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Supply potential, suitability and status of lignocellulosic feedstocks for advanced biofuels

D2.1 Report on lignocellulosic feedstock availability, market status and suitability for RESfuels

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Summary

Between 2000 and 2015, gross inland consumption of bioenergy increased by 225% from 60.8 Mtoe in 2000 to 136.7 Mtoe in 2015 and is currently the largest renewable energy source (RES) in the EU. In the current bioenergy landscape, bioenergy is mainly supplied from forest sources such as fuelwood used in wood stoves, wood residues used in industrial and residential heat sectors, cogeneration and power generation. Liquid biofuels used in transport are almost solely produced from food-based crops (oil, starch, sugar) and wastes (used cooking oil, animal fats). Agricultural residues contribute only up to 1% to current biofuel production in the EU (AEBIOM, 2017).

On the short term between 2016 and 2020, bioenergy demand in the EU is expected to continue to grow by 27% to meet binding RES targets, but no major structural changes are expected before 2020. Furthermore, bioenergy growth is expected to slow down in the period 2020 – 2030 as a result of strong developments in other RES such as wind and PV. Under such development conditions, sufficient biomass should be available to meet the demand in bioenergy sectors (electricity, heat, biofuels). Post 2030 however, albeit being also more uncertain, strong growth of biomass demand is anticipated in particular lignocellulosic biomass used for advanced biofuels used in the transport sectors.

If climate targets become more strict towards 2050, such as agreed upon at the COP21 in Paris (2015), the magnitude to what bioenergy can contribute to climate reduction targets will for a large extent be determined by the amount of biomass that can be supplied in a sustainable way. Bioenergy should not directly compete with other sectors of the bio-economy (food, feed and fibre first principle) and should be compliant with environmental and socio-economic criteria. Insights in the sustainable supply potential of biomass feedstock supply and the development of their potential to 2040/50 becomes therefore increasingly relevant. However, only few biomass resource assessment studies include projections of future biomass supply beyond 2030. In this study, ranges of biomass supply found in literature between 2006 and 2017 are summarised per main feedstock category (agriculture residues, forests, energy crops, waste and imports from outside Europe (extra-EU).

According to the most conservative estimates of the domestic biomass potential in the EU, the supply potential by 2020 (115 Mtoe) will be lower than current gross inland consumption of bioenergy in the EU (130 Mtoe domestic, 6 Mtoe imports in 2015) and increasing to 206 Mtoe by 2030 and 195 Mtoe by 2050. In High supply scenarios, that assume the mobilisation of additional forest sources and additional land available for energy crop cultivation estimate that the domestic potential could be between 525 Mtoe (2020) to 597 Mtoe (2050).

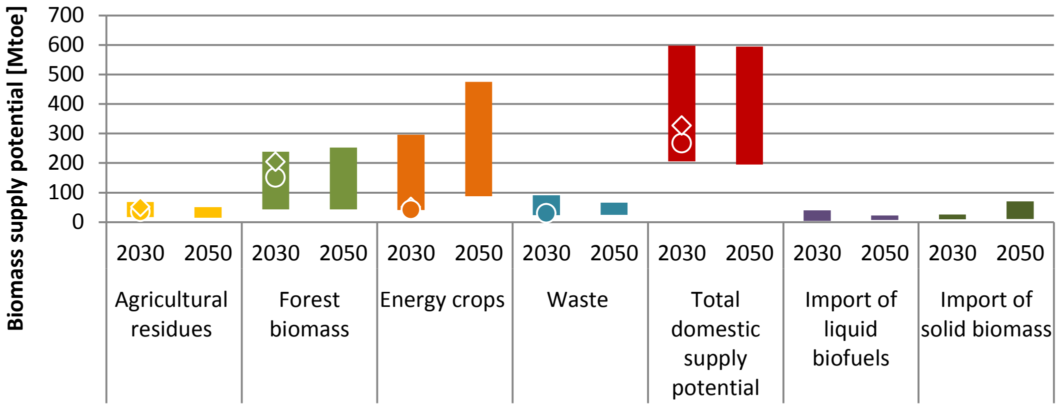


Figure 1 EU domestic biomass potential and extra-EU imports available for bioenergy in the EU by main feedstock category from available EU biomass resource assessments (2006 - 2017) and currently applied biomass supply scenarios in the RESolve-Biomass modelling framework (markers).

Approximately 25% - 36% of the potential is estimated to be available from forests (stemwood and forest residues such as logging residues, sawdust), but partly it is already utilised in electricity and heat sectors (95 Mtoe). Material uses (timber, pulp and paper etc.) are roughly of the same magnitude to bioenergy in terms of biomass demand (by weight) in the EU bioeconomy.

Solid biomass imports could (mainly wood pellets) potentially contribute 4 – 40 Mtoe in 2030 and 7 – 23 Mtoe for solid biomass according to available import scenarios in literature. Liquid biofuels are estimated to contribute between 9 – 26 Mtoe by 2030 and 10 – 69 Mtoe by 2050.

Energy crops, and in particular perennial crops such as grasses and short rotation coppice, could potentially contribute between 33% and 56% to the total EU biomass potential. However, markets of perennial crops are still relatively small today.

Although potentially available, substantial efforts are therefore required before these biomass sources are readily available to produce advanced biofuels at commercial scale. These efforts include, amongst others, infrastructure, farmers experience, as well as regulatory compliance and support. The results of this report will serve as a basis for further research in ADVANCEFUEL on quantifying the supply potential of perennial crops grown on marginal lands (Task 2.2) and related sustainability performance (Task 4.3), the development of feedstock supply chains (Task 2.3) and supply scenarios and updates of ECN's RESolve-Biomass model in Task 6.1, in particular on extra-EU supply scenarios of solid biomass and liquid biofuels beyond 2030.

Abbreviations

ar	as received
ARA	Antwerp - Rotterdam - Amsterdam
bln L	billion litres (1 x 10^9 L)
CAAFI	Commercial Aviation Alternative Fuels Initiative's
CAP	Common Agricultural Policy
CHP	combined heat and power
CIF	Cost insurance and freight
CO_2	Carbon dioxide
DDGS	Distiller`s Dried Grains with Solubles
dm	dry matter
EC	European Commission
EEA	European Environmental Agency
EFISCEN	European Forest Information SCENario
EU	European Union
FAME	fatty acid methyl ester
FAWS	forest available for wood supply
FQD	Fuel Quality Directive
FRSL	feedstock readiness level
FSC	Forest Stewardship Council
GHG	greenhouse gas
GJ	Giga joule (1 x 10^9 joule)
HNV	High nature value
HVO	hydrotreated vegetable oil
iLUC	indirect land use change
kt	kiloton (1 x 10^3 kg)
Ktoe	kiloton of oil equivalent (41.868 TJ)
L	Litre
LCA	life cycle assessment
LHV	lower heating value
M m^3	Million cubic metre (also hm^3 is used)
MAGIC	Marginal Lands for Growing Industrial Crops
Mha	Million hectare
MJ	Mega joule (1 x 10^6 joule)
Mm3	million m^3
Mt	million metric tonne (1 x 10^6 kg)
Mtoe	Million tonne of oil equivalent (41.868 PJ)
N_2O	Nitrous oxide
NAI	net annual increment
PJ	Peta joule (1 x 10^{15} joule)
PV	Photovoltaics
R&D	research and development
RED	renewable energy directive
RES	Renewable energy supply
SEEMLA	Sustainable exploitation of biomass for bioenergy from marginal lands
SFI	Sustainable Forestry Initiative
SFM	Sustainable Forest Management
SRC	short rotation coppice
SRP	short rotation poplar
swe	solid wood equivalent
t	Metric tonne (1000 kg)
toe	Tonne of oil equivalent (41.868 GJ)
TRL	technology readiness level
UCO	Used cooking oil

1. Introduction

The European Union (EU) is committed to reduce greenhouse gas emissions (GHG) with 20% by 2020, 40% by 2030 and 80-95% by 2050 compared to 1990 levels in line with the international ambitions to keep global temperature rise to below 2 °C compared to preindustrial levels. This is achieved mainly through the substitution of fossil fuels with renewable energy sources (RES) and energy efficiency measures with RES targets and energy efficiency targets. The RES share in final consumption has increased from 8% in 2004 to 17% in 2016 and will need to grow to 20% by 2020 and 27% by 2030 as agreed on in the 2009 Renewable Energy Directive (RED, 2009/28/EC). The EU now aims to increase the RES target to at least 32% by 2030 in its revised RED (RED Recast, COM(2016/03882/COD).

As a result of RES support in the EU, biomass used for energy purposes (bioenergy) has increased more than twofold in the last decade (AEBIOM, 2017) and despite strong developments in wind power and photovoltaic energy (PV), remains the largest source of renewable energy. On the short term between 2016 and 2020, bioenergy demand in the EU is expected to continue to grow with 27% to meet binding RES targets (Figure 2) marking two decades of continuous growth. Beyond 2020 however, effective energy efficiency measures, in particular in the heating sector in combination with developments of alternative RES technology developments in the electricity sector, can lead to a stagnation in bioenergy growth between 2020 and 2030: -2% to 4% depending on the energy efficiency target of 27% (EUCO27) or 30% (EUCO30). Post 2030, albeit being also more uncertain, strong growth of biomass demand is anticipated particular advanced biofuels used in the transport sector.

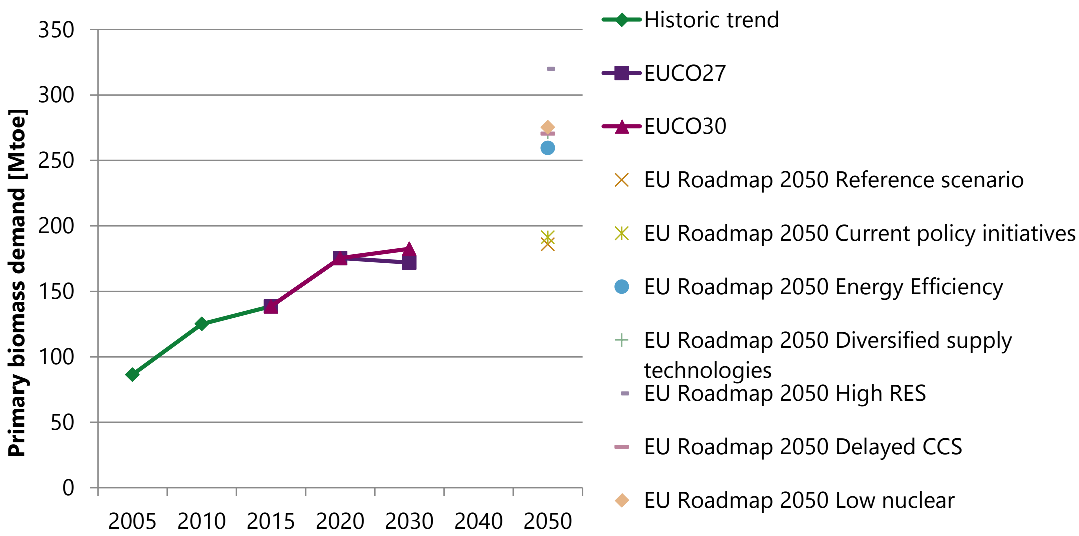


Figure 2 Historic and future biomass demand in the EU (PRIMES projections for the EU Roadmap 2050 (EC, 2012a) *and EUCO scenarios* (EC, 2016)*)*

The magnitude to what bioenergy can contribute to climate reduction targets depends for a large extent on the amount of biomass that can be supplied in a sustainable way, i.e. the sustainable supply potential. Biomass used for energy purposes should not directly compete with other sectors of the bioeconomy (food, feed and fibre first principle) and should meet environmental and socio-economic constraints.

This report includes the state-of-the art of biomass resource potentials and the development of their potential to 2030 and beyond to 2040/50. The focus of this review is on the potential availability of non-food biomass from forests and agriculture and key determining factors including the availability of land and in particular marginal lands and constraints (sustainable removal rate, competing uses etc.). Furthermore, up-to-date lignocellulosic biomass extra-EU import scenarios are assessed. Finally this report provides a method to basses the availability and suitability of lignocellulosic feedstocks and intermediates for advanced biofuels conversion. Biomass cost and market prices (economic potentials) are not discussed in detail in this deliverable.

2. The bioenergy landscape in the EU

The overall bioeconomy covers the production of renewable biological resources and waste and its conversion food, feed, materials and bioenergy (COM(2012) 60 final) (EC, 2012b). Bioenergy is embedded in a complex way in the bioeconomy as depicted in Figure 3 and Figure 9. Only traditional sectors of the bioeconomy are reported on in statistics with no distinction between for example man-made fibres and bio-based textiles. JRC (Ronzon *et al.*, 2015) has estimated the size of the land-based bioeconomy (excluding aquatic biomass) based on multiple sources for the year 2013 as shown in Figure 3. In total, 1600 to 2200 Mt biomass are produced in the EU of which 450 to 680 Mt remain unused. The unused biomass consists of agriculture residues such as straw and forest residues. In most cases, part of it has to be left on the field or in the forest, for example to maintain and improve soil organic matter, but part of it could be removed without negative consequences (Kluts *et al.*, 2017). In contrast to the EU fossil economy[1], the EU imports only about 15% biomass and exports roughly the same amount.

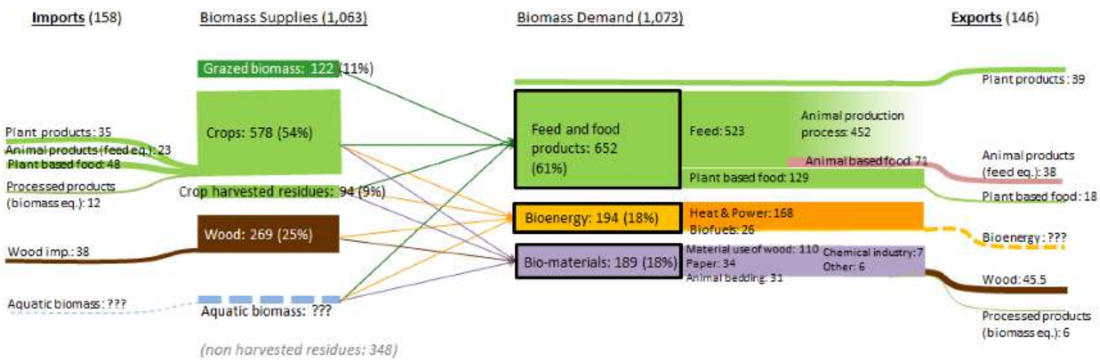


Figure 3 Biomass flows in the EU bio-based economy 2013, million tonnes dry (Ronzon *et al.*, 2015)

Food and feed are the largest sectors of the bioeconomy, 49% of biomass demand is used for feed purposes and 12% is used for food products. Biomaterials (timber, pulp and paper, textiles etc.) make up 17% of biomass demand in the EU bioeconomy and is smaller compared to the use of biomass for energy purposes (18%). Bioenergy has, however, grown rapidly in the past 15 years stimulated by renewable energy support. Between 2000 and 2015, gross inland consumption of bioenergy increased with 225% from 60.8 Mtoe in 2000 to 136.7 Mtoe in 2015 (Eurostat, 2018). Although modern bioenergy, including efficient heating, electricity generation and biofuels, were the main driver for the development of bioenergy in the EU, tradi-

[1] The energy dependency (imports minus exports, divided over gross inland consumption plus maritime bunkers) of the EU28 was 54% in 2015 with 89% for petroleum products, 69% natural gas, 43% solid fuels (mainly coal) and 3% renewable energy (AEBIOM 2017).

tional uses of fuel as wood used in wood stoves in the residential sector is still the largest biomass market. In 2015, 41% (49 Mtoe) of wood & other solid biomass was consumed in the residential sector excluding the use of wood pellets and dominated by local fuel wood (Figure 5).

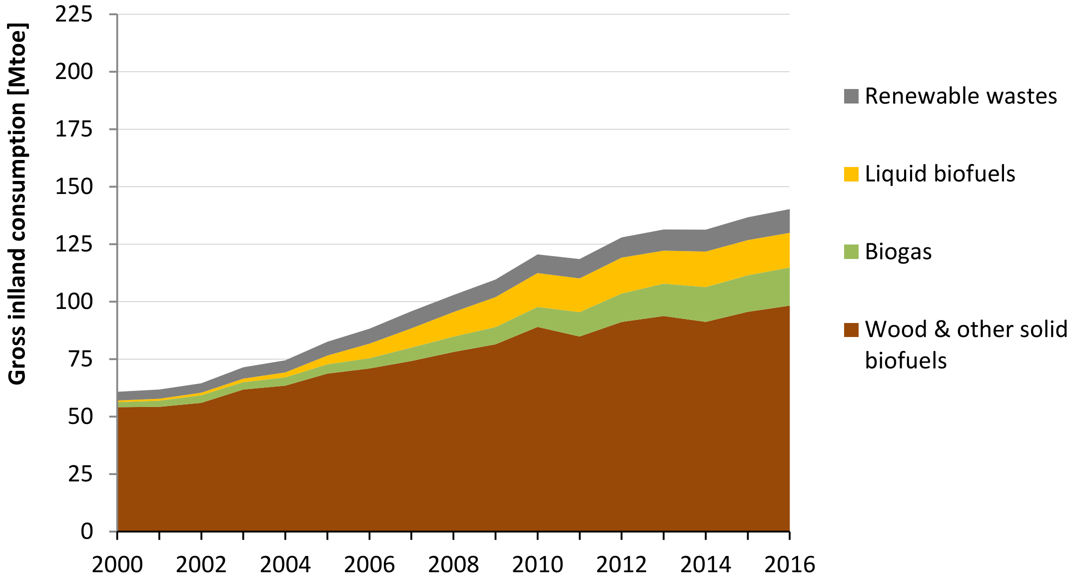


Figure 4 Development of gross inland consumption of bioenergy between 2000 and 2016 in the EU28 (Eurostat, 2018)

The market for liquid biofuels exists of biodiesel and biogasoline (both used for 98% in transport) and other liquid biofuels (0.3% used in transport). Gross inland consumption of bioenergy in liquid biofuels has increased from 0.7 Mtoe in 2000 to 15.3 Mtoe in 2015 and decreased slightly to 15.1 Mtoe in 2016. Biodiesel is produced from rapeseed, used cooking oil and animal fats. However, also imported palm oil and soy oil still contribute substantially to EU biofuel production as shown in Figure 6. The contribution of solid biomass to produce advanced biofuels is still very small (1% ethanol 2nd generation).

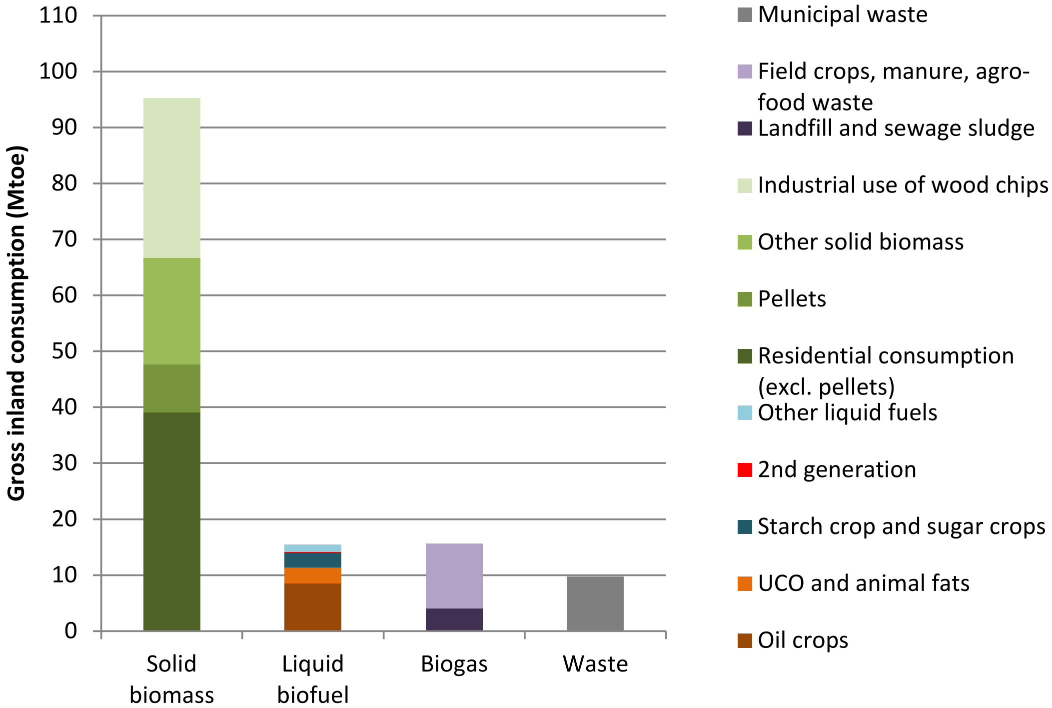


Figure 5 Gross inland consumption of bioenergy in the EU28 in 2015 per source, data from AEBIOM (2017). Other solid biomass covers installations smaller than 1 MW, for example black liquor.

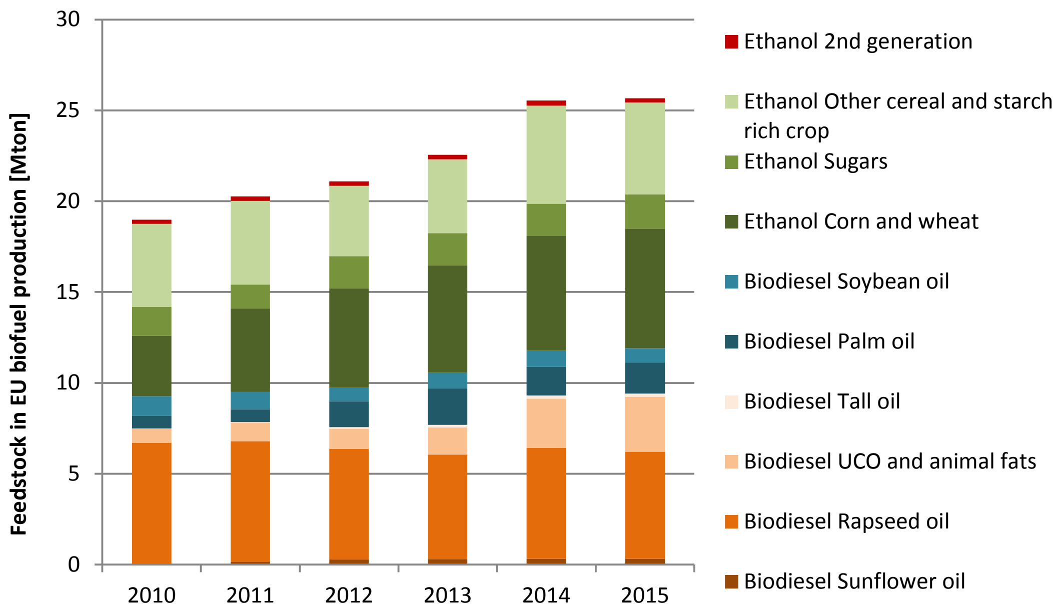


Figure 6 Feedstock consumption in EU liquid biofuel production in Mt liquid biofuel (AEBIOM 2017)

To estimate land use for biofuel crop cultivation data on crop production, location specific yields and the allocation of land use over the produced biofuels and co-products both in the EU and outside the EU for imported biofuels are required. These co-products include for example soy bean meal, DDGS (Distiller`s Dried Grains with Solubles) and beet pulp that are used amongst others for animal feed. Hamelinck et al. (2013) have quantified land use for biofuels for 2012. They estimated total land use for biofuels to be 7.8 Mha with 4.4 Mha within the EU and 3.5 Mha outside the EU for imported biofuels or feedstock to produce biofuels in the EU. After 2012, imports of biofuels from outside the EU have decreased substantially (Figure 7) as a result of effective anti-dumping measures. Since November 2013, extra-EU import duties (between 120 and 250 €/t) were applied to Indonesian and Argentinean biodiesel reducing imports substantially. Similarly in 2014, the European Commission imposed anti-dumping duties to US ethanol were imposed. Those duties were applied regardless of its transit country to prevent US exports of ethanol to Norway that re-exported the biofuels as blend with gasoline to the EU in 2013 (EurObserv'er, 2014).

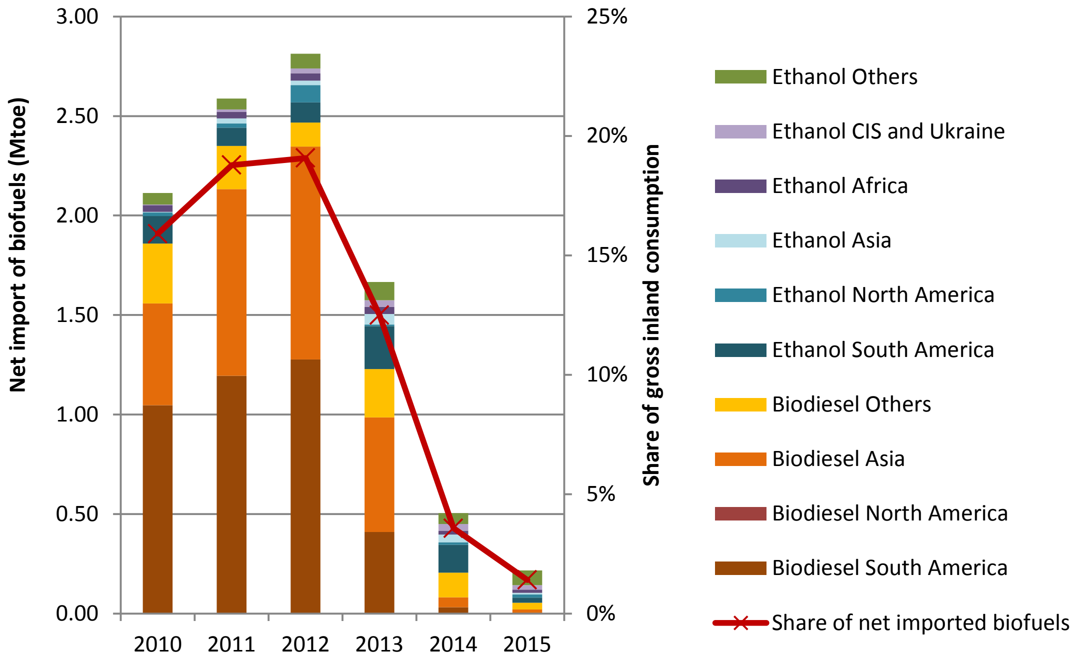


Figure 7 Developments of biofuel imports to the EU (Keller 2016, EUROSTAT 2017)

3. Method to determine future biomass potential availability and readiness

3.1. Biomass availability and readiness

To evaluate the availability and suitability of lignocellulosic feedstocks for advanced biofuel conversion processes (biochemical, thermochemical, etc.) we combine insights from feedstock potential estimates available from literature with a framework based on the Commercial Aviation Alternative Fuels Initiative's (CAAFI) Feedstock Readiness Level (FSRL) assessment. The main objective of this approach is to address one of the main limitations of feedstock potential estimates with respect to what could potentially be mobilized and the volumes of biomass readily available to produce advanced biofuels at commercial scale. This also enables a linkage with the Technology Readiness level (TRL) of advanced biofuel conversion technologies that are assessed in WP3.1 of the ADVANCEFUEL project.

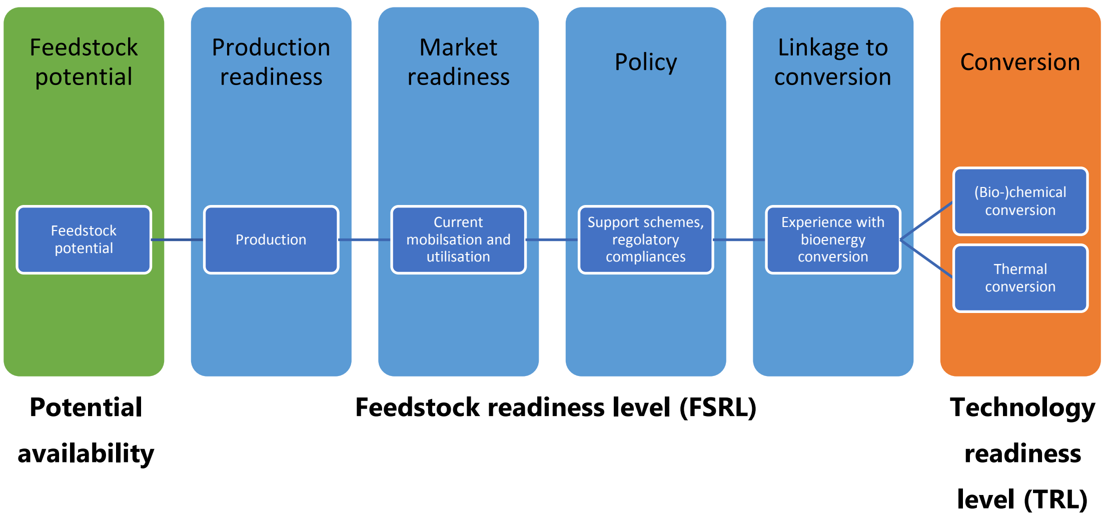


Figure 8 Method to determine lignocellulosic feedstock readiness and suitability

3.2. Biomass feedstock potential

Lignocellulosic biomass is the most abundant source of biomass available within multiple biomass categories from waste, agriculture and forests. Table 1 shows the feedstock categories covered in this project. Other biomass types that are not used to produce advanced biofuels such as food-based crops and residues as well as biomass used to produce biogas such as wet biomass streams (manure) and biogas from landfills as summarised in Table 2.

Table 1 Categorization of lignocellulosic biomass feedstock

Biogenic wastes	Agriculture	Forestry
Biomass from roadside	**Processing crop residues** • Husk (rice), coconut, coffee, bagasse, grape marcs and wine lees, nut shells	**Processing residues** • wood chips, sawdust, trimming, cut-offs, odds & ends, liquor (black and brown), fibre sludge
Organic waste from industry • e.g. bulk transport packaging, recovered post-consumer wood residues (construction and demolition debris) (excluding wood which goes to non-energy uses), molasses	**Harvesting crop residues** • Corn stover, straw (wheat, rice, cassava), empty palm fruit bunches	**Low-value woods** • Low-quality stems and stumps which have no current market
Biomass from landscape management • leaf fall and grass clippings	**Lignocellulosic fractions of agroforestry systems** • Shrubs and trees (for productive, diverse, ecologically-sound and healthy land use)	**Primary forest residues** • thinning, clearing, logging from conventional harvest operations
Biomass fraction of mixed municipal solid waste (excluding separated household waste subject to recycling)	**Grassy Energy crops** • (such as ryegrass, switchgrass, miscanthus, giant cane and cover crops before and after main crops), **Woody energy crops** • such as short rotation coppice (SRC), willow, short rotation poplar (SRP))	**Industrial round wood and pulpwood**

Table 2 Categorization of food-based biomass feedstock excluded from advanced biofuel production

Biogenic wastes	Agriculture
Animal and mixed food waste • Such as used cooking oil, slaughterhouse waste and animal fats	**Processing crop residues** • Potato peels, sugar beet molasses
Organic waste from agriculture • Manure	**Starch and sugar crops** • Starch crops such as maize, wheat • Sugar crops (free sugars) such as sugar beet, sugar cane
Other wastes • Sludge • Landfill biogas	**Oil crops** • Domestic crops such as rapeseed, sunflower, • Imported oil (crops) such as soy, palm

To determine the potential of biomass available for energy, one should first estimate what the maximum production under bio-physical limits including solar radiation, soil type, temperature, respiration and best management practices. This theoretical potential serves as a basis to determine the potential under current technical constraints such as available harvesting techniques, infrastructure and other (competing) land uses to determine the technical potential. The technical potential generally assumes a food/feed/fibre first principle and exclude deforestation and land use change of other ecological reserves. Additional assumptions and constraints with respect to supply cost, and socio-political framework conditions further determine the type of supply potential and its specificity to predetermined framework conditions (Textbox I: Type of biomass potential).

Generally, three different approaches are used to determine biomass potentials (Vis & van den Berg, 2010):

- Resource focused, taking into account technical and environmental constraints and competing uses (food/feed/fibre) to determine the potential;
- Demand-driven, taking into account the competitiveness of bioenergy with fossil energy systems and other renewable energy sources (RES) such as wind and PV;
- Integrated, modelling interactions/feedback between all sectors of the bioeconomy and other economic activities under socio-economic development pathways using integrated assessment models (AIMs).

Cost supply methods that combine biomass implementation potentials with cost of production and mobilisation (feedstock supply to end users) in cost-supply curve are part of demand-driven approaches. Energy system models, such as RESOLVE used in the ADVANCEFUEL project, use biomass cost-supply scenarios as an input to the model. The most up-to-date spatial explicit method to determine the cost and supply of lignocellulosic biomass in Biomass Policies (all biomass sources) and S2Biom for lignocellulosic biomass. S2Biom builds on Biomass Policies, but includes more up-to-date supply scenarios. Both Biomass Policies and S2Biom potentials are not exactly in line with the definitions of BEE (Textbox I).

The technical feasible potential covers all biomass that is technically feasible to be produced for all end uses (food, feed, materials, energy). The amount of biomass that needs to be left behind for soil conservation, biodiversity, and erosion control (T1) and the amount that is used in competitive uses (food, animal feed, traditional materials) (T2) are deducted to calculate the available potential for energy purposes (Elbersen et al. 2015):

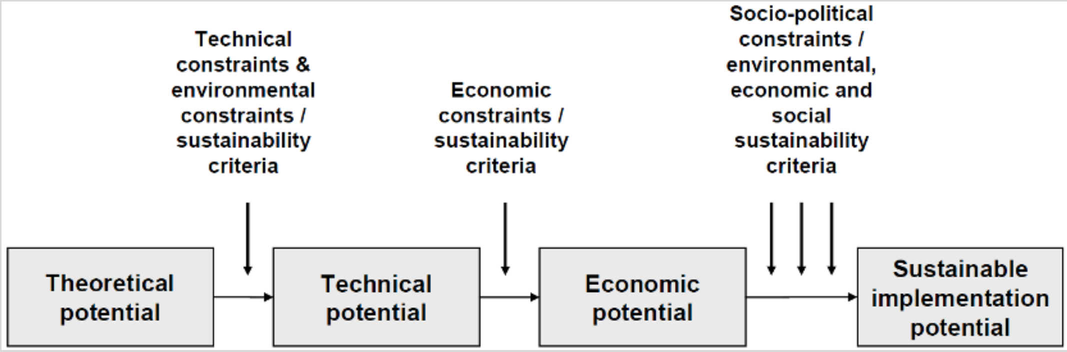
Available potential = Technical feasible potential – T1 –T2

In S2Biom includes a Technical potential, Base potential and multiple User Defined (UD) potentials (Dees, Hohl, et al. 2017):

- The **Technical** potential assumes a minimum of technical constraints and thus represents a what could be available for energy without sustainability constraints;
- The **Base** potential is a sustainable technical potential that includes current policies and agreed sustainability standards such as the common agricultural Policy (CAP) and the sustainability criteria in the RED;

- **User Defined (UD)** potentials include additional constraints that help users to identify the impact of specific (more strict) sustainability constraints.
- The **High** potential scenario in S2Biom applies mainly to forest biomass and is roughly consistent with the Biosustain Resource and JRC-EU-TIMES High scenario.

Box I: Type of biomass potentials (adapted from Torén et al. 2011)

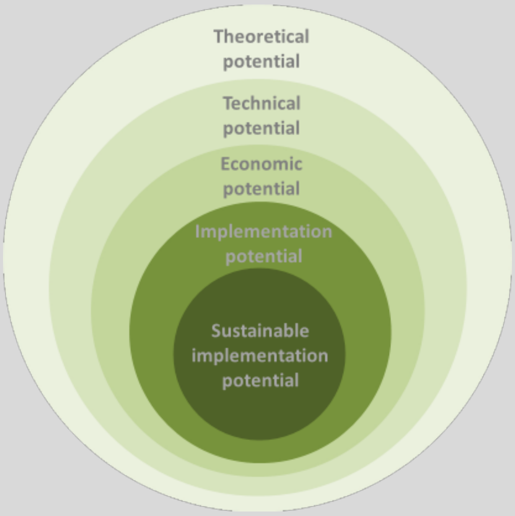


Theoretical potential: Maximum amount of biomass theoretically available for bioenergy production with fundamental bio-physical limits.

Technical potential: Amount of biomass available under techno-structural conditions. It also takes into account spatial confinements due to other land uses.

Economic potential: Share of biomass which meets economic profitability criteria within a given frame work.

(Sustainable) Implementation potential: Fraction of economic potential that can be implemented within a certain time frame and under socio-political framework conditions (with Sustainable criteria framework for biomass resource assessment).



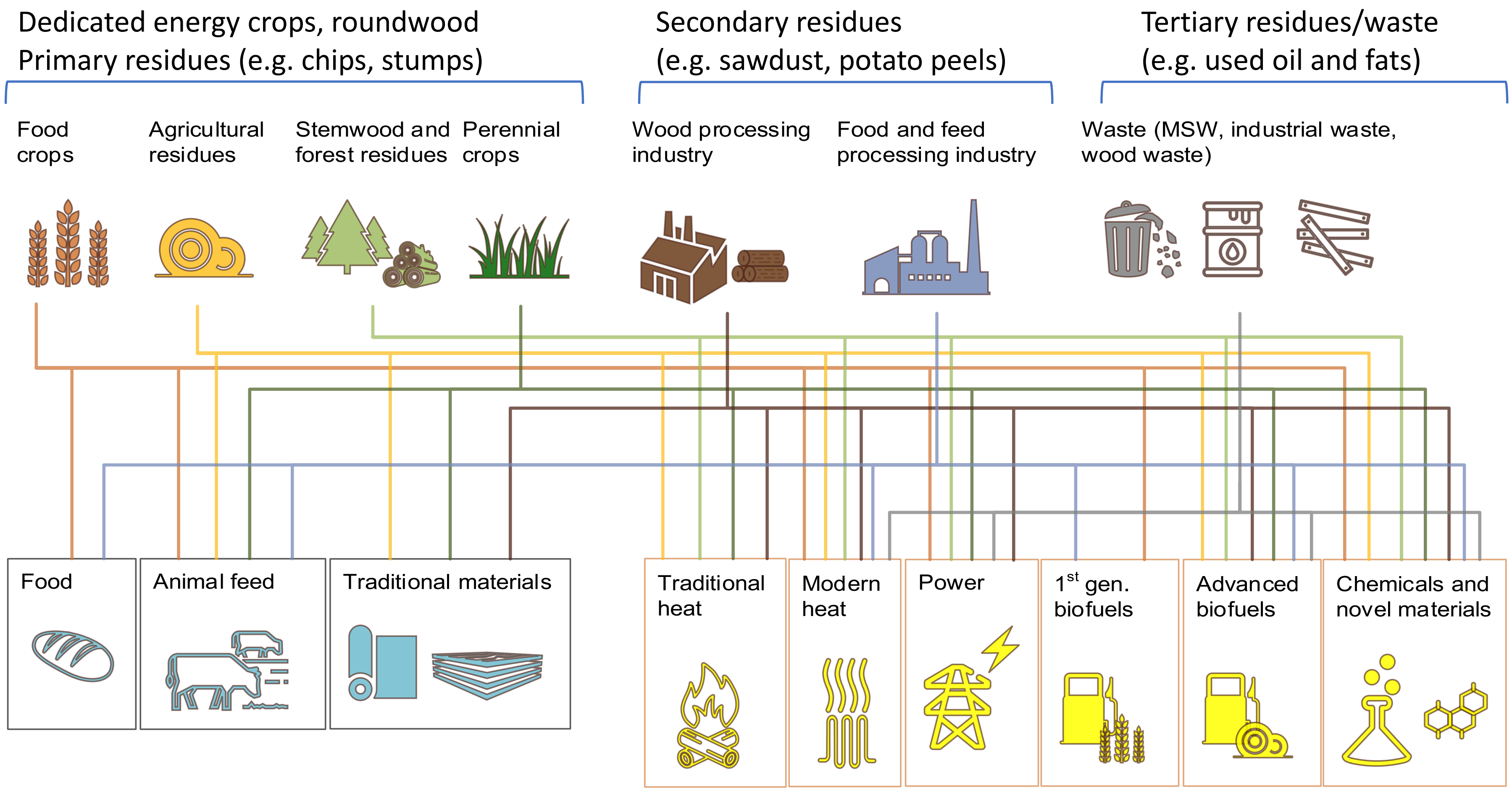


Figure 9 Biomass for energy purposes (bioenergy) in the larger bioeconomy

3.3. Feedstock readiness

1.1.1 Feedstock suitability and readiness levels

The Technology Readiness Level framework, developed by NASA (2010), is a powerful assessment tool to provide insight in technology maturity status over 9 levels. The lowest level 1 indicates that basic principles are observed and reported, but not tested whereas its highest level 9 indicates actual proven success through normal operation and commercially available to consumers. It is estimated to take between 3 to 5 years to progress one TRL level (Mawhood *et al.*, 2016).

Although some advanced biofuel conversion technologies are on the verge of commercialisation, conversion systems are at very different levels of technology maturity. A recent assessment by IRENA (2016) puts hydrothermal upgrading at TRL 4 (demonstrated at small scale in a lab environment) and ethanol from agriculture residues up to TRL level 8 (First of a kind commercial system). In contrast however, ethanol from woody biomass such as forest residues is demonstrated, but only at pre-commercial scale (TRL 7). So production systems (i.e. feedstock – conversion combinations) with similar conversion technologies can be at different levels of technology maturity. Although such an approach works properly for feedstocks that are already used at large scale, such as straw or forest residues, it becomes limited when production systems with less developed feedstocks are assessed. To produce biofuels from biomass at commercial scale requires a well-developed infrastructure.

To complement the TRL assessment tool, the Feedstock Readiness Level (FSRL) has been developed. It was developed for CAAFI's[2] stakeholders that wanted to assess the feedstock status separately from its conversion process for aviation biofuels. Nevertheless, it is also applicable to other bioenergy sectors.

Similar to the TRL scale, the FSRL has 9 levels towards full commercialisation that are assessed over four components relevant in commercial feedstock development:

1. Production readiness (biological factors / technical potential)
2. Market readiness (biomass mobilization and utilization)
3. Regulatory compliances (e.g. sustainability criteria, EU timber regulation, CAP)
4. Linkage to conversion process (match feedstock to conversion technologies)

Each component has different tollgates. An Excel based evaluation form is available online[3].

1.1.2 Feedstock suitability

Lignocellulosic biomass covers a wide range of biomass feedstock sources that are heterogeneous in physical and chemical characteristics including moisture content, size, contaminations, cellulose, hemicellulose and lignin content and minerals (e.g. chlorine). The EU FP7 pro-

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[2] CAAFI: Commercial Aviation Alternative Fuels Initiative®

[3] https://data.nal.usda.gov/dataset/feedstock-readiness-level-instructions-checklist-and-report-template-evaluations

ject S2Biom has developed a detailed database of biomass characteristics. The database includes minimal biomass quality requirements for a broad portfolio of thermal, (bio-)chemical conversion technologies. The database and classifications are used to determine the suitability of biomass for conversion. Ranges per feedstock category are depicted in Figure 10. Note that some conversion technologies are more flexible than others and based on non-comprehensive criteria. Other important characteristics: energy/bulk density, particle size, moisture content, contaminations.

Feedstock category	Range	Thermochemical conversion					(Bio)chemical conversion			
		Ash content	Ash melting temperature	Nitrogen content	Chlorine content	Total score	Ash content	Lignin content	Carbohydrate content	Total score
Stemwood	Min	4	4	3	3	3.5	4	3	4	3.7
	Max	4	4	4	4	4.0	4	3	4	3.7
Primary residues from forests	Min	2	3	3	4	3.0	2	3	4	3.0
	Max	2	3	4	4	3.3	2	3	4	3.0
Lignocellulosic biomass crops	Min	2	1	2	1	1.5	3	4	4	3.7
	Max	3	4	3	3	3.3	3	4	4	3.7
Agricultural residues	Min	1	2	2	1	1.5	3	3	4	3.3
	Max	3	4	3	3	3.3	3	3	4	3.3
Grassland	Max	2	2	2	1	1.8	2	3	2	2.3
Secondary residues from wood industries	Min	1	1	3	1	1.5	4	3	4	3.7
	Max	4	4	4	3	3.8	4	3	4	3.7
Secondary residues of industry utilising agricultural products	Min	1	1	2	1	1.3	3	3	3	3.0
	Max	3	4	3	2	3.0	3	3	3	3.0
Municipal waste	Min	1	2	2	1	1.5	1	3	1	1.7
	Max	1	3	2	2	2.0	1	3	1	1.7
Waste from wood	Min	2	3	2	2	2.3	3	2	3	2.7
	Max	3	3	3	3	3.0	3	2	3	2.7

Figure 10 Lignocellulosic biomass feedstock suitability for conversion assessed by selected indicators in S2Biom (Lammens *et al.*, 2016)*. Score: 4 = highest quality, 1 = lowest quality. Only ranges are shown, detailed information is available within the Bio2Match tool.*

4. Biomass availability in the European Union

4.1. Biomass availability for bioenergy in the EU

Numerous biomass resource assessments have been published that estimate available biomass for bioenergy purposes in the EU. One of the most elaborate reviews of biomass resource assessments in the EU was the EU FP7 Biomass Energy Europe (BEE) project (Torén *et al.*, 2011). The BEE project aimed to provide reliable insight in biomass potentials for Europe and its neighbouring countries and to harmonise the methods used to determine these potentials. We updated the review of BEE with publications to 2017 and compared the ranges to the current supply potentials applied in the RESolve-Biomass model. The ranges in Figure 11 represent the different estimates of the selected studies and within studies for various supply scenarios. Details are available in the Appendix (Table A7 - Table A8).

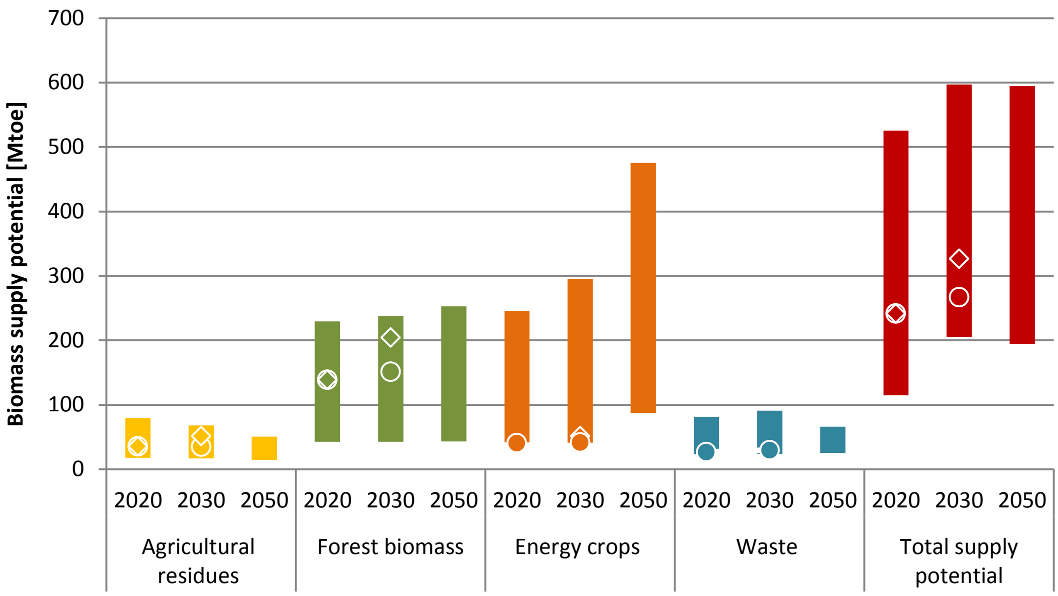

Figure 11 EU biomass potential available for bioenergy by main feedstock category from available EU biomass resource assessments (2006 - 2017) and currently applied biomass supply scenarios in the RESolve-Biomass modelling framework based on Biomass Policies Baseline (circle markers) and B2 scenarios (diamond markers).

The highest potentials of individual studies are dominated by perennial energy crops and optimistic yield developments. De Wit and Faaij (2010), estimated that 597 Mtoe could be supplied within the EU27[4]. The maximum supply in 2050 (595 Mtoe by), Ericsson and Nilsson (2006) (Figure 12) is dominated by energy crops (80%). In the more recent High scenario of JRC-EU-TIMES (Ruiz *et al.*, 2015), forest biomass (stemwood and forest residues such as log-

[4] Harmonised to EU27 region in the BEE project.

ging residues, sawdust and wood waste) contributes largest to the total potential, but could also be significantly lower if other forest mobilisation assumptions are made (Low and Medium scenarios in Figure 12. In a Low scenario, current inland consumption of forest biomass (95 Mtoe)[5] is above the estimated forest biomass potentials (43 Mtoe).

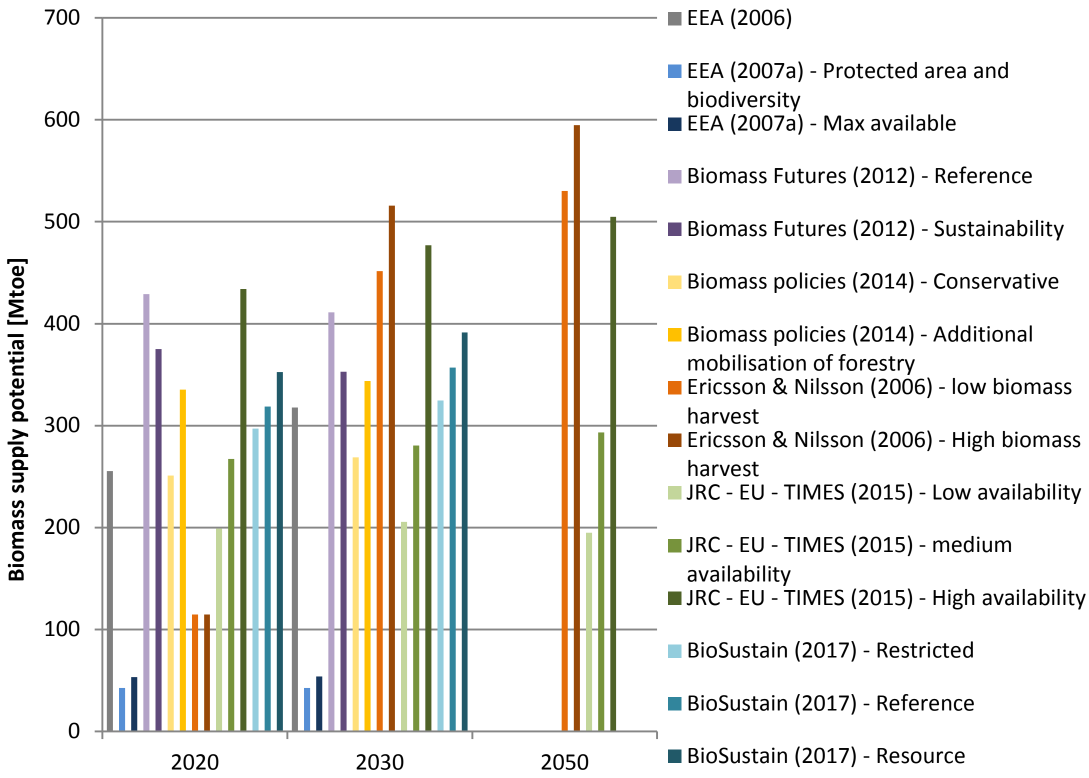

Figure 12 EU total biomass potentials for bioenergy per study and scenario (2020 – 2050)

4.2. Forest biomass

1.1.3 Production and markets

The total growing stock of EU forests is estimated at 26.5 billion m^3 solid wood equivalent (swe) with estimated annual production of 452 million m^3 (Mm^3) roundwood in 2016. Sweden has the largest removals of roundwood (72 Mm^3), but also Finland, Germany and France are large producers of roundwood as shown in Figure 14. About 22% of wood removals from forests in the EU are used as fuelwood, 43% is used as sawlogs and veneer logs, 33% is used as pulpwood and 2% is used in other industrial sectors.

[5] Assuming wood and other solid biofuels are entirely supplied from forests. Other solid biomass such as straw and straw pellets are not well reported in statistics.

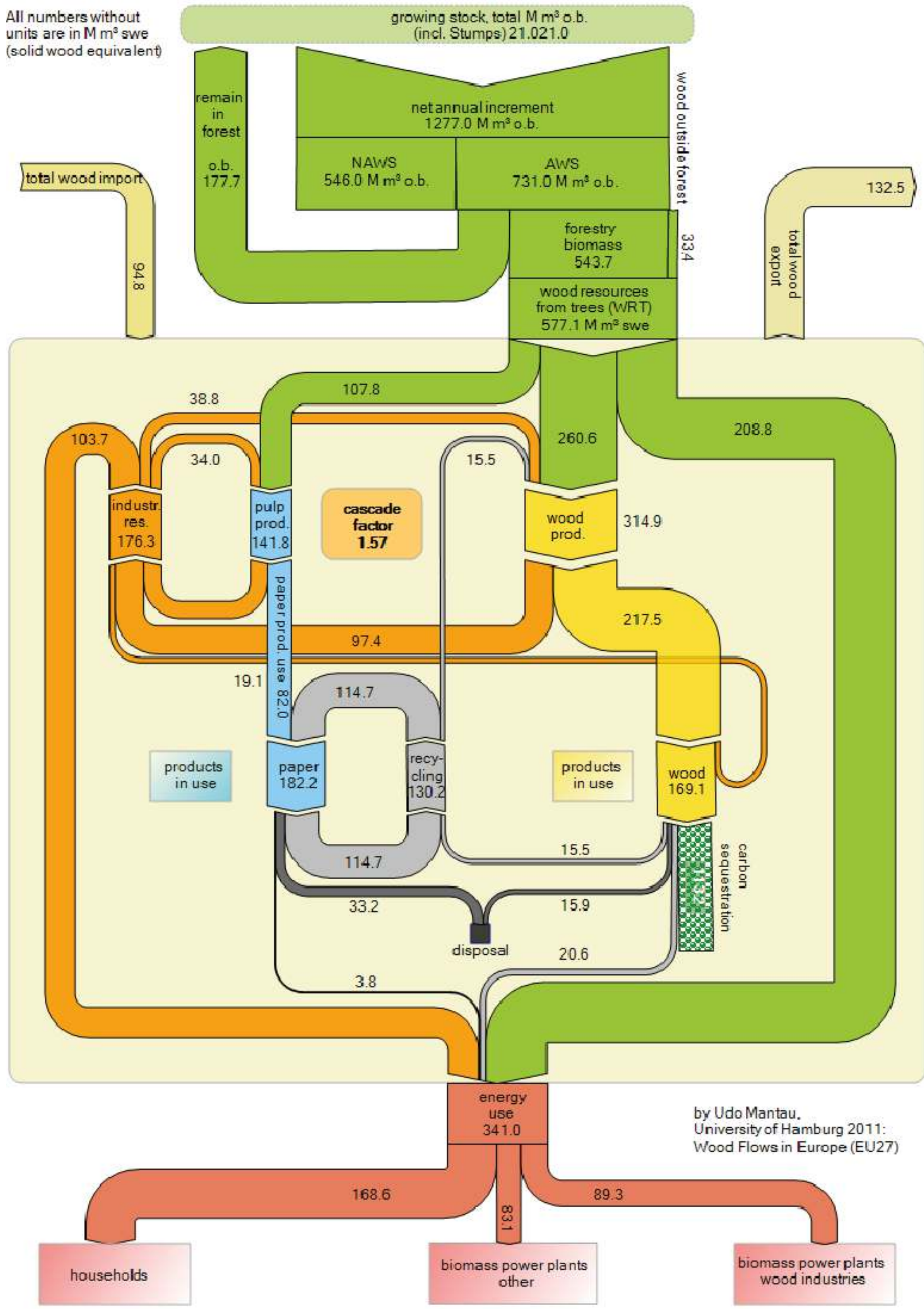

Figure 13 Wood use in the EU27 in 2010 (Mantau, 2014)

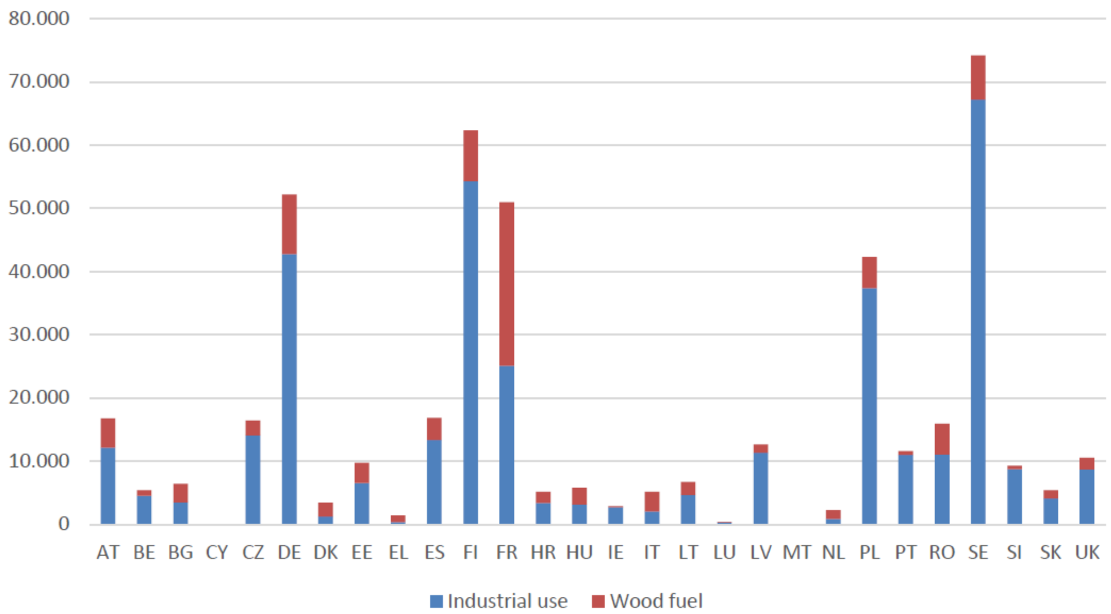

Figure 14 Roundwood removals in the EU28 according to end use in 2016 (1000 m^3) (AEBIOM, 2017)

1.1.4 Supply potential

The supply of biomass from forests and other woody biomass covers stemwood, primary forest residues, other primary woody biomass such as landscape care wood, secondary forest residues and recycled wood. The use of forest biomass for material purposes and energy purposes are interlinked. For example, by-products of saw mills can be used to produce energy but are also used to produce wood pellets or used in panel industries. A wood resource balance approach, such as developed by Mantau et al. (2010) can be used to assess current and future wood uses and its potential availability for bioenergy. Table 3 shows wood sources (left) and use sectors (right). The current (2010) wood balance is shown in **Error! Reference source not found.**.

woody biomass			
resources		**uses**	
Primary forest products and residues	stemwood, coniferous	saw mill industry	**wood industry (material uses)**
	stemwood, con-coniferous	veneer and plywood industry	
	forest residues	pulp industry	
	bark	panel industry	
Other primary woody biomass	landscape care wood	other traditional uses	
	short rotation plant.	other innovative uses	
Secondary forest (industrial) residues	saw mill by-products	biomass power plants	**energy end user**
	other industrial resid.		
	black liquor	private households	
Recycled wood	post-consumer wood	liquid biofuels	
solid wood fuels	pellets and other	pellets and other	**solid wood fuels**
total			**total**

Table 3 Wood resource balance with resources on the left and uses on the right (Mantau 2010)

The current availability and future development of forest sectors in most EU forest resource assessments is modelled with the EFISCEN (European Forest Information SCENario) model (Verkerk et al. 2011). Starting point are national forest inventory data for forest available for wood supply (FAWS), growing stock and net annual increment (NAI). Future developments are modelled with the European Forest Outlook Scenarios (EFSOS II) (Verkerk, H., Schelhaas 2013). The Low, Medium and High mobilisation scenarios are used in BioSustain (Restricted, Reference and Resource) and JRC-EU-TIMES (Low, Medium, High) scenarios as depicted in Figure 15.

The EFISCEN model is also used in S2Biom, but the model runs have been adjusted to the S2Biom Technical, Base and User Defined scenarios (UD1 – UD8)[6] as explained in Dees et al. (2016). Wood production dedicated for material use is only deducted and considered a constraint in User defined (UD) potentials 5 and 7. The Base supply scenario of S2Biom shown in Figure 15 is therefore not directly comparable to the other wood supply potentials that exclude material use of forest biomass for energy purposes (materials first principle). If competing uses are taken into account by subtracting roundwood for material use from the Base potential (D05 potential), the supply potential of roundwood is reduced with 50% (see UD5 in Figure 15).

[6] Scenarios UD2 – UD8 and HIGH potential are excluded from this review.

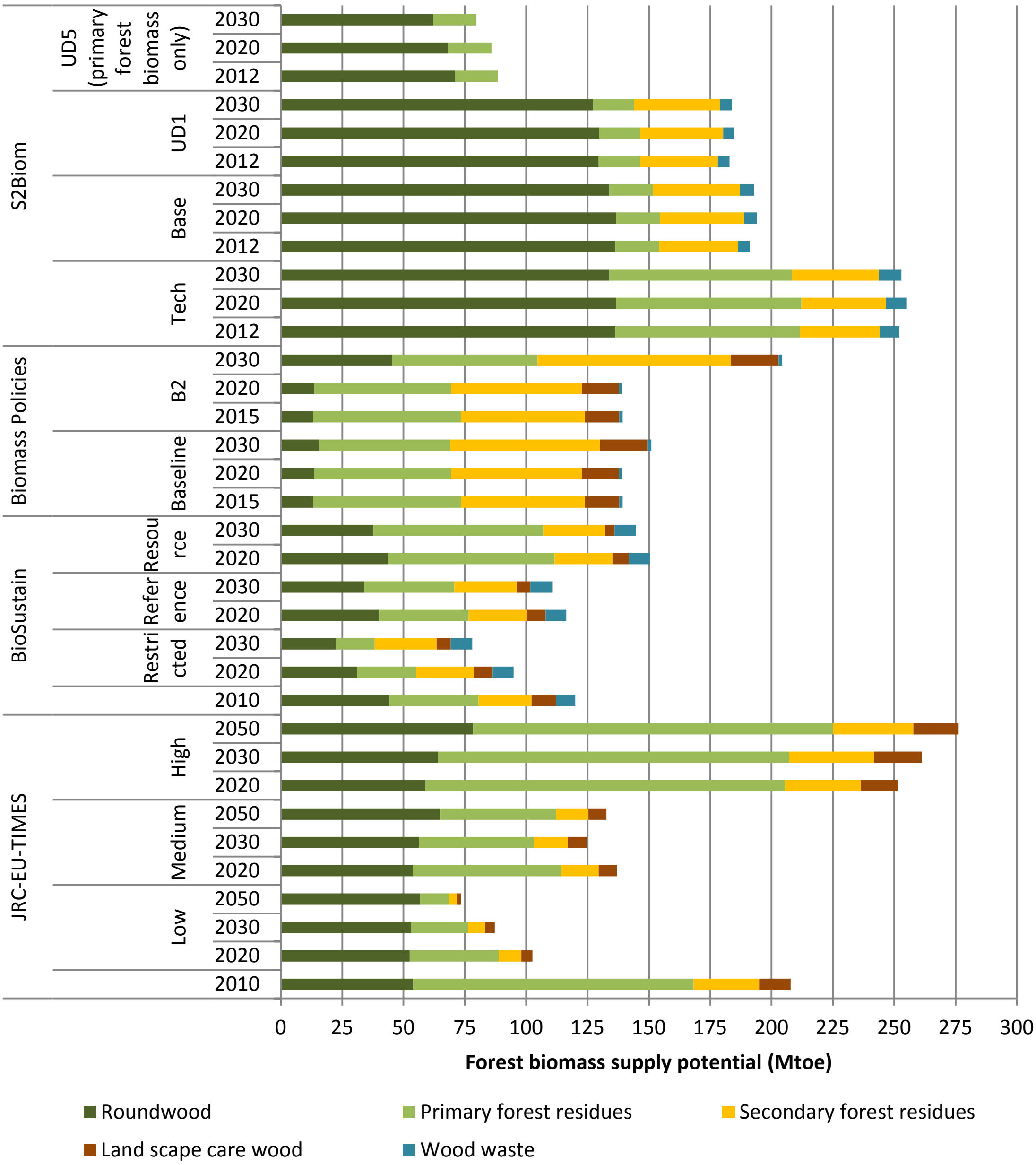

Figure 15 Comparison of recent forest resource assessments and supply scenarios

4.3. Agriculture residues

1.1.5 Production and markets

The use of agriculture residues from bioenergy today include mainly straw (bales or bundles) or agropellets produced from straw and other agricultural residues such as sunflower husks. The main markets are heat in domestic boilers and district heating, CHP and electricity plants with the largest consumption in Denmark and smaller markets in Hungary, Spain and the UK.

The use of agricultural residues in bioenergy are however not reported in EU statistics and therefore difficult to quantify (AEBIOM, 2017). Total straw consumption in Denmark for bioenergy increased from 292 ktoe (0.79 Mt) in 2000 to 469 ktoe (1.27 Mt) in 2016 (DEA, 2016), about 9% of gross inland consumption of bioenergy. The largest growth in solid biomass consumption in Denmark in recent years was however in imported wood pellets that increased from 52 ktoe in 2000 (0.13 Mt) to 987 ktoe in 2016 (2.4 Mt). Denmark does not import agropellets according to DEA. The production of agropellets is focused in Ukraine (934 kt), Poland (450 kt) and Czech Republic (200 kt) (Figure 18) with its main market in Poland for industrial uses (electricity, CHP). The development of the European agropellet market has stagnated in the past years due to the crash in green certificate prices in Poland. Furthermore, emission restrictions to boilers limited market growth in other European countries such as Austria (AEBIOM, 2017). There are several advanced biofuel production plants that use agricultural residues. The current use of agricultural residues to produce advanced biofuels is estimated at 240 kt (AEBIOM, 2017).

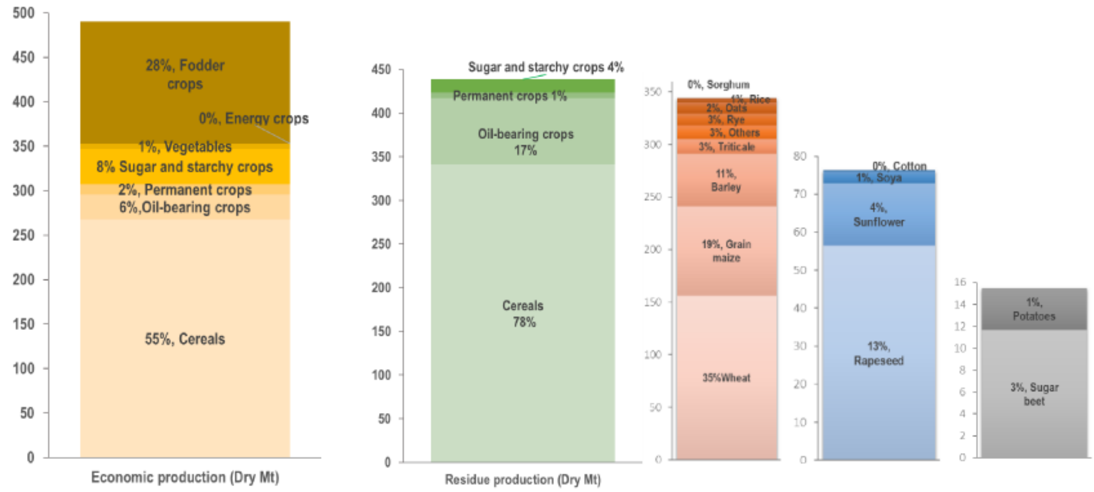

Figure 16 Average (2011 – 2015) economic production Y and residue production R (theoretical potential of agricultural residues) in the EU (García-Condado *et al.*, 2017)

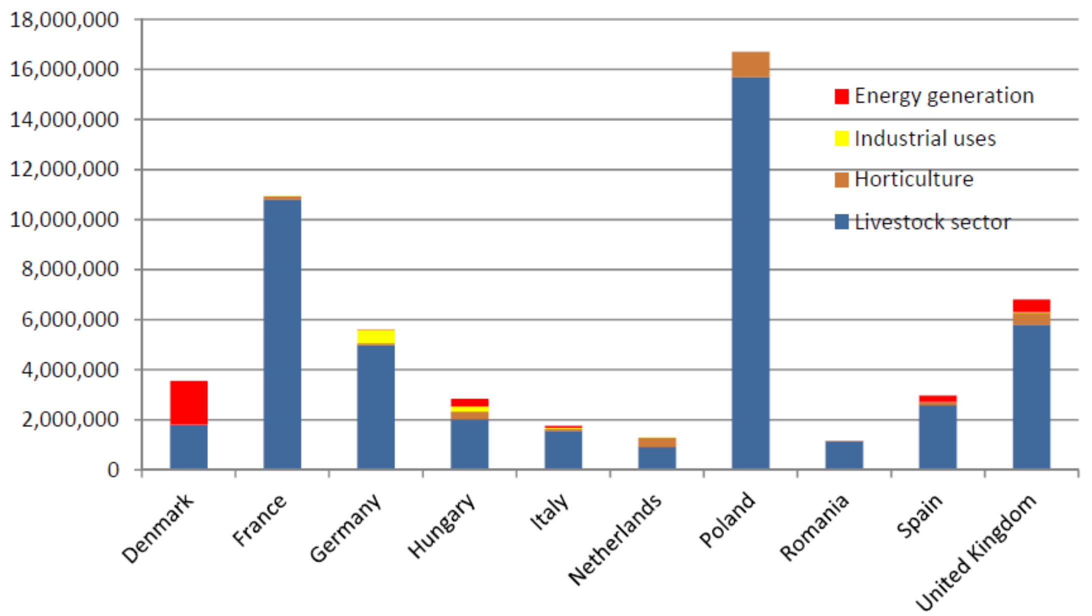

Figure 17 Estimated straw consumption (in tonnes as received) in ten selected member states (Spöttle *et al.*, 2013)

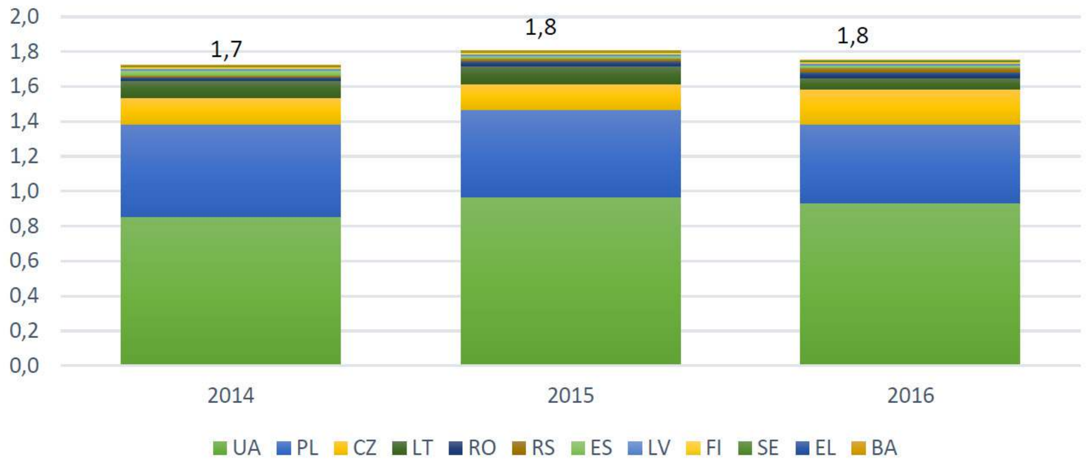

Figure 18 Pellet production from agricultural residues (Mt) in Europe between 2014 and 2016 (AEBIOM, 2017)

1.1.6 Supply potential

Agricultural residues cover a wide range of biomass sources that can be categorized in three classes (Vis & van den Berg, 2010):

- Primary agricultural residues that remain in the field after harvest (straw and stubbles);
- Secondary residues that come available form food and feed processing industries (for example sunflower husks);
- Manure (for example pig manure).

The theoretical potential of primary agricultural residue production (AgrTheo) of crop *i* can be calculated as follows (Daioglou *et al.*, 2016):

$$AgrTheo_i = RPR_i * CropArea_i * CropYield_i$$

The residue to crop ratio (RPR) is the ratio of residues R over economic crop yields Y (Figure 16). JRC estimated current residue production in the EU is estimated at 439 Mt/y (dry matter) or about 178 Mtoe[7]. The current production of residues is dominated by cereal crops (wheat, maize, barley) and oil seeds (rapeseed) that make up 80% of total residue production (Figure 16). The estimated residue production remains highly uncertain due to large variations in RPR ratios and straw to stubble ratios due to variations between crop varieties and management factors (García-Condado *et al.*, 2017). The technical potential (*PAgr*) of agricultural residues is calculated from the theoretical potential AgrTheo as follows (Vis & van den Berg, 2010):

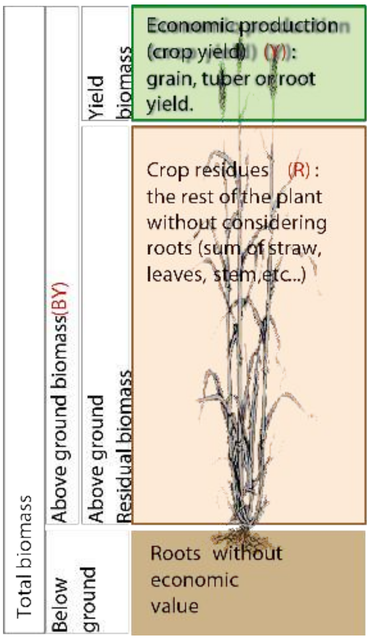

Figure 19 Biomass and crop residue production (García-Condado *et al.*, 2017)

$$PAgr_i = AgrTheo_i * EX_i * UF_i$$

Where, EX_i is the maximum sustainable removal rate and UF_i is the use factor of the residues of crop *i* for non-energy purposes (food/feed/fibre first principle). Part of crop residues need to be left on the field as they serve several functions in maintaining soil quality. These include the avoidance of soil organic content (SOC) depletion, provision of organic nutrients and water retention. The maximum sustainable extraction rate is crop, location and management specific (Kluts *et al.*, 2017). However, only few studies use site-specific sustainable removal rates as. Sustainable removal rates of cereals are estimated at 40% for cereals (Scarlat *et al.*, 2010; Elbersen *et al.*, 2012a, 2015a; Monforti *et al.*, 2013) or country specific between 33-50% (Spöttle *et al.*, 2013) or 0-100% (Monforti *et al.*, 2015).

Ranges of estimated potential of agricultural residues in literature are depicted in Figure 20. One of the most recent and most comprehensive supply potential of agricultural residues is provided by S2Biom for the years 2012, 2020 and 2030 at NUTS3 level (S2Biom, 2016). The three supply scenarios depicted in Figure 20 show the impact of the sustainable removal rate and competing uses to the supply potential for bioenergy:

[7] Assuming a net calorific value of 17.0 MJ/kg (dry matter) (BioGrace II)

- S2Biom_Tech: assumes 100% removal rate, no competing uses of cereal straw for animal bedding and feed;
- S2Biom_Base: excludes biomass that is required to main SOC levels;
- S2Biom_UD: demand of cereal straw for animal bedding and feed is excluded from the supply potential.

The decline of primary agricultural residues over time in JRC-EU-TIMES and S2Biom are mainly caused by declines in straw potentials from the production of cereals (Dees *et al.*, 2017).

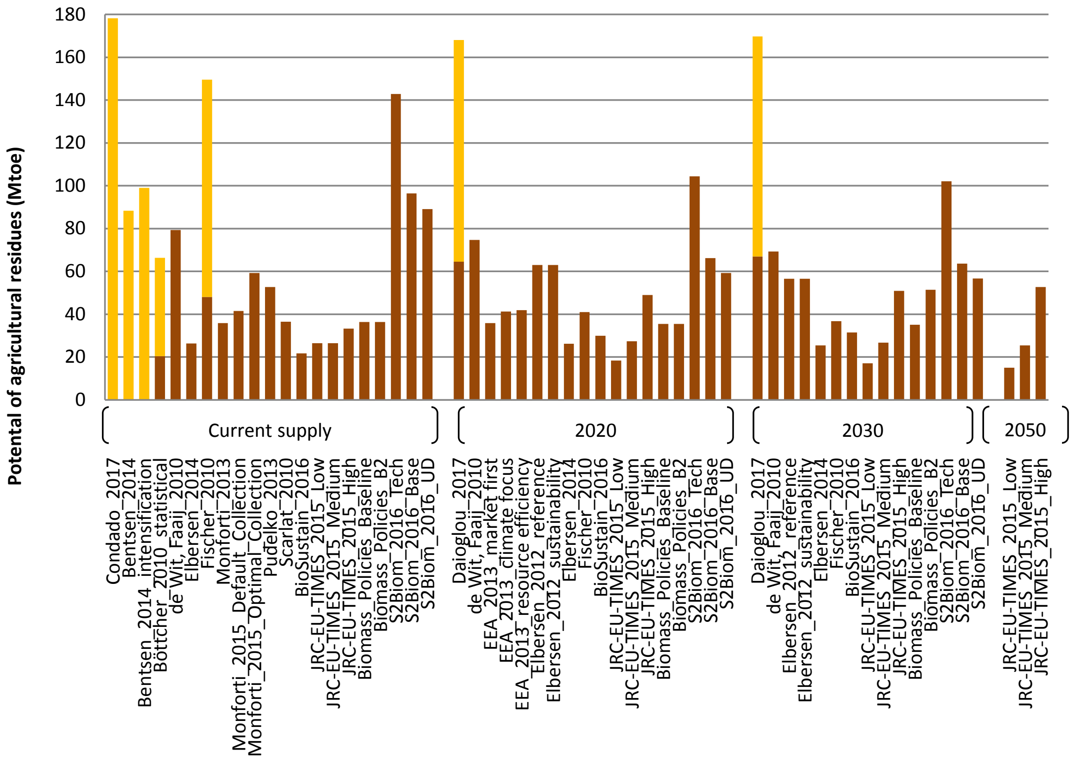

Figure 20 Biomass potential available for bioenergy form agricultural residues. Data from Kluts et al. (2017), *but updated with recent studies* (Elbersen *et al.*, 2015a; Ruiz *et al.*, 2015; S2Biom, 2016).

4.4. Energy crops

1.1.7 Land availability in the EU

In determining the potential of energy crops, the food/feed/fibre first principle does not allow for direct competition with food and feed crops. Energy crops can therefore only grow on surplus agricultural land and land that is not suitable for food/feed production. The supply potential of energy crops (P) can be calculated using the following equation (Vis *et al.*, 2010):

$$P = \sum A_i * Y_i$$

Where P is the potential of energy crop *i* (in t), A is the surplus agricultural land that is suitable for the cultivation of crop *i* (in ha) and Y is the yield of energy crop *i* (in t/ha). Both the yield and area are variable over time and scenario.

The utilised agricultural area (UUA) is the area for arable land, permanent grassland and permanent crops. Currently, UUA covers 45% of land in the EU. Between 2010 and 2017, the UUA in the EU28 decreased from 179.5 Mha to 176.2 Mha and this declining trend is projected to continue to 2030 to 172.1 Mha by 2030 as shown in Figure 21. Main drivers for the declining UUA are permanent grasslands, permanent crops and fallow land (EC, 2017).

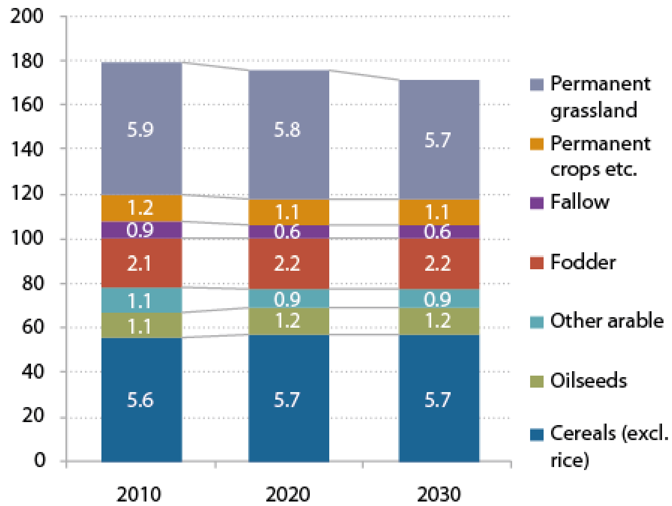

Figure 21 Agricultural land use developments in the EU (Mha) (EC, 2017)

Total land available for bioenergy crop cultivation estimated in publications ranges between 7 to 35 Mha in 2020, 7 to 39 Mha in 2030 and 15 to 34 Mha in 2050 (Figure 22). In addition, 15 to 19 Mha pasture land could be released according to de Wit et al. (2010) and Fischer et al. (2010). Most studies published before 2012 use a statistical or geographic approach to determine land availability for energy crops by extrapolating historic yield trends in Europe (de Wit & Faaij, 2010; Fischer *et al.*, 2010; Krasuska *et al.*, 2010). More recent studies included in Figure 22 (EEA, 2013; Elbersen *et al.*, 2013; Ruiz *et al.*, 2015) use the partial equilibrium model of the agricultural sector CAPRI and AgLink to estimate yield developments. Land availability in BioSustain (PWC, 2017) are derived from the Biomass Policies project (Elbersen, 2015).
The JRC-EU-TIMES study (Ruiz *et al.*, 2015) is used to explain the procedure. First the development of the total UUA area, including all land use categories, similar to those depicted in Figure 21 and include land use for bioenergy crop cultivation (silage maize, biofuel crops) that are calculated with the energy system model PRIMES.
Released land agricultural lands, fallow lands and abandoned lands are assumed to be available for the cultivation of perennial crops (SRC and grassy crops). Abandoned crop land before 2004 are derived from ETC-SIA (2013). Future land releases are calculated from the projected developments in UUA from CAPRI. It depends on scenario constraints whether this land can

be used to cultivate perennial crops. Maps of high nature value (HNV) farmland[8] are used to exclude bioenergy crop cultivation in restrictive sustainability scenarios. Most studies exclude the cultivation of food-based crops on these lands in all scenarios. More restrictive sustainability scenarios (such as Elbersen_2013_sustainability, JRC-EU-TIMES_Low) exclude also the cultivation of perennial crops on these areas.

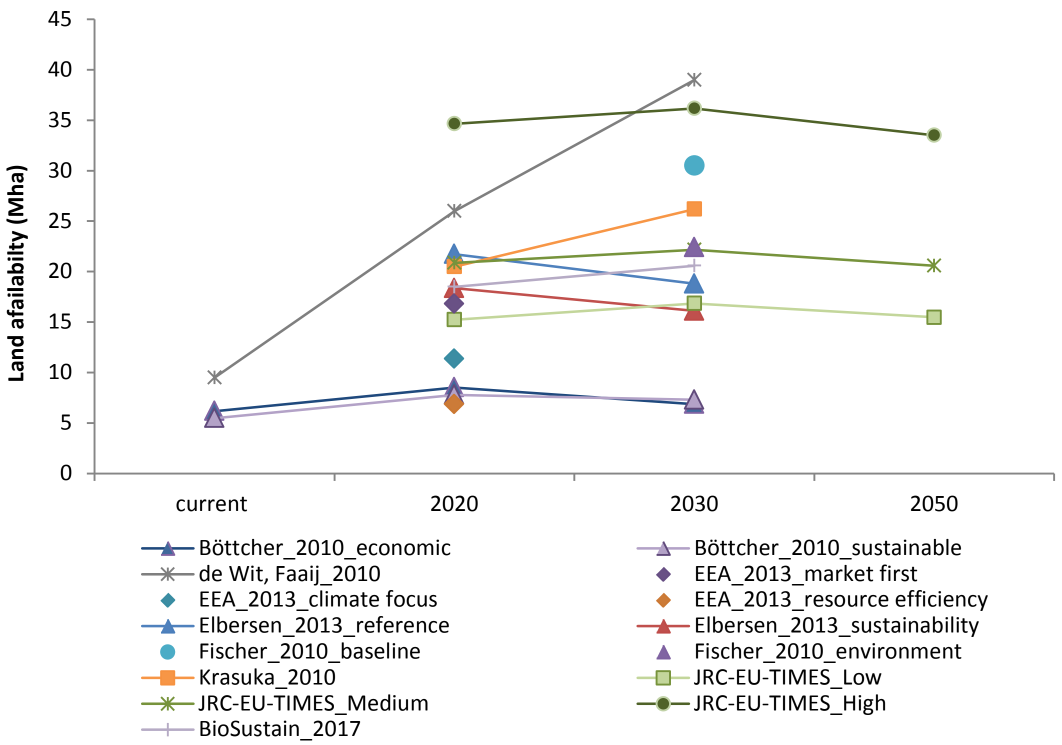

Figure 22 Land available for energy crop cultivation in the EU as estimated by studies reviewed by Kluts et al. (Kluts *et al.*, 2017) *updated with recent studies* (Ruiz *et al.*, 2015; PWC, 2017)

Figure 23 summarises the estimated supply potentials of food-based crops and perennial crops in literature. Food-based crops include oil crops (rapeseed, sunflower), starch crops (maize, wheat) and sugar crops (mainly sugar beet). Perennial crops include woody crops (willow, poplar, eucalyptus) and grassy crops (miscanthus, switchgrass).

8 See for example https://www.eea.europa.eu/data-and-maps/data/high-nature-value-farmland

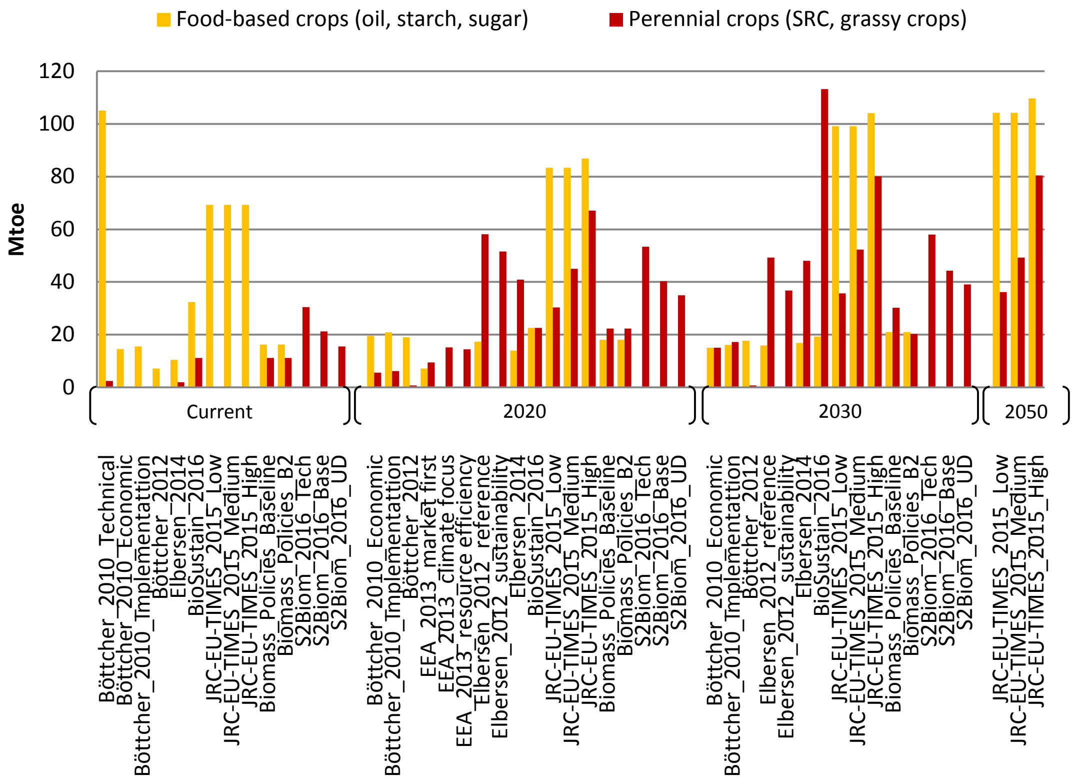

Figure 23 Primary biomass potential for energy purposes from energy crops (food-based crops and perennial crops) in the EU as estimated by studies reviewed by Kluts et al. (Kluts *et al.*, 2017) *updated with recent studies* (Ruiz *et al.*, 2015; PWC, 2017)

4.5. Biomass from marginal lands

The production of biomass for biofuels can lead to competition with food, fodder and fibre for the use of agricultural land. In addition, the pressure on fertile land increases with time due to population and income per capita growth. As many industrial goods are based on fossil oil, there is an increased effort in research to substitute conventional products with bio-based alternatives. The bioeconomy sector distinguishes two types of bio-based products: High and low value bio-based goods. The high value bio-based goods require less biomass and, hence, less land while generating high profits, compared to low value bio-energy production. As research advances and bio-based products become more common with time, the pressure on land use due to high value bio-based products will also increase. This additionally needed land for biomass production can lead to a shift of food production in other areas of the world. This leads to an indirect land use change (ILUC) from natural areas as forests or wetlands to agricultural land, causing negative effects as increased greenhouse gas emissions, loss of natural habitats, and negative effects on biodiversity. In order to avoid competition for land with food and fodder productions and, hence, to avoid ILUC, political and scientific efforts to promote biomass production for biofuel and industrial goods are now focusing on feedstock production potential on marginal land.

There are multiple definitions of marginal land in the literature. As summarized by SEEMLA (2017), all the definitions can be categorized into marginality due to (1) physical and production limitations or to (2) economical limitations. In the ADVANCEFUEL project the following definition of marginal land is adopted, which includes both categories of limitations:

"Marginal land is land on which cost-effective food and feed production is not possible under given site conditions and cultivation techniques." (Wicke *et al.*, 2011). It must be considered, however, that not all marginal land area is available for biomass production. Marginal lands can provide ecosystem services in the area of fauna and flora conservation, groundwater recharge, carbon sequestration, recreation, or hunting. Therefore the assessment of marginal land potential requires: 1) the quantification of marginal land and 2) the assessment of current uses and ecosystem services.

1.1.8 Quantification of marginal land and available marginal land for biomass production

Estimates of the availability of marginal land in Europe are scarce. Two H2020 projects in progress, SEEMLA and MAGIC, aim at filling in this gap. Both projects intend to promote sustainable exploitation of biomass from marginal lands in Europe. While SEEMLA focuses on biomass production for biofuel, MAGIC considers industrial crops in general as valuable resources for high added value products and bioenergy. In SEEMLA the identification of marginal land is based on the Muencheberg Soil Quality Rating (SQR) index. This index includes soil and climate specific production limits. Preliminary results estimate that 45% of Europe (220 Mha) is covered by marginal lands (Galatsidas *et al.*, 2018). When considering nature conservation regulations and restrictions by other policies, SEEMLA estimates for marginal land that is available for biomass production sums up to 63 Mha. According to MAGIC, 29% of the agricultural land (69 Mha) is marginal in EU28 (Elbersen et al. 2018). The most common physical limitations are rooting (12%), adverse climate (11%), and excessive soil moisture (8%). Later in the project, the area of contaminated land that is not agricultural land will be assessed and added to the share of marginal land in Europe. The MAGIC project now analysis current land use on marginal land and has still no estimate regarding the share of marginal land that is available for biomass production. The marginal land estimation of 69 Mha by MAGIC equals, however, that one of Cai et al. (2011) for agricultural land with marginal productivity that was also based on soil and climate specific production limits. To estimate the land available for biomass production, Cai et al. (Cai *et al.*, 2011) assessed land productivity through a fuzzy logic modelling and improved the outputs by a learning approach using data on existing land use. This approach resulted in 33 Mha of marginal land in Europe that is available for biomass production. Adopting a moderate range for net energy gain of 60-140 GJ ha^{-1} for mixed second-generation biofuel crops, this leads to a potential of 2.0-4.6 x 10^9 GJ. Limitations associated with socio-economic considerations and ecosystem services might be partially included in the estimation done through the learning approach by Cai et al. (2011), but will be explicitly included in future classification steps in the MAGIC project.

Availability of marginal lands has a high spatial variation (Elbersen *et al.*, 2018). According to the marginal land estimated by MAGIC of 69 Mha, the share of marginal to total land in the EU28 is 15.7%. Two value chains for lignocellulosic biomass to bioethanol were found to be successful by the FORBIO project for much lower shares of marginal to total land of 2.7% (50 km radius) and 3.2% (70 km radius) in the Ukraine and Italy, respectively (Barsali, 2017; Mulè, 2017).

1.1.9 Availability of biomass from marginal lands

In ADVANCEFUEL deliverable 1.1 existing and planned biofuel plants in Europe are listed that use lignocellulosic feedstock. No information was found that indicates whether the feedstock for these biofuel plants is produced on marginal land or even if lignocellulosic feedstock from dedicated cropping from arable land is used as a feedstock for biofuel plants. There are, however, a few projects that cultivate dedicated crops on marginal land (Tab. 1). The cultivation area differs depending on the project scale and ranges from the plot scale of ≤50 hectares (SeemLa, ForBio, Magic) to the demonstration scale of a few thousand hectares (First2run, Dendromass4Europoe). Other projects funded by the Bio-Based Industries Joint Undertaking under the European Union's Horizon 2020, do not publish data regarding marginal land area which were taken under cultivation and the respective yields (Bioskoh, Grace). As these projects run on a demonstration scale their production area on marginal land is also expected to cover a few thousand hectares each. These are flag-ship projects pursuing different goals. Two projects aim to demonstrate the feasibility and profitability of growing lignocellulosic crops on marginal land and using the feedstock for the production of 2G bioethanol (Bioskoh) and resources for high added value bioproducts (First2run). And the other two projects focus on the optimization of supply and value chains of miscanthus and hemp (Grace) as well as short rotation coppices (Dendromass4Europe).

Table 4 Study cases where marginal land is used for biomass production

Country	Marginal Land Type	Feedstock Type	Mean yield (Mg DM/ ha*year)	Cultivated area (ha)	Production costs (€/Mg DM year)	Alternative land use	End Use
ForBio project [1)]							
Sulcis, Italy	contaminated	Giant reed	Up to 25		71	Abandoned industrial site	Bioethanol
Kyiv oblast Ivankiv region, Ukraine	underutilised	Salix Viminalis L.	10	50	28.7 (FINAL Cost at plant gate)		2G Ethanol

Metropolis Region Berlin	unused sewage irrigation field	Miscanthus	5-15		38-52 (selling price: 50-80)	none	Heat/Electricity
Brandenburg, Germany	Lignite reclamation sites	Sorghum	10		75	Maize	Biomethane
SEEMLA project [2]							
Welzow, Germany	Post-mining landscape, lignite mine	Black locust		4.5		Poor grassy vegetation	chips alter, fuel pellet and briquette / electric
Cottbus, Germany	Abandoned post-industrial site	Poplar, black locust		1		Woody vegetation	Fuel, pellets, and briquette/ electricity
Poltava, Ukraine	Abandoned land	Willow, miscanthus		0.5		Woody vegetation	fuel pellet and briquette/ electricity
Vinnitsa, Ukraine	Low productive land	Willow, miscanthus		0.9 (willow); 0.3 (miscanthus)		Woody vegetation	fuel pellet and briquette/ electricity
Volyn, Ukraine	Abandoned Land	Willow, poplar		4.4		Woody vegetation	fuel pellet and briquette/ electricity
Lviv, Ukraine	Abandoned	Willow		7.5		Woody vegetation	fuel pellet and briquette/ electricity
Pelagia, Greece	Abandoned land	Pinus brutaria		0.1		Mixed vegetation (forests, bushes, grassland)	Fuel, pellets, and briquette/ electricity
Drosia, Greece	Abandoned land	Pine, robinia, black locust, black pine		0.2; 0.1		Sparse grassy vegetation	Fuel, pellets, and briquette/ electricity
Sarakini, Greece	Abandoned land	Black locust		0.1		Sparse grassy vegetation	Fuel, pellets, and briquette/ electricity
First2run project [3]							
Sardinia, Italy	Abandoned land	Giant reed		3500			High-value bio products
Dendromass4europe [4]							
West-Slovakia	Unused land	Poplar		2500			High-value bio products

1) http://seemla.eu/wp-content/uploads/2018/06/6-FORBIO_SEEMLA-Symposium.pdf, only best performance supply chains mentioned

2) http://www.seemla.eu/wp-content/uploads/2017/07/SEEMLA-D5.4..pdf

3) http://www.first2run.eu/project/

4) https://www.dendromass4europe.eu/wp-content/uploads/2018/05/Meyer-M_Chancen-ungenutzer-Landpotenziale-erschliessen_Holz-Zentralblatt_2018-04-20.pdf

1.1.10 Sustainability of using marginal land for biomass production

Up to now the results of life cycle assessment of environmental, social and economic impacts of the above mentioned most recent projects focusing on biomass production on marginal land are not yet available. According to LCAs of past projects, production of lignocellulosic feedstock on marginal land has advantages in terms of GHG emissions compared to cultivation on common agricultural land since strong negative effects due to ILUC are avoided and fertilizer application rates are lower (Don *et al.*, 2011). Dedicated biomass production on marginal land does, however, show advantages and disadvantages at the same time for different environmental impacts. One of the main factors influencing climate change mitigation is the yield that can be achieved per hectare, which can be expected to be rather low on marginal land (Rettenmaier *et al.*, 2015). In most cases yield can be increased by fertilization, which can crucially influence eutrophication, acidification and other environmental impacts. Up to now, there is no quantitative mechanism in place to compare the impact level regarding GHG emissions compared to other environmental impacts of biomass production on marginal land (Rettenmaier *et al.*, 2015). In addition, comparison between study cases from different projects is challenging due to their different foci and hence, different parameters which are assessed in the according projects. In order to improve this situation, the community should agree upon a common language illustrated by a minimum set of easily to acquire indicators to be gathered from all case studies.

Using marginal land for the cultivation of lignocellulosic plants can have potential environmental benefits related to erosion protection, soil carbon increase, fertility increase, water holding capacity increase, and recapture of excess fertilizer, flood risk mitigation (Blanco-Canqui, 2010; Jakubowski *et al.*, 2010; Fagnano *et al.*, 2015; Impagliazzo *et al.*, 2017). It has, however, also been proposed that using marginal land for dedicated cropping can have negative effects on biodiversity and these environmental impacts have high spatial variation (van der Hilst *et al.*, 2012). Harvolk et al. (2014) conclude from this controversy that environmental impact of bioenergy production on marginal land need to be assessed at the local to regional level. To derive scenario maps and recommendations on which fields to choose and what maximal amount of Miscanthus should be cultivated in a landscape, the authors combined results from a yield prediction model, widely available spatial data, knowledge from literature and local landscape planning data. At present, local knowledge seems indispensable to decide on which fields dedicated cropping is feasible without negative or even with positive environmental impacts and, hence, on the sustainability of using marginal land for lignocellulosic biomass production.

According to the SEEMLA project, the costs for biomass production on marginal land are very case-specific and the profitability also depends on local and volatile prices. In addition, the risk of crop failure is higher on marginal land. Therefore, biomass production on marginal land is only attractive, if it promises high returns. For a LCA on using *Brassica carinata* as a test crop, Fahd et al. (2012) found cropping on marginal land provided no economic return if the biomass is used for bioenergy, but a performance increase in energy yield and economic return for the conversion of lignocellulosic residues to high added value biochemicals.

A significant number of additional jobs could be generated and rural income could be increased if additional land would be used for biomass production (Fahd *et al.*, 2012; Rettenmaier, 2018). Low-intensity farming on some marginal lands can conserve high habitat and species richness (Bignal & McCracken, 2000). Low-input biomass production could maintain productivity under unfavourable natural conditions, maintain species diversity and avoid agricultural land abandonment.

1.1.11 Scaling up SRC and Miscanthus production until 2030 and 2050

The area of arable land annually converted for energy cropping depends much on the availability of related funding, other regulations e.g. on co-firing , and of cereal prices (Lindegaard *et al.*, 2016). Therefore time series of hectares land panted for SRC or Miscanthus are not uniform, but usually are marked by peaks of increases in specific years. Estimates regarding the increase of arable land used for energy cropping in the future should, hence, be based on the average of several past years. To upscale growth rates from single countries to the EU28, the annual increase of hectares was divided by the total area of arable land per country. The average ratios of some countries were than used to calculate the potential European growth rate. Such an estimate using data available from a few European countries leads to a total area of land cultivated for SRC and Miscanthus of a bit more than half a million hectares in 2030 and 1.4 million hectares in 2050 (Table 5). One third higher estimates would result using peak rates of past increases in cultivated land for energy crops from a few countries (Table 6). Such peak rates might be expected from long-term political intervention in terms of adequate funding and supportive regulations. In EU28, large areas are cultivated by other energy crops, namely switch grass, reed canary grass and hemp. For switch grass and reed canary grass no historical data on cultivation area were available and hemp is only partly used as an energy crop. The area cultivated with these crops was in 2016 slightly higher than the total cultivation area of SRC and Miscanthus. Assuming similar growth rates for switch grass, reed canary grass and hemp as found for SRC and Miscanthus, total cultivated land for energy crops could be double of the estimates in Table 5, resulting in 1.3 and 2.8 million hectares in 2030 and 2050, respectively.

Table 5 Estimates of total number of hectares cultivated with SRC and Miscanthus in 2030 and 2050 in EU28 using average rates of annual increases of the last decade in Austria, Belgium, Germany and Sweden.

	Mean rate (ha/year)	2016 (ha)	2030 (ha)	2050 (ha)
SRC	29,714	68,226	484,222	1,078,502
Miscanthus[1)]	9,442	21,806	153,994	342,834
Sum		**90,032**	**638,216**	**1,421,336**

[1)] Sweden not included.

Table 6 Estimates of total number of hectares cultivated with SRC and Miscanthus in 2030 and 2050 in EU28 using the average of peak increases of the last decade in Germany, UK and Ireland for SRC and the peak rate in Germany for Miscanthus.

	Peak rate (ha/year)	2016 (ha)	2030 (ha)	2050 (ha)
SRC	50,541	68,226	775,800	1,786,620
Miscanthus	11,663	21,806	185,088	418,348
Sum		**90,032**	**960,888**	**2,204,968**

4.6. Biomass imports

Biomass trade for energy purposes has almost increased twofold from 19.1 in 2004 to 31.0 Mtoe in 2015. These trade flows include both direct trade and indirect trade. Indirect trade is biomass that is traded for non-energy purposes (food, feed, materials), but is partly also used for energy. These include for example secondary residues from wood processing industries (sawdust, shavings etc.) and food processing industries (for example husks, shells etc.). The strongest growth of bioenergy trade is in direct trade flows of biomass including wood pellets, and processed biodiesel and ethanol and had already almost the same volume (14.3 Mtoe) compared to indirect trade (16.7 Mtoe) by 2015 (Proskurina *et al.*, 2018). The EU has a key role in international bioenergy trade. Substantial growth in extra-EU and intra-EU bioenergy trade is still expected in the future, but the size and directions of these trade flows is highly uncertain.

Figure 24 Global trade flows of bioenergy in 2015 (in ktons) (Proskurina, 2018)

1.1.12 Solid biomass

Similar to domestic biomass supply scenarios, import scenarios of solid biomass are generally based on a food, feed and fibre first principle. Most studies estimate the development of potential exports of wood pellets from a list of countries that have already developed the infrastructure and capacity to export wood pellets, such as British Columbia in Canada and the US Southeast or could potentially become exporting regions, for example Brazil. The most elaborate export potential to the EU so far has been conducted in the BioTrade2020plus study. The sustainable export potential of six potential export regions has been assessed including Kenya, Indonesia, Colombia, Brazil, the United States and Ukraine. The export potential was determined based on a number of prerequisites as shown in Figure 25. In addition to material uses, bioenergy demand in exporting countries is prioritised over export. Furthermore, all biomass for domestic and exports should be sustainably sourced.

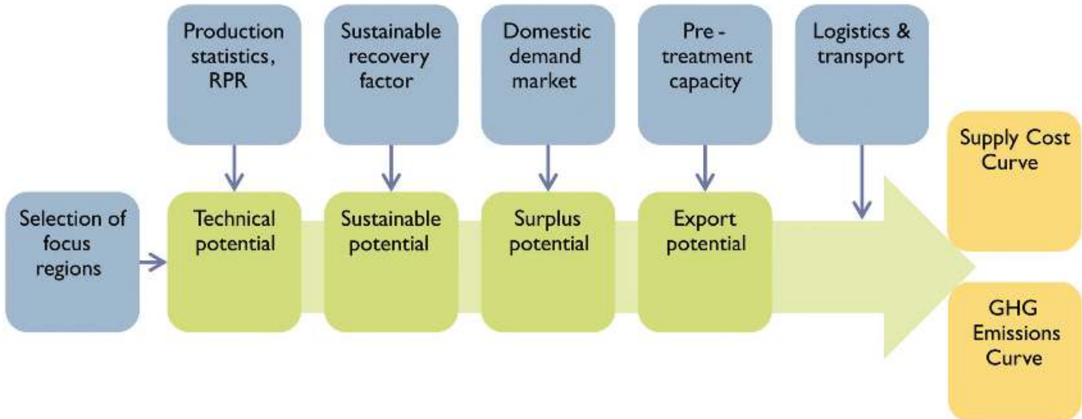

Figure 25 Method to calculate sustainable export potentials applied in the BioTrade2020Plus project (Mai-Moulin *et al.*, 2018)

The solid biomass supply scenarios shown in Figure 26 are all based on a common set of studies. Both the supply scenarios in JRC-EU-TIMES study (Ruiz *et al.*, 2015) and RESolve-Biomass are based on Biomass Policies (Fritsche & Iriarte, 2014). The method developed in Biomass Policies is the predecessor to the method used in BioTrade2020plus depicted in Figure 25. The BioSustain scenarios (PWC, 2017) are partly based on sustainable export potentials calculated in the BioTrade2020plus study (Mai-Moulin *et al.*, 2018), and additional insights from Pöyry (Lechner & Carlsson, 2014) and Lamers et al. (Lamers *et al.*, 2014a). Note that scenarios of BioTrade2020Plus are not comprehensive and exclude major export regions such as Canada and Russia.

For the year 2020 the RESolve-Biomass High scenario and Biomass Policies scenarios might be too optimistic, in particular for export of wood pellets from Eastern Canada. Total pellet production capacity in Eastern Canada is about 1 million tonne (Mt) with 120 kt being exported to the EU (Bradley *et al.*, 2014) which is 0.2% of the estimated export capacity in Biomasss Policies by 2020. Another uncertain region which contributes significantly in some supply scenarios are exports from Sub-Saharan Africa (Mozambique, Kenya) and Latin America (Brazil, Colombia). Wood pellet infrastructure is not yet developed in these regions (Garcia *et al.*, 2016).

Nevertheless, bagasse pellets are being considered for export and could potentially contribute substantially to EU import scenarios of solid biomass (Mai-Moulin *et al.*, 2018).

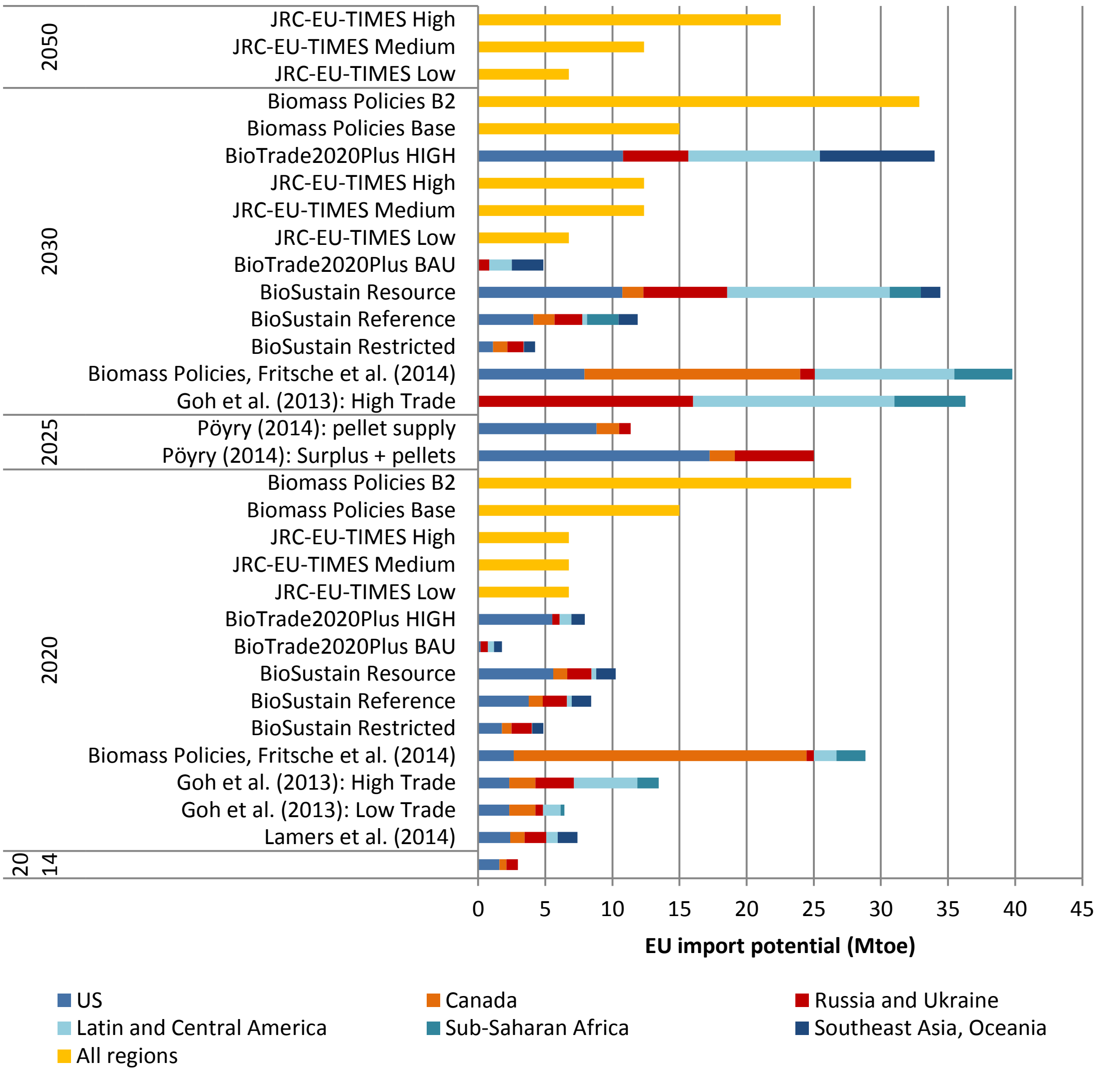

Figure 26 Comparison of export potential scenarios of solid biomass to the EU compared to current imports (2014)

1.1.13 Liquid biofuels

After a period of fast growth, the development of liquid biofuel production has slowed down after 2010 (Lamers *et al.*, 2014b). Today, the world biofuel market is dominated by ethanol produced mainly from sugar cane in Brazil (27 bln L in 2016) and maize in the US (58 bln L in 2016).

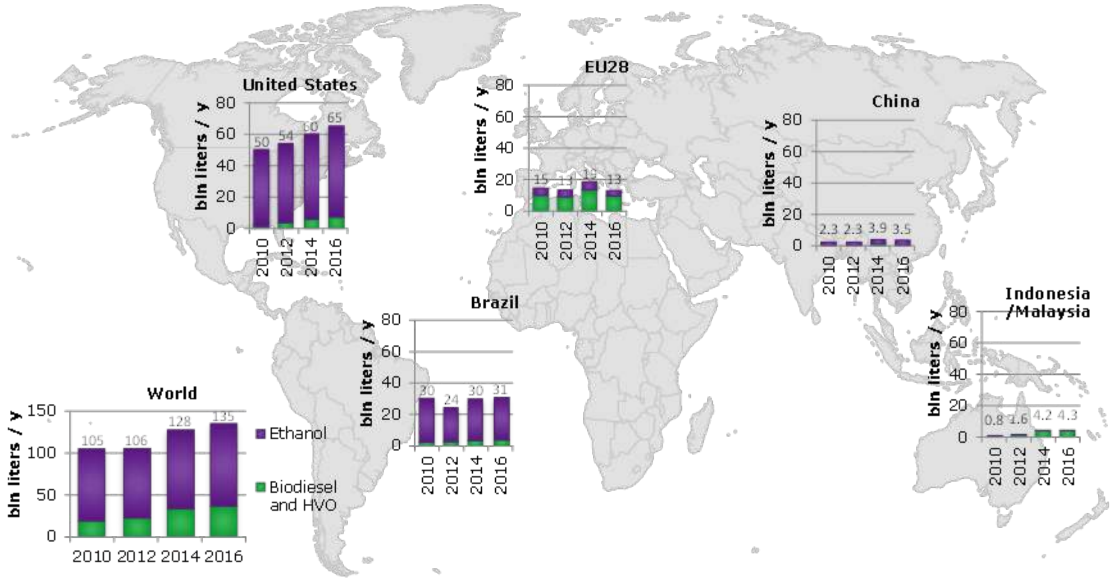

Figure 27 Global production of biodiesel, ethanol and HVO (bln liters/year). Data from REN21 reports (2011 – 2017)

Figure 28 compares import scenarios of liquid biofuels (ethanol, biodiesel and advanced biofuels to the EU). Similar to solid biomass, JRC-EU-TIMES builds on the scenarios developed in Biomass Policies that project biofuel exports to 2030. The scenarios are extended beyond 2030 by assuming linear growth between 2020 and 2050. The BioSutain scenarios for liquid biofuel imports build on E4Tech scenarios A, B and C in Bauen et al. (2013). The scenarios in Figure 28 are compared to actual EU imports of liquid biofuels that peaked in 2012 at about 5 Mtoe[9]. Export regions include mainly regions that produce and export large amounts of biofuels or biomass to produce biofuels such as the US, Brazil, Argentina and Indonesia. Emerging export regions in Sub-Saharan Africa (for example Mozambique) are also considered in these scenarios. It is however questionable if the available infrastructure to produce and export these biofuels could be developed in the given time frame of the scenarios. Imports of advanced biofuels are projected to contribute 11% to liquid biofuel imports in 2030 in the BioSustain scenarios and up to 26% in the Biomass Policies scenarios in 2030, that are projected to be produced mainly in Brazil.

[9] Figure 21 includes both import of liquid biofuels and imported feedstocks consumed to produce liquid biofuels in the EU (for example palm oil) based on Ecofys (Hamelinck *et al.*, 2014). In contrast, Figure 6 only tracks imported biofuels and is therefore substantially lower (2.7 Mtoe in 2012).

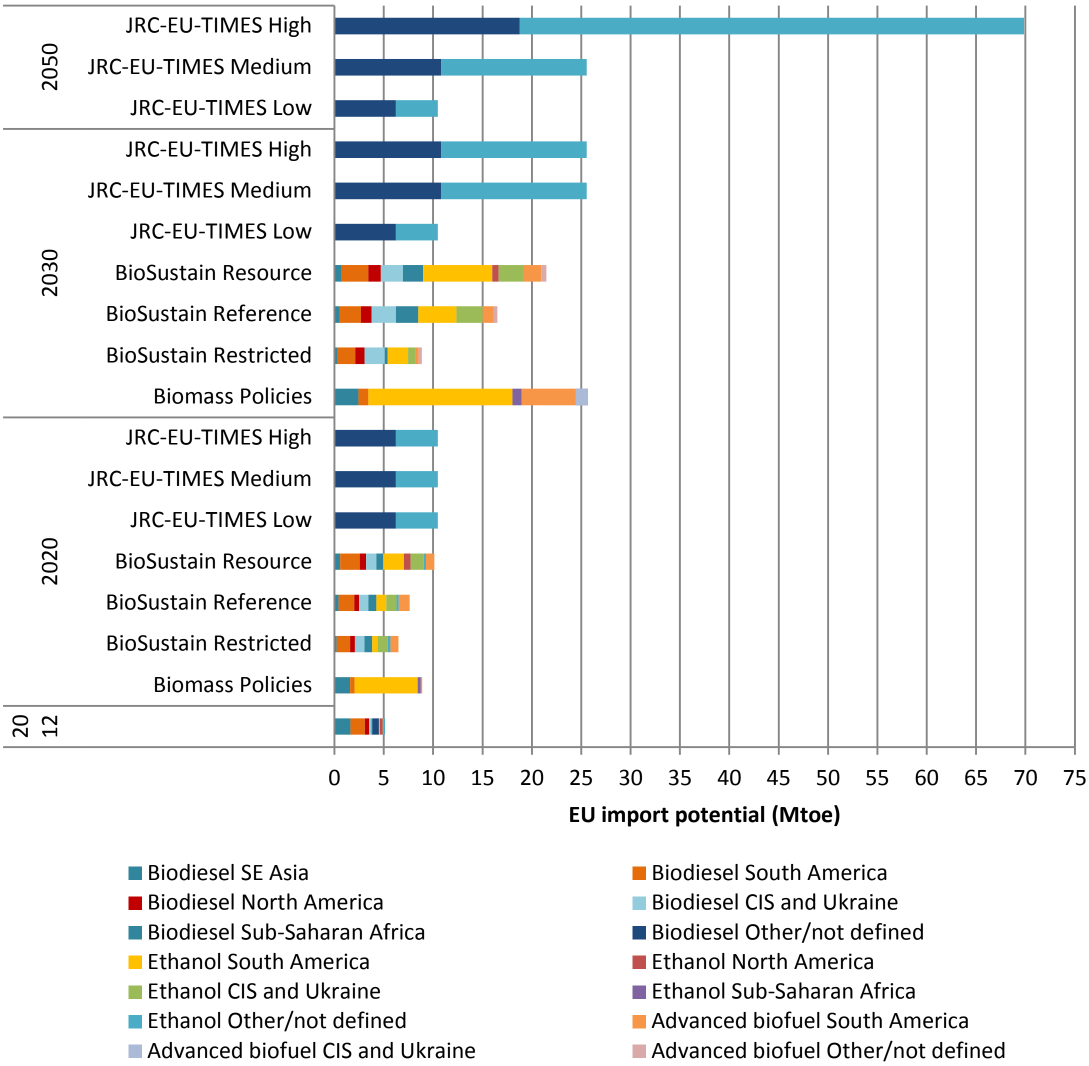

Figure 28 Comparison of liquid biofuel import scenarios developed in Biomass Policies (Fritsche & Iriarte, 2014), *JRC-EU-TIMES* (Ruiz *et al.*, 2015) *and BioSustain* (PWC, 2017)

1.1.14 Cost-supply curves

In both BioSustain and Biomass Policies, supply cost have been calculated to develop region specific cost-supply curves of imported biomass as shown in Figure 29 and Figure 30 respectively. The cost-supply curves in Figure 29 start at sea ports in export countries (Freight on Board) and calculate the cost to each individual EU member states using a geographically explicit intermodal transport calculation tool. The upper ranges in Figure 29 show the supply cost of solid biomass to land-locked countries in the EU, for example Austria. The lower ranges with available port infrastructure such as the ARA region.

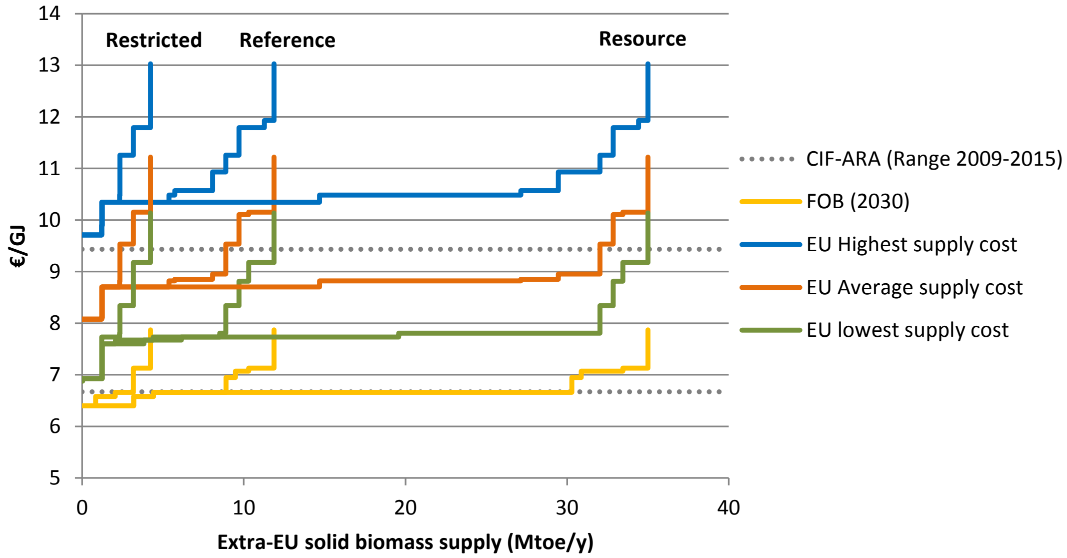

Figure 29 BioSustain: Cost-supply curve of extra-EU solid biomass pellets delivered to the EU28 in the 2030 compared to the lowest and highest CIF-ARA spot prices of wood pellets between 2009 and 2015 (PWC, 2017)

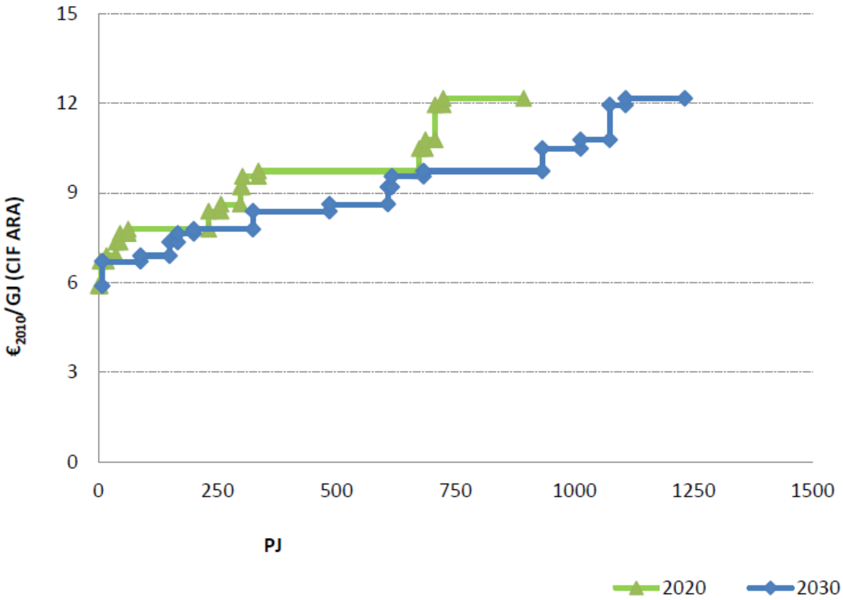

Figure 30 Biomass Policies: Cost-supply curves of wood pellets delivered to Antwerp – Rotterdam – Amsterdam region (ARA) (Fritsche & Iriarte, 2014)

5. Conclusion

About 18% of total biomass consumption in the EU today is used for energy purposes (bioenergy). Bioenergy has, however, grown rapidly in the past 15 years stimulated by renewable energy support. Between 2000 and 2015, gross inland consumption of bioenergy increased by 225% from 60.8 Mtoe in 2000 to 136.7 Mtoe in 2015. On the short term between 2016 and 2020, bioenergy demand in the EU is expected to continue to grow by 27% to meet binding RES targets and is expected to slow down in the period 2020 – 2030. Post 2030 however, albeit being also more uncertain, strong growth of biomass demand is anticipated particular lignocellulosic biomass used for advanced biofuels used in the transport sectors.

According to biomass resource assessments conducted between 2006 and 2017, domestic biomass potential in the EU may be between 115 – 525 Mtoe in 2020 increasing to 195 – 595 Mtoe in 2050. Approximately 25% - 36% of it estimated to be available from forests (stemwood and forest residues such as logging residues, sawdust), but partly it is already utilised in electricity and heat sectors (95 Mtoe). Material uses (timber, pulp and paper etc.) are roughly of the same magnitude to bioenergy in terms of biomass demand (by weight) in the EU bioeconomy.

Energy crops, and in particular perennial crops such as grasses and short rotation coppice, could potentially contribute between 33% and 56% to the total EU biomass potential. However, markets of perennial crops are still relatively small today. Although potentially available, substantial efforts are required before these biomass sources are readily available to produce advanced biofuels at commercial scale. These efforts include infrastructure, farmers experience, as well as regulatory compliance and support.

The current (2015) net imports of biomass are about 6.0 Mtoe (4.4% of gross inland consumption of bioenergy) in the EU28. Future import scenarios of solid and liquid biofuels add up to between to between 3% and 16% to future supply potentials up to 2050. Advanced biofuel production could potentially lead to increased trade of solid biomass that need economies of scale and reduced supply risks. On the other hand, advanced biofuels could also be imported from overseas, reducing capacity development within the EU.

In the assessment of scenarios with the RESolve-Biomass model in ADVANCEFUEL Work Package 6, we recommend to use state-of-the-art insights on cost-supply of biomass. The S2Biom project provides the most up-to-date and comprehensive biomass estimates on supply potentials and roadside cost at NUTS3 level in the EU and surrounding countries. However, careful interpretation is required. The scenarios do not always consider competing uses for non-energy uses in a consistent way. For example, competing uses of roundwood and agricultural residues is only considered in selected User Defined scenarios. Secondly, S2Biom provides road side cost in their feedstock supply database. Feedstock supply cost can add substantially to the total cost of lignocellulosic feedstock supply and should be properly addressed in RE-

Solve-Biomass modelling framework. Thirdly, EU and extra-EU import supply scenarios need to be extended beyond their time horizon of 2030 with dedicated tasks on perennial crop developments from ADVANCEFUEL (Work Package 2) and insights from biomass resource assessments such as JRC-EU-TIMES.

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Appendix

Table A7 Overview of biomass resource potentials for bioenergy in the European Union (EU28/EU27) (compiled by Mandley et al., forthcoming)

Study	Reference / year	Method	Biomass catergory	Scenario	Supply potential (EJ)			Supply potential (Mtoe)		
					2020	2030	2050	2020	2030	2050
Biomass Energy Europe Project (BEE)	(EEA, 2006)	Statistical analysis & Spatially explicit analysis	Agricultural Residues		1.78	1.83		42.5	43.7	
			Forestry		3.21	3.91		76.7	93.4	
			Energy crops		4.22	6.27		100.8	149.8	
			Waste		1.16	1.16		27.7	27.7	
			Total Bioenergy		10.7	13.3		255.6	317.7	
	(Ericsson & Nilsson, 2006)	Statistical analysis	Agricultural Residues	Low = High harvest	0.9	0.9	0.6	21.5	21.5	14.3
			Forestry	Low biomass harvest	1.8	1.8	1.8	43.0	43.0	43.0
				High biomass harvest	1.8	2.33	2.33	43.0	55.7	55.7
			Energy Crops	Low biomass harvest	1.8	5.6	15.4	43.0	133.8	367.8
				High biomass harvest	1.8	7.2	19.9	43.0	172.0	475.3
			Total Bioenergy	Low biomass harvest	4.8	18.9	22.2	114.6	451.4	530.2
				High biomass harvest	4.8	21.6	24.9	114.6	515.9	594.7
	EEA (Lindner *et al.*, 2007)	Statistical analysis & Spatially explicit analysis	Forestry	Protected area and bio-diveristy	1.79	1.78		42.8	42.5	
				Protected area and bio-diveristy with complemen-tary fellings	1.99	2.01		47.5	48.0	
				Max available	2.24	2.26		53.5	54.0	
	EEA (b)	Statistical analysis & Spatially explicit analysis	Energy crops		3.45	4.62		82.4	110.3	
	(Fischer *et al.*, 2007)	Statistical analysis	Energy crops	Baseline		6.23			148.8	
				Arable land Low		3.92			93.6	
				Arable land High		9.45			225.7	
	(De Wit *et al.*, 2008)	Statistical analysis (Cost supply meth-ods)	Agricultural Residues	Base line estimate	3.2	2.84		76.4	67.8	
			Forestry	Base line estimate	2.7	2.7		64.5	64.5	
			Energy crops	Base line estimate	8.5	11.1		203.0	265.1	
				low estimate	1.75	2.24		41.8	53.5	
				high estimate	10.3	12.88		246.0	307.6	
	(de Wit & Faaij, 2010)	Statistical analysis (Cost-supply meth-ods)	Total Bioenergy	Baseline	18.9	22.2		451.4	530.2	
				Minimum |(low yield Energy crops)	9.4	9.7		224.5	231.7	
				Maximum (High yield ener-gy crops)	21.6	24.9		515.9	594.7	
Biomass futures	(Elbersen *et al.*, 2012b)	Statistical analysis & Spatially explicit analysis	Agriculute (EC & Residuse)	Reference	7.58	7.33		181.0	175.1	
				Sustainability	6.62	5.99		158.1	143.1	
			Forestry	Reference	8.79	8.54		209.9	204.0	
				Sustainability	7.58	7.41		181.0	177.0	
			Waste	Reference	1.51	1.38		36.1	33.0	
				Sustainability	1.51	1.38		36.1	33.0	
			Total Bioenergy	Reference	17.96	17.21		429.0	411.1	
				Sustainability	15.7	14.78		375.0	353.0	
Biomass Policies	(Elbersen *et al.*, 2015b)	Statistical analysis & Spatially explicit analysis	Agriculture (EC & Residues)	Conservative	4.16	4.56		99.4	108.9	
			Forestry	Conservative	4.82	5.02		115.1	119.9	
				Additional mobilisation of Forestry biomass	8.35	7.9		199.4	188.7	
			Waste	Conservative	1.53	1.68		36.5	40.1	
			Total	Conservative	10.51	11.26		251.0	268.9	
				Additional mobilisation of Forestry biomass	14.04	14.14		335.3	337.7	
JRC - EU - TIMES	(Ruiz *et al.*, 2015)	Statistical analysis (Cost-supply meth-ods)	Agricultural Residues	Low availability	0.74	0.7	0.6	17.7	16.7	14.3
				Medium availability	1.1	1.08	1.02	26.3	25.8	24.4
				High availability	2	2.07	2.13	47.8	49.4	50.9
			Forestry	Low availability	3.95	3.36	2.86	94.3	80.3	68.3
				Medium availability	5.26	4.78	5.11	125.6	114.2	122.1
				High availability	9.6	9.96	10.58	229.3	237.9	252.7
			Energy crops	Low availability	2.67	3.55	3.65	63.8	84.8	87.2
				Medium availability	3.18	4.13	4.19	76.0	98.6	100.1
				High availability	4.21	5.46	5.66	100.6	130.4	135.2
			Waste	Low availability	0.97	1	1.05	23.2	23.9	25.1
				Medium availability	1.66	1.76	1.96	39.6	42.0	46.8
				High availability	2.36	2.48	2.76	56.4	59.2	65.9
			Total Bioenergy	Low availability	8.33	8.61	8.16	199.0	205.6	194.9
				Medium availability	11.2	11.75	12.28	267.5	280.6	293.3
				High availability	18.17	19.97	21.13	434.0	477.0	504.7
			Additional Imports needed	Low availability	0.72	0.72	0.72	17.2	17.2	17.2
				Medium availability	1.35	1.59	1.59	32.2	38.0	38.0
				High availability	0.72	1.59	3.9	17.2	38.0	93.1
BioSustain	(PWC, 2017)	Statistical analysis	Agricultural Residues	Restricted	1.26	1.32		30.1	31.5	
				Reference	1.26	1.32		30.1	31.5	
				Resource	1.26	1.32		30.1	31.5	
			Forestry	Restricted	3.62	2.9		86.5	69.3	
				Reference	4.52	4.26		108.0	101.7	
				Resource	5.94	5.7		141.9	136.1	
			Energy crops	Restricted	4.16	5.56		99.4	132.8	
				Reference	4.16	5.56		99.4	132.8	
				Resource	4.16	5.56		99.4	132.8	
			Waste	Restricted	3.4	3.81		81.2	91.0	
				Reference	3.4	3.81		81.2	91.0	
				Resource	3.4	3.81		81.2	91.0	
			Total Bioenergy	Restricted	12.44	13.59		297.1	324.6	
				Reference	13.34	14.95		318.6	357.1	
				Resource	14.76	16.39		352.5	391.5	

Table A8 Domestic (EU28) biomass potentials (in Mtoe) applied in RESolve-Biomass (see for example de Jong et al. (2018))

Scenario	Biomass Policies Baseline			Biomass Policies B2		
Year	2015	2020	2030	2015	2020	2030
Wastes	25.6	26.8	29.6	25.6	26.8	29.6
Agricultural residues	36.3	35.5	35.1	36.3	35.5	51.5
Bioethanol 1G crops	6.4	7.2	10.5	6.4	7.2	10.5
Forage maize	4.2	4.2	4.2	4.2	4.2	4.1
Biodiesel 1G crops	5.8	6.7	6.4	5.8	6.7	6.4
Perennial crops	11.2	22.4	30.2	11.2	22.4	20.3
Landscape care wood	14.1	15.0	19.5	14.1	15.0	19.5
Roundwood	13.0	13.6	15.6	13.0	13.6	45.3
Prim forestry residues	60.5	55.8	53.3	60.5	55.8	59.3
Secondary forestry residues	50.4	53.2	61.1	50.4	53.2	78.8
Tertiary forestry residues	1.3	1.3	1.5	1.3	1.3	1.5
Total	**228.8**	**241.8**	**267.0**	**228.8**	**241.8**	**326.7**
Agricultural residues	36.3	35.5	35.1	36.3	35.5	51.5
Forestry	139.3	139.1	151.0	139.3	139.1	204.3
Energy crops	27.5	40.5	51.3	27.5	40.5	41.3
Waste	25.6	26.8	29.6	25.6	26.8	29.6
Total	**228.8**	**241.8**	**267.0**	**228.8**	**241.8**	**326.7**