced biofuels. Long term stable policies are a prerequisite for investments in FOAKs and new technologies that still entail a certain degree of risk. Repeated future revisions of the RED and other related directives may result in slow and uncertain uptake of the innovative technologies that are addressed in this report.

The analysis is based on two different sets of assumptions, one to 2030 based on the biofuel value chains and the other to 2050 based on the deployment of e-fuels and electrification of transport. It is expected that e-fuels will remain comparatively very expensive till 2030 and within the next 8 years of the time of writing this report they will have reached the FOAK level like advanced biofuels have achieved at present. This is justified considering the development work still to be done for electrolysers, batteries and convert renewable electricity to hydrogen. Therefore e-fuels are not considered in the first set of sensitivity analysis.

Table 41 discusses various possible scenarios that may or may not happen in the future, the potential opportunities or adversities in the deployment of various value chains, and the eventual prospects for the various advanced biofuels. The scenarios address only the timeframe to 2030 since any assumption or prediction for 2050 is precarious and can be considered unwarranted. The selected scenarios are actually extreme cases which would favour the use of a feedstock for one value chain or the other since the various feedstocks can be used, subject to pretreatment and upgrading process (such as enzymatic hydrolysis), in more than one value chain.

Table 42 discusses possible scenarios that may happen or may not happen by 2050 based on the successful deployment of e-fuels and the potential prospects for advanced biofuels. These are not any more based on the value chains for advanced biofuels but on the eventual successful penetration of e-fuels and electrification post 2030.

In the tables the eventual role of advanced biofuels post 2030 is also addressed.

Table 40 Biofuel sensitivity analysis for 2030 based on various hypothetical scenarios.

Scenario	Description	Potential effects on feedstock and value chains deployment	Eventual Prospects
Hydrotreated Lipids (HL1)	The availability of lipids and UCO increases with new residues and process streams. Production of sustainable lipids out of the EU and importing them becomes a successful and justifiable practise. Electrification is slow till 2030.	Lipids availability is increasing and increased quantities of HVO are used for the diesel and aviation market.	HVO is the preferred value chain for lipids due to reliability, blend-in flexibility and low cost.
Hydrotreated Lipids (HL2)	The availability of lipids and UCO remains limited. Production of sustainable lipids out of the EU and importing them faces competition and other problems and remains marginal. Accelerated deployment of electrification is achieved by 2030	Lipids availability is limited and all quantities of HVO are used for aviation market. Passenger cars are electrified while heavy duty transport relies on other fuels.	HVO remains the preferred value chain for lipids due to its drop-in flexibility. Lipids are diverted from biodiesel to HVO.
Cellulosic Ethanol (CE1)	The blend wall increases to E25; ED95 is adopted by several heavy-duty engine manufacturers. Electrification is slow till 2030.	Significant market demand, grain and sugar-based ethanol can't satisfy the market, lignocellulosic biomass is used in ethanol; production to satisfy the market needs.	Cellulosic ethanol is the preferred conversion technology for lignocellulosic feedstock due to demand and relative low cost.
Cellulosic Ethanol (CE2)	The blend wall remains at E10; ED95 is not adopted by other manufacturers other than SCANIA. Accelerated deployment of electrification achieved by 2030.	Market demand decreases significantly, grain and sugar-based ethanol can satisfy the market. Lignocellulosic ethanol still too expensive for upgrading to SAF. Lignocellulosic biomass is used in other value chains.	Lignocellulosic feedstock is used in other value chains.
Synthetic biofuels via gasification (SB1)	Fischer-Tropsch is deployed successfully by 2025 and in the market by 2030. Production costs are reduced relative fast. Electrification is slow till 2030.	Significant market demand for drop-in Fischer-Tropsch which is used for the diesel and aviation market. Lignocellulosic feedstock is used extensively for this value chain.	Fischer-Tropsch is the preferred conversion technology for lignocellulosic feedstock due to high demand, reduced costs and drop-in flexibility.
Synthetic biofuels via gasification (SB2)	Fischer-Tropsch and the built FOAKs face reliability problems by 2030. Production costs remain high. Accelerated deployment of electrification achieved by 2030.	Fischer-Tropsch doesn't deploy in the market. The diesel and aviation markets are supplied by other feedstocks.	Lignocellulosic feedstock is used in other value chains.
Pyrolysis coprocessing (PC1)	Pyrolysis oils (from fast- and hydro-pyrolysis) are co-processed successfully in refineries. Resulting yields to the fuel component are low but the refineries benefit from the renewable carbon ending	Significant market demand for pyrolysis oils from lignocellulosics and wet feedstock. Several satellite pyrolysis plants are built to supply refineries.	Lignocellulosic feedstock and feedstock with high moisture content are use respectively for pyrolysis plants to supply refineries.

	in several products. Coprocessing results in relative low final cost.		
Pyrolysis coprocessing (PC2)	Co-processing pyrolysis oils (from fast- and hydro-pyrolysis) in refineries doesn't progress. Resulting yields to the fuel component are low and the overall benefits from the renewable carbon ending in several products is limited. Coprocessing is considered complex with intricate logistics.	Limited demand in site specific cases, nice market. Lignocellulosic and feedstock of high moisture content are used in other value chains.	Lignocellulosic feedstock and feedstock of high moisture content are used in other value chains.
Anaerobic digestion upgrading to biomethane (ADB1)	Strong policies on greening the grid prevail in the EU. High moisture feedstock and crops are used for anaerobic digestion and biomethane. Anaerobic treatment of sludges accelerates due to environmental concerns.	High demand for biomethane for injection in the grid. Biomethane from sludge treatment is used in captive fleets.	High moisture feedstock and crops are used for anaerobic digestion.
Anaerobic digestion upgrading to biomethane (ADB2)	Policies related to greening the grid progress but natural gas retains primary function in the grid. Anaerobic treatment of sludges accelerates due to environmental concerns.	Limited demand for biomethane for injection in the grid. Biomethane from sludge treatment is used in captive fleets.	High moisture feedstock are used for anaerobic digestion while crops are used in other value chains.

Table 41 e-Fuel sensitivity analysis for 2050 based on various hypothetical scenarios.

Scenario	Description	Potential deployment effects	Eventual Prospects for advanced biofuels
e-Fuels predominant (EF1)	Renewable electricity is abundant. Electrolysers are becoming reliable and relative cheap. Balancing of intermittent renewable electricity is achieved. Batteries achieve limited progress. Cost of e-fuels is reduced significantly.	e-fuels are becoming the mainstream fuel for heavy duty transport, aviation and maritime.	There is little need for advanced biofuels. They are mainly used for the aviation sector. Biomethane is used in the green grid.
e-Fuels minor (EF2)	Renewable electricity is abundant. Electrolysers still face problems of scaling up and reliability. Balancing of intermittent renewable electricity is partially achieved. Batteries become very reliable and cheap. Cost of e-fuels remains relative high.	Batteries are mainly used to store renewable electricity and manage transport electrification. e-Fuels are in limited deployment. Advanced biofuels provide the bulk for internal combustion engines.	Small quantities of e-Fuels are blended with advanced biofuels. Preference for Fischer-Tropsch which is a drop-in fuel and can satisfy all markets. Biomethane is used in the green grid.
e-Fuels Balanced (EF3)	Renewable electricity is abundant. Electrolysers are becoming reliable and relative cheap. Balancing of intermittent renewable electricity is achieved. Batteries are becoming reliable and relative cheap. Cost of e-fuels and batteries is reduced significantly.	Passenger cars and light duty vehicles are using renewable electricity. E-Fuels are used for heavy duty transport, aviation and maritime along with advanced biofuels. Renewable hydrogen is used in biomass conversion technologies such as gasification and pyrolysis increasing the biomass carbon conversion efficiency significantly.	Large quantities of e-fuels are blended with advanced biofuels. Preference for Fischer-Tropsch and stand-alone pyrolysis units which provide drop-in fuel and can satisfy all markets. Biomethane is used in the green grid. Competition with e-methane for use in a green grid.

X: COUNTRY ABBREVIATIONS

AT	Austria
BE	Belgium
BG	Bulgaria
CZ	Czech Republic
DE	Germany
DK	Denmark
GR	Greece
ES	Spain
FI	Finland
FR	France
HR	Croatia
HU	Hungary
IT	Italy
LV	Latvia
LT	Lithuania
LU	Luxemburg
NL	Netherlands
PL	Poland
PT	Portugal
RO	Romania
SE	Sweden
SI	Slovenia
SK	Slovakia
UK	United Kingdom

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