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Research and Innovation perspective of the mid- and long-term Potential for Advanced Biofuels in Europe

D1.1 Overview on the research and innovation potential of biomass production for transport fuels

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Directorate-General for Research and Innovation
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1 Introduction

1.1 Background

This deliverable is part of the study on “Research and Innovation perspective of the mid- and long-term Potential for Advanced Biofuels in Europe”. The study investigates how research and innovation can contribute to the development of advanced biofuels in the medium and long term. It will feed into the discussion by the DG Research and Innovation on the role of research and innovation for advanced biofuels. The study has three specific objectives:

- To provide an assessment of the potential for research and innovation for biomass feedstock for energy for the time horizons of 2030 and 2050;
- To assess the potential contribution of advanced biofuels for achieving the EU 2020 targets;
- To compare different fuel options for transport.

1.2 Objectives and research questions

This deliverable report provides a review and assessment of the **research and innovation (R&I) options towards sustainable and low cost biomass availability for bioenergy** in Europe and major players worldwide, performed in separate chapters for the fields of agriculture, forestry, waste, and aquatic biomass.

The following topics are specifically addressed:

- Breeding of food and energy crops, forest plants and aquatic organisms (in particular macro- and microalgae) to increase the yields and the biomass proportion in favour of energy dedicated ingredients (e.g. optimise straw/grain ratio);
- Breeding and enhanced agricultural practices of energy crops to increase their resistance to abiotic and biotic stresses (drought, marginal lands, pests and diseases);
- Crop rotation and intercropping as well as other agricultural/forest strategies and approaches to optimise bioenergy taking into account carbon stock, nutrient and water cycles and biodiversity;
- Optimisation of harvesting and mobilisation of biomass;
- Development of biomass or derived biomass carriers with improved energy to weight ratio and optimised versatility and tradability;
- Optimisation of logistics (including reduction of post-harvest losses, as well as suitability for transport and storage) and infrastructure, where relevant;
- Strategies to bring degraded and currently unusable land back into production, e.g. by maintaining or improving soil quality;
- Optimisation of supply chains for primary and secondary biomass; and
- Development of technology transfer between biomass sectors and locations.

1.3 Methodological approach

Step 1: Desk research on R&I options

The desk research on the R&I options is performed separately for the fields of agriculture, forestry, waste, and aquatic biomass, using the following sources:

- Data bases (national and international statistics, own data sets);
- Projects (research, innovation, demonstration, commercial projects; EU and national projects; international projects);

- Models (agricultural, forest and waste models);
- Publications (literature, studies, papers, articles);
- Patents.

Step 2: Desk research on major players in R&I
The desk research on the major players in R&I is performed separately for the fields of agriculture, forestry, waste, and aquatic biomass, using abovementioned sources.

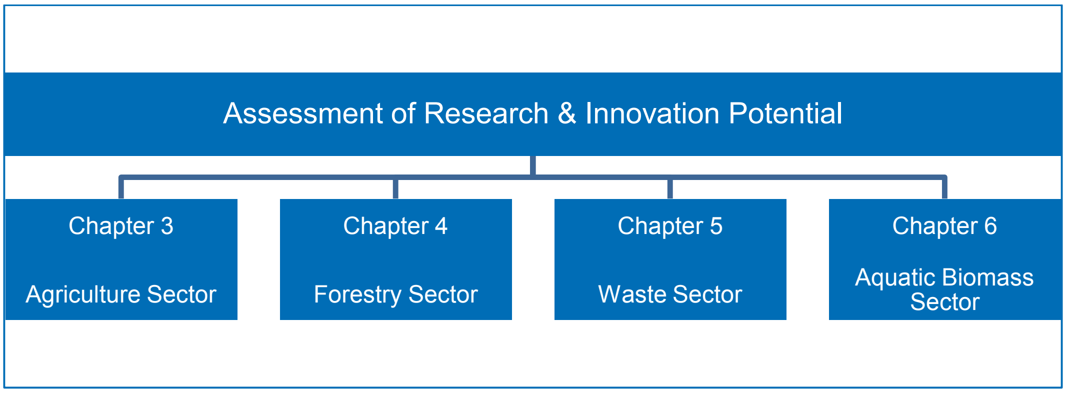
Step 3: Qualitative definition of scenario elements
Promising R&I options are identified separately for the fields of agriculture, forestry, waste, and aquatic biomass and described qualitatively.

Step 4: Provision of quantified input data for modelling
In the fields of agriculture, forestry, waste, and aquatic biomass input data are made available for modelling the research and innovation potential of biomass production. These data feed into D1.2 of the present study on Research and innovation scenarios for biomass potential and are thus not presented in D1.1.

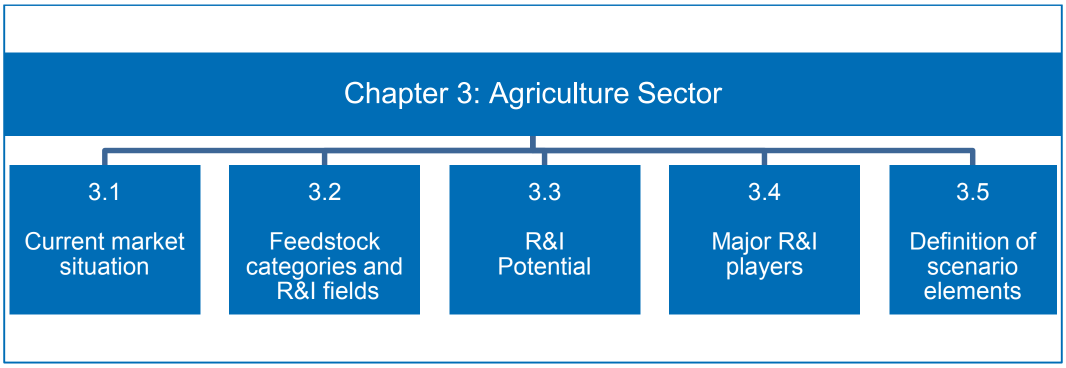
1.4 Reading guide

Deliverable 1.1 is structured in the following way. **Chapter 2** provides a brief overview of the feedstock categories and R&I fields covered by the study.

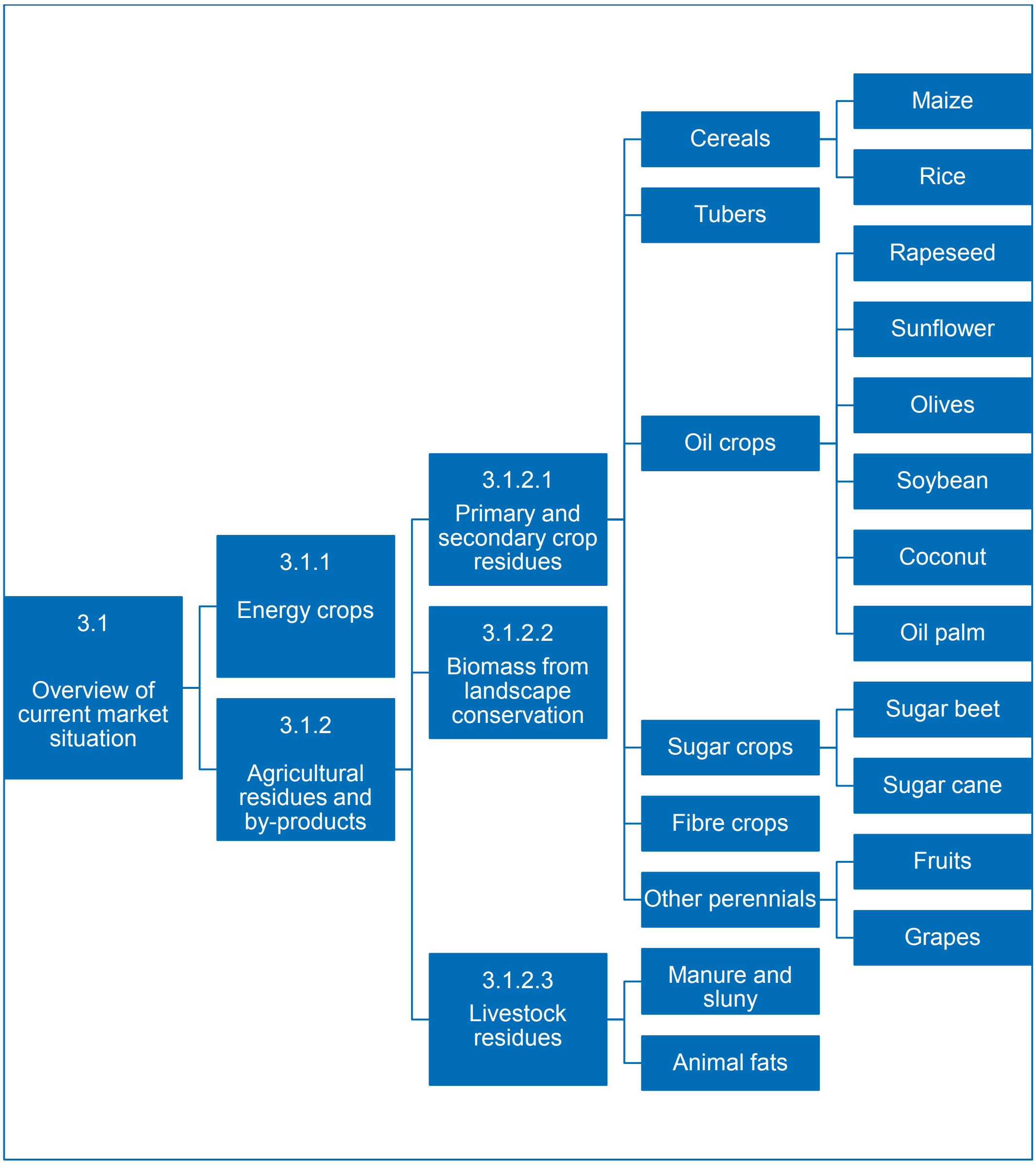
Chapter 3 to Chapter 6 present the main body of the present report, namely the detailed assessment of the Research & Innovation potential in the fields of agriculture, forestry, waste, and aquatic biomass, respectively.



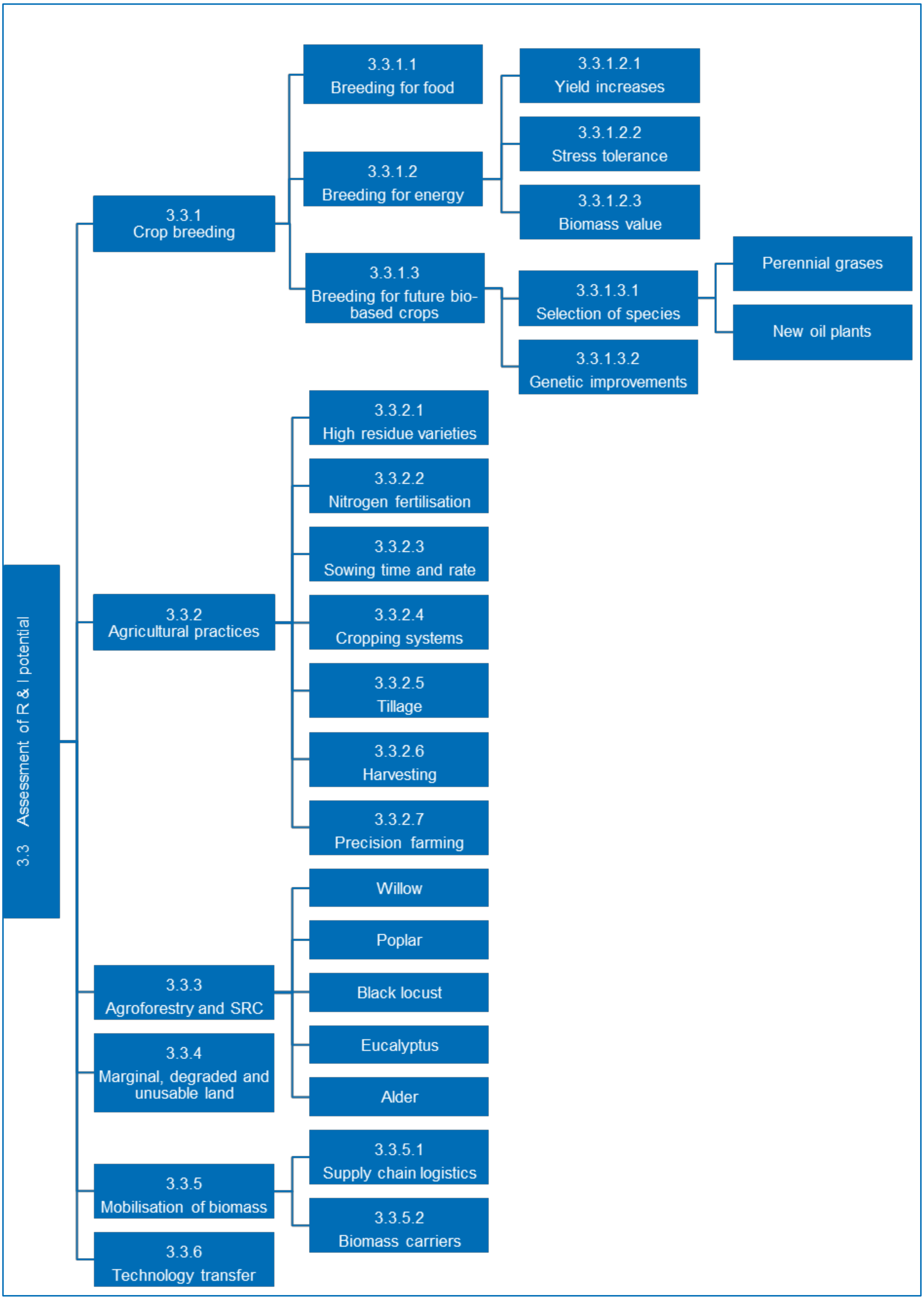
Chapter 3 on the assessment of the Research & Innovation potential in the field of agriculture includes sub-chapters on the overview of current market situation, the selection of feedstock categories, the assessment of R&I potential, the identification of major R&I players, as well as the definition of scenario elements.



The structure of chapter 3.1 on the overview of current market situation and agricultural biomass potential is displayed in the figure below.



The structure of chapter 3.3 on the assessment of Research & Innovation potential in the field of agriculture is displayed in the figure below.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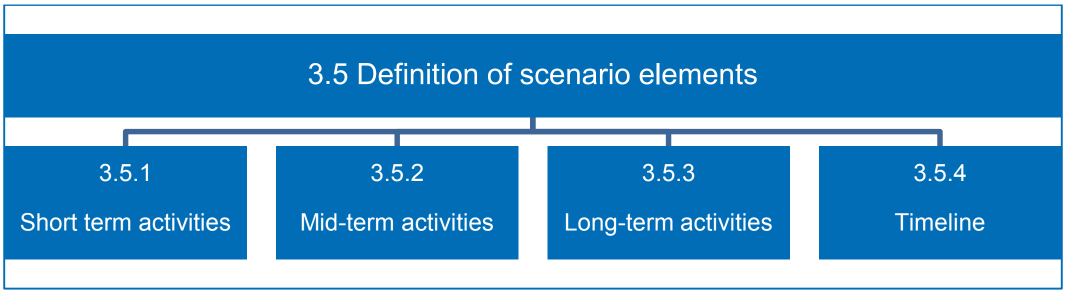
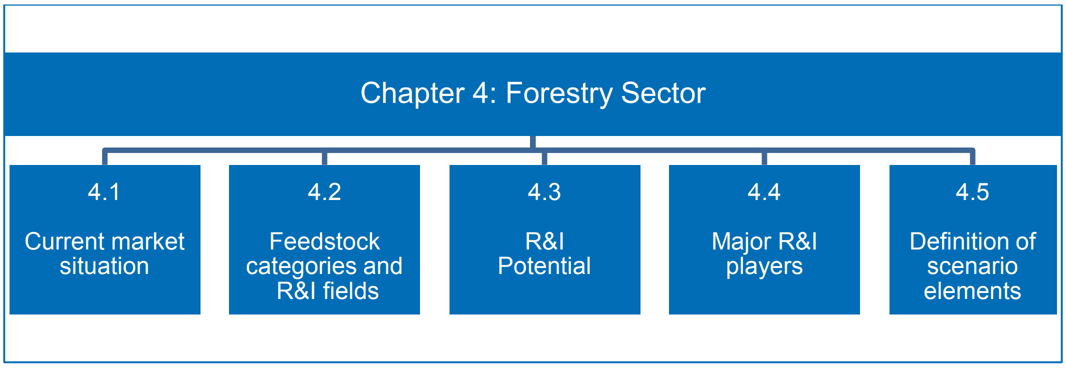
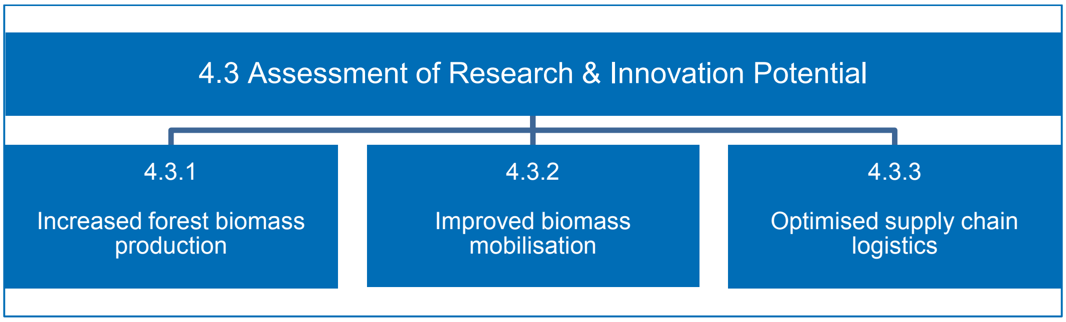
The structure of chapter 3.5 on the definition of scenario elements in the field of agriculture is displayed in the figure below.



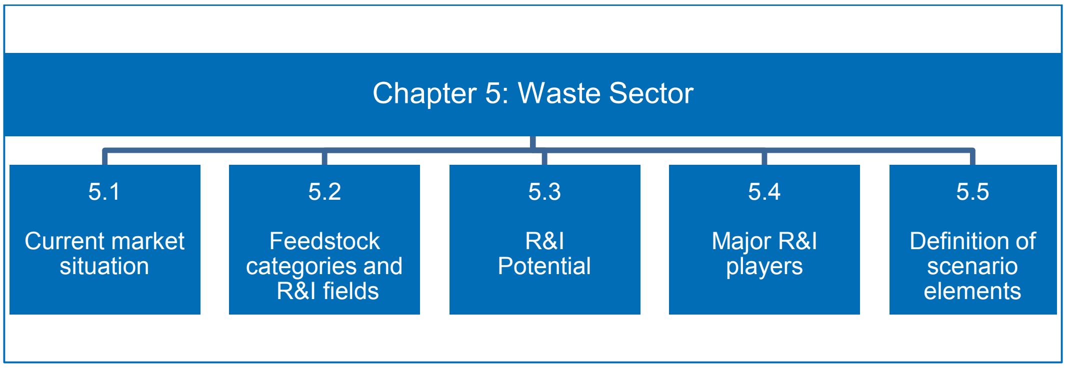
Chapter 4 on the assessment of the Research & Innovation potential in the field of forestry includes sub-chapters on the overview of current market situation, the selection of feedstock categories, the assessment of R&I potential, the identification of major R&I players, as well as the definition of scenario elements.



The structure of chapter 4.3 on the assessment of Research & Innovation potential in the field of forestry is displayed in the figure below.



Chapter 5 on the assessment of the Research & Innovation potential in the field of waste includes sub-chapters on the overview of current market situation, the selection of feedstock categories, the assessment of R&I potential, the identification of major R&I players, as well as the definition of scenario elements.



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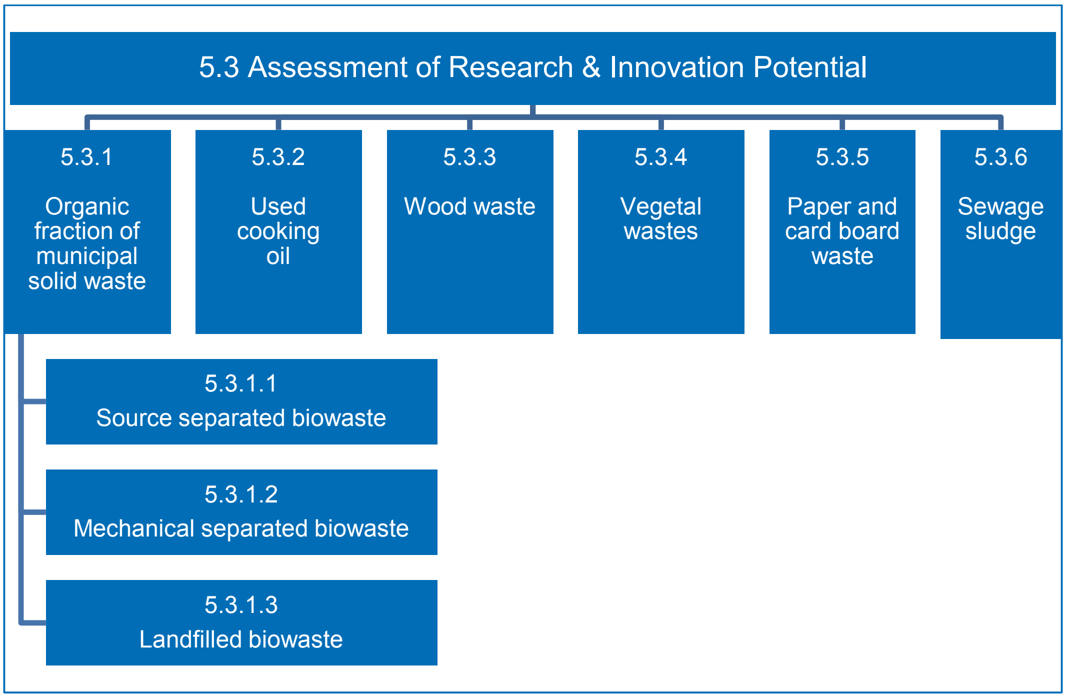
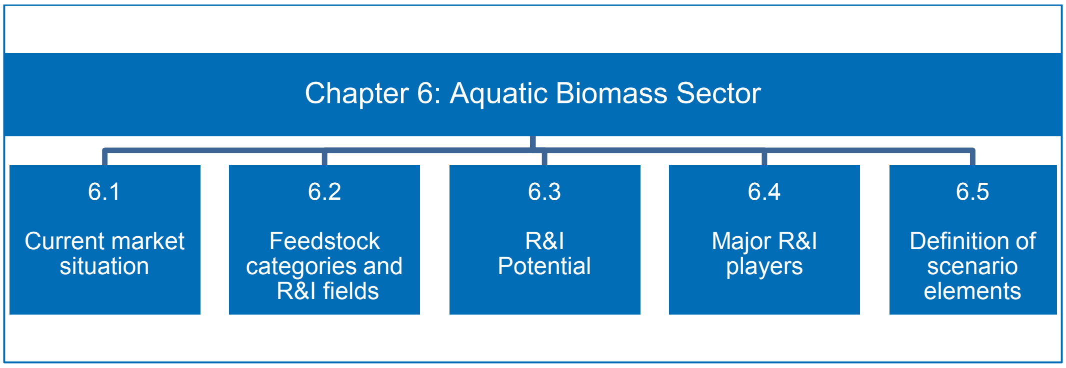
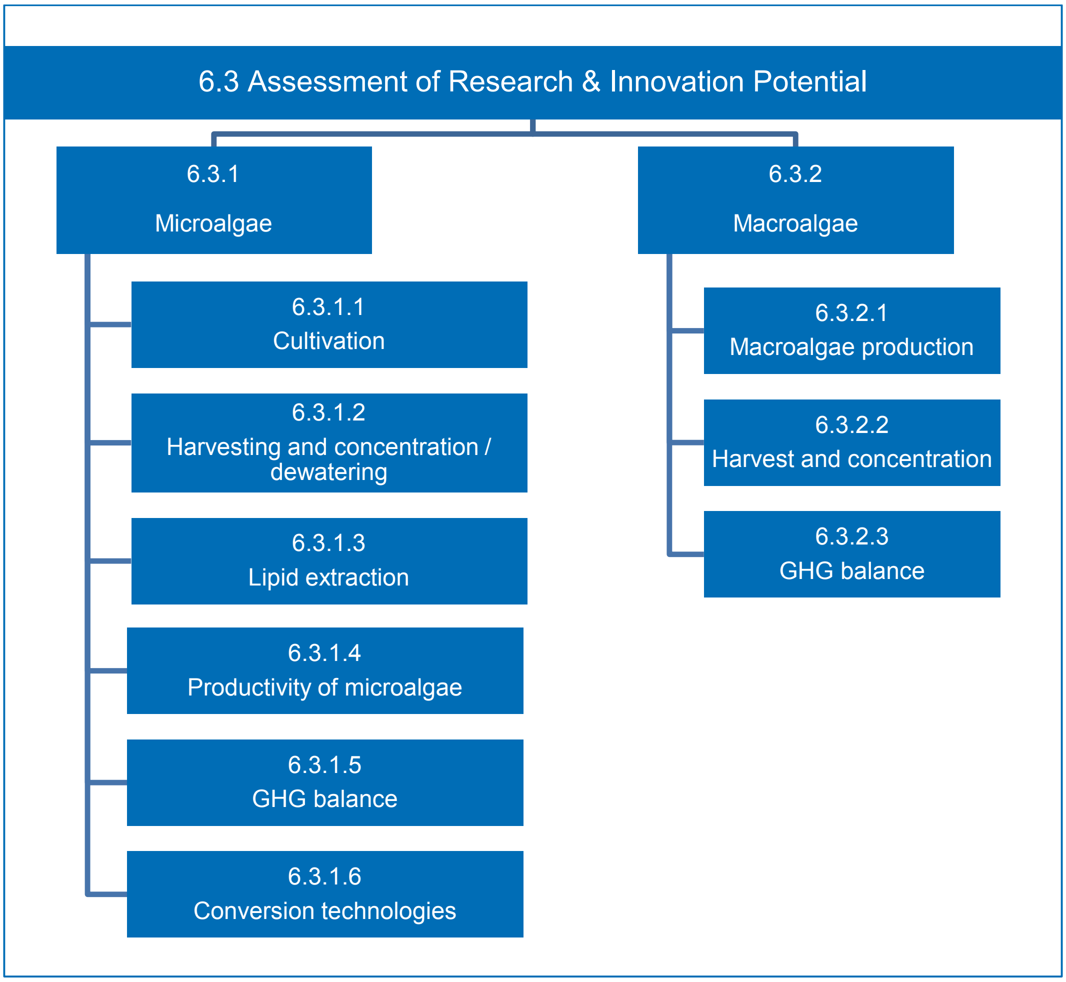


Chapter 6 on the assessment of the Research & Innovation potential in the field of aquatic biomass includes sub-chapters on the overview of current market situation, the selection of feedstock categories, the assessment of R&I potential, the identification of major R&I players, as well as the definition of scenario elements.



The structure of chapter 6.3 on the assessment of Research & Innovation potential in the field of aquatic biomass is displayed in the figure below.



Chapter 7 summarises main findings of the report and references are provided in **Chapter 8**.

Annex 1 presents an overview about most widespread annual crops in Europe and worldwide, indicating their production shares by region, top 5 producer countries, type of generated residues, typical RSR or RPR values and moisture content.

Annex 2 presents a calculation sheet for the evaluation of the crop residue potential and **Annex 3** provides a brief description of additional new oil crops.

Annex 4 presents results from an output analysis with Elsevier SciVal indicating major agriculture sector players involved in research & innovation.

2 Assessment overview

A detailed review and assessment of the **research and innovation (R&I) options towards sustainable and low cost biomass availability for bioenergy** was performed for the fields of agriculture, forestry, waste, and aquatic biomass.

Table 2.1 presents an overview of the **main agriculture, forestry, waste, and aquatic biomass feedstock categories** addressed in this study.

Table 2.1 Main feedstock categories covered by the study

	Biomass Category	Biomass Type	Biomass Subtype
Biomass from agriculture	Energy crops	Cellulosic energy crops	Herbaceous grasses
			Short Rotation Coppice (SRC)
		New low-ILUC energy crops, including new oil crops	
	Primary crop residues	Cereal straw	Wheat
			Barley
			Triticale
			Rye
			Oats
		Maize stover	
		Rapeseed straw	
		Sunflower stalks	
		Prunings	Wine prunings
			Olive prunings
	Secondary crop residues	Cereal processing residues	Wheat and barley bran
		Sugar beet processing residues	Pulp and molasses
		Maize cobs	
		Oil crop processing residues	Rapeseed and sunflower meal
		Potato pulp and peels	
		Grape processing residues	
		Olive processing solid residues	
	Manure		
	Grassland biomass		
Biomass from forestry	Round-wood production	Stemwood	Roundwood from final fellings
			Roundwood from thinnings
	Primary forestry residues	Logging residues	Tops, branches
			Stumps
			Early thinnings
	Secondary forestry residues	Woodchips and pellets	Woodchips
			Pellets
		Sawdust	
		Black liquor	

Table 2.1 Main feedstock categories covered by the study (continued)

	Biomass Category	Biomass Type	Biomass Subtype
Bio	Household and similar wastes (EUROSTAT)	Municipal Solid Waste (MSW)	Organic fraction of municipal solid waste (OFMSW)

	Biomass Category	Biomass Type	Biomass Subtype
	Animal and mixed food waste (EUROSTAT)	Mixed wastes of food preparation	Used Cooking Oil
	Wood wastes (EUROSTAT)	Post-consumer wood	Packaging waste
	Vegetal wastes (EUROSTAT)		
	Paper and cardboard waste (EUROSTAT)		
	Sludges and liquid wastes from waste treatment (EUROSTAT)	Sewage sludge	
Aquatic biomass	Microalgae		
	Macroalgae		

Table 2.2 presents an overview of the **main Research & Innovation fields for agriculture, forestry, waste, and aquatic biomass** covered in this study, as well as the respective study chapters addressing the R&I fields.

Table 2.2 Main R&I fields for agriculture, forestry, waste, and aquatic biomass covered by the study

	Concerned part of the biomass supply chain	R&I field	Respective sub-chapter of the study
Biomass from agriculture	Biomass cultivation (cropping)	Breeding of food and energy cops	Chapter 3.3.1
		Agricultural practices	Chapter 3.3.2
		Crop rotation and intercropping	Chapter 3.3.2.4
		Agroforestry & short rotation coppice	Chapter 3.3.3
		Using marginal, degraded and unusable land for energy crops production	Chapter 3.3.4
	Biomass harvesting and collection	Harvest of agricultural biomass	Chapter 3.3.2.6
	Biomass pre-treatment and densification	Improved biomass carriers: thermo-chemically pre-treated and mechanically treated agricultural biomass	Chapter 3.3.5.2
	Horizontal issues covering whole biomass supply chain	Biomass mobilization	Chapter 3.3.5
		Agricultural logistics	Chapter 3.3.5.1
		Supply chains of primary and secondary biomass	Chapter 3.3.5.1
		Technology transfer	Chapter 3.3.6
Biomass from forestry	Increased forest biomass production	Breeding of improved genetic plant material	Chapter 4.3.1
		Fertilisation	Chapter 4.3.1
		Improved silviculture	Chapter 4.3.1
	Improved biomass mobilisation		Chapter 4.3.2
	Optimised supply chain logistics		Chapter 4.3.3
B	Optimised supply chain	OFMSW – Source separated biowaste	Chapter 5.3.1.1

	Concerned part of the biomass supply chain	R&I field	Respective sub-chapter of the study
		OFMSW – Mechanical separated biowaste	Chapter 5.3.1.2
		OFMSW – Landfilled biowaste	Chapter 5.3.1.3
		Used Cooking Oil	Chapter 5.3.2
		Wood waste	Chapter 5.3.3
		Vegetal wastes	Chapter 5.3.4
		Paper and cardboard waste	Chapter 5.3.5
		Sewage sludges	Chapter 5.3.6
Aquatic biomass	Cultivation (Microalgae)	Open pond systems	Chapter 6.3.1.1
		Photo-Bioreactors	
	Harvesting and concentration/ dewatering (Microalgae)	Thickening	Chapter 6.3.1.2
		Separation from growth medium	
		Dewatering	
	Lipid extraction (Microalgae)	Solvent extraction	Chapter 6.3.1.3
		Supercritical fluid extraction	
		Mechanical and biological extraction	
	Productivity(Microalgae)		Chapter 6.3.1.4
	GHG balance (Microalgae)		Chapter 6.3.1.4
	Conversion technologies (Microalgae)	Biodiesel	Chapter 6.3.1.6
		Hydroprocessed Esters and Fatty Acids (HEFA)	
		Hydrothermal liquefaction	
	Cultivation (Macroalgae)	Wild cultivation	Chapter 6.3.2.1
		Aquafarms (maricultures)	
	Harvesting and concentration (Macroalgae)		Chapter 6.3.2.2
	GHG balance (Macroalgae)		Chapter 6.3.2.3

3 Assessment of the R&I potential in the field of agriculture

This review study gives an overview about research and innovation activities related to agricultural feedstocks to increase their potential use for the production of bioenergy, including advanced biofuels.

The main feedstock categories included in this chapter are presented in Table 3.1.

Table 3.1 Main agricultural feedstock categories covered by the study

	Biomass Category	Biomass Type	Biomass Subtype
Biomass from agriculture	Energy crops	Cellulosic energy crops	Herbaceous grasses
			Short Rotation Coppice (SRC)
		New low-ILUC energy crops, including new oil crops	
	Primary crop residues	Cereal straw	Wheat
			Barley
			Triticale
			Rye
			Oats
		Maize stover	
		Rapeseed straw	
		Sunflower stalks	
		Prunings	Wine prunings
			Olive prunings
	Secondary crop residues	Cereal processing residues	Wheat and barley bran
		Sugar beet processing residues	Pulp and molasses
		Maize cobs	
		Oil crop processing residues	Rapeseed and sunflower meal
		Potato pulp and peels	
		Grape processing residues	
		Olive processing solid residues	
	Manure		
	Grassland biomass		

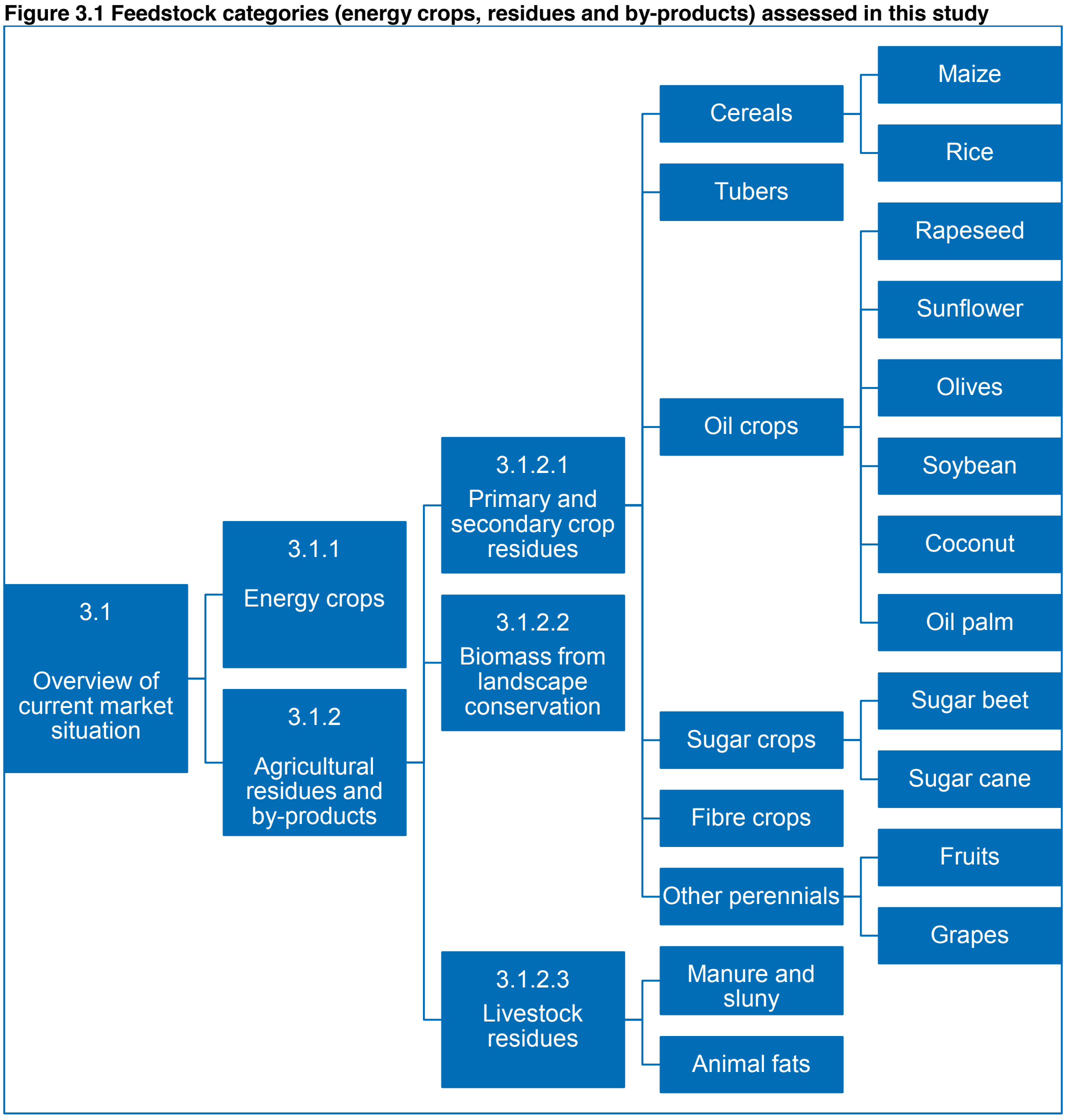
3.1 Brief overview of current market situation and agricultural biomass potential

Agriculture is acknowledged to be a key for genuine, large expansion of biomass supply in future (EC Biomass potential, 2017). On the other hand – there is a high uncertainty regarding how much agricultural feedstock can be mobilized for bioenergy production still fulfilling the sustainability criteria. Conventional biofuels have experienced strong criticism regarding their environmental benefits; primary related to the concerns about indirect land use change (ILUC) impacts and associated emissions. Given these concerns, attention has turned to the greater use of biomass residues, including agricultural residues, for producing bioenergy as a means of alleviating the pressures on land and other environmental resources at the same time as producing considerable greenhouse gas (GHG) savings compared to fossil fuels (Kretschmer et al., 2012).

In this chapter a general overview of current market situation of energy crops and agricultural by-products and residues is provided, indicating their availability and potential, present use and main challenges for their large scale utilisation as bioenergy feedstock.

The overall structure of chapter 3.1 is presented in Figure 3.1.

Figure 3.1 Feedstock categories (energy crops, residues and by-products) assessed in this study



3.1.1 Energy crops

Energy crops are usually classified based on different criteria. According to their biomass that is used for bioenergy purposes energy crops can be classified in four large groups (Yan, 2015):

- Sucrose derived (sugar crops) – e.g., sugarcane, sugar beet, sweet sorghum;
- Starch derived (starch crops) – e.g., maize, cereals, cassava;
- Plant oil derived (oil crops) – e.g., oil palm, soybean, rapeseeds, sunflower, jatropha;
- Lignocellulose derived (lignocellulosic crops) – e.g., fast growing trees like willow and poplar, switch grass, miscanthus.

Many energy crops cover different groups when they are cultivated and used for multiple purposes. For example, cassava – can be starch-derived energy crop when its roots are used for bioethanol production and can also be lignocellulose-derived crop as its stems and fermentation residues from roots can be combusted or used for bioethanol, methane and bio-hydrogen generation.

Sugar, starch and oil crops are 1st generation energy crops, and are the subject of concern regarding sustainability and competition with food/feed crops for the use of land. Therefore from the four above mentioned groups probably the most promising biomass for bioenergy is the lignocellulosic crops. Lignocellulosic crops belong to the 2nd generation feedstocks and represent the largest quantity of biomass on the Earth. Lignocellulosic feedstocks are in most cases perennial crops (they can be cut and harvested for biomass over successive years without re-cultivation or sowing) and they provide a range of environmental benefits compared to annual crops. Cellulosic crops are seen as the best option for large-scale, sustainable bioenergy production because: i) they have much higher yields (whole plant can be used for energy production); and ii) they do not compete for the land use with food production.

While sugar, starch and oil crops are usually called conventional energy crops, lignocellulosic crops which are grown purely for energy and have no use as food or fibre are called dedicated energy crops. Two broad types of dedicated energy crops are distinguished: **perennial herbaceous agricultural crops** and **woody short rotation crops** (see Table 3.1). Besides that, in Europe an increasing research effort is made on developing new generation oil crops like camelina and crambe.

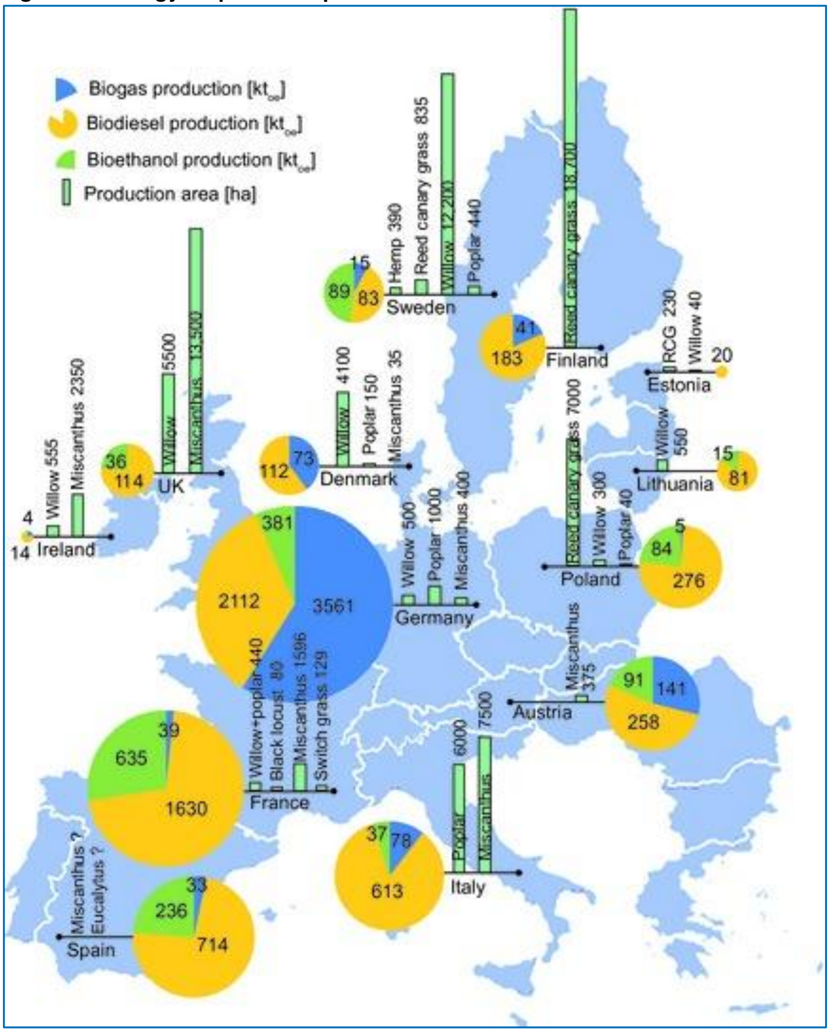
Table 3.2 Dedicated energy crop categories and examples (Allen et al., 2014)

Category	Definition	Examples
Perennial agricultural crops (Herbaceous grasses)	Perennial crops are crops that can be harvested on average once a year over several years without the need for ploughing up and new planting. Perennial energy crops of interest are mainly herbaceous grasses.	Miscanthus Switchgrass Reed canary grass Giant reed Perennial rye grass (*Lolium perenne*)
Short rotation coppice (SRC) and Short rotation forestry (SRF)	SRC refers to plants and trees that are harvested by cutting the growing stem to its base, allowing the growth of new stems. SRF refers to the whole felling of trees, often at a size of 10-20 cm diameter at breast height. Tree species used in SRF are fast growing.	Willow (*Salix sp.*) Poplar (*Populus sp.*) Eucalyptus Nothofagus (southern Beech) Poplar

It is estimated that in Europe there are approximately 5.5 million ha of agricultural land on which bioenergy cropping takes place. This amounts to 3.2 % of the total cropping area in Europe (Khawaja and Janssen, 2014; Panoutsou et al., 2011). Most of this land is cultivated with the 1st generation crops – oil crops for biodiesel production (82 %) and sugar and starch crops that are used for the production of bioethanol (11 %). The biggest cultivation areas can be found mostly in France and Germany but also in the UK, Poland and Romania. Whole crops grown as feedstock for biogas production (e.g. maize) also take up an important part of that land (7 %), especially in Germany.

2nd generation lignocellulosic crops grown for electricity and heat generation play a minor role (<1 %), accounting for only about 50,000 – 60,000 ha of land. The largest areas of non-food lignocellulosic crops are in the UK (mainly miscanthus and willow), Sweden (willow, reed canary grass), Finland (reed canary grass), Germany (miscanthus, willow), Spain and Italy (miscanthus, poplar) – see Figure 3.2 for production area (ha) of dedicated energy crops and energy production (ktoe) of conventional energy crops in Europe in 2009/2010. Statistical data of non-food lignocellulosic crops plantations are almost inexistent in many European countries (Khawaja and Janssen, 2014).

Figure 3.2 Energy crops in Europe



Source: Energy crops in Europe: production area (ha) of dedicated... - Scientific Figure on ResearchGate. Available from: https://www.researchgate.net/figure/230186503_fig3_Figure-1-Energy-crops-in-Europe-production-area-ha-of-dedicated-energy-crops-and [accessed Aug 19, 2016].

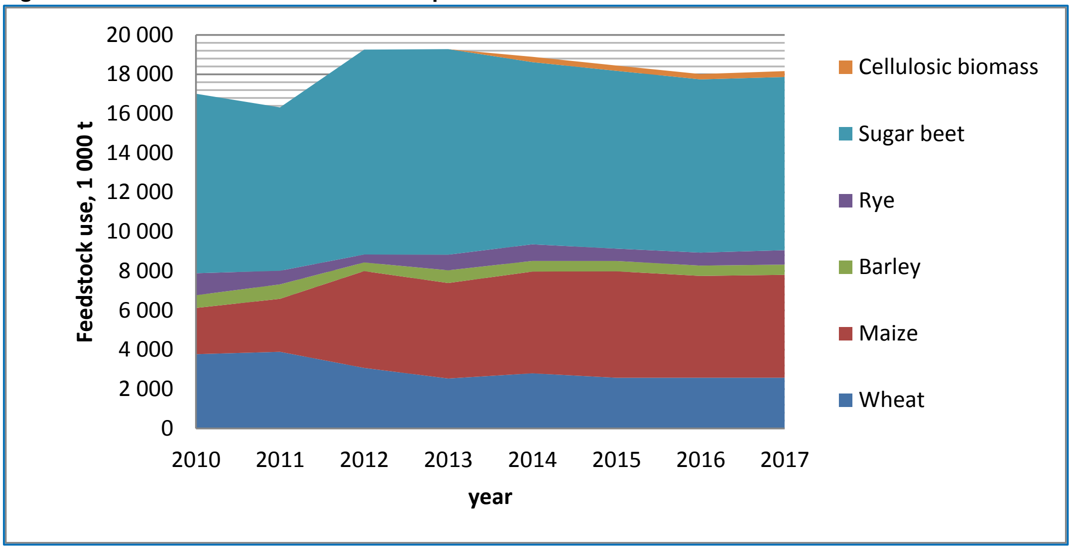
As mentioned before, currently biofuel production strongly builds on using 1st generation energy crops. A recent report from USDA Foreign Agricultural Service (GAIN, 2016) provides an overview about the feedstock use for bioethanol, biodiesel and hydrogenated vegetable oil production in EU, including forecasts for years 2016 and 2017.

According to (GAIN, 2016) In the EU, bioethanol is mainly produced from grains and sugar beet derivatives. Wheat is mainly used in North-Western Europe, while maize is predominantly used in Central Europe. Maize is the preferred grain in Hungary, the Netherlands and Spain. Maize for ethanol production is mainly sourced from the Ukraine. This is partly because of its non-genetically modified (GM) content. Producers in North-Western Europe prefer to market their by-product of ethanol production – distillers dried grains as non-GM to the domestic feed market.

In France, Germany, Belgium and the Czech Republic sugar beets are used for the production of bioethanol. Beet ethanol produces higher savings towards the German GHG standards compared to wheat and corn.

In the EU, the required feedstock for 2016 production (5.05 billion litres of bioethanol) is estimated at 8.9 million tonnes of cereals and 8.8 million tonnes of sugar beets (see Figure 3.3). This is about 2.9 % of total EU cereal production and about 7.0 % of total sugar beet production (GAIN, 2016).

Figure 3.3 Use of feedstock for bioethanol production in EU



Source: own elaboration based on (GAIN, 2016).

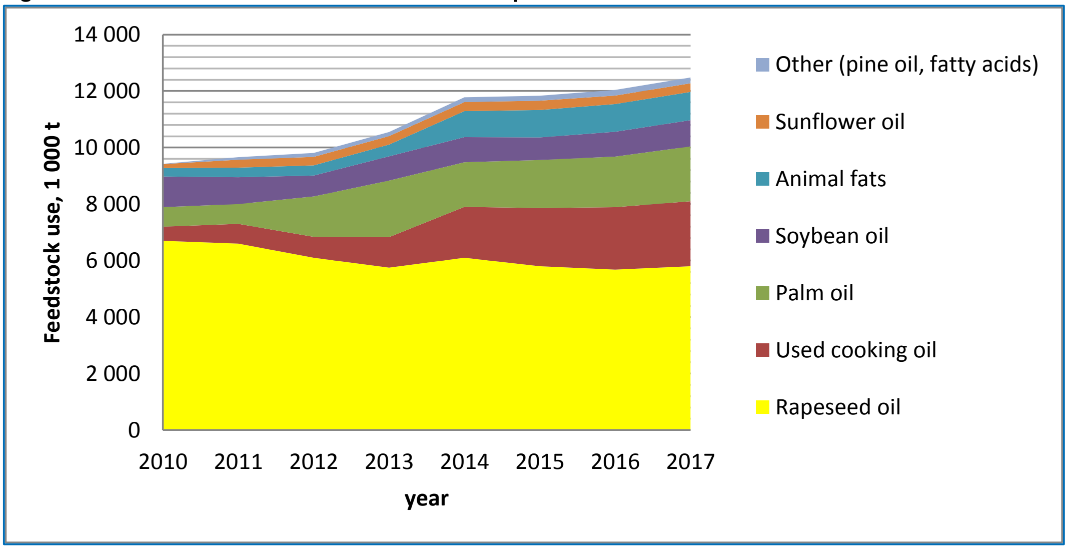
So far, commercial production of cellulosic ethanol is limited in the EU. 270,000 tonnes of cellulosic feedstock has been used in 2014. The same use of cellulosic biomass has been also estimated for 2015 and forecasted to remain stable in 2016. Increase to 300,000 tonnes is forecasted to 2017.

In 2013, Beta Renewables started the commercial production of cellulosic ethanol. Beta Renewables is a joint venture between Biochemtex, a company of the Italian Mossi Ghisolfi Group and the U.S. fund Texas Pacific Group (TPG). The Crescentino plant (located in Italy) has an annual production capacity of 75 million litres using 270,000 t of biomass. The feedstock consists of wheat straw, rice straw and husks, and *Arundo donax* – giant reed (an energy crop grown on marginal land).

The forecasted increase in lignocellulosic feedstock use is due to a new cellulosic ethanol plant in Finland. By the end of 2016, a cellulosic ethanol plant with an annual capacity of 10 million litres plans to be operational using saw dust as feedstock. (GAIN, 2016).

Rapeseed oil is the dominant biodiesel feedstock in the EU, accounting for 49 % of total production in 2015. However, its share in the feedstock mix has considerably decreased compared to 72 % in 2008, mostly due to the higher use of recycled vegetable oil/used cooking oil and palm oil (GAIN, 2016) – see Figure 3.4.

Figure 3.4 Use of feedstock for biodiesel and HVO production in EU



Source: own elaboration based on (GAIN, 2016).

The majority of rapeseed oil is of domestic origin. The 5.68 million tonnes of rapeseed oil feedstock projected for 2016 is equivalent to about 14.2 million tonnes of rapeseed. This also generates about 8.5 million tonnes of rapeseed meal as by-product, most of which is used for animal feed.

Palm oil and soybean oil came in third and fourth place in terms of feedstock use in 2015. The use of soybean and palm oil in conventional biodiesel is limited by the EU biodiesel standard European Norm EN14214 concerning iodine values. The iodine value functions as a measure for oxidation stability. In Spain higher iodine number is permitted and therefore it allows for an intensive use of soybean and palm oil in biodiesel production for domestic consumption. Palm oil-based conventional biodiesel does not provide enough winter stability in northern Europe.

Palm oil is mainly used in the Spain, the Netherlands, Finland, Italy, and France, and to a much lesser extent in Germany, Portugal, Romania, and Poland. The majority of soybean oil is used in Spain, France, and Italy. Smaller amounts are being used in Portugal, Germany, Bulgaria, Romania and the United Kingdom. The majority of palm oil is imported, while a large share of soybean oil is crushed from imported soybeans. The 0.88 million tonnes of soybean oil needed for the production in 2016 will have to be crushed from 4.4 million tonnes of soybeans. This will generate about 3.5 million tonnes of soybean meal. (GAIN, 2016).

Sunflower oil only comprised 3 % of the total biodiesel feedstock and is mainly used in France and Greece, together accounting for 81 % of EU sunflower oil based biodiesel production. (GAIN, 2016) Other oils used for biodiesel production in EU include pine oil and wood (in Sweden), fatty acids (in Germany), and cottonseed oil (in Greece).

Numbers given in Figure 3.3 and Figure 3.4 for 2015 are estimates, for 2016 and 2017 – forecasted values.

Future R&I challenges related to energy crops

The main challenges for using energy crops for future advanced biofuel production are related to further development of the 2nd and 3rd generation (algae) feedstocks, while the 1st generation conventional energy crops will be excluded due to sustainability, especially ILUC and competition with food/feed reasons.

The main challenge regarding dedicated energy crops is how to integrate these new bioenergy feedstock production systems into agricultural landscapes in ways that promote environmental, social and economic sustainability of the agricultural production. (Dimitriou, 2016)

3.1.2 Agricultural residues and by-products

This chapter provides an overview of the agricultural residues and by-products, their availability and markets. The description is structured in three parts – addressing crop residues, biomass residues from landscape conservation and maintenance works, and livestock residues.

Agricultural residues are generally divided into two categories: **primary agricultural residues** and **secondary agricultural residues**.

Primary residues are produced during the production of food crops (e.g. straw, stalks, stover and leaves). Such biomass is available in the field and must be collected to be available for further use. (Speight and Singh, 2014)

Secondary residues are generated during the processing of biomass for production of food products or biomass materials. For example, they include nutshells, bagasse, pulp etc. and are the by-product of agro-processing and food industries.

Both primary and secondary agricultural residues can be used for energy production. Many agricultural residues may have alternative uses or markets such as soil nutrient recycling and improvement purposes, and any decision to use them for energy must be made in the context of these alternatives. On the other hand, using agricultural residues as feedstock for bioenergy is strongly promoted since, compared to energy crops, the competition for resources and land use is largely avoided (Khawaja and Janssen, 2014).

3.1.2.1. Primary and secondary crop residues

Crop residue is plant material remaining after harvesting, including leaves, stalks and roots (OECD, 2001).

The amount of generated and available crop residues among other factors depends on the type of the crop, crop yield, crop rotation, agricultural management practices, climate, and physical characteristics of the soil (Batidzirai et al., 2016). Generally there are two methods used to calculate the amount of crop residues – expressed as a ratio of biomass production per hectare (t/ha) or per unit of product (kg of residue per kg of product). The former is usually referred as **Residue to Surface Ratio** (RSR) and the later as **Residue to Product Ratio** (RPR). (CIRCE, 2014; Biopact, 2006)

Table 3.3 summarizes the most significant crops on European and global level and residues related to their cultivation and processing, which can potentially be used for bioenergy purposes.

Table 3.3 Main crops and their primary and secondary residues

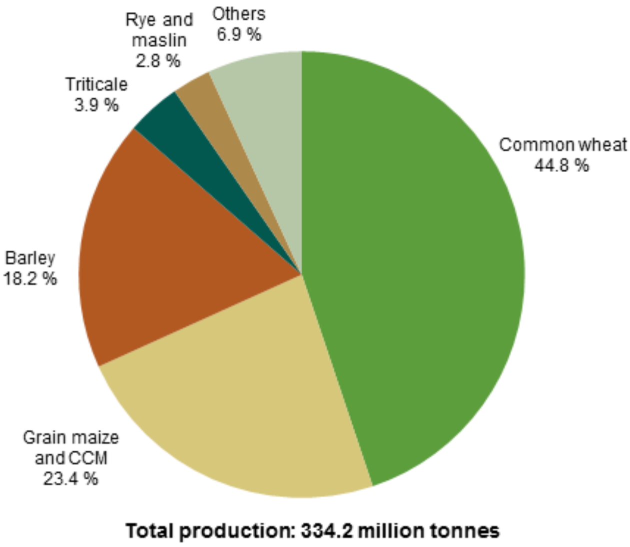
	Crop	Primary residues (generated at crop harvesting)	Secondary residues (generated during processing)
Annual crops	**Cereals (starch crops):**		
	Barley	Straw	Bran, brewers spent grains
	Maize	Stover, cob, husk	Brewers spent grains
	Millet	Straw	
	Oats	Straw	Bran
	Rice	Straw	Husk
	Rye	Straw	Bran, brewers spent grains
	Sorghum	Straw	
	Triticale	Straw	Bran
	Wheat	Straw	Bran, brewers spent grains
	Tubers (starch crops):		
	Cassava	Stalks (straw)	Peelings
	Potatoes		Peelings
	Sweet potatoes		Peelings
	Yams		Peelings
	Oil (/protein) crops:		
	Cottonseed	Stalk	Press cake
	Groundnuts	Straw	Husks/shells, press cake
	Rapeseed	Stalk (straw)	Rapeseed meal
	Soybean	Straw, pods	Soybean meal
	Sunflower	Stalks and dry heads	Hulls
	Sugar crops:		
	Sugar beet		Pulp, molasses
	Sugar cane	Trash (tops, leaves)	Bagasse, molasses
	Fibre crops:		
	Cotton lint	Stalk	
	Jute	Stick	Caddies
Perennial crops	Citrus fruits	Prunings	Peel
	Cocoa	Old trees, prunings	Pods
	Coconut (oil crop)	Wood, fronds	Husks, shells
	Coffee	Prunings, stalk	Husk, pulp
	Dry fruits	Prunings	Shells
	Grapes	Prunings	Grape pomace (marc)
	Oil palm (oil crop)	Tree trunks, fronds	Mesocarp fibre, kernel shells, empty fruit bunches, POME
	Olives (oil crop)	Prunings	Pomace, olive pits, waste water
	Rubber trees	Wood, leaves	
	Seed fruits	Prunings	Pomace
	Sisal (fibre crop)		Bogas, ball
	Stone fruits	Prunings	Stones

Additional information about the most widespread annual and perennial crops worldwide and in Europe is provided in Annex I. This information includes production share of the certain crop product by global regions, top 5 producer countries and references to RPR or RSR values of the respective crop residues, where available from the literature.

Cereal residues

The harvested production of cereals (including rice) in the EU-28 was estimated to be around 334.2 million tonnes in 2014 (see Figure 3.5). This represented about 13 % of global cereal production, making the EU one of the world's biggest producers of cereals. In Europe the most grown cereals are wheat, followed by grain maize and corn cob mix, barley, triticale and rye.

Figure 3.5 Production of cereals in EU-28, 2014 (% of total production of cereals)



Source: (EUROSTAT, 2016a).

Among the EU member states the most cereals are produced in France, Germany, Poland, UK and Romania (see

Table 3.4).

Table 3.4 Production of cereals in Europe, by country, 2014 (1,000 tonnes)

	Total (incl. rice)	Common wheat and spelt	Rye and maslin	Barley	Grain maize and CCM	Triticale
EU-28	334,182	149,862	9,345	60,711	78,170	13,163
Belgium	3,173	1,919	:	400	779	40
Bulgaria	9,523	5,319	28	851	3,136	60
Czech Republic	8,779	5,442	130	1,967	832	244
Denmark	9,764	5,153	678	3,548	73	96
Germany	52,010	27,711	3,854	11,563	5,142	2,972
Estonia	1,222	616	50	458	0	25
Ireland	2,567	710	0	1,710	0	0
Greece	4,670	581	35	395	2,170	22
Spain	20,397	5,699	229	6,934	4,692	450
France	72,715	37,501	128	11,775	18,542	2,023
Croatia	3,048	643	3	176	2,100	61
Italy	19,233	3,106	12	846	9,240	0
Cyprus	71	0	0	27	0	0
Latvia	2,227	1,468	114	419	:	27
Lithuania	5,123	3,231	85	1,019	115	395

	Total	Common	Rye and	Barley	Grain maize	Triticale
Luxembourg	169	78	6	46	2	30
Hungary	16,448	5,169	95	1,279	9,169	488
Malta	0	0	0	0	0	0
Netherlands	1,767	1,304	7	197	240	9
Austria	5,710	1,737	250	846	2,334	303
Poland	31,951	11,636	3,229	3,275	4,468	5,246
Portugal	1,349	95	18	38	897	47
Romania	22,439	7,769	26	1,834	12,041	282
Slovenia	647	173	7	90	348	20
Slovakia	4,708	2,020	54	676	1,814	49
Finland	4,157	1,089	76	1,861	0	0
Sweden	5,790	3,088	176	1,573	11	226
United Kingdom	24,525	16,606	56	6,911	26	49
Norway	1,168	375	37	481	0	0
Turkey	32,382	15,706	301	6,300	5,950	110
Bosnia and Herzegovina	1,081	170	10	49	798	34

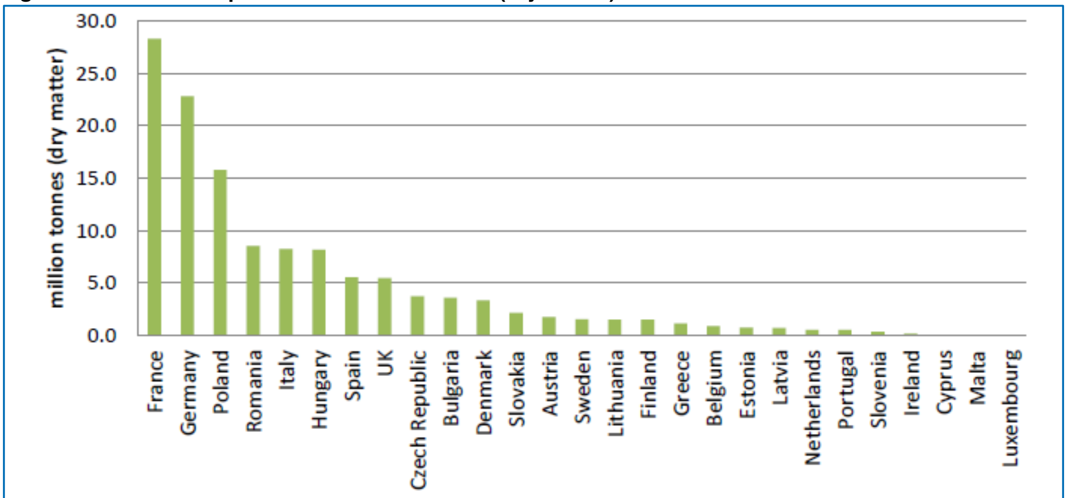
(EUROSTAT, 2016a).

On a global scale the most cultivated cereals are maize, rice and wheat. Global leaders in cereal cultivation are China, USA, India, Russia and Indonesia. Maize is produced for both – for grain and for forage/silage. The biggest grain maize producers are USA, China, Brazil, Mexico and Argentina, while maize for forage is produced mostly in USA, Germany, France, Russia and Ukraine. In 2013 more than 1.017 billion tonnes of maize have been produced globally. 11.7 % of the global maize production has been cultivated in Europe (FAOstat, 2013). Global rice production in 2013 accounted for around 0.738 billion tonnes. Top 5 rice producers are China, India, Indonesia, Bangladesh and Viet Nam (FAOstat, 2013).

Straw cereal

The main by-product from cereal cultivation is straw. A comprehensive study on the mobilization of cereal straw in EU for advanced biofuels production (Kretschmer et al., 2012) reviews estimates on cereal straw potential in Europe from different studies and provides the technical potential in a range of 50 - 110 million tonnes (dry matter) of straw per year. For 2020 the projected technical potential of the cereal straw is 106 - 127 million tonnes (dry matter) (Kretschmer et al., 2012). Distribution of the technical potential among EU countries is given in Figure 3.6.

Figure 3.6 EU27 straw potential in million tonnes (dry matter) for 2020



Kretschmer et al., 2012.

Future availability of the cereal cultivation by-products for bioenergy purposes is however restricted by sustainability requirements and alternative markets and uses. Examples of the main conventional uses of cereal straw are summarized in Table 3.5. (NL Agency, 2013) draws attention to two particular challenges of straw with regard to applications for bioenergy purposes: i) high carbon-to-nitrogen content that leads to a very low bio-degradability in comparison to other agricultural residues (problematic in anaerobic digestion); and ii) high ash, potassium and chlorine content and high inorganic composition making thermal conversion (e.g., combustion and gasification) of straw challenging. Denmark is the most experienced country in using straw for combustion and a lot of research activities regarding estimation of straw resources, logistics and organisation of supplies, utilisation of ash and other residues are carried out in Denmark. However, the future of large scale utilisation of straw is seen in the production of advanced biofuels.

Table 3.5 Examples of the main conventional uses of cereal straw and alternatives (Kretschmer et al., 2012)

	Use	on/off site	Alternative
Uses *within* the agriculture sector	Soil improver	ON	Manure, commercial (fossil fuel based) fertilisers, green manure and cover crops
	Animal fodder supplement	OFF/ON	Hay, silage, commercial feed, out grazing
	Animal bedding	OFF/ON	Sawdust, wooden slats, other dried plant residues.
	Mushroom production (growth substrate)	OFF	Compost, sawdust, other lingo-cellulosic material
	Frost prevention in horticulture	OFF	Limited commercial alternatives, plastic sheeting is used, but still requires some straw
	Strawberries (preventing damage to fruit)	OFF	Matting or plastic sheeting
	Compost industry	OFF	Wood chip, other plant fibre with low nitrogen content
Outside the agriculture sector	Thatching	OFF	Straw thatching is locally specific. Reeds are a common alternative
	Traditional building materials (combined with mud to make cobb bricks, used as insulation, or combined with wood chippings to make fibreboard.)	OFF	Alternatives include all common building materials.
	Energy (heat and power, fuels)	OFF	Other combustible residues depending on boiler structure / other biofuel feedstocks

Previous studies are highlighting the fact that technically there appears to be significant volumes of straw that could be mobilised, and potentially used for the production of cellulosic ethanol (Kretschmer et al., 2012). However, the economic potentials are much lower and constrained by the market, competing uses of straw and underdeveloped supply chains. In addition, it is unclear how great a demand will be for straw to be used as a material input in other industrial sectors, such as the emerging bio-materials and bio-chemicals sectors. (Kretschmer et al., 2012)

Maize cultivation and processing by-products

Cultivation of maize generates comparatively high share of residues related to the product (maize grain). The RPR values reported in different studies (Koopmans and Koppejan, 1997; Mai-Moulin et al., 2016) show that production of 1 ton of maize grain can produce as much as 2.5 – 4.3 tons of residues (stover, corn cobs and husks). Bloomberg New Energy Finance study (BNEF, 2010) has estimated the technical potential of maize stover in Europe in 2020 equal to 18 million tonnes (dry matter). In Europe experiences exist in using corn cobs, corn cob grits and pellets as fuel in farm-scale and household boilers, for example in Austria (Sucellog, 2015). In USA corn cobs and husks to limited extent are used for industrial purposes – for bedding, oil sorbents and polishing agents (Extension, 2014). However there is much unexploited potential to use these residues for direct combustion, co-firing applications, gasification and cellulosic advanced biofuels production. Two of the limiting issues for enhanced use of these corn cobs, maize stover and husks are the need for a significant local resource base and the development of harvesting equipment, which would be compatible with current corn-harvesting (Extension, 2014).

Rice cultivation and processing by-products

Besides straw, the cultivation of rice results in residues in form of husk. Rice straw and husk both have attractive potential in terms of energy (BioEnergy Consult, 2015). Rough estimations on rice straw availability based on rice paddy production data in 2009 are given in the study of NL Agency (NL Agency, 2013). Authors estimated global production of rice straw to be 727.4 million tonnes, including 4.5 million tonnes generated in Europe.

Rice husk is the main by-product of rice milling (secondary residue) and the resource is concentrated at processing plants. Husk is the outermost layer of protection encasing a rice grain. It is a yellowish colour and has a convex shape. It is slightly larger than a grain of rice, thus lengths up to 7 mm are possible. Typical dimensions are 4 mm by 6 mm. It is lightweight, have a ground bulk density of 340 – 400 kg/m^3 (Ricehusk, 2017).

Rice husk accounts for roughly 22 % of paddy weight, while rice straw to paddy ratio ranges from 1.0 to 4.3. Although the technology for rice husk utilization is well-established worldwide, rice straw is sparingly used as a source of renewable energy. One of the main reasons for the preferred use of husk is its easy procurement. In case of rice straw, however, its collection is difficult and its availability is limited to harvest time (BioEnergy Consult, 2015).

Compared to rice straw the logistic effort for husk collection is much lower and therefore it is more attractive for potential users. According to (Ricehusk, 2017), the uses of rice husk are continuously growing. It is used as main fuel or for co-firing in power plants in Asia. Besides energy production, rice husks are used in horticulture (aeration of soil), as animal bedding and as raw material for composite materials production industries. New rice husk based products like grounded rice husks, rice husk pellets and bales are also offered to the European market.

Tuber and tuberous root crop residues

Tubers are starch crops and therefore along with cereals are used as feedstock for the 1st generation biofuels production. For example, potatoes contain up to 19 % starch, cassava around 40 % and sweet potato up to 70 %, the latest in terms of starch content being comparable to wheat and corn.

The most cultivated tuber globally and also in Europe is potato. In 2014, 59 million tonnes of potatoes were harvested in the EU. Germany was the biggest producer, with a share of 19.7 %, ahead of France (13.6 %), Poland (12.6 %), the Netherlands (12.0 %) and the United Kingdom (10.0 %). (EUROSTAT, 2016b)

Besides potatoes globally significant tubers are cassava, sweet potato and yam. Cassava is an important food and feed crop in many tropical countries – the main producers are Nigeria, Brazil, Thailand, Indonesia and Democratic Republic of Congo. Cassava can also be cultivated on drier or poorer soils. Sweet potatoes are mainly produced in China. Yam is a food crop originating from West Africa and Asia. The main producers of yam are Nigeria, Côte d'Ivoire, Ghana, Benin and Togo. (FAOstat, 2013)

In recent years, the food versus fuel debate has focused attention on the use of waste from potato processing industries (e.g. starch extraction, whole potato powder production, chips) as a biofuels feedstock (EBTP, 2016). However, outside Europe the research and developments regarding first generation bio-ethanol production from tubers is ongoing. For example, China is a big promoter of cassava as biofuel feedstock. In Thailand, the amount of ethanol produced from cassava has been expected to double to 3 million tonnes in 2014. There are further plans to build a cassava-to-bioenergy refinery in Nigeria (with a potential 9 more to follow) and one cassava-to-ethanol facility is in operation in Mozambique. (EBTP, 2016).

Potato processing by-products

According to (Izmirlioglu and Demirci, 2016) potato processing industry usually yields up to 50 % of the incoming potatoes as waste (10 % waste potato pulp, 5 - 20 % cull potatoes, and 15 - 40 % peel). Industrial processing of potatoes generates between 70 and 140 thousand tons of peels worldwide annually and is traditionally used for production of low quality animal feed, as fertilizer or feedstock for anaerobic digestion (Wu, 2016). Several studies demonstrate the potential of using industrial potato waste (including potato peels, potato mash, potato pulp, and potato processing wastewater) for the production of bioenergy (biogas, bioethanol) and bio-based chemicals and materials like glucoamylase, lactic acid, phenolic acids, steroidal alkaloids and pullulan. (Izmirlioglu and Demirci, 2016; Wu, 2016).

Oil crop and olive oil residues

Two main oilseed crops produced in Europe are rape (and turnip rape) and sunflower. From 24.3 million tonnes of rape and turnip rape produced in 2014, Germany produced more than a quarter (25.7 %). The production of sunflower seeds in Europe in 2014 reached 9.0 million tonnes. Bulgaria and Romania were the leading producers of sunflower in 2014, with shares of 22.2 % and 23.6 %, respectively. (EUROSTAT, 2016a)

Another important oil crop in Europe is olives. Olive trees are perennial crops. In 2014, the EU was the largest producer of olive oil in the world, accounting for almost three quarters of global production. Olive trees are grown in Spain, Italy, Greece, Portugal, France, Croatia, Cyprus, Slovenia and Malta – although 99.5 % of the olive production in the EU-28 in 2014 was concentrated in the first four of these nine EU Member States. (EUROSTAT, 2016a)

In recent years more than 2.3 million tonnes of olive oil have been annually produced in EU. (Zolichová, 2016).

Globally the most cultivated oil crops are oil palm, soybeans (the second largest source of vegetable oil in the world), rapeseed (canola) and coconut. The biggest soybean producers are USA, Brazil, Argentina, China and India. The main rapeseed producers are China, Canada, India, Germany and France. Coconuts are mostly cultivated in Indonesia, Philippines, India, Brazil and Sri Lanka and oil palm – in Malaysia, Indonesia, Nigeria, Thailand and Colombia (FAOstat, 2013). Other oil crops found among the top 50 global commodities (FAOstat, 2013) are cotton seed, ground nuts (peanuts) and sunflower seed.

Cultivation of oil cops results in primary residues like straw, stalks and wood. Following processing operations of crops generate secondary residues like press cakes, husks, shells, pomace, kernels, pits, empty fruit bunches etc.

Rapeseed cultivation and processing by-products

Rapeseed can be harvested using two methods: i) Direct thresh where grains are black and are rustling in the pod (straw can be partly green) and ii) Swath thresh where plants are cut and put on swath when grains start to burnish on both sides. After swath thresh, the straw has a dry matter content of about 90 % and can be pressed into square bales for transportation. At the harvest, about 50 cm of the rape straw is left on the field. The maximum rape straw recovery rate is 50 - 80 % of the whole crop residues (5 - 8 t/ha/year). (Kazimi, 2012)

Rapeseed oil extraction generates rapeseed meal as by-product. It is used as high quality protein source for livestock feed. The world rapeseed meal production was 39.1 million tonnes in 2015/2016 and has almost doubled since 2003. In 2014, the main producer of rapeseed meal was the European Union (13.9 million tonnes), followed by China (9.9 million tonnes), North America (4.9 million tonnes) and India (3.7 million tonnes). (Feedpedia, 2016a)

Sunflower cultivation and processing by-products

Sunflower is the fourth largest oil-seed source worldwide (Eom and Yu, 2014), with more than 25 million ha being cultivated. It has been estimated that each hectare of sunflower culture can produced 3 - 7 tons of dry biomass, including heads (10 %) and stalks (Díaz et al., 2011). After seed harvesting, sunflower stalks are usually left on the field, sometimes burned. To avoid negative environmental impacts, several attempts have been made to find new uses for sunflower residues. Some studies investigate the use of stalks as a raw material for paper pulp and for bioethanol production (Jung et al., 2013). Recent study (Kim et al., 2016) reports the use of saccharification residues of sunflower stalks for production of biopolyols and polyurethane. Sunflower heads contain pectins and a strong smelling essential oil; whole stalks can find use in paper pulp production, while low density materials can be obtained from ground stalk pith. (Díaz et al., 2011).

In addition sunflower residues can be used as forage. Sunflower forage is usually fed as silage. Threshed and dried heads of sunflower are a valuable feed. The dry heads can be made into a meal or mixed with other residues of sunflower harvest and oil extraction (sunflower screenings). The stems are a poor feed and are usually either ploughed in or used as fuel. (Feedpedia, 2016b)

Secondary residues generated during processing of sunflower seeds are hulls. Sunflower hulls are the by-product of the de-hulling of sunflower seeds before they are used for oil extraction or as bakery ingredients. Sunflower seeds contain about 20-30 % hulls that are often removed before oil extraction due to their deleterious effects on oil presses and because they reduce the quality of both oil and meal. A well-managed de-hulling process yields seeds with 8-12 % hulls remaining on the kernels. In new sunflower varieties, breeders have enhanced oil content at the expense of hulls, resulting in seeds with thinner hulls that are difficult to remove: these varieties remain un-decorticated and do not yield sunflower hulls. (Feedpedia, 2016c)

About half of the hulls are used in oil mills as fuel for covering internal energy demands. The other half of the hulls has to be disposed or used for other purposes, e.g., composting, bedding material, or as a low-quality roughage for livestock (Feedpedia, 2016c). Sunflower hulls have been also used as raw material for ethanol production. (Díaz et al., 2011).

Olive tree cultivation and olive processing by-products

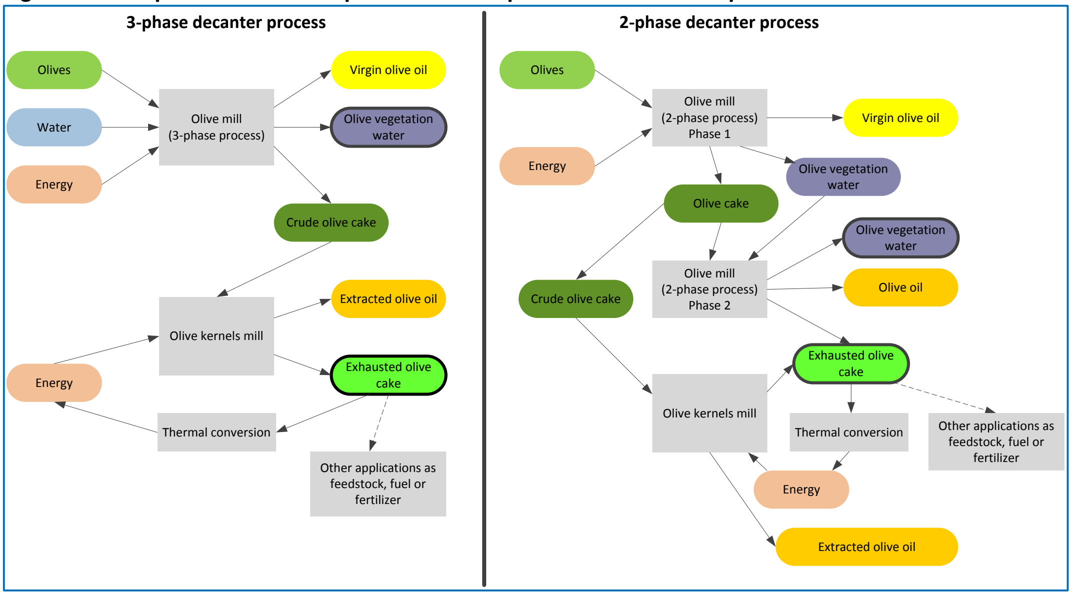
Olive trees are the main cultivated perennial crop in the EU. More than 4.4 million ha of olive plantations were in EU in 2011. In the last 15 years olive production has increased by 2 % annually (CIRCE, 2014). It is expected that in future olive plantations will continue to increase slightly, with a growing trend in Portugal and Spain, and decaying in Italy and Greece (due to CAP limitations). In addition there is expected conversion from traditional to more intensive exploitation. It includes an increase in the density of plantation, reduction of the tree size and increase of the pruning (not biennial anymore, but annual) and therefore will result in different size and shape of the prunings. Traditional fields with densities from 100-400 trees per hectare and with age older than 50 years currently represent 59 % of the olive plantations in Europe (CIRCE, 2014). In case of expansion of intensive systems, traditional exploitations will be replaced gradually. Therefore traditional systems will still remain the major cultivation practice for many years.

Primary residue of olive cultivation comes from pruning. The material obtained during the pruning operations of olive trees includes both – branches and leaves. If brunches after pruning are left for some weeks in a field, the leaves wither and are not possible to be collected during the harvesting of brunches. Pruning is usually carried out from January to March/April and frequently done both on annual and biennial basis (called green pruning). A renovation pruning (removing of old branches) is done each 5-10years. Olive pruning yields in 1-2 t(FM)/ha/year of thick branches and 2 t(FM)/ha/year of smaller branches, including leaves. During renovation pruning the yield may increase up to 4.37 – 7 t/ha. The average outcome of olive trees pruning residues used in (CIRCE, 2014) is 1.38 t(DM)/ha.

Around 75 % of pruning material is currently piled and burned at the side of the field, 5 % is shredded and left on the soil as organic fertiliser. Around 15 % consisting of thick branches is used as firewood for domestic applications and 5 % are sold to commercial energy production plants. (CIRCE, 2014)

Secondary residues are generated during olive processing operation and extraction of olive oil. Processing of olives results in 21 % of oil, 3-5 % of leaves and 35-45 % of crude olive cake. In addition, for each processed kg of olives, 0.85-1.75 kg of olive vegetation water is generated in olive oil production process (Eleftheriadis). There are 3 olive processing methods used for extraction of the olive oil: i) traditional pressing; ii) 3-phase decanter and iii) 2-phase decanter. The principle of the two latest methods with inputs, processing steps and outputs (products and wastes) is illustrated in Figure 3.7.

Figure 3.7 Comparison of 3 and 2-phase decanter processes in olive oil production



Source: own elaboration after (Eleftheriadis).

Further comparison of all three olive oil extraction methods and resulting by-product amounts is provided in Table 3.6. During olive oil extraction processes certain amounts of solid waste products (exhausted olive cake) and liquid waste products (olive vegetation water/waste water from process) are generated. Depending on the used extraction process, the moisture content of the olive cake is changing from relatively dry (M = 25 %) to very wet product (M = >50 %).

Table 3.6 Comparative data for three olive extraction processes

Production process	Inputs		Outputs	
Traditional pressing	Olives	1000 kg	Oil	200 kg
	Washing water	0.1-0.12 m^3	Solid waste (M=25% + 6% oil content)	400 kg
	Energy	40-63 kWh	Waste water (12% DM)	600 kg
Three-phase decanter	Olives	1000 kg	Oil	200 kg
	Washing water	0.1-0.12 m^3	Solid waste (M=50% + 4% oil content)	500-600 kg
	Fresh water	0.5-1 m^3	Waste water (5% DM + 1% oil content)	1000-1200 kg
	Water to polish impure oil	10 kg		
	Energy	40-63 kWh		
Two-phase decanter	Olives	1000 kg	Oil	200 kg
	Washing water	0.1-0.12 m^3	Solid waste (M=60% + 3% oil content)	800-950 kg
	Energy	<90-117 kWh		

Source: own elaboration after (Eleftheriadis).

Currently part of the extracted olive cake is used as fuel to satisfy the internal energy demand of olive kernel mills. Remaining part of the cake is composted, used as fertilizer or is further processed and used as fuel (e.g. pellets, olive pits). Olive cake can be potentially used as feedstock for advanced biofuels and bio-material production. Liquid waste can be used for production of biogas in anaerobic digestion.

Soybean cultivation and processing residues

Soybean is typically harvested when beans mature (e.g. in Thailand after 90 days from planting), when the leaves of the soybean turn brown and fall off. Harvesting is done by uprooting the whole plant or by cutting the plant at the ground level. The next step is threshing which consists of separating the beans from the part of the plant that holds them. Based on extensive literature review, (Searle and Malins, 2013) report that 2.5 tonnes of field residues (straw) are produced per tonne of harvested beans and additional 1 tonne of residues (pods) are generated in further processing.

If used for oil extraction, after threshing, soybeans are delivered to the oil mill. Main steps of the soybean oil extraction process are described by (Patthanaissaranukool and Polprasert, 2016). Oil from the grains is extracted using solvent extraction process, where most often Hexane is used as a solvent. First the soybeans are cleaned, dried and de-hulled before oil extraction. Keels are removed by cracking the soybean and machine separation. Then, the soybeans are heated to about 75^{o}C to coagulate the soy protein to make the oil extraction easier.

In the next step soybeans are cut in flakes and mixed with hexane. After that, the extracted flakes (also called soybean meal) contain only about 1 % of oil. Around 764 kg of meal per tonne of processed soybeans are generated. Soybean meal is normally used as livestock and aquatic feeds. The hexane is separated from soybean oil in evaporators. The evaporated hexane is recovered and returned to the extraction process. In the end the oil is purified by degumming, bleaching and refining.

Coconut cultivation and processing by-products

Coconut trees generate residues in the form of wood, fronds, husks and shells. The productive life of the tree varies between 50 and 100 years. Part of the wood is used as timber while another part is available as a source of energy (Koopmans and Koppejan, 1997).

Coconuts (on a wet basis) consist of husks (33-35 %), shell (12-15 %), copra (28-30 %) and water (22-25 %). The total amount of generated residues depends on the scale of the plantation, varieties of plants, management practices and type of harvesting. In average it can be assumed that 0.419 tonnes of husks and 0.12 tonnes of shells per tonne of coconuts are generated (Koopmans and Koppejan, 1997).

A study about coconut residues in Kenya (Mai-Moulin et al., 2016) describes current uses of coconut husks: mulching and using it as fertilizer (14-18 %) and utilisation as fuel in households (10-30 %).

Oil palm cultivation and processing by-products

Oil palm cultivation is generating field residues in form of leaves (called fronds) and trunks. Fronds are used as mulching agent and fertilizer. Most of the fronds are left on the field to maintain soil fertility (Diaz-Chavez et al., 2016; Mai-Moulin, Junginger et al., 2016).

After harvesting, the fresh fruit bunches are transported to milling facilities to be processed into palm oil (Mai-Moulin, Junginger et al., 2016). The types of residue generated by the palm oil industry include empty fruit bunches (EFB), palm mesocarp fibre and palm kernel shell. EFB is the residue generated at the thresher, where fruits are removed from fresh fruit bunches. Mesocarp fibre is generated at the nut/fibre separator while kernel shell is generated from the shell/kernel separator (Mai-Moulin, Junginger et al., 2016). Besides solid by-products, an effluent called POME is produced. It has high organic matter and can be used for biogas production.

One tonne of fresh fruit bunches results in around 200 kg of empty fruit bunches, 136 kg of fibre and 56 kg of shell. EFB has average dry matter content of 35 %, fibre – 65 % and shell – 86 %. A study carried out in Colombia indicates that 24.8 % of EFB are used for composting, 63.8 % are returned in field and 11.4 % have other uses. Fibre and shells are mostly (more than 70 %) used for energy production in oil mills (Diaz-Chavez et al., 2016).

In Indonesia high quantity of EFB is disposed of to an unmanaged, deep landfill located next to the palm oil mill. This type of disposal causes environmental problems in the surrounding areas and contributes to global warming. Fibres are generally burned in the mill for power generation, small fraction is sometimes sold as fuel. Shells are mostly used as fuel for the mill and to cover the roads in the plantation. In some cases shells are used by cement companies as fuel (Mai-Moulin, Junginger et al., 2016).

Sugar crop residues

Globally two most important sugar crops are sugar cane and sugar beet. The latest being the major crop for sugar and bioethanol production in Europe. Beet sugar represents 20 % of the world's sugar production and 80 % are produced from sugar cane.

Sugar beet cultivation and processing by-products

In 2014, the EU-28 produced 128.4 million tonnes of sugar beet. More than half of the amount has been produced in France and Germany. The EU is the world's leading producer of sugar beet, with around 50 % of the global production. Most of the EU's sugar beet is grown in the northern part of Europe, where the climate is more suitable. The most competitive producing areas are in northern France, Germany, the United Kingdom and Poland. (EUROSTAT, 2016a)

In commercial sugar beet harvesting sugar beet leaves are not separately collected, but left on the field as organic fertilizer. Sugar beet leaves has low organic dry matter content (around 15 %). (Schaffner et al., 2011) reports that 42 t(FM)/ha is a common yield of sugar beet leaves in Germany. Low organic dry matter content increases transportation costs and make difficult to use the material for silage. If leaves are collected, they are mostly used directly as animal feed. In a study dedicated to biogas production potential from sugar beets (Schaffner et al., 2011) it is estimated that collection of sugar beet leaves would impose additional costs of around 80 € per hectare. (data for Bavaria, Germany, 2011).

When harvested, beet root accounts for 70.7 % of the total mass, whereas beet tops are 25.6 % and soil 3.8 % (Boldrin et al., 2016). Beets are used mainly for sugar production and for bioethanol generation.

Beet-sugar industry generates as by-products sugar beet pulp and molasses. It is estimated that one tonne of the processed sugar beet yields from 170 to 330 kg of wet sugar beet pulp (Borowski et al., 2016). Traditionally sugar beet pulp is dried, pelletized and then used as an animal feed. However, these operations consume 30-40 % of the overall energy costs of sugar beet processing and therefore alternative uses are investigated. For example, high contents of cellulose, hemicelluloses and pectic substances in pulp make this product attractive for bioethanol production. (Borowski et al., 2016).

Molasses is a co-product of sugar production from sugar beet. Sugar beet molasses contain 23-26 % water, 47-48 % sugar, 9-14 % minerals (Mg, Mn, Al, Fe and Zn) and 8-12 % nitrogenous compounds (aminoacids, proteins, etc.) (Taskin et al., 2016). It is used in the animal feed, yeast, citric acid, alcohol, and pharmaceutical industries (Abe et al., 2016) and can also be used as binder for straw pellets production (Mišljenović et al., 2016). List of further uses of molasses reported in scientific literature is given in (Sarka et al., 2012). One tonne of processed sugar beet will result in 0.04-0.06 tonnes of molasses. (Hansa Melasse, 2016).

Sugar cane cultivation and processing by-products

In comparison to other crops, sugar cane gives a very high dry matter yield per unit of land area (Koopmans and Koppejan, 1997). Sugar cane cultivation and processing generates two types of by-products. Sugar cane trash is a by-product obtained in a field and it is made of brown leaves, green leaves and the green tops of the cane. Trash is left in the field during mechanical harvesting. Trash amounts for 149 kg (dry matter) per tonne of harvested sugarcane. Trash is generally left in the field and arranged into rows manually as to not cover the new sprouts (Diaz-Chavez et al., 2016). Sometimes leaves are used as cattle feed or are burnt in the field (Koopmans and Koppejan, 1997). In Kenya sugar cane stalks/leaves mostly (75-85 %) are left on field as fertilizer, 10-20 % is sold to farmers for animal feed and 5-10 % burnt on ground as fertilizer. (Mai-Moulin et al., 2016).

Additional by-products are generated during sugarcane processing. These are bagasse and molasses. Bagasse is generated in sugar mills amounting to 140 kg (dry matter) per tonne of harvested sugar cane (Diaz-Chavez et al., 2016). Bagasse is currently used in the mills to produce energy for the sugar and ethanol production processes. For example, in Colombia 80 % of produced bagasse is used for energy generation. Remaining 20 % of the bagasse is sold for pulp production (Diaz-Chavez et al., 2016). In Kenya 60-70 % of bagasse is used by sugar mills for steam generation. (Mai-Moulin et al., 2016).

Similar to beet-sugar production also in sugar cane processing molasses are produced as by-product. One tonne of sugar cane will give 100-110 kg of sugar and 30-40 kg of molasses (Hansa Melasse, 2016). In Kenya 72 % of molasses is used for ethanol production, 28 % for animal feed. (Mai-Moulin et al., 2016).

Fibre crop residues

The most important fibre crops in Europe are cotton, flax/linseed and hemp. Fibre crops are produced on approximately 400,000 ha. Cotton is cultivated mostly in Greece and Spain, flax/linseed – in France, Belgium and the Netherlands, hemp – mostly in France (ESA, 2016a). Globally the only fibre crop among top50 agricultural commodities is cotton. Majority of cotton lint is produced in China, USA, India, Pakistan and Uzbekistan.

Production of one kg of cotton lint generates 2.755 kg of stalks (Koopmans and Koppejan, 1997). Stalks are relatively dry having moisture content of only 12 %. Depending on the variety and the crop condition, the cotton stalks are 1 - 1.75 m long and their diameter just above the ground may vary from 1 to 2.5 cm. The properties (fibrous structure, energy content) of cotton stalks are comparable to ones of the low quality hard wood.

Current practice in India, Pakistan and Uzbekistan is to burn stalks after harvest on the field. Alternatively stalks are used as fuel for rural domestic applications (heating and cooking). There are commercial technologies on the market for pelletizing cotton stalks to increase their energy density and potential applications as higher quality solid biomass. (Amisy Machinery, 2016)

Other fibre crops which could be interesting for bioenergy due to their cultivation amounts and generated by-products are jute (annual crop) with jute sticks (Nayak et al., 2013) and sisal (perennial crop), generating bogas and ball (Mai-Moulin et al., 2016). Some reference values of residue to product ratios for these crops are given in Tables in Annex II.

Other perennial crop residues

Other perennial crops which have not been addressed before, but have potential for generating by-products which are attractive for energy uses include fruit trees (citrus, dry, seed and stone fruits) and grapes for vine production. Perennial crops require regular pruning and after a certain period of time – replacement of old non-productive plants. Thus significant amounts of primary residues are generated.

Fruit cultivation and processing by-products

The most cultivated fruits in Europe are apples. Around 14 million tonnes of apples were produced in the EU-28 in 2014. Apples are produced in almost all EU Member States, although Poland, Italy and France are by far the largest producers. Second important category is citrus fruits. Citrus fruit production in the EU is much more restricted by climatic conditions; the vast majority of citrus fruits (59.8 %) are produced in Spain (see Table 3.7). In the third position from the harvested amounts are peaches and nectarines.

Table 3.7 Production of fruit in Europe, by country, 2014 (1,000 tonnes)

	Apples	Peaches	Citrus fruits
EU-28	14,304	2,894	11,773
Belgium	318	0	0
Bulgaria	55	28	0
Czech Republic	128	1	0
Denmark	35	0	0
Germany	1,116	0	0
Estonia	1	0	0
Ireland	14	0	0
Greece	1,533	828	1,059
Spain	621	931	7,043
France	1,892	125	51
Croatia	97	3	70
Italy	2,454	860	3,140
Cyprus	8	2	105
Latvia	10	0	0
Lithuania	52	0	0
Luxembourg	3	0	0
Hungary	779	32	0
Malta	0	1	0
Netherlands	353	0	0
Austria	310	3	0
Poland	3,195	10	0
Portugal	274	41	304
Romania	503	23	0
Slovenia	71	4	0
Slovakia	49	2	0
Finland	5	0	0

	Apples	Peaches	Citrus fruits
Sweden	25	0	0
United Kingdom	404	0	0
Norway	13	0	0
Serbia	336	91	0
Turkey	2,480	532	2,454
Bosnia and Herzegovina	45	9	0

Source: (EUROSTAT, 2016a).

Other important fruit trees cultivated in Europe are pears, plums, apricots, cherries, almonds and hazelnuts. More information about pruning residue rates per ha for the mentioned fruit tree is given in Annex I.

Secondary residues are generated from fruit processing industries. About 71 % of apple is consumed as fresh apple while about 20 % is processed into value added products of which 65 % are processed into apple juice concentrate and into other products which include packed natural ready-to-serve apple juice, apple cider, wine and vermouth, apple purees and jams and dried apple products (Shalini and Gupta, 2010). In large scale apple juice industry, about 75 % of apple is utilized for juice and the remaining 25 % is the by- product, apple pomace. Fresh apple pomace contains around 85 % of moisture. Apple pomace is a rich source of carbohydrate, pectin, crude fibre, and minerals, and as such is a good source of nutrients. Though traditionally utilized as cattle feed, only a fraction of apple pomace is used due to rapid spoilage of the wet pomace. According to (Shalini and Gupta, 2010) besides cattle feed apple pomace has been used for energy generation, as food supplement, for extraction of pectin and for microbial transformations (biogas, ethanol, butanol, citric acid and pectinases production). In addition it can be used as source of fibres.

Regarding citrus fruit, over 115 million tons are produced worldwide annually, and about 30 million tons are processed industrially for juice production (Choi et al., 2015). Approximately 50–60 % w/w of the processed fruit becomes waste. Citrus fruit waste consists of: i) peel and pulp, ii) fruit that has not been processed because it was damaged and/or did not conform to quality standards and iii) returned surplus goods. After the production of orange juice, the waste is composed of 60–65 % w/w of peels, 30–35 % w/w of internal tissue and the remaining of seeds (Negro et al., 2016).

Currently citrus fruit waste is used for feeding animals, for extraction of pectin and it is also used as feedstock for biogas production. However, still large amount of citrus waste is disposed in the landfills (Negro et al., 2016). Ongoing research efforts are made to develop methods for extraction of citrus essential oils (in particular limonene) and to improve digestion and fermentation properties of citrus waste. Removing limonene prior anaerobic digestion of the citrus waste helps increasing the organic loading rate (Negro et al., 2016) and to avoid technical issues of biogas upgrading plants reported by (Beil, 2016). Namely condensation and accumulation of terpenes on the surfaces of activated carbon filters, molecular sieves and membranes, blocking adsorption and permeation capability of biogas upgrading systems.

Residues from peach, apricot, cherry, plum and other stone fruit processing processes are stones. There is not much information available on residue to product ratios for stone fruits. (Sostaric et al. 2015) have estimated that average annual production of 25,035 t of apricots in Serbia generates approximately 1,577 t apricot stone waste and most of it ends up in landfill sites. There are number of studies reporting the use of fruit stones from apricot, cherry, olives and peaches as precursors for the preparation of activated carbons (De Velasco Maldonado et al., 2016; Uysal et al. 2014). Studies have shown that relatively inexpensive waste products from fruit (and also nut) processing industries are capable of producing activated carbons with high microporosity and high surface areas. However, more detailed studies are needed to examine the production, optimisation, and application of activated carbon derived from precursor nutshell and fruit stone waste before this source can be commercially competitive with currently available activated carbon products in the market (Sabir, 2016). Other potential applications of stone fruit waste are production of biosorbent from untreated fruit stones used in waste water treatment (Sostaric et al. 2015) and fruit stone pellets for direct combustion (Rabaçal et al., 2013).

Two important nut trees in Europe are almonds and hazelnut.

Almonds are mostly cultivated in Spain, to less extent – In Italy and Greece. According to FAOstat (FAOstat, 2013) 258,767 tonnes of almond (including shells) have been produced in European Union in 2013 of that 149,000 tonnes in Spain. (GAIN, 2014) uses conversion factor 0.6 to convert shelled to in-shell almonds. It can be calculated that shells are 40% of the in-shell production and RPR for almond shells is equal to 0.4. Moisture content of almond shell is around 25 % (Hashemian et al., 2014). Almond shells are currently used as feedstock for bioenergy production. Scientific studies report attempts of almond shell torrefaction (Chiou et al., 2016), and production of bioethanol (Kacem et al., 2016), pyrolysis oil (Grioui et al., 2014) and activated carbon (Omri et al., 2014; Hashemian et al., 2014) from almond shells.

Another by-product from almond processing is almond skin. It is industrially removed from the nut by hot water blanching, and it constitutes 4-8 % of the total shelled almond weight (Valdes et al., 2016). Almond-processing industries are interested in the valorisation of almond skin by-products, which at present are mainly used in cattle feed and in gasification plants to produce energy. This residue is considered to have one of the highest fibre contents of all edible nuts (around 12 %), among other interesting compounds such as flavonoids and phenolic acids with high antioxidant activity (Mandalari, 2010). (Valdes et al., 2016) have evaluated the performance of bio-composites produced using almond skin.

Hazelnut (with shells) production in European Union reached 14,690 tonnes in 2013. However, the most of the global hazelnut production comes from Turkey (549,000 tonnes in 2013). Hazelnut is an important ingredient for processed foods. Only around 10 % of annual hazelnut production is consumed raw. Hazelnut processing, which includes harvesting, cracking, shelling/hulling, and roasting processes, generates by-products such as hazelnut skin, hazelnut hard shell, hazelnut green leafy cover and hazelnut tree leaf (Odabas and Koca, 2016). Hazelnut skin is a by-product of roasting process and represents about 2.5 % of the total hazelnut kernel weight. In a recent studies (Odabas and Koca, 2016) investigated the recovery of phenolic compounds from the hazelnut skin, (Tas and Gokmen, 2015) revealed the bioactive profile of natural hazelnut skins by analysing phenolics, flavonoids, phenolic acids and antioxidant activity.

Hazelnut shells make about 50 % of the weight of the produce (calculated based on (Haykiri-Acma et al., 2013)) and have moisture content of 12.3 % (Haykiri-Acma et al., 2013). So far hazelnut shells have been used for combustion (Haykiri-Acma et al., 2013) and for gasification (Karatas et al., 2013).

Grape cultivation and wine industry by-products

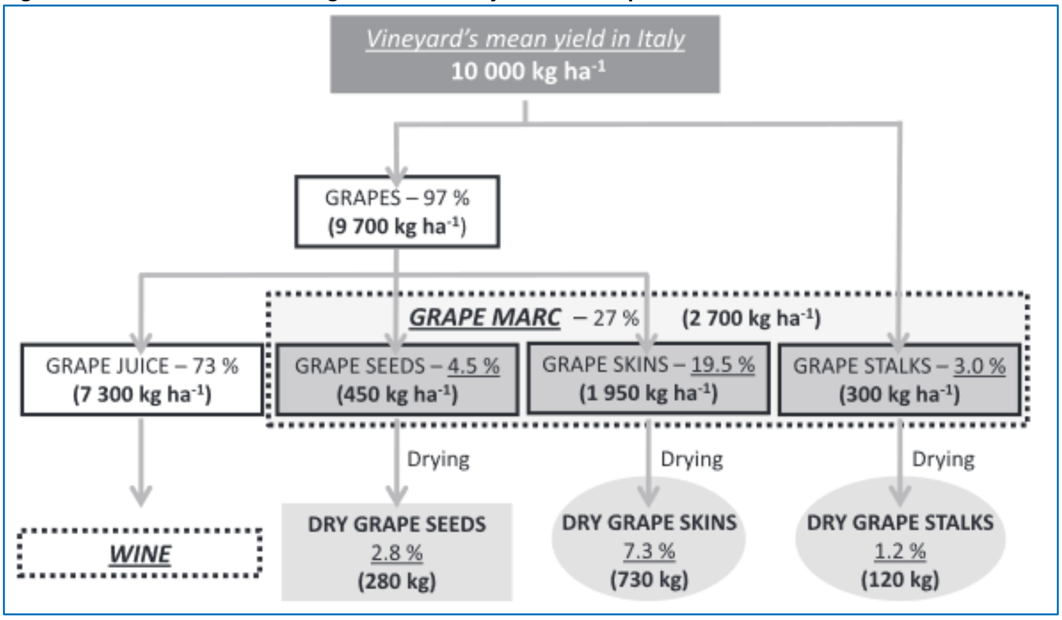
The EU is the largest wine producer in the world, accounting for about two thirds of global production. Of the estimated 22.6 million tonnes of grapes produced in the EU-28 in 2014, the vast majority (93 %) was destined for wine production. The principal wine grape producers in Europe are Italy, Spain and France. (EUROSTAT, 2016a)

Vineyard is the second most extended permanent crop group in EU28. Countries with largest areas are Spain, France, Italy, Portugal and Romania. Other countries which have more than 10 thousand hectares are Greece, Germany, Hungary, Bulgaria, Austria, Croatia, Slovenia, Czech Republic and Slovakia. (CIRCE, 2014)

Vineyards require annual pruning. Main pruning operations are winter pruning and green pruning. Winter pruning involves elimination of dry vine shoots in December to March, whereas green pruning is done in late spring (June). For energy purposes more interesting is the material from winter pruning, since it contains more woody shoots. Produced shoots are not thicker than 1-2 cm and longer than 50 cm (up to 1 m). Literature reports vine pruning residue outcome in Europe from 0.2 to 3.95 t (dry matter) per hectare (1.95 t/ha in average). (CIRCE, 2014)

Secondary residue of wine production industries is grape marc. (Toscano et al., 2013) estimates that in Italy 2.7 tonnes of grape marc is produced per ha of vineyard (see Figure 3.8). It consists of 1.95 tonnes of fresh skins, 0.3 tonnes of fresh stalks and 0.45 tonnes of fresh seeds. The moisture content of skins, stalks and seeds is 60.9 %, 68.9 % and 48.6 % respectively.

Figure 3.8 Mass balance referring to 1 ha of vineyard for wine production



Toscano et al., 2013.

Current uses of grape marc include animal feeding, composting, production of grape seed oil, and fermentation. Use of grape marc for energy generation has been evaluated by (Toscano et al., 2013). Authors conclude that main challenges of this feedstock are high moisture and ash contents, as well as Cl and S concentrations in combination with K leading to corrosion mechanisms. To reduce these problems, pre-treatment is suggested, e.g. water leaching. In addition, separation of grape marc components is suggested. For instance, separation of seeds would allow for extracting grape seed oil and subsequent use oil press cake for pellets production. With the mechanical extraction it is possible to obtain up to 75 % of the oil contained in the grape seeds, corresponding to about 10 % of the anhydrous seed mass. (Toscano et al., 2013).

Future R&I challenges related to crop residues

The availability of crop residues for energy production is restricted by:

- *sustainability aspects (how much (primary) crop residues can be removed respecting the needs to maintain soil organic content, avoid erosion, maintain soil fertility and balance water and nutrient cycles);*

- *technical aspects (how much crop residues can be technically collected);*
- *economic aspects (how feasible is the collection, logistic efforts and resulting costs in given market conditions); and*
- *alternative uses (what is the demand for the residues in other markets, e.g., animal feed, bio-based product industries, other traditional uses).*

The term – **sustainable residue removal rate** – is often used to describe the environmental constraint that limits the use of crop residue for energy (Batidzirai et.al, 2016). Other similar terms used are 'sustainable extraction rate' (the extent to which residues can be extracted in a sustainable way) (Kretschmer et al., 2012) and 'recoverability index' (percentage of the crop weight that can realistically be recovered after harvesting) (BNEF, 2010).

Studies of crop residue potential commonly assume an average sustainable residue removal rate, whereas in fact this figure is highly variable at the regional and sub-regional level (Kretschmer et al., 2012). Evidence gathered from a number of national experts in different parts of the EU suggests sustainable residue removal rate in a range of 25-30 % after competing uses are taken into account. These figures are supported by slightly higher, but consistent figures, from other reports. For example the European Environment Agency estimates between 33-37 % to be available Europe wide within a range of sustainability scenarios (Kretschmer et al., 2012).

Further challenges for utilization of agricultural biomass include:

- Organisation of biomass logistic and transportation, especially in case of cellulosic biomass which is considered more robust in handling, but this inherent bulk makes it very difficult to transport (Speight and Singh, 2014);
- Seasonality and discrete geographic availability of biomass makes it complicate to identify feedstocks that can consistently service the large demand for fuel (Speight and Singh, 2014);
- Other factors affecting agricultural biomass supply chains (IEA, 2015) like world grain market fluctuations; biophysical limitations (e.g., extreme weather events); distance to processing plants and inefficient transport restricting location of supply regions; uneven distribution of benefits along the entire supply chain from farmers to energy consumers; and lack of incentives for producers to harvest residues;
- Necessity to make large investments in R&D, demonstration and deployment to replace first generation biofuels since most processes and technologies related to 2nd and 3rd generation biofuels are still in pre-commercial research stage. (Speight and Singh, 2014)

3.1.2.2. Biomass from landscape conservation and management work

Biomass from landscape conservation and maintenance work includes a wide variety of materials, both woody and herbaceous. It originates during the maintenance of urban green areas, roadsides, waterways, hedgerows, etc. and nature protection areas. This biomass represents no competition to the agriculture areas and to the food production. (Žůrková, 2016)

Landscape conservation and maintenance biomass in urban infrastructure context

Review on landscape conservation and maintenance biomass potentials in urban infrastructure context has been prepared in *greenGain* project (Žůrková, 2016). On EU level the potentials for certain types of landscape conservation and maintenance feedstocks (occurring in urban infrastructure context) have been assessed in various research projects, e.g., *BioBoost*, *Biomass Futures* and *EUWood*. Summary of different feedstock potential assessments is given in Table 3.8.

Generally, the availability of information on landscape conservation and management biomass feedstock amounts and potentials are limited, scattered and often of an uncertain quality (Žůrková, 2016). According to the previous assessments, the potential of mixed herbaceous/woody biomass from urban areas is 17 PJ and roadside maintenance biomass (grass, shrubs and trees) – 46-47 PJ.

Woody biomass (landscape care wood, excluding permanent agricultural prunings) potential is estimated to be between 113-380 PJ.

Table 3.8 Potential of landscape conservation and maintenance biomass in Europe (based on Žůrková, 2016)[1]

Feedstock type	Specification	Area	Biomass potential	Project
Biomass from green urban areas	Leaves, shrubs, grass from the conservation of green urban areas, sport and leisure facilities	EU27+CHE	17 PJ (1.18 Mt)	BioBoost
Roadside vegetation	Cut grass, shrubs and trees grown by the roadside	EU27+CHE	47 PJ (3.17 Mt)	BioBoost
Verge grass	Roadside verges assuming grassland cover of 10 meters on either side	EU27	46 PJ	Biomass Futures
Woody biomass outside the forest	Urban and amenity trees, hedgerows, trees from fruit orchards, etc.	EU27+NO+CHE	113 PJ (13 Mm^3)	UNECE/ FAO (UNECE, 2007)
Landscape care wood	Landscape care potentials outside agricultural permanent land	EU27	380 PJ	Biomass Futures
Landscape care wood	Maintenance operations, tree cutting and pruning activities in agriculture and horticulture industry; Other landscape care or arboricultural activity in parks, cemeteries, etc.; Maintenance along roadsides and boundary ridges; rail- and waterways, orchards; Gardens	EU27	756 PJ	EUWood

The timing and frequency of cutting operations is given by the seasonal fluctuations during the year. The frequency is further determined by the requirements on work to be done in order to ensure the safety regulations (e.g. on roadsides and visibility). In Central Europe, grass is mown between March and September with a peak in July. Maintenance of trees proceeds during October and February, with its peak in October. The seasonality of the landscape conservation and management biomass feedstock occurrence is important because it determines its logistic concepts. (Žůrková, 2016)

Landscape conservation and maintenance biomass in Europe remains mostly unutilised. It is either left on site, composted or disposed as waste. Despite several good practice examples in Europe, conversion of the landscape conservation and maintenance biomass to energy or energy carriers is still exceptional. Several studies report experiences of using grass for biogas production through anaerobic digestion (Piepenschneider et al., 2016; Van Meerbeek et al., 2015; Meyer et al., 2014), woody material is used for direct combustion, and potentially for gasification. Ongoing research

[1] The entries in this table refer to studies from 2010 to 2013. The studies hence accounted for all EU27 countries, as Croatia joined the Union in 2013 only.

activities are implemented regarding production of energy carriers and intermediate products through mechanical pre-treatment and compacting (pelletizing, briquetting) operations, pyrolysis – slow (Van Poucke et al., 2016) and fast (Corton et al., 2016), torrefaction and hydrothermal carbonisation. More references can be found in (Žůrková, 2016).

Biomass from the conservation and management of grasslands and nature protection areas
Additional potential source of biomass for bioenergy production is herbaceous biomass from management of nature protection areas and extensively managed grasslands. (Pedroli et al., 2013) concludes that it is difficult to draw specific conclusions on harvesting biomass for energy from nature protection areas because very little experience has been gained so far. Therefore the authors suggest that removal of biomass should be done very carefully and measured out well within strict limits of conservation objectives. At the same time authors admit that without harvesting, these areas will develop into other nature types which are less desirable from a biodiversity point of view. This is in line with a concern of (Meyer et al., 2015) providing that the lack of nature conservation in the form of grazing or hay harvest is considered to be one of the biggest threats towards the biodiversity of the open natural and semi-natural grassland habitats.

In the EU there are approximately 72 million hectares of grassland – 63 million hectares of permanent grassland and 9 million hectares of temporary grassland (ESA, 2016b). Semi-natural grasslands are low yielding permanent grasslands, dominated by indigenous, naturally occurring grass communities, other herbaceous species and, in some cases, shrubs and/or trees. These mown and/or grazed ecosystems are not substantially modified by fertilisation, liming, drainage, soil cultivation, herbicide use, introduction of exotic species and (over-)sowing. Semi-natural vegetation is not planted/ sown by humans but is influenced by human actions such as grazing, cutting or burning. In contrast with natural vegetation, semi-natural communities thus need regular anthropogenic disturbances to be maintained. (Peeters et al., 2014)

Statistics on the areas occupied by semi-natural grasslands are limited by the lack of precise definitions and different approaches followed in different countries which reflect differences in interest and concern for semi-natural grasslands as a habitat (Hopkins, 2009). Nevertheless, several studies confirm that in Europe the area covered by semi-natural grasslands has decreased considerably over the last century. The remaining semi-natural landscapes are a conservation priority and are losing condition due to habitat decline (Corton et al., 2013). Due to natural succession and eutrophication, habitats which are no longer mowed or grazed are at a risk of changing character from having a high biodiversity with low vegetation into being overgrown by dominating tall and fast growing plant species. (Meyer et al., 2015)

Management by cutting has proven to be an effective means of maintaining biodiversity in semi-natural areas. Cutting as a management option is beneficial for species specific control trials, aimed at reducing the encroachment of dominant plant species that lower floristic biodiversity (e.g. bracken, purple moor-grass and soft rush in Wales, UK). (Corton et al., 2013)

(Corton et al., 2013) reports that cutting regimes are responsible for the development of species-rich meadows and have been successfully employed in sedge meadows and wet grassland management. Cutting/mowing management in European fens resulted in higher species richness when compared to grazing. The process reduces dominance, removes litter, allows light to permeate through to the ground level and disturbs the ground, creating new patches for seedling recruitment. Furthermore both invertebrate and avian biodiversity is known to respond positively to this kind of management. Cutting management would potentially produce a lot of feedstock for energy conversion.

However, the actual potential might be limited by restricted harvesting applications. There may be potential on some sites suited to machinery access for the harvesting of semi-natural grass as a fuel for combustion or as a feedstock for anaerobic digestion, but there is also a threat to semi-natural grassland habitats that this might adversely affect their other environmental values (Hopkins, 2009). (Pedroli et al., 2013) stresses that to preserve biodiversity, generally it is important to use small-scale harvesting techniques, which do not offer much room for biomass harvesting for energy production purposes.

Annual biomass yields from semi-natural areas were evaluated by (Corton et al., 2016). Six experimental sites have been selected representing broad habitat types that are common in Wales. Three of the sites were Natura 2000 areas and consequently a summer cutting restriction was in force until the 15th of July in order to allow the swards species to set seeds. The same criterion was also applied to the non-Natura sites, and a single harvest was taken from all sites as soon as possible after this date. The yields were measured for 3 years (2009-2011). The annual biomass yields changed from 1.97 t(DM)/ha to 4.01 t(DM)/ha. The average yield from all sites and all years has been 3.21 t(DM)/ha.

In another study biomass yields have been evaluated for semi-natural grasslands in lower mountain areas in Germany (Hensgen et al., 2016). Five years experiment conducted in five sites showed the overall yield for each year between 4.27 and 4.99 t(DM)/ha. This result is comparable with annual biomass yields reported in other studies for similar grassland types in mountain areas (4-8 t(DM)/ha) and lower mountain areas (3.4-5.8 t(DM)/ha) in Germany.

In Estonia reported annual biomass yields of grasslands are 1.9-5.5 t(DM)/ha (Melts et al., 2013). More recent study of (Hensgen et al., 2014) reports annual biomass yields from semi-natural grasslands 3.58-6.44 t(DM)/ha in Germany; 1.97-4.95 t(DM)/ha in UK and 1.63-3.79 t(DM)/ha in Estonia. In Ukraine the reported biomass yield from unimproved meadows is 2.2-3.4 t(DM)/ha. (Petrychenko et al., 2014)

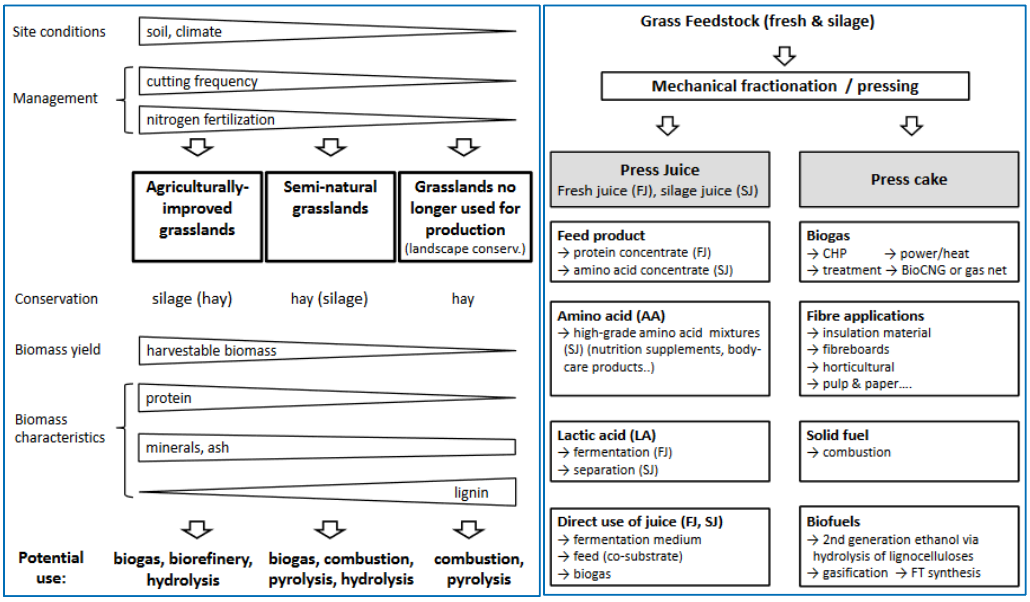
At present, most grassland biomass is used for dairy farming (Thumm et al., 2014). However, during the last three decades there have been notable changes in grassland use. Nowadays there are new options to use grassland biomass for energy and as bio-based products. Estimates indicate a surplus total grassland (not only semi-natural) area of 9.2-14.9 million ha in the European Union for the year 2020. In the EU the area of surplus grassland represents about 13-22% of permanent grassland.

According to (Thumm et al., 2014) grassland could provide a proportion of 16-19% of the energy crop potential and 6-7% of the total bioenergy potential without encroaching on land needed for animal feed (Thumm et al., 2014). Therefore, surplus grassland holds a remarkable bioenergy potential and biomass supply for energy production is regarded as one suitable way to make use of it.

On the other hand results from BioBoost project (Pudelko et al., 2013) show that technical potential of surplus hay from permanent grasslands which could be used for energy production is quite low. Excess hay has been estimated as the difference between the potential productivity of biomass under permanent pasture and hay demand associated with the farming of ruminants. BioBoost project calculations showed that excess hay is available in small clusters, which generally show an inability to use hay in Europe as a significant and accessible resource base. The total potential of surplus hay, which can be used for energy purposes, is only 6.9 million tonnes (92.6 PJ).

Characterization of permanent grassland types and pathways for biomass use and possible biorefinery products from different feedstock fractions based on (Thumm et al., 2014) is given in Figure 3.9.

Figure 3.9 Biomass use pathways from permanent grasslands and potential bio-based products from different feedstock fractions



Thumm et al., 2014.

Grass from semi-natural grasslands is likely not appropriate for biorefinery models, e.g., for producing protein feed for animals and insulation material. The low content of exploitable components in fresh biomass from semi-natural grasslands normally renders it unsuitable for biorefinery. Adaption of the processes for biomass with higher lignin contents from semi-natural grasslands is challenging. Currently it is possible to use this biomass for combustion in adapted heating plants. New opportunities will semi-natural grassland biomass use will be opened together with the development of the production of second generation biofuels by pyrolysis and enzymatic hydrolysis. Future challenges are the integration of these new value chains in the landscape without the loss of the other functions of grassland. (Thumm et al., 2014)

Currently, there are not many breeding programs being carried out with the special focus on improvement of grassland productivity. Therefore, it is important to carry out breeding programs with the special focus on grasslands by using modern breeding techniques. For example, in hot dry regions, introduction of comparatively drought resistance grass species can contribute substantially towards improvement in grassland productivity. The breeding program should be carried out for those regions where grasslands species are in danger of vanishing due to extreme site specific conditions and without having any effect on current land use. (Iqbal et al., 2016)

3.1.2.3. Livestock residues

Manure and slurry

Livestock residues or residues from animal husbandry include primarily animal manure (Khawaja and Janssen, 2014). According to the inventory of manure processing activities in the EU (Foged et al., 2011), the entire manure production in the EU that is potentially available for manure processing, for energy recovery and other purposes is estimated at 1.4 billion tonnes (wet) (see Table 3.9). Calculations in mentioned study have been based on the number of livestock in EU in 2009 and on several other assumptions. The largest production of animal manure is in France, followed by Germany.

Table 3.9 Estimated amount of livestock manure in the EU Member States[2]

Country	Pig	Cattle	Poultry	Total
	1,000 t/year			
Austria	3,538	24,648	1,378	29,564
Belgium	7,189	31,289	2,762	41,241
Bulgaria	904	6,971	1,668	9,545
Cyprus	537	685	276	1,499
Czech Republic	2,203	16,652	2,286	21,142
Denmark	14,279	19,010	1,828	35,117
Estonia	422	2,937	167	3,524
Finland	1,595	11,333	468	13,395
France	17,098	229,436	16,732	263,264
Germany	31,039	159,756	11,218	202,013
Greece	1,087	7,652	3,023	11,762
Hungary	3,905	8,652	2,963	15,519
Ireland	1,696	82,885	-	84,580
Italy	10,681	75,578	2,472	88,731
Latvia	442	4,693	380	5,515
Lithuania	1,036	9,515	840	11,390
Luxembourg	93	2,425	9	2,527
Malta	76	219	47	343
Netherlands	13,978	49,315	9,222	72,515
Poland	16,485	70,344	11,801	98,630
Portugal	2,701	17,756	3,707	24,164
Romania	7,127	33,123	8,021	48,272
Slovakia	855	5,971	1,260	8,086
Slovenia	499	5,800	418	6,716
Spain	30,351	74,297	13,120	117,766
Sweden	1,764	18,985	680	21,430
United Kingdom	5,312	122,190	16,161	143,663
EU-27	176,893	1,092,112	112,905	1,381,911

Foged et al., 2011.

According to (Foged et al., 2011) in total there is being processed 7.8% of the livestock manure production in the EU, equal to 108 million tonnes, containing 556,000 tonnes of nitrogen and 139,000 tonnes of phosphorus. The largest share of the livestock manure production is being processed in Italy, Greece and Germany, with 36.8, 34.6 and 14.8 % respectively.

Anaerobic treatment of manure happened on 5,256 installations treating 88 million tonnes of livestock manure and other materials, equal to 6.4% of the entire livestock manure production in EU. In terms of the volume of processed manure and other products, anaerobic treatment is most used in Germany, where there are 3,800 installations, processing an amount equal to 29.0% of the livestock manure production in the country. (Foged et al., 2011)

Biomass Futures (Elbersen et al., 2012) estimated the energy potential from manure in EU-27 for 2020 and 2030 at 47 million toe (1,950 PJ) and 50 million toe (2,100 PJ), respectively. Authors predicted that manure production is likely going to decrease because of reduced livestock numbers

[2] The calculations feeding into this table are based on data in 2009 in the EU27. Croatia is not accounted for as it only joined the Union in 2013.

especially in parts of Germany, Netherlands, Portugal and Normandy. Increase is expected in Poland and Romania.

The BioBoost project (Pudelko et al., 2013) estimated the total theoretical potential of residues from livestock production in Europe at 1.23 billion tonnes (~1,450 PJ). However, despite the high theoretical potential, there were no possibilities of obtaining this type of biomass in most regions, considering the needs of soil conservation. The total technical potential was assessed at 21.4 million tonnes (~21 PJ) only. (Pudelko et al., 2013)

Nevertheless, the European Biogas Association has acknowledged the potential of using manure for anaerobic digestion. A recent study carried out by EBA estimates that currently just over 3% of total EU manure is digested. Conservative potential of recoverable manure estimated by EBA is 33% of EU total (Kirchmeyr et al., 2015). This implies using farms which are best adapted for effective manure recovery and therefore no substantial changes at farm level are required.

Animal fats and protein

Secondary animal by-products which are used for bioenergy production are animal fats and protein. In 2015, the Netherlands were by far the largest user of animal fat for biodiesel production, followed by France, the United Kingdom, Germany, Denmark, Spain and Austria. Although at a smaller scale, in 2015, animal fat use registered a steady increase in Portugal. (GAIN, 2016)

Industrially produced animal fats include beef tallow, pork lard, and chicken fat. Animal fats are attractive feedstocks for biodiesel because their cost is substantially lower than the cost of vegetable oil. This is partly because the market for animal fat is much more limited than the market for vegetable oil, since much of the animal fat produced is not considered edible by humans. (Van Gerpen, 2014)

Tallow is derived from rendering edible or inedible portions of beef carcasses, however, often term 'tallow' in biodiesel production context describes animal fats more broadly (i.e. including pig, poultry, sheep and goat fats). While edible animal fats are mainly used as shortening for baked goods, inedible animal fats are used in animal feed, soap production and lubricants (Seber et al., 2014). By degree of quality animal fats are classified following (Alberici and Toop, 2013):

- Animal fats intended for human consumption;
- Category 3: Animal fats that can be used for animal feed, cosmetics and pet food;
- Category 2: Animal fats that can be used for soil enhancement and for technical purposes, such as oleochemical products and special chemicals (after appropriate treatment);
- Category 1: Animal fats that presents a high risk for human health, specified risk material. Animal fats in this category can be used for energy purposes and are not allowed to enter the human or animal food chains.

Article 21(2) of the EU Renewable Energy Directive (RED, 2009) allowed Member States to count biofuels produced from wastes, residues, non-food cellulosic material, and lignocellulosic material twice towards their 10% renewable energy in transport target for 2020. Member States have the responsibility to decide which feedstocks should count twice towards their target (Alberici and Toop, 2013). Member States that allow double-counting for animal fat is Denmark, Finland, France, the Netherlands and the United Kingdom (GAIN, 2016). However, for instance, in the UK Category 1 animal fat biodiesel has been eligible for double counting, but Categories 2 and 3 (or unknown categories) – have not (Alberici and Toop, 2013). Annex IX of the Directive to reduce indirect land use change for biofuels and bioliquids ((EU)2015/1513) (ILUC, 2015) allow biofuel from Category 1 and 2 animal fats to be counted twice towards the target. Category 3 would be single counted.

According to (EFPRA, 2017) 5 million tonnes of Category 1 material and 12 million tonnes of low risk (intended for human consumption, Category 2 and 3) material are produced by rendering plants in EU every year. Rendering process is generating animal fat and protein in form of meat and bone meal. Produced Category 1 material consists of 1 million tonnes of meal, and the remaining 4 million tonnes produced per year are animal fat which is suitable for biodiesel production.

According to (GAIN, 2016), the use of animal fats for biodiesel production in EU has increased from 300,000 tonnes in 2010 to 970,000 tonnes in 2015. Further increase is forecasted, reaching 1 million tonnes in 2017. Nevertheless, this would cover only 25 % of the Category 1 animal fats available from EU rendering plants.

3.2 Selection of feedstock categories and R&I fields

3.2.1 Investigated feedstock categories

3.2.1.1. Methodology for selection of feedstock categories

There is a wide range of bioenergy feedstocks originating from agriculture and food processing operations. They have been categorized and shortly described in Chapter 3.1, thus giving an idea about the variety, characteristics and current uses of agricultural and food processing residues. Due to the time constraints, it is not possible in this study to address each type of agricultural by-product, especially all types of primary and secondary crop residues. Therefore limited number of most relevant feedstocks for the assessment of research and innovation fields will be selected.

In this study the relevance of the feedstock is determined by its energy potential. Energy potential of cellulosic energy crops, landscape management biomass and animal residues has been compiled based on earlier potential studies (Elbersen et al., 2012; Pudelko et al., 2013; Khawaja and Janssen, 2014) and expressed as minimum and maximum scenarios (see Figure 3.11). Energy potential of primary and secondary crop residues has been calculated based on average crop cultivation areas in EU, specific residue to product (or surface) ratios and sustainable residue removal rates (for primary residues) reported in literature. Crop residue energy potential calculation sheet is provided in Annex 2: Crop residue potential calculation sheet and results are summarized in Figure 3.11 and Table 3.10.

Oil crops in this study

Besides cellulosic energy crops, this study estimated the potential supply of new generation oil crops in Europe for 2020, 2030 and 2050. Based on the state of the art of the current research in Europe, camelina (*Camelina sativa*) and crambe (*Crambe abyssinica*) have been identified as major candidates among currently researched oil crops for the future European bio-based economy (see also chapter 3.3.1.3).

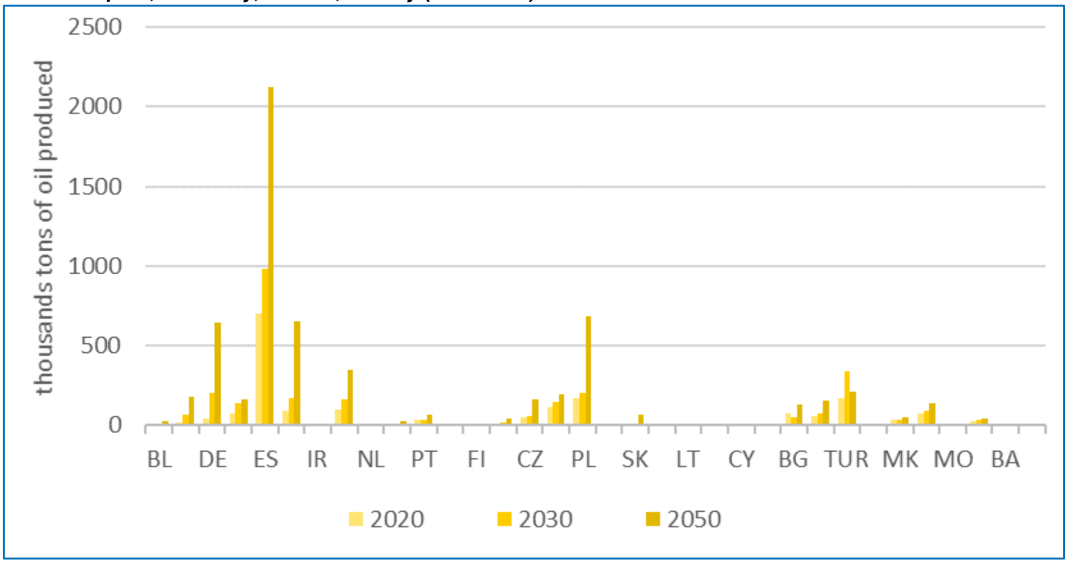
Within this study potential oil yield of camelina and crambe in Europe has been calculated based on the following key assumptions:

- Potential land areas were based on the same "base potential" used for modelling of the woody or herbaceous lignocellulosic crops;
- Potential areas were further limited to the territories with experiences and capacities of cultivating cereals, oil crops and pulses, since due to similar technology and management practices the probability of adoption of new oil crops there is more likely than for instance in the areas dominated by fruits and vegetables, potatoes, olives and wine;
- Furthermore the areas which are affected by more than 5 days of frost of less than -5 degrees were excluded;
- Based on the literature, an average oil yield of 0.75 t/ha was assumed with annual yield increase of 2%.

The above listed assumptions exclude several Northern countries – Finland, Estonia, Latvia and Lithuania, and some Balkan countries – Albania, Montenegro, Bosnia and Herzegovina and Kosovo completely from the potential areas of camelina and crambe cultivation.

The calculation results show potential availability of 1.86 million tons of oil in 2020, 2.82 million tons in 2030 and 6.13 million tons of oil could become available in 2050. Countries with the highest new oil crop cultivation potential are Spain, Germany, France, Turkey (until 2030) and Poland.

Figure 3.10 Oil crop production potential: ***Countries with the highest new oil crop cultivation potential in 2050 are Spain, Germany, France, Turkey (until 2030) and Poland.***



NB: Since the same land areas as for lignocellulosic energy crops are assumed in this calculation, the result should not be considered as additional potential, but rather an alternative to lignocellulosic feedstocks.

Most relevant crops for the calculation of the crop residue potentials have been pre-selected based on the agricultural commodity production rating (FAOstat, 2013). In the second step the long-list of crops has been shortened by identification of those crops that can deliver high amounts of residues which are relevant in energy production context. Similar approach has been used by (Iqbal et al., 2016). In total 19 relevant crops have been included in the list, and for each crop respective primary and secondary residues have been attributed.

Energy potential of crop residues has been calculated using net or gross calorific values (where available obtained from ECN Phyllis data base (Phyllis, 2017)) and have been adjusted according to the dry matter content of the respective biomass. For several secondary crop residues which are currently used as animal feed, energy content has been calculated based on their nutrition values (obtained from Feedpedia (Feedpedia, 2017)).

Figure 3.11 Energy potential (PJ/year) from main agricultural feedstocks

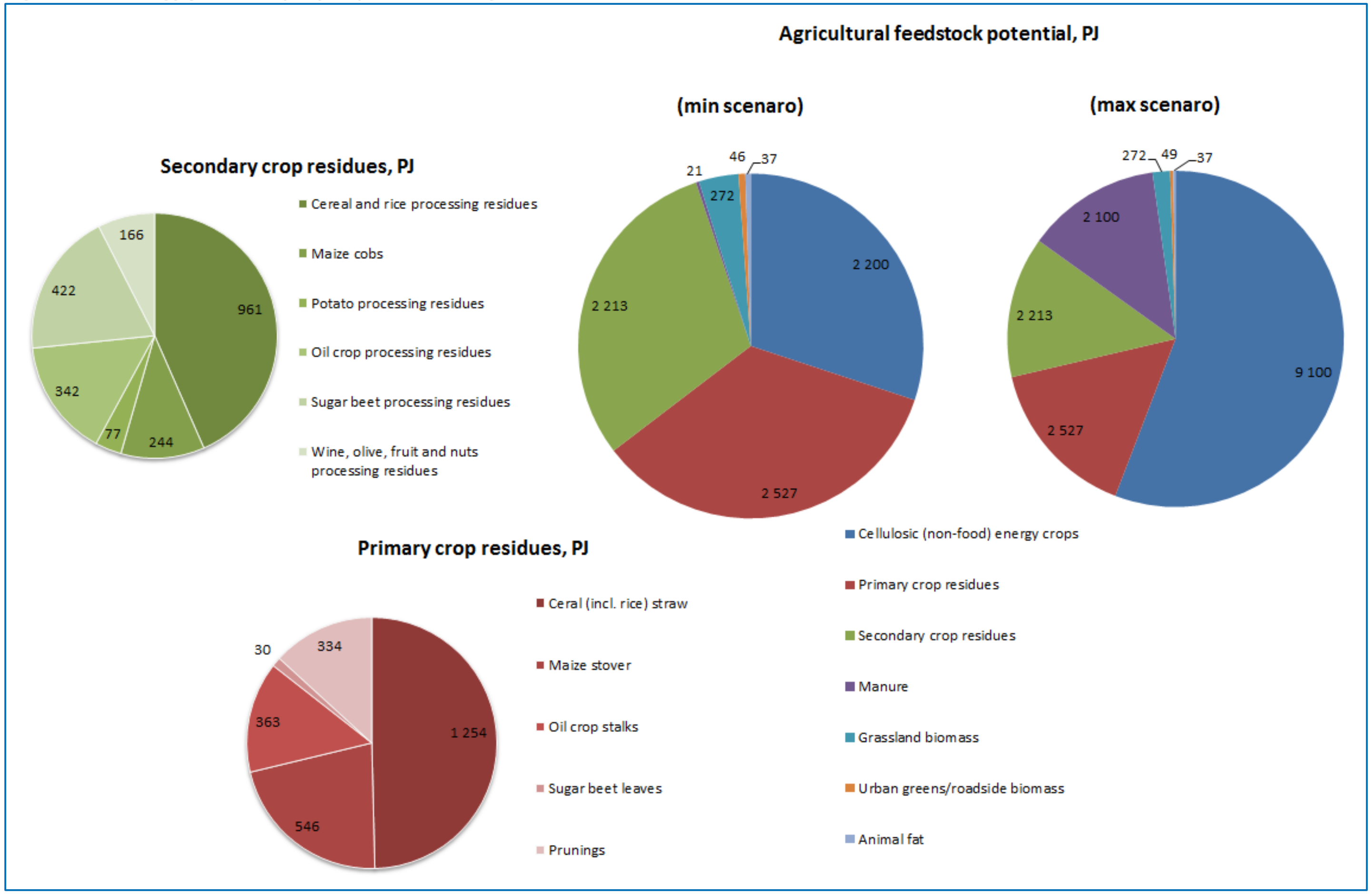


Table 3.10 Summary of the energy potential of most relevant agricultural feedstocks

Feedstock groups	Energy potential, PJ	Source
Cellulosic (non-food) energy crops	2,200 – 9,100	Khawaja and Janssen, 2014
Livestock manure	21 – 2,100	Pudelko et al., 2013, Elbersen et al., 2012
Cereal straw (incl. maize and rice)	1,800	Calculated
Wheat straw	*729*	
Maize stover	*546*	
Barley straw	*329*	
Triticale straw	*63*	
Rye straw	*57*	
Oat straw	*56*	
Rice straw	*19*	
Cereal bran, rice husk and maize cobs	1,205	Calculated
Wheat bran	*592*	
Barley bran	*246*	
Maize cobs	*244*	
Triticale bran	*46*	
Oat bran	*35*	
Rye bran	*35*	
Rice husk	*7*	
Sugar crop processing by-products	422	Calculated
Sugar beet pulp	*354*	
Beet molasses	*68*	
Oil/protein crop straw and stalks	363	Calculated
Rapeseed straw	*203*	
Sunflower stalks	*136*	
Soybean straw	*24*	
Oil processing by-products	342	Calculated
Rapeseed meal	*239*	
Sunflower meal	*57*	
Sunflower hulls	*34*	
Soybean meal	*12*	
Prunings	334	Calculated
Wine prunings	*123*	
Olive prunings	*122*	
Apple tree prunings	*35*	
Orange tree prunings	*23*	
Almond tree prunings	*20*	
Peach and nectarine prunings	*10*	
Hazelnut tree prunings	*2*	
Grass and hay from permanent grasslands	272 11- 153	Calculated Elbersen et al., 2012, Pudelko et al., 2013
Potato processing residues (pulp and peel)	77	Calculated
Grape processing residues (grape marc)	73	Calculated
Olive processing residues (olive cake)	60	Calculated
Grass, shrubs from urban areas and roadside verges	46-49	Elbersen et al., 2012, Pudelko et al., 2013
Animal fat	37	Calculated

Feedstock groups	Energy potential, PJ	Source
Fruit and nut processing residues	33	Calculated
Orange peel and pulp	*14*	
Apple pomace	*11*	
Peach stones	*5*	
Almond shells	*2*	
Hazelnut shells	*1*	
Sugar beet leaves	30	Calculated

It should be noted that crop residue potentials calculated in this study are based on rough estimates and therefore should be considered only as indicative values. However, the calculated potentials are in line with the results of other potential assessment studies and therefore are justified for using for the final selection of feedstock categories.

3.2.1.2. List of further assessed feedstock categories

The following low ILUC, large potential agricultural biomass feedstocks are selected as the most relevant on the EU level for the bioenergy supply in future:

- Energy crops:
  - Cellulosic (non-food) energy crops (herbaceous grasses and SRC);
  - New low ILUC energy crops.
- Primary crop residues:
  - Cereal straw (wheat, barley, triticale, rye and oats);
  - Maize stover;
  - Rapeseed straw;
  - Sunflower stalks;
  - Prunings (wine and olive).
- Secondary crop residues:
  - Cereal processing residues (wheat and barley bran);
  - Sugar beet processing residues (pulp and molasses);
  - Maize cobs;
  - Oil crop processing residues (rapeseed and sunflower meal);
  - Potato pulp and peels;
  - Grape processing residues (marc);
  - Olive processing solid residues (cake).
- Manure;
- Landscape and grassland management biomass.

3.2.2 Investigated R&I fields

Investigated R&I fields cover all parts of the agricultural biomass supply chain – starting from crop breeding and cultivation processes up to biomass logistics and overall supply chain issues.

Investigated R&I fields and the means of increasing biomass availability for bioenergy are summarized in Table 3.11. The matrix of R&I fields relevant to selected feedstocks is given in Table 3.12.

Table 3.11 Investigated R&I fields for agricultural feedstock availability

Concerned part of the biomass supply chain	R&I field	Means of increasing biomass availability for bioenergy in future
Biomass cultivation (cropping)	Breeding of food and energy cops	• Increased yields; • Increased biomass value for energy; • Increased resistance to stress; • Increased straw/grain ratio; • Improved dedicated ingredients.
	Agricultural practices	• Increased yields; • Increased resistance to stresses.
	Crop rotation and intercropping	• Increased yields; • Increased carbon stock, nutrient recycling, soil fertility and biodiversity; • Positive influence on water cycle.
	Agroforestry & short rotation coppice	• Increased yields; • Increased carbon stock, nutrient recycling, soil fertility and biodiversity; • Positive influence on water cycle.
	Using marginal, degraded and unusable land for energy crops production	• Unused land brought back into production; • Improved soil quality.
Biomass harvesting and collection	Harvest of agricultural biomass	• Increased amounts of harvested biomass; • Improved harvesting technologies; • Improved harvesting logistics.
Biomass pre-treatment and densification	Improved biomass carriers: thermo-chemically pre-treated and mechanically treated agricultural biomass	• Improved energy to weight ratio; • Optimised versatility and optimized tradability.
Horizontal issues covering whole biomass supply chain	Biomass mobilization	Increased biomass mobilization from agriculture.
	Agricultural logistics	• Reduced post-harvest losses; • Improved transport, storage and infrastructure.
	Supply chains of primary and secondary biomass	Optimized supply chains.
	Technology transfer	Improved technology transfer between biomass sectors and locations.

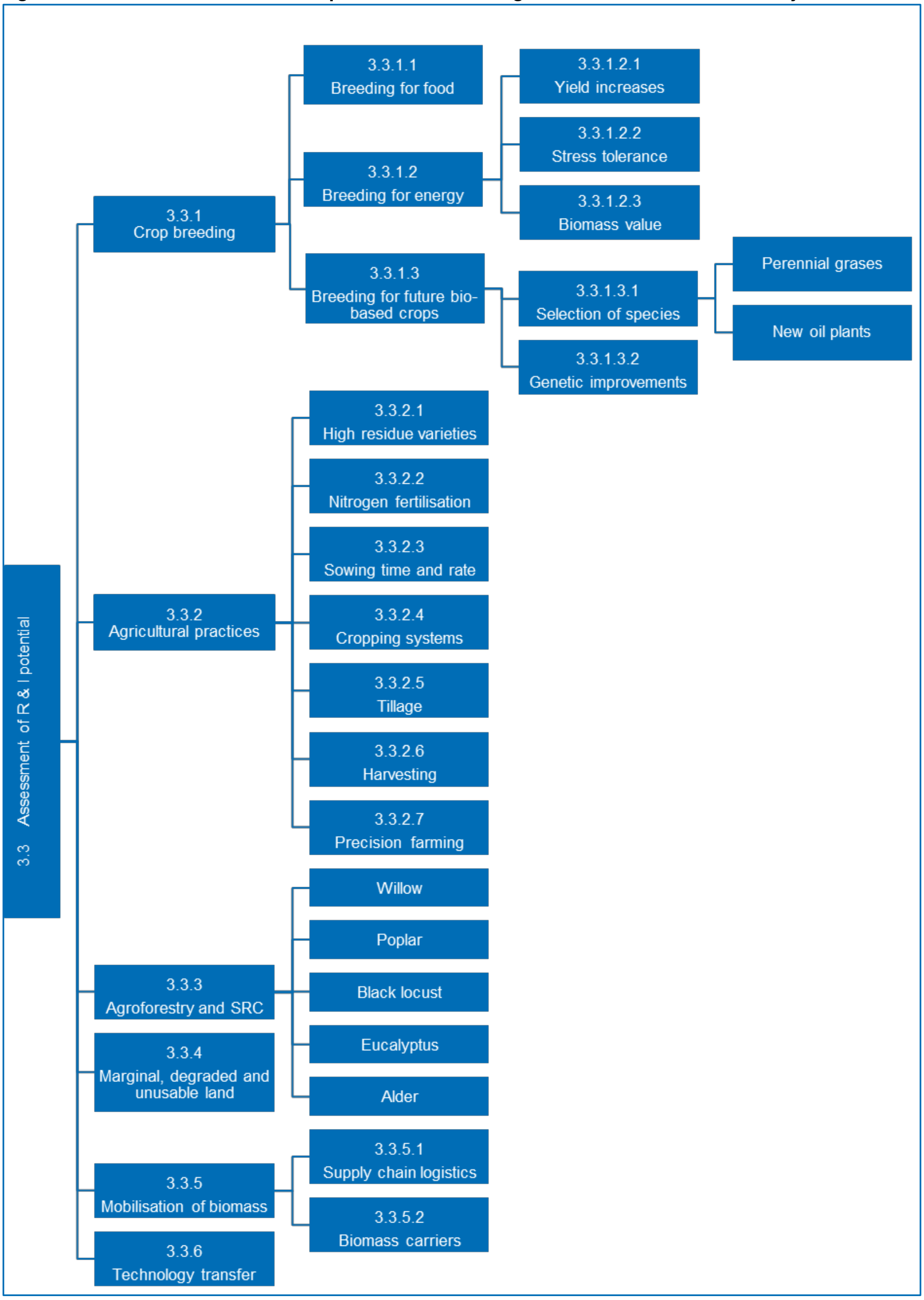
Table 3.12 Matrix of selected feedstocks and corresponding R&I fields

Biomass	R&I fields										
	Breeding of food and energy cops (Chapter 3.3.1)	Agricultural practices (Chapter 3.3.2)	Crop rotation and intercropping (Chapter 3.3.2.4)	Agroforestry & SRC (Chapter 3.3.3)	Degraded and marginal land use (Chapter 3.3.4)	Harvest of agricultural biomass (Chapter 3.3.2.6)	Improved biomass carriers (Chapter 3.3.5.2)	Biomass mobilization (Chapter 3.3.5)	Agricultural logistics (Chapter 3.3.5.1)	Supply chains (Chapter 3.3.5.1)	Technology transfer (Chapter 3.3.6)
Energy crops:											
Cellulosic energy crops: herbaceous grasses	X	X	X		X	X	X	X	X	X	X
Cellulosic energy crops: SRC	X	X	X	X	X	X	X	X	X	X	X
New (low ILUC) energy crops	X	X			X	X	X	X	X	X	X
Primary crop residues:											
Straw, stalks and stover from cerals, rapeseed and sunflower	X	X				X	X	X	X	X	X
Prunings from wine and olives		X				X	X	X	X	X	X
Secondary crop residues:											
Cereal bran							X	X		X	X
Sugar beet pulp and molasses							X	X		X	X
Maize cobs							X	X		X	X
Rapeseed and sunflower meal							X	X		X	X
Potato pulp and peels							X	X		X	X
Grape marc							X	X		X	X
Olive cake							X	X		X	X
Manure		X					X	X	X	X	X
Landscape and grassland management biomass	X	X			X	X	X	X	X	X	X

3.3 Assessment of R&I potential (in Europe and third countries)

Chapter 3.3 presents a detailed assessment of the Research & Innovation potential in the field of agriculture. The structure of chapter 3.3 is displayed in Figure 3.12.

Figure 3.12 Research & Innovation aspects in the field of agriculture assessed in this study



3.3.1 R&I on crop breeding

Plant breeding uses principles from a variety of sciences to improve the genetic potential of plants. The process involves combining parental plants to obtain the next generation with the best characteristics. Breeders improve plants by selecting those with the greatest potential based on performance data, pedigree, and more sophisticated genetic information. Plants are improved for food, feed, fibre, fuel, shelter, landscaping, eco-systems services and a variety of other human activities. (NAPB, 2017)

From a technical perspective plant breeding is a science driven creative process of developing new plant varieties that goes by various names including cultivar development, crop improvement, and seed improvement. Breeding involves the creation of multi-generation genetically diverse populations on which human selection is practiced to create adapted plants with new combinations of specific desirable traits. The selection process is driven by biological assessment in relevant target environments and knowledge of genes and genomes. Progress is assessed based on gain under selection, which is a function of genetic variation, selection intensity, and time. (NAPB, 2017)

In further sub-chapters research and innovation activities in food and energy crop breeding are described. Breeding efforts are aimed to increasing yields, building up the resistance to stresses and improving biomass value for energy.

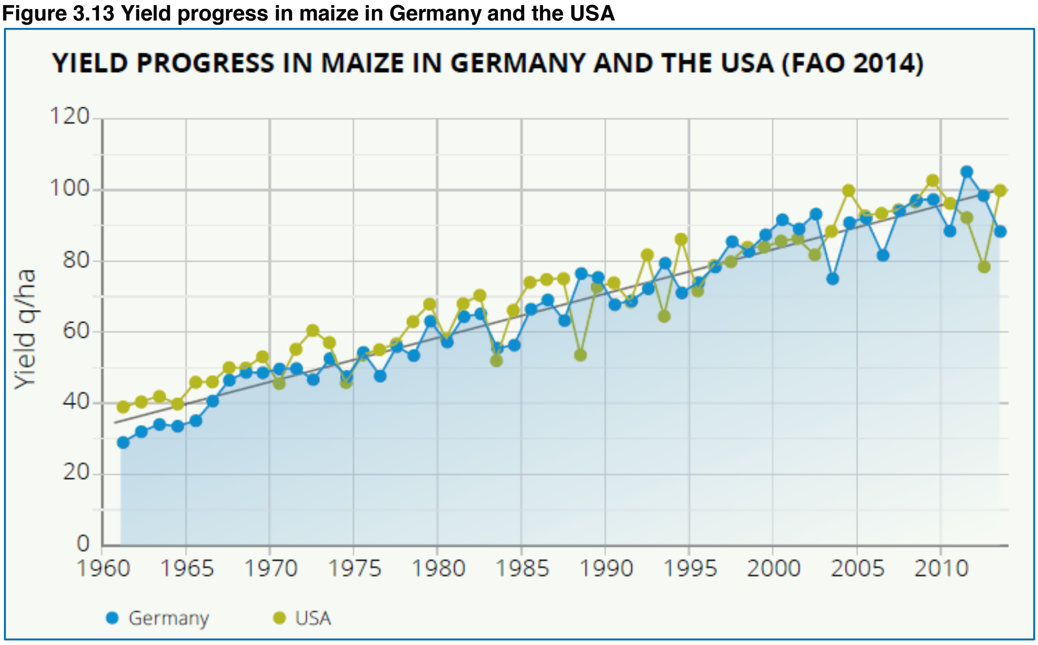
3.3.1.1. Breeding of crops for food

All breeding programmes for field crops have essentially 3 primary objectives:

1. High and stable yields: The major task of food crops breeding is constant improvement of yields. High and stable yield remains the main driver for the farmer income. Yield increase is achieved by development of higher performing varieties and hybrids.

Achievements through breeding are generally measured in decades. Genetic gain in yield has been measured in many crops and in many areas by comparing in a single test varieties that have been released over a period of years (i.e. comparing obsolete varieties with modern varieties). In general, this gain is around 1-3 % per year, but the gain is rarely linear over short periods of time. Rather, there are apparent yield plateaus (no improvement in yield among varieties released over several years), followed by a sudden jump as breeders discover new alleles or new combinations of alleles that perform better than their predecessors (ESA, 2016a). In past decades cereal breeding has resulted in a yield increase of on average 1 % per year. This yield increase has slowed down in the past years to approximately 0.5 % (ESA, 2016c). Maize yields have also been constantly increasing (see Figure 3.13). Genetic progress in hybrid maize has resulted in a significant yield increase in the past decades. Since the 1950s maize plant breeding shifted from open pollinated varieties to hybrids. (ESA, 2016d)

Figure 3.13 Yield progress in maize in Germany and the USA



ESA, 2016d.

2. Improved quality: Depending on the crop, breeding also focuses on the needs of the downstream industry, e.g. cereal breeders strive to improve protein content and specific baking qualities, oilseed breeders – to increase oil content and optimal fatty acid profile of the oilseeds and maize breeders develop specific maize breeding programmes for the different uses – focusing on grain (grain yield), silage (digestibility) or biomass for bioenergy.

3. Adaptation to local stress: Adaptation to both – biotic and abiotic stress is an additional target in breeding. In most cases, resistance to one or more diseases is among a breeder's primary objectives. "Stress" can also apply to the length of growing season. In an area with short growing season, early maturity will be a primary breeding objective. Resistance to abiotic stress factors as lodging, drought, temperature, salt, etc. is getting more important due to global warming.

A fourth objective could be listed in some cases breeding of specialty traits. These are generally for a niche market, but could also be attributed to bioenergy market in future.

Breeding techniques are constantly developed. Breeders benefit today from highly sophisticated tools such as molecular markers and genotyping as well as advanced statistics and data management tools. The development of hybrid breeding programmes in the past decades provides hybrid varieties with further increased yield potential. Different techniques in the area of biochemistry, tissue culture, cell biology, molecular biology and genomics are applied. For instance doubled haploids are a technique frequently used in oilseed crops to reach homozygosity without the need for generations of self-pollination. (ESA, 2016a)

Marker Assisted Breeding is used more and more to select specific traits. Marker Assisted Selection is useful when molecular genetic markers can be associated with pest or disease resistance or other useful, but difficult to measure traits.

Most crops utilize molecular genetics in various ways. Genetic finger prints are used to identify genotypes that are genetically diverse (i.e. good candidates to cross for discovering improved genetic combinations), even if they look similar. Increasingly, "Genomic Selection" is used to detect and assemble desirable combinations of a large number of alleles with small individual effects. (ESA, 2016a)

Improvements in "quality" generally occur as a result of new methods for measuring a quality parameter, or the industry defining a new quality parameter (e.g. health benefits of novel fatty acid profile). Once these new objectives are quantified, breeders have been fairly quick (still sometimes a decade or more, but "quick" in breeding terms) to address the new breeding targets. (ESA, 2016a)

Breeding for disease and insect tolerance is a continuous battle because the pest or pathogen is changing to overcome the genetic resistance. In many cases, sophisticated resistance gene stacking and/or gene rotation is required to stay ahead of pest/pathogen evolution (ESA, 2016a). In potato production nematodes are important limiting factor. Potato plant breeders have been able to develop new varieties resistant to nematodes. It enables growing potatoes also on less suitable soils. (ESA, 2016e)

In general, the main purpose of conventional crop breeding is to increase the yield of the product (e.g., grain, edible part of potato) and often it means to minimise the volume of residues (straw, peels) since they have lower economic value. It is in contrary to breeding of dedicated energy crops. Increased yields of the food crop does not automatically mean increased residue yield as a result of breeding. Currently, the breeding of food crops has primarily aimed at maximizing yield of main food product. It has led to decrease in straw length mainly because breeding programs has focussed on increased plant allocation to the grain to have high yield, and also to avoid lodging (bending of stalks or whole plant). Even among new cultivars with high grain yield, considerable differences in straw and grain yield are recorded. (Iqbal et al., 2016)

3.3.1.2. Breeding of crops for energy

Ideally, biomass crops would produce large quantities of biomass containing readily digestible polysaccharides and tailored composition with value-added chemicals. As a prerequisite, biomass crops must have a sustained capacity and efficiency to capture and convert available solar energy into harvestable biomass with minimal inputs and minimal environmental impact. Conventional food crops have a number of disadvantages as biomass crops – most are annual, requiring large inputs of energy in cultivation, planting, chemical inputs and harvesting each year, which limits their sustainability. (Johnson et al., 2007)

Near and mid-term goals for advancing biomass for bioenergy include improvement of conventional crops and cropping practices, and the development of a new generation of bioenergy crops that (Johnson et al., 2007):

- maximize total annual biomass production per unit area;
- are sustainable while minimizing inputs;
- are environmentally sound; and
- maximize the amount of biofuel product per unit of biomass (conversion efficiency).

3.3.1.2.1. Breeding measures to increase energy crop biomass yield

Achieving the maximal yield of dedicated energy crops is a significantly different goal than maximizing the seed yield of most annual agronomic crop species, where typically, the maximum number of reproductive or storage organs is the prime component limiting yield. The yield of a dedicated biomass crop, like it is for a forage crop, is a function of the total number of cells per unit area multiplied by the mean amount of accumulated carbon per cell. Thus, biomass yield can be enhanced by (Johnson et al., 2007) increasing the number of cells per ha per year, increasing the amount of accumulated carbon per cell, or both. The real need is to maximize photosynthetic CO_2 fixation to support carbon accumulation in both grain and biomass. Numerous plant traits can be targeted to enhance plant biomass production, including (Johnson *et al.* 2007):

- Increased photosynthesis;
- Optimized photoperiod response;
- Optimized plant architecture;
- Biotic resistance, abiotic tolerance;
- Floral sterility;
- Regulated dormancy;
- Delayed leaf senescence;
- Greater carbon allocation to stem diameter instead of height growth;
- Optimal nitrogen acquisition and nutrient use efficiency; and
- Less extensive root system to maximize aboveground biomass.

However, in terms of soil management, it may not be desirable to divert biomass to aboveground organs, due to the value of root carbon for maintaining soil organic carbon (Johnson et al. 2007).

Increasing photosynthesis: Total photosynthetic capacity can be improved by improving **light intercept efficiency** at the plant or canopy level. Interception efficiency depends on the duration, size, and architecture of plant canopy. A crop that can maintain **optimum canopy architecture** throughout the growing season will absorb the largest proportion of incident radiation thereby, enhancing the total photosynthetic capacity. The major factor determining light intercept efficiency in temperate regions is the crop's ability to develop leaves rapidly at the start of the growing season. The complete canopy cover needed to maximize light intercept efficiency also minimizes the availability of light to weeds and their competitiveness, thus minimizing herbicide requirements. (Johnson et al., 2007)

Understanding the mechanisms underlying the source-sink regulation in plants is needed to force plants to store more carbon per unit of leaf area than they would for normal regular growth and development purposes. For example, short rotation poplar (*Populus* ssp.) appears to accumulate more carbon per unit leaf area following defoliation (e.g., harvest of biomass) than they normally would without any changes in plant architecture. When the mechanisms underlying the source-sink regulation are understood, plants can be developed that exhibit significantly larger rates of net photosynthetic CO_2 fixation and larger amounts of total accumulation of carbon per ha per year. Therefore, a high-priority long-term research goal is to understand mechanisms that regulate net photosynthetic CO_2 fixation. (Johnson et al., 2007)

Floral sterility, regulated dormancy and delayed leaf senescence: A complementary approach is to identify factors that regulate plant growth and duration. Different plant species vary widely in growth rates, suggesting that growth rates are under genetic control and, therefore, **subject to genetic modification**. Several genes have been identified in functional genomics screens that cause significant increase in growth rates in different types of plants. Plants typically invest considerable energy in making reproductive structures, and if flowering can be delayed or prevented, this energy may be transferred into increasing the overall plant biomass. Taking advantage of this genetic variability may create new opportunities to develop highly productive biomass crops. (Johnson et al., 2007)

Optimal nitrogen acquisition and nutrient use efficiency: Nutrient use efficiency can be optimized by (Johnson et al., 2007):
- maximizing of energy flow into biomass via photosynthesis per unit of nitrogen invested in the photosynthesis apparatus;
- maximizing the amount of nitrogen and other nutrients translocated out of the photosynthetic source tissues upon their senescence to sink tissues (i.e., storage organs or new photosynthetic tissue); and
- maximizing nutrient uptake from the soil; which will help minimize both nutrient inputs and loss to the environment.

With low maintenance perennial biomass species, nitrogen availability could become the most limiting factor and could become more pronounced as atmospheric CO_2 concentration continues to increase. Management of dedicated biomass crops likely would include fertilizer application. (Johnson et al., 2007)

3.3.1.2.2. Breeding to increase biotic and abiotic stress tolerance
Recent progress in understanding the mechanistic basis of plant drought, salt, and cold tolerance has raised the possibility of modifying plants to enhance productivity under drought and other stresses. Plants with C4 photosynthesis (e.g., corn, switchgrass and miscanthus) typically require less water per unit of CO_2 fixed than do C3 plants (e.g., wheat and soybean), because C4 plants can achieve high rates of CO_2 fixation with partially closed stomata, thus reducing water loss. This adaptation using genetic engineering to transfer C4 photosynthetic machinery to C3 plants has been attempted with rice. (Johnson et al., 2007)

Different plants exhibit widely different abilities to survive extended periods of drought, indicating that it is possible to develop drought-tolerant biomass crops. Unfortunately, drought tolerance or avoidance mechanism generally result in reduced productivity because of the direct linkage between exchange of CO_2 and water vapour through the stomata and reduced rate of photosynthesis if stomatal openings close to reduce evaporation from the leaf. Reduced evaporation from leaves generally elevates leaf temperature compounding the negative impact of drought on yield. Conservation of water is generally a survival mechanism, not a means to maximum productivity. A priority in dedicated energy crops is to understand mechanisms by which plants survive drought and other abiotic stresses and adapt this knowledge to improving biomass energy crops. (Johnson et al., 2007)

Physiological knowledge of the processes of abiotic stress tolerance, especially in perennial grasses, are still developing, and it is clear that significantly more effort needs to be invested to both complement and guide breeding and genetic programs. The possibilities for increasing tolerance to these stresses are enormous. Although it is notable that the actual production of transgenic plants with demonstrably improved abiotic stress tolerance has been slow, more progress can be gained by exploiting further the synergies of interfacing of physiological and molecular genetic research. (Johnson et al., 2007)

3.3.1.2.3. Breeding to improve biomass value for energy

Genomics, proteomics, and metabolomics are being used to improve our understanding of and ability to manipulate the lignin biosynthesis pathway. Currently, corn stover is pre-treated to convert lignocellulose to sugars, but transgenic technologies may provide *in planta* alternatives to pre-treatment. Altering cell-wall composition to increase cellulose and decrease lignin could have significant effects on productivity of biomass crops, especially if used as sugar platform feedstock, especially if cellulose eventually can be broken down into glucose molecules efficiently, because we possess far greater knowledge of converting glucose to ethanol than the 5-C sugars in hemicellulose. For example, down regulation of lignin synthesis increased the subsequent digestibility; thus, releasing more sugar for fermentation. Eventually the development of a comprehensive physiological cell-wall model incorporating structural properties with biophysical aspects and knowledge about the proteins involved will help in developing highly productive biomass species whose cell walls are optimized for conversion to biofuels. Therefore, a systems-level understanding of model plants will facilitate improvement of plant cell-wall composition in biomass crops dedicated to conversion into biofuels without compromising plant viability. (Johnson et al., 2007)

Progress is needed to answer the three key questions (Johnson et al., 2007):

- What controls the synthesis and architecture of the plant cell wall?
- How can we manipulate cell wall structure in biomass crops?
- Can we identify key traits affecting biomass yield and conversion efficiency and target them for selection and improvement?

The organization and interactions among the many polymers of the cell wall are constructed for physical strength and resistance to biotic and abiotic attacks, and therefore, constitutes a barrier to easy and efficient bio-conversion to a usable liquid biofuel. Screening large populations to identify useful genetic variants to be used as sources for breeding is a slow and time-consuming process, especially for biomass crops most of which are not fully domesticated. However, populations of C4 perennials such as big blue stem (*Andropogon gerardi* Vitman) can be improved for anaerobic fermentation characteristics in grazing animals in as little as three breeding cycles. Development of markers or DNA polymorphism indicative of desired traits will facilitate this process; thus, allowing breeders to monitor plants for a trait that can be difficult to recognize due to tissue-specific or developmental-stage-specific expression. Modern molecular genomic applications of modern molecular genomic tools, e.g., microarrays, single nucleotide polymorphism and comparative databases are being used to support tree breeding and gene transfer efforts enhancing physiological understanding of ecological adaptations. (Johnson et al., 2007)

Some of the challenges in developing biomass crops include, but are not limited to (Johnson et al., 2007):

- Better understanding of gene regulation and control of plant metabolic pathways;
- Improving gene modification through functional genomics;
- Developing new screening systems;
- Improving biotechnological method for gene stacking, organelle transformation and molecular evolution;
- Expanding knowledge of carbon flow at the molecular level;
- Carbon partitioning in higher plants to direct more carbon to storage tissues for increasing yield or carbon partitioning between different components (e.g., changing of biomass from one form to another (starch-to-oil for biodiesel));
- Identifying mechanisms of gene switching;
- Developing broad bioinformatics;
- Developing agronomics to effectively and efficiently plant, grow, and harvest;
- Designing of cropping systems with a group of grain and energy crop in a sequence that maintains feedstock supply, grower profitability, environmental services, and sustains soil quality (find more in chapter 0).

3.3.1.3. Breeding of future bio-based energy crops

The first step in plant breeding for bio-based renewable energy is to select appropriate crop species and genotypes suited for specific geographical regions (Johnson et al., 2007). (López-Bellido et al., 2014) states that the highest impacts on the quantitative and qualitative improvement of energy crops are likely to come from: the selection of appropriate species and genotypes, the establishment of crops, water needs, dosage and timing of fertilisation practices, the control of diseases and weeds, and harvesting times and methods. The in-depth evaluation of these factors, as well as their interactions, is necessary to develop cropping practices, such as establishment, harvesting or fertilisation, and crop rotations with the goal of maximising performance and optimising raw material quality with limited use of inputs.

3.3.1.3.1. Selection of appropriate species

Crops appropriate for biofuels should exhibit the following characteristics (López-Bellido et al., 2014):

- Crops with rapid growth (short period from planting to harvest);
- High yield of usable biomass or seeds (especially for starch- or oil-based biofuels) per hectare;
- Sustainable and efficient agricultural production systems to avoid competition with food production systems;
- Crops that can grow under severe weather and poor soil conditions (where other crops will have low and unstable yield);
- Crops with inherently high resistance for pests, diseases and predators.

Crops developed and grown specifically for biofuel production are expected to be based on perennial species grown from roots or rhizomes that remain in the soil after harvesting the above-ground biomass. Perennial species are considered advantageous for several reasons. First, input costs are lower than for annuals because costs of tillage are eliminated once a perennial crop is established. Additionally, long-lived roots of perennials may establish beneficial interactions with root symbionts (rhizobium and mycorrhizae) that facilitate acquisition of mineral nutrients, thereby decreasing the amount of fertilizer needed. Perennial plants in temperate zones also may have significantly higher total biomass yield per unit of land area than comparable annual species.

Perennials establish a photosynthetically active canopy more quickly in the spring and may persist longer in the fall. Thus, their annual solar energy conversion efficiency is higher than that of annual plants with similar capabilities. (López-Bellido et al., 2014).

A wide range of crop species can be used as energy crops. Modern agriculture annually generates 10-30 t/ha of biomass, depending on crop species, crop management and soil-climate conditions. Lignocellulosic and perennial crops are the highest yielding crops, with switchgrass, giant reed and miscanthus up to 20 t/ha a year (López-Bellido et al., 2014). The European Environment Agency (Petersen et al., 2007) estimated the yields of miscanthus and switchgrass up to 10 t/ha a year in Northern regions and up to 30 t/ha a year in Southern regions. However, not all crops possess all of the requisites demanded to produce the high quality raw materials for bioenergy production as well as the amount of biomass to make them profitable. Accordingly, appropriate plants and production practices need to be identified in each agro-ecological zone and improved over time so that their characteristics can be developed to ease and lower the costs of pre-treatment and conversion processes (see Table 3.13).

Table 3.13 Potential crops for 2nd generation bioenergy production for European environmental area

Potential crops	Boreal-Nemoral (FI, SE, EE, LV, LT)	Atlantic North (DK)	Atlantic Central (BE, DE, FR, IE, NL, UK)	Continental (AT, PL)	Pannonian (CZ, HU, SL, SK)	Medi-terranean (ES, EL, IT, PT)
Cardoon						**
Giant reed					***	**
Reed canary grass	***	***				
Miscanthus		***	***	***	***	**
Switchgrass		***	***	***	***	**
Eucalyptus			*			*
Poplar, willow	**	**	**	**	**	

(adapted from López-Bellido et al., 2014).
Note: * Medium to high energy yield; ** High agri-environmental ranking; *** High yield and agri-environmental ranking.

A better understanding of the currently available raw materials with respect to their crop practices, potential and actual performance, geographical distribution and costs is required.

Perennial grasses

Included among the crops to produce second-generation biofuels are perennial forage crops, such as switchgrass (*Panicum virgatum)*, reed canary grass (*Phalaris arundinacea*), alfalfa (*Medicago sativa*), elephant grass (*Pennisetum purpureum)* and Bermudagrass (*Cynodonspp.*). These species have been studied extensively for the production of cellulosic raw materials (Johnson et al., 2007).

In Europe, about 20 perennial grasses have been tested and four perennial rhizomatous grasses, namely miscanthus (*Miscanthus spp.*), reed canary grass (*Phalaris arundinacea*), giant reed (*Arundo donax*) and switchgrass (*Panicum virgatum*) were chosen for more extensive research programs (Koçar and Civaş, 2013).

Table 3.14 List of perennial grasses studied as energy crops in Europe regarding their yields

Common English name	Latin name	Countries
Giant reed	*Arundo donax*	IT
Tall fescue	*Festuca arundinacea*	UK, FR
Alfalfa	*Medicago sativa*	FR
Chinese silver grass	*Miscanthus sinensis*	BE
Giant miscanthus	*Miscanthus x giganteus*	BE, UK, FR, DE, IT, PL
Switchgrass	*Panicum virgatum*	BE, UK, FR, DE
Reed canary grass	*Phalaris arundinacea*	BE, UK
Common reed	*Phragmites australis*	BE, IT

Laurent et al., 2015.

Based on published yield data collected for 36 lignocellulosic crops the most productive crops in Europe are giant miscanthus and giant reed. The least productive is common reed.

Miscanthus (*Miscanthus x giganteus*) is a C4 grass, native to Asia, vegetatively propagated, cold-resistant and requires low quantities of N fertilizer due to its highly efficient nitrogen cycle. (López-Bellido et al., 2014)

Giant reed (*Arundo donax*) and **reed canary grass** (*Phalaris arundinacea*) are grasses with the C3 photosynthetic pathway, and are native to Europe (Koçar and Civaş, 2013).

Switchgrass (*P. virgatum*) is a C4 perennial grass, native to warm climates, high productivity through multiple environments and suitable for marginal and erosive lands. It has low water and nutrient requirements per tonne of biomass produced and high environmental benefits. (López-Bellido et al., 2014)

In temperate and warm regions, C4 grasses out yield C3 grasses due to their more efficient photosynthetic pathway. However, the further north perennial grasses are planted, the more likely these cool season grasses are to yield more than warm season grasses. Low winter temperatures and short vegetation periods are major limitations to the growth of C4 grasses in northern Europe. With increasing temperatures towards central and southern Europe, the productivity of C4 grasses and therefore their biomass yields and competitiveness increase. (Koçar and Civaş, 2013)

SRC and fast growing trees

Please see information provided in Chapter 3.3.3.

New plant species for oilseed production

Besides conventional oilseed crops, new plant species for oilseed production are investigated to assess their suitability as biodiesel production crops. Nonedible oil conversion to biodiesel is comparable to the conversion of edible oils in terms of production and quality. Moreover, less land is required to cultivate these crops, and a mix of crops can be used to produce useful by-products, which can be used in other chemical processes or can be converted to energy. Examples of new oilseeds are camelina and crambe (both are promising for European climate conditions), castor bean, jatropha and cardoon.

Camelina (*Camelina Sativa*) is an oil plant that grows well on marginal land, is cold-tolerant and has an oil-yield of 35-38 %. 'Sustainable Oils' (a partnership between Targeted Growth, Inc. and Green Earth Fuels, LLC) has 30 Camelina breeding trials in the US and Canada. The company first provided Camelina-based biodiesel for a Japan Airlines test flight in January 2009. Biojet fuel derived from Camelina has been successfully used on many demonstration flights in the last five years. The Eureka BIOFUEL-CAMELINA Project, coordinated by ISCO, Poland, studied the cultivation of Camelina sativa and cameline oil production, biofuel production and evaluation. The 'Camelina Association of Ukraine' was established in 2014 for cultivation and commercial exploitation of *Camelina sativa* products in Ukraine. (EBTP, 2015)

Crambe (*Crambe abyssinica*) is thought to have originated from the Mediterranean region, western Asia and eastern Africa (from Ethiopia to Tanzania). As a Mediterranean and tropical highlands species, crambe is well adapted to cold weather during winter. Crambe occurs naturally in Mediterranean Europe, Morocco and the Middle East (Feedpedia, 2017).

Based on the state of the art of the current research in Europe, camelina (*Camelina sativa*) and have been identified as major candidates among currently researched oil crops for the future European bio-based economy. These findings are based on results of a recent EU funded Horizon 2020 Project COSMOS (Camelina and crambe Oil crops as Sources of Medium-chain Oils for Specialty oleochemicals). Both crops can be grown in a wide range of climatic and soil conditions, including saline and polluted soils, and are draught tolerant; however, they are frost sensitive and for achieving higher yields, milder temperatures are preferred.

Castor bean (*Ricinus communis* L.) has been used for many years as an industrial oilseed crop because of its high seed oil content (~50 %), unique fatty acid composition (high in ricinoleic acid) and lubricity, potentially high oil yields, and its ability to grow under varying moisture and soil conditions. Castor bean use is limited to some extent because the unprocessed seed contains a highly toxic protein – ricin. Nevertheless with appropriate processing and handling along with new efforts to breed ricin-free seeds, castor holds promise as a biodiesel fuel along with its current industrial and pharmaceutical uses. The overall major constraint for using castor oil as a feedstock for biodiesel is not its physical and chemical properties but the high price paid for castor oil as an industrial and pharmaceutical feedstock. Due to its high lubricity characteristics, biodiesel derived from castor oil could achieve the required lubricity for biodiesel standards at concentrations much lower than that of rapeseed or soybean. However, the high viscosity may limit its use to lower percentages in biodiesel blends or to warm climates.

Developing new cultivars that have desirable growth habits and canopy structure for mechanical harvesting will allow increased acreage. Breeding ricin-free cultivars along with modified oil profile characteristics to enhance processing and use will overcome current limitations. Further evaluations of fertility needs and plant spacing/population could enhance yields. Improving the quality of the meal residue could make it useful as a livestock feed and enhance the economic value of the crop. (Helsel, 2014)

Jatropha (*Jatropha curcas* L.) is a tropical plant with high oil content (~40 %). It is being promoted as a potential renewable energy source as the tropical jatropha woody perennial tree or shrub species may survive in harsh climate and soil conditions. According to (EBTP, 2015) in Singapore jatropha strains with even 75 % oleic acid content have been developed. Jatropha contains toxic substances and therefore is unsuitable as a food/feed crop.

Jatropha seemed a very promising candidate as a biofuel feedstock and an investment boom followed in the mid-2000s. However, initial claims of high yields could not be verified on marginal lands; the early cultivars tested required lots of water, good soils and high fertiliser inputs to achieve high yields. (EBTP, 2015)

A review of 147 studies regarding jatropha cultivation experiences (Eijck et al., 2014) revealed that there is insufficient knowledge about some of the agronomic, socio-economic and technical aspects of the jatropha value chain and its implications for the sustainable livelihoods of local communities. Therefore future research efforts among others shall be targeted to (Eijck et al., 2014):

- Collection and use of more reliable, observed yield figures to conduct cost-benefit-analysis assessments;
- Improving profitability by finding higher-value uses for by-products, achieving greater oil-processing efficiency, developing seed varieties with higher and more reliable seed yields under semi-arid conditions, and optimising cultivation practices;
- Gaining better insight into trade-offs and related environmental impacts, for instance using marginal land with increased fertiliser use instead of more fertile land;
- Analysing all linkages and aspects related to food security to arrive at a greater understanding of the food security impacts caused by plantations.

Despite previous experiences, research and investment in jatropha continues. In 2014, Lufthansa signed a Memorandum of Understanding with JatroSolutions GmbH (a subsidiary of EnBW, the third-largest German energy company) to make jatropha production commercially viable. Jatropower AG, from Switzerland offers a wide range of hybrid seeds and jatropha cultivars and is attempting an uptake of the second generation of improved jatropha projects. (Francis, 2016)

Cardoon (*Cynara cardunculus*) serves as multifunctional bioenergy crop that can produce solid and liquid biofuels. Besides agro-pellet production, cardoon biomass contains 15 – 20 % seed, which is by 25 % rich in oil that can be used for sustainable production of cheap biodiesel. Moreover, biomass from cardoon is rich in cellulose and hemi-cellulose and may produce considerable amounts of bio-ethanol (Johnson et al., 2007).

Other investigated new oil crops include **Macaw palm** (*Acrocomia aculeata*), **Dwarf saltwort / Dwarf glasswort** (*Salicornia bigelovii*), **Pennycress** (*Thlaspi arvense*), **Ethiopian mustard** (*Brassica carinata*) and **Indian Beech** (*Millettia pinnata, Pongamia pinnata*). More information about these oil crops is provided in Annex 3.

3.3.1.3.2. Domestication and genetic improvement of energy crops

It is unrealistic to assume that plantations of bioenergy crops can be started with little or no domestication; large deployment of wild species in the landscape as bioenergy crops is bound to lead to unforeseeable biological and environmental problems. Biomass and bioenergy yields of lignocellulosic crops could increase significantly over time since breeding research, including genetic modification of bioenergy crops, is at an early phase compared with food crops. (Jaradat, 2010)

Discovery of genetic variants in native populations and domestication of potential wild biomass species may save many years of expensive breeding steps to develop more productive plants for processing to biofuels. In addition to targeted breeding, many of these potential biomass crops will require reproductive control in the field, either to ensure parentage or prevent gene flow to wild populations. (Johnson et al., 2007)

Many features considered ideal for herbaceous biomass crops are characteristics of invasive weeds, particularly perennial C4 grasses. A consideration in adapting these grasses for use as dedicated biomass crops is to ensure that the species can be contained as a crop and will not become a problem. Some highly productive perennial grasses such as *Miscanthus* × *giganteus* have been studied intensively in Europe and are thought not to exhibit invasive characteristics. All candidate biomass crops should be studied for potential invasiveness and provide insights into insects and diseases that might threaten productivity. (Johnson et al., 2007)

Because of the limited breeding experience to date, advances in biomass crop yield and quality can be expected over the next few decades. Improved genetic material and management of dedicated biomass crops likely also will improve production. (Johnson et al., 2007)

The most important features of plants to improve their yield and quality as bioenergy crops include the following (López-Bellido et al., 2014):

- Tools for yield improvement:
  - Maximise the solar radiation interception (early vigour, frost resistance, close canopy, leaf characteristics for efficient light capture);
  - Maximise the efficient use of radiation (low-temperature tolerance in C4 metabolism, high nutrient use efficiency and diseases and pests resistance);
  - Maximise the water use efficiency (avoidance and drought tolerance, root depth);
  - Optimisation of environmental sustainability (efficient recycling of nutrients, root/shoot distribution).
- Characteristics for quality improvement:
  - Ease of harvesting and storage;
  - Suitability for thermal conversion technologies;
  - Suitability for biologic conversion technologies;
  - Health and safety (low dust, postharvest disease resistance).

Genetic improvement of conventional crops for potential use in biofuel production can result in rapid progress based on pre-existing knowledge and germplasm collections. A broad base of genetic resources, especially of wild and semi-domesticated perennial grasses, and starch-, oil- and lignocellulose-producing woody plant species, is available for selection, improvement and genetic modification with the objective of developing energy crops that are favourable to the environment. The genetic improvement of plants can increase biomass and ethanol yields and their agronomic performance and stability, through stress-tolerance, resistance to pathogens and pests, as well as low requirements for biological, chemical or physical pre-treatments. (López-Bellido et al., 2014)

Similarly, improvements in the composition and biochemical structure, such as the cell wall composition of energy crops, will enable the production of higher energy per tonne of biomass, which will improve their caloric value and GHG profile and will potentially mitigate global climate change (López-Bellido et al., 2014). Alterations of the ratios and structures of the various macromolecules forming the cell wall are a major target in bioenergy crop domestication and development. This allows for easy post-harvest deconstruction of these macromolecules at the cost of a less rigid plant. The genetic engineering industry is actively seeking ways of using GM to simplify and streamline processes to breakdown cellulose, hemicellulose and lignin, so as to produce inexpensive and environmentally-friendly biofuels more easily and efficiently from plant biomass. (Jaradat, 2010)

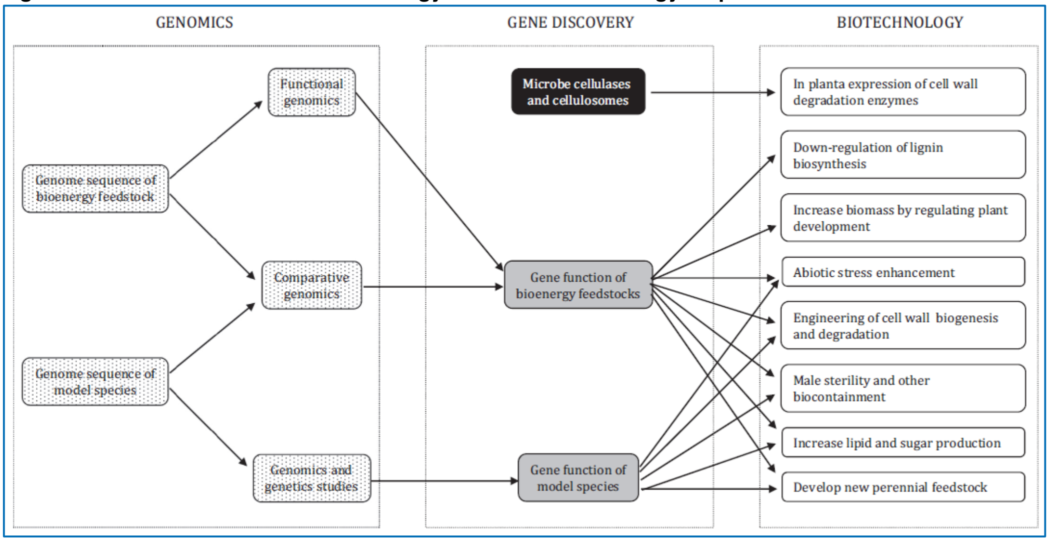
Hybrids of specific crops dedicated to energy are feasible in the mid- to long-term and will undoubtedly improve biomass and the mitigation of global climate change. The criteria for the development of new hybrid for energy crop include the following (Jaradat, 2010):

- sowing of large seeds that will vigorously establish themselves to simplify biofuel production systems;
- delayed flowering using photoperiodicity to achieve the greatest biomass accumulation and potentially prevent the risk of weed- and seed-transmitted diseases; and
- genetic or cytoplasmic sterility or broad hybridisation to allow higher bioenergy production and to reduce the potential for invasiveness.

The future of energy crops should see the application of genomics to the discovery and manipulation of genes to create optimally designed energy plants. The efficiency of photosynthesis may be enhanced by selecting or engineering plants with an optimal metabolism for specific environments. Similar to conventional crop breeding, C4 pathways of photosynthesis may improve the efficiency of carbon fixation, especially at high light intensities in warm and dry environments. Plant architecture may be optimised to capture solar energy in order to increase the production that must be easily harvested and converted to useful bioenergy molecules (Jaradat, 2010).

Biomass composition may also be selected to best suit available biofuel conversion technologies, for example by improving access to enzymes, at the molecular level, on cellulose compounds that are linked in a complex manner to the structure of lignin (López-Bellido et al., 2014). Comparative genomic studies, using modern biotechnological tools, will improve knowledge and allow logical inferences that may lead to the transfer of genes to distantly related cereal species, for example, the lignocellulosic features of sugarcane, sorghum, corn and rice (see Figure 3.14). (López-Bellido et al., 2014)

Figure 3.14 Genomics-based biotechnology research for bioenergy crops



López-Bellido et al., 2014.

Genetically modified (GM) crops are obtained by genetic engineering techniques. Genetic engineering offers an opportunity to generate unique or novel genetic variations that could not otherwise be obtained by conventional breeding (Barth et al., 2014). Generation of transgenic plants, coupled with selection, has led to the development of transgenic cultivars in several major cash crops, such as maize, soybean and cotton. These transgenic cultivars have been widely adopted in many parts of the world. Transgenic technology has also been used to improve forage and turf species and, more recently, to improve biofuel production from potential bioenergy grasses. (Barth et al., 2014)

The two main methods currently used to produce transgenic plants are: microprojectile bombardment (biolistics) and *Agrobacterium*-mediated transformation. Biolistics utilizes high-velocity gold or tungsten particles to deliver exogenous DNA into the plant cells for stable transformation. *Agrobacterium tumefaciens* is a soil bacterium that harbours a tumor-inducing plasmid. Starting from the late 1990s, *Agrobacteria* have been successfully used to transform grasses. To date, transgenic plants have been obtained for many forage, turf and bioenergy species, such as tall fescue, meadow fescue, red fescue, perennial ryegrass, Italian ryegrass, creeping bentgrass, Kentucky bluegrass, orchardgrass, bahiagrass, zoysiagrass and switchgrass. (Barth et al., 2014)

Examples of genetic improvement of switchgrass by transgenic technology have been provided by (Barth et al., 2014). In the first example cell wall composition of switchgrass has been modified. Cell wall composition directly affects processing properties of lignocellulosic biomass. Due to the association of lignin with cellulose and hemicellulose, cell wall materials are largely recalcitrant to hydrolytic enzymes. Modifying lignin content and composition by down-regulation of enzymes involved in lignin biosynthesis is a direct and effective approach to solve the cell wall recalcitrance problem. In switchgrass, the down-regulation caffeic acid methyltransferase (COMT) led to reduced lignin content and altered lignin composition, improved forage quality, and up to a 38 % increase in ethanol yield using conventional biomass fermentation processes. Furthermore, the transgenic lines required less severe pre-treatment and less cellulase for equivalent ethanol yield compared to unmodified switchgrass. The transgenic COMT plants were transferred to the field. Under field conditions, transgenic switchgrass were phenotypically normal and continued to show reduced lignin content, increased sugar release and improved ethanol yield.

In second example a miR156b precursor was overexpressed in switchgrass. Relatively low levels of miR156 overexpression were sufficient to increase biomass yield while producing plants with normal flowering time. Moderate levels of miR156 led to improved biomass but the plants were nonflowering. These two groups of plants produced 58 – 101 % more biomass yield compared with the non-transgenic control. The non-flowering phenotype offers an effective approach for transgene containment in grasses. (Barth et al., 2014)

A major limitation for deployment of transgenics is the complicated GMO regulatory processes, especially in European Union. Energy crops do not enter the food chain directly and the main focus of risk assessment is on their potential environmental or ecological impacts. Most widely grown bioenergy species are highly self-incompatible and outcrossing. Pollen-mediated transgene flow is a major concern for such outcrossing species. Several biological containment measures have been developed or proposed to control transgene flow. Such measures include (Barth et al., 2014) male sterility, seed sterility, maternal inheritance, delayed flowering or non-flowering.

In Europe there is a general distrust against genetically modified crops and in this climate also research suffers. (Lucht, 2015) reports that regular destructions of field trials of GM plants by vandals have made field research with GM plants virtually impossible in many European countries, the once strong number of field trials is dwindling, and scientists' willingness to publicly support plant genetic engineering is decreasing. Due to the unfavourable conditions, major plant biotechnology companies have moved research and development activities away from Europe and closer to the booming markets on other continents, and even have withdrawn requests for cultivation authorizations for GM crops in Europe.

Political attitudes towards GM crops are not uniform across all European countries. Rather, EU member states can be separated into three categories depending on their acceptance of plant biotechnology: "adopters", "conflicted", and "opposed" member states (see Table 3.15). (Lucht, 2015)

Table 3.15 Attitude towards GM crops in EU and Switzerland

Adopters	Conflicted	Opposed
ES, PT, CZ, SK, RO, DK, EE, FI, Flanders (BE), NL, SE, UK	FR, DE, PL, Wallonia (BE), BG, IE, LT	AT, CR, CY, EL, HU, IT, MT, SI, LV, CH
Governments and industry of “adopter” countries have pragmatic positions and are generally open to GM technologies.	“Conflicted” member states include countries where scientists, farmers, and the feed industry would support adoption of GM crops, but are resisted by consumers and governments under the influence of political parties and NGOs opposed to genetic engineering.	In “opposed” countries, most stakeholders and policy makers reject GM crop technology, and only a minority of farmers would consider its use. Public acceptance of GM crops here is lower than the European average.

Taken together, the recent trends in many European countries have left Europe with a very difficult environment for GM crops. In some countries, such as Germany, public support for plant biotechnology has virtually disappeared, as politicians from all sides of the political spectrum, farmers, the food industry, and retailers have rushed towards the non-GMO camp to take political or commercial advantage, while no one is left or willing to oppose anti GMO-campaigns. It is difficult to see how consumers’ attitudes towards GM crops and GM food in Europe might change under these conditions, in the absence of possibilities to make own practical experiences with GM food, or how a change of attitudes—if it would occur—could have an effect on the cemented negative political and regulatory framework. (Lucht, 2015)

Plant biotechnology is a rapidly evolving field, and developments have sped up substantially with the availability of molecular tools as basis for new breeding techniques. Intragenesis and cisgenesis, where only genetic information from the same species but no “foreign genes” are transferred; and new precise genome editing tools such as the CRISPR/Cas9 endonuclease system have expanded the possibilities for crop breeding. They contribute to the large number of biotech plants with novel or further improved traits in the R&D pipeline. Many researchers and seed companies hope that the new breeding techniques will facilitate consumer acceptance and the way to market for plants with improved traits, thereby circumventing the roadblocks transgenic GMOs have faced in many countries. Indeed, plants developed with the help of the new breeding techniques do not fit the traditional definition of GMOs, and in many places, political discussions are ongoing on how they should be regulated. (Lucht, 2015)

Plants produced with the new breeding techniques do not contain genes transferred across species boundaries, and the genomic changes by modern genome-editing tools often are indistinguishable from those present in plants developed by classical breeding. Nevertheless, a technical procedure, which might be perceived as unnatural, is involved in producing these new plants. (Lucht, 2015)

Genetically modified energy crop species may be more acceptable to the public than are GM food crops, particularly in Europe, but there are still concerns about the environmental impact of such plants including gene flow from non-native to native plant relatives. (Barth et al., 2014)

3.3.2 R&I on agricultural practices

Raising the collective standard of farming across the EU27 region – particularly in the new member states – will increase food yields and the availability of agricultural residues. The improvement in farming practices should simultaneously drive the development of additional equipment to collect agricultural residues from the field. (BNEF, 2010)

Best agricultural practices for increasing residue yield of 10 agricultural feedstocks have been studied by (Iqbal et al., 2016). In the study a comprehensive analysis of agricultural sector in EU, Ukraine, Belarus and Russia has been carried out. The study focused on the identification of agricultural practices for increasing the availability of cereal (wheat, barley, rye and oats) straw, rapeseed and sunflower stalks, maize stover and cobs, sugar beet leaves, wine pruning and biomass from grassland management. Similar to findings described in Chapter 3.2 of this report, the (Iqbal et al., 2016) study concludes that within the EU, residues from wheat, maize and barley contribute most to the realistic potential. Depending on the actual yield, the yield increase effect due to best practice strategies adds up to 16% for straw residues and even up to 21 % for sugar beet leaves.

In the study the EU Member States are divided into regions with low, medium and high yields (see Table 3.17). In high yielding regions like France the impact of best agricultural practices is low as French farmers already apply proper crop management. Whereas for instance in Romania (which is a low-yielding country), the impact is higher. The yield increase potential for agricultural residues and country groups is summarized in Table 3.16.

Table 3.16 Realistic crop residue potential in the EU

Crop residue	Yield increase in realistic potential through best practice strategies	High yielding countries, Mt/year	Medium yielding countries, Mt/year	Low yielding countries, Mt/year	Total realistic potential, Mt/year
Wheat straw	4-11%	5.095	6.891	19.298	31.285
Barley straw	7-13%	2.379	4.755	4.856	11.990
Maize stover/cobs	9-16%	3.096	5.020	7.339	15.455
Rye straw	7-13%	0.130	0.880	0.924	1.935
Oats straw	7-13%	0.388	0.568	0.504	1.460
Sunflower stalks	9-16%	0.118	0.802	0.832	1.752
Rape stalks	9-16%	0.614	2.113	5.933	8.661
Sugar beet leaves	14-21%	0.047	0.321	0.333	0.701
Wine pruning	13-17%	0.031	0.655	0.558	1.244
Total		**11.9**	**22.0**	**40.6**	**74.5**

Iqbal et al., 2016.

Table 3.17 Division of countries regarding crop yields

Crop	Low yield	Medium yield	High yield
Wheat	< 3.5 t/ha BG, CY, CZ, EE, EL, PT, RO, ES, RU, UA, BY	3.5-7.0 t/ha AT, FI, HU, IT, LV, LT, LU, MT, PL, SK, SI, SE	> 7.0 t/ha BE, DK, DE, IE, NL, UK, FR
Barley	<3.0 t/ha CY, EE, EL, LV, LT, PT, RO, ES, RU, UA	3.0-6.0 t/ha AT, BG, CZ, DK, FI, HU, IT, LU, PL, SK, SI, SE, UK, BY, MT	>6.0 t/ha BE, FR, DE, IE, NL
Rye	<2.4 t/ha BG, LT, RO, ES, BY, RU, UA, HU, PT, EL	2.4-4.8 t/ha AT, FI, CZ, IT, LV, PL, SK, SI, EE, NL, IE	>4.8 t/ha DK, FR, DE, LU, UK, BE, SE
Oat	<2.1 t/ha BG, LT, RO, CY, EE, LV, RU, UA, ES, EL, PT, SK	2.1-4.6 t/ha AT, CZ, HU, IT, LU, PL, SI, FI, SE, BY	>4.6 t/ha DK, BE, DE, NL, IE, UK, FR
Maize	<6.0 t/ha BG, LT, RO, RU, UA, PL, BY	6.0-9.3 t/ha CZ, DK, HU, IT, LU, SK, SI, PT	>9.3 t/ha AT, BE, FR, DE, NL, ES, EL
Rapeseed	<2.2 t/ha BG, EE, FI, IT, LT, RO, ES, BY, RU, UA	2.2-3.3 t/ha AT, BE, CZ, EL, HU, LV, PL, SI, SK, SE	>3.3 t/ha DK, FR, DE, IE, LU, NL, UK
Sunflower	<1.5 t/ha PT, RO, SI, ES, BY, RU, UA	1.5-2.2. t/ha BG, DE, EL, PL, UK	>2.2 t/ha AT, CZ, FR, HU, IT, SK
Sugar beet	<45.0 t/ha BG, FI, LV, LT, RO, BY, RU, UA, SI	45.0-65.0 t/ha CZ, DK, DE, HU, IE, PL, PT, SK, SE, UK, IT	>65.0 t/ha AT, BE, FR, EL, NL, ES
Wine (grape)	<4.1 t/ha BG, CY, MT, UK	4.1-8.0 t/ha AT, CZ, FR, HU, PT, RO, SK, SI, ES, BY, RU, UA	>8.0 t/ha DE, IT, EL, LU

Developed based on (Iqbal et al., 2016).

In the following pages some of the factors affecting agricultural residue to product ratios will be described.

3.3.2.1. Selection of high residue yielding varieties

Selection of cultivar plays significant role in defining the residue to crop ratio. A study carried out in Denmark during 2008 and 2009 compared different cereal cultivars to estimate their effect on residue to crop ratio. The results showed that grain yield did not differ significantly between the species, but winter rye yielded up to 59 % more straw dry matter than the other species. The fact that straw yield was significantly different among the diverse species while there were no differences in grain yields, demonstrates a possibility for farmers to grow cultivars with higher straw yield without compromising the grain yield. Explicitly, total biomass yield from winter wheat production may be increased by selection of the right cultivars. However, grain yield is still the primary goal of cereal production, and increased straw yield should not bring along negative consequences such as increased susceptibility to lodging and diseases. Also, from a farmer’s perspective, increased straw yield may increase fuel consumption, reduce the capacity of harvesting machinery as well as increase the demand for fertilisation, and these aspects must also be included in economic considerations. (Iqbal et al., 2016)

Within a study performed in UK (Berry et al., 2008), genetic markers for increased wheat yield were identified. One of these ‘yield genes’ was shown to increase both grain yield and straw biomass.

The authors of the study claim it to be a significant finding because until the late 1980s breeders increased grain yield without altering total biomass by increasing the proportion of total biomass partitioned to the grain at the expense of straw. There is evidence that after the late 1980s breeders began to increase the total amount of biomass. This was an important breakthrough because at the time it was believed that varieties were approaching the theoretical maximum for the proportion of total biomass that could be allocated to grain without weakening the supporting stem (and causing lodging). The discovery of a gene that controls the increase in total biomass, together with an understanding of how it works, will help to achieve further increases in yield potential. Improvements in total biomass may also mean that stem strength and yield can be improved together, increasing also the availability of straw (Berry et al., 2008).

3.3.2.2. Adjusting nitrogen fertilization rates for increased residue yield

Iqbal et al., (2016) reviewed several studies regarding impact of nitrogen fertilization on residue to crop ratio for different cereals. Authors concluded that for wheat, effect of nitrogen fertilisation was not clear and there was no significant increase in residue to crop ratio observed. For rye, the residue to crop ratio increased with increase in fertilisation except for one location. The spring barley and spring oat have shown significant increase in residue to crop ratio with increase in nitrogen fertilisation.

3.3.2.3. Effect of fungicide application on residue yield

Previous studies show that the use of fungicides has significant effect on residue to crop ratio (Iqbal et al., 2016). A study carried out in Denmark reported average straw yield increase to 0.42 t/ha for two fungicide treatments, but the increase in straw yield did not depend on straw length. Although fungicide treatments on average increased straw yields significantly, the differences between one and two fungicide treatments were only 0.1–0.2 t/ha, and this difference was not significant. The difference between tall (Terra) and short (Pentium) varieties was approximately 1.5 t/ha. This indicates that if a high straw yield is important for the farmer, tall varieties like Terra should be given higher priority than use of fungicides. (Iqbal et al., 2016)

The use of triademefon for control of mildew (*Erysiphe graminis*) has been discovered to increase both grain and straw yield in wheat. In case of application during elongation, straw yields were increased by more than 20 % in winter wheat. (Iqbal et al., 2016)

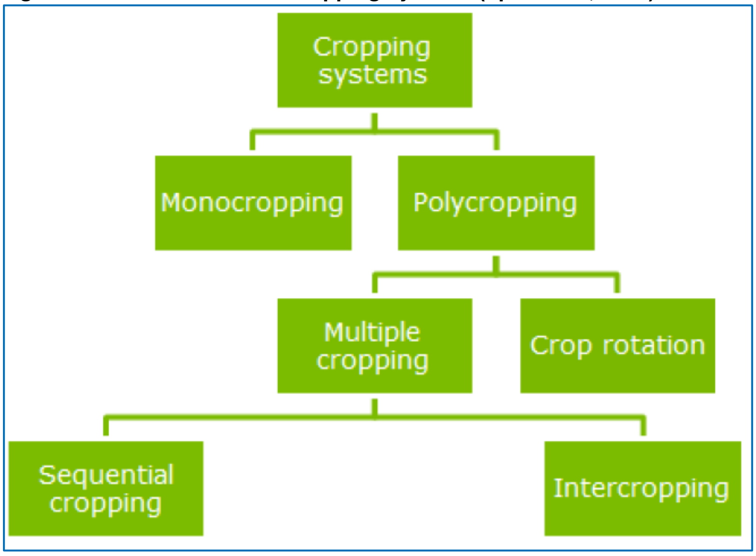
3.3.2.4. Varying sowing time and rate for increasing residue yield

Sowing rate also has an influence on residue to crop ratio. For example in winter wheat the sowing date and sowing rate had influenced the residue to crop ratio. A lower sowing rate results in higher grain yield and lower straw yield if it was early sown. Seeding in August gives highest yield and straw levels and higher residue to crop ratios. The residue to crop ratio increases with increase in sowing rate. Early sowing favours higher yield returns. (Iqbal et al., 2016)

3.3.2.5. Optimized cropping systems

The term **cropping system** refers to the crops and crop sequences and the management techniques used on a particular field over a period of years. This term is not a new one, but it has been used more often in recent years in discussions about sustainability of agricultural production systems (Nafziger, 2009). General classification of cropping systems is provided in Figure 3.15.

Figure 3.15 Classification of cropping systems (Iqbal et al., 2016)



Mono-cropping, or monoculture, refers to the presence of a single crop in a field. This term is often used to refer to growing the same crop year after year in the same field; this practice is better described as continuous cropping, or continuous mono-cropping. (Nafziger, 2009)

Poly-cropping can be realized as multiple cropping or crop rotation. The main purpose of multiple cropping is to increase the productivity per unit area. **Multiple cropping** is an umbrella term for all systems growing several crops consecutively or at the same time on the same plot in the same year (Iqbal et al., 2016). It includes the following cropping practices:

Double-cropping (also known as **sequential cropping**) is the practice of planting a second crop immediately following the harvest of a first crop, thus harvesting two crops from the same field in one year. This is a case of multiple cropping, which requires a season long enough and crops that mature quickly enough to allow two harvests in one year. (Nafziger, 2009)

Intercropping is the presence of two or more crops in the same field at the same time, planted in an arrangement that results in the crops competing with one another. (Nafziger, 2009)

Relay intercropping is a technique in which different crops are planted at different times in the same field, and both (or all) crops spend at least part of their season growing together in the field. An example would be dropping cover-crop seed into a soybean crop before it is mature. (Nafziger, 2009)

Strip cropping is the presence of two or more crops in the same field, planted in strips such that most plant competition is within each crop rather than between crops. This practice has elements of both intercropping and mono-cropping, with the width of the strips determining the degree of each. (Nafziger, 2009)

Multiple cropping systems are designed to intensify agricultural production while maintaining soil fertility, helping to maintain nutrients in the soil, to protect against pests and diseases, and to suppress weeds. A challenge is to select the most beneficial combination of crops where competition for light, nutrients, and water is kept to a minimum (Iqbal et al., 2016). It is also important to avoid potential negative impacts caused by allelopathy and auto-toxicity.

Allelopathy is the release of a chemical substance by one plant species that inhibits the growth of another species. It has been proven or is suspected to cause yield reductions when one crop follows another of the same family – for example, when corn follows wheat. Technically, damage to a crop from following itself (such as corn following corn) is referred to as **autotoxicity**. In many cases the actual cause of such yield reduction is not well understood, but it is generally thought that the breakdown of crop residue can release chemicals that inhibit the growth of the next crop. So keeping old-crop residue away from new-crop roots and seedlings should help to minimize such damage. (Nafziger, 2009)

In temperate regions and in the prevailing, mechanically-managed cropping systems, multiple cropping systems are generally not performed as mixed cropping (sub-type of intercropping) and double cropping (sub-type of sequential cropping) mainly occurs in biogas. For example a project entitled "Site specific cropping systems for biogas substrate production" was funded by the German Government during 2009 to 2012 with the main focus on developing different crop rotation systems, substrate characteristics and biogas yield (Iqbal et al., 2016). The application of multi-cropping systems in the EU is limited. In the EU the main limitation is the climatic conditions because they do not allow more than one vegetation period. The main technical limitation in the EU is the trend of carrying out all field operations through machinery and large land-scale cultivation practices. In multi-cropping systems, the currently available machinery is not that useful and it is also labour-demanding. (Iqbal et al., 2016)

In order to compare the efficiency of different multiple cropping systems, an index called the Multiple Cropping Index has been developed. It is expressed as the sum of area harvested for different crops during one year, divided by the total arable land. (Iqbal et al., 2016)

Another type of poly-cropping is **crop rotation**. Crop rotations, as a primary aspect of cropping systems, have received considerable attention in recent years, with many people contending that most current rotations are not sustainable. Many proponents of "sustainable" agriculture point to the stability that accompanied the mixed farming practices of the past, in which livestock played a key role in utilizing crops produced and in returning manure to the fields. Such systems can still work well, but reduced livestock numbers, fewer producers, and increased crop productivity have meant that such systems are likely to work well for a relatively small segment of agriculture. (Nafziger, 2009)

In Europe crop rotation is used to manage soil nutrients. Among the plant nutrients, nitrogen plays a very important role in crop productivity and its deficit is one of the major yield limiting factors for cereal production. With continuous cereal cropping systems the nitrogen supplied from the decomposition of organic matter must be supplemented from other sources. Common practice is to ensure adequate nitrogen supply using chemical fertiliser; however, in areas where farmers do not have sufficient resources, the ability of legumes to fix atmospheric nitrogen is used. Modulated roots of legumes and plant residues left after harvesting represent a valuable source of organic nitrogen. Cereal-legume-cropping systems also provide benefits to the subsequent crop. (Iqbal et al., 2016)

Catch crops and cover crops

Crops grown in the period between two main crops in order to retain nutrients in the root zone are called **catch crops.** Crops grown between two main crops to protect the soil against erosion and minimise the risk of surface run-off by improving the infiltration are called **cover crops**. Catch and cover crops can be under sown the previous main crop or sown immediately after harvest of previous the main crop. Crops grown in between two main crops may serve mainly as either catch or as cover crop or both. (Rubæk and Jørgensen, 2011)

Catch crops grown after harvest of agricultural crops can reduce nitrate leaching from the root zone in areas characterised by excess precipitation and run-off during autumn, winter and early spring. The rationale is, that the catch crop immobilises available nitrogen remaining in the soil after the harvest of the main crop by taking it up and storing it in the catch crop tissue. The immobilised nitrogen will be released to the soil again, when the growth of the catch crop is terminated e.g. by tillage the following spring. Effectiveness of a catch crop depends on fast establishment, the time chosen for termination of the catch crop and crop specific properties like growth rate, rooting depth and root density (Rubæk and Jørgensen, 2011). It is also possible to optimise the effectiveness of catch crops by using them systematically after crops known to leave substantial amounts on nitrate or organic nitrogen, which is easily mineralised. Catch crops are mainly introduced to retain nitrogen, but catch crops do also retain and recycle available phosphorus in the root zone. (Rubæk and Jørgensen, 2011)

Cover crops are grown on soils which otherwise would be bare in the winter season in order to protect the soil surface against erosion and nutrient losses though surface run-off. Fast establishment of the crop is important. Cover crops reduce both wind and water erosion of soil particles at the same time it retains N and P in the root zone for use by the following crop. Cover crops also promote infiltration and roots enhance percolation of water into the soils, which reduce losses of nutrients through surface run-off. (Rubæk and Jørgensen, 2011)

As winter cover crops rye, wheat, ryegrass and other grasses, and legumes are often used. Winter cover crops have been shown to reduce total water run-off and soil loss by 50 % or more, although the actual effect on any one field will depend on soil type and slope, the amount of cover, planting and tillage methods, and intensity of rainfall. The use of winter cover crops in combination with no-till corn may reduce soil loss by more than 90 %. Cover crops are promoted as a way to improve soil tilth, and they sometimes contribute nitrogen to the following crop. (Nafziger, 2009)

Incorporation of cover crops into a rotation also increases light intercept efficiency on a field level by extending the length of time a plant is producing photosynthate. (Johnson et al., 2007)

Termination of catch and cover crops can be done by mowing, tillage, roller chopping, application of herbicides or relying on temperature extremes. (Rubæk and Jørgensen, 2011)

Some studies have investigated using catch crops for energy production through anaerobic digestion. Catch crops have comparatively low biomass yield and it is the main limiting factor for using these crops as co-substrate in manure-based biogas plants. The profit obtained from the sale of biogas barely compensates for the harvest costs. A new agricultural strategy to harvest catch crops together with the residual straw of the main crop was investigated by Molinuevo-Salces et al. (2014) to increase the biomass and thereby the methane yield per hectare. Seven catch crops harvested together with the stubble of the main crop (spring wheat) were evaluated. The effects of stubble height and harvest time for different catch crops/straw blends were studied. Biomass yields were up to 3.6 t of TS/ha of which the catch crop constituted around 10% of the total biomass. Leaving the straw on the field until harvest of the catch crop in the autumn could benefit biogas production due to the organic matter degradation of the straw taking place on the field during the autumn months. This new agricultural strategy may be a good alternative to achieve economically feasible biogas production from catch crops and straw. (Molinuevo-Salces et al, 2014)

In general it can be concluded that selection of optimal cropping system allows obtaining yield increase of the main crop (thus also the increase of crop residue amounts) by managing carbon stock, recycling nutrients and maintaining soil fertility.

3.3.2.6. Tillage

Proper soil management is a key to sustainable agricultural production. Soil management involves six essential practices: proper amount and type of tillage, maintenance of soil organic matter, maintenance of a proper nutrient supply for plants, avoidance of soil contamination, maintenance of the correct soil acidity, and control of soil loss (erosion). All of these practices depend on soil type, soil texture, and slope as well as on the crops that are grown. (Simmons and Nafziger, 2009)

Several techniques are available to reduce soil erosion, including residue management, crop rotation, contour tillage, grass waterways, terraces, and conservation structures. Conservation tillage and crop residue management are recognized as cost-effective ways to reduce soil erosion and maintain productivity. (Simmons and Nafziger, 2009)

Conservation tillage is an opposite of conventional tillage. The latest one is the sequence of operations traditionally or most commonly used in a given geographic area to produce a given crop. The operations used vary considerably for different crops and in different regions.

The objective of conservation tillage is to provide a means of profitable crop production while minimizing soil erosion due to wind and/or water. To be considered conservation tillage, the system must provide conditions that resist erosion by wind, rain, and flowing water. Such resistance is achieved either by protecting the soil surface with crop residues or growing plants or by maintaining sufficient surface roughness or soil permeability to increase water filtration and thus reduce soil erosion.

Conservation tillage is often defined as any crop production system that provides either a residue cover of at least 30% after planting to reduce soil erosion due to water or at least 1,000 pounds per acre of flat, small-grain residues (or the equivalent) on the soil surface during the critical erosion period to reduce soil erosion due to wind. (Simmons and Nafziger, 2009)

The term conservation tillage represents a broad spectrum of tillage systems (Simmons and Nafziger, 2009):

No-till: With no-till, the soil is left undisturbed from harvest to seeding and from seeding to harvest. The only “tillage” is the soil disturbance in a narrow band created by a row cleaner, coulter, seed furrow opener, or other device attached to the planter or drill. Many no-till planters are now equipped with row cleaners to clear row areas of residue. No-till planters and drills must be able to cut residue and penetrate undisturbed soil. In practice, a tillage system that leaves more than 70% of the surface covered by crop residue is considered to be a no-till system.

Strip-till: Strictly speaking, a no-till system allows no operations that disturb the soil other than planting or drilling. On some soils, including poorly drained ones, the no-till system is sometimes modified by the use of a strip tillage operation, typically in the fall, to aid soil drying and warming in the spring. This system is called strip-till. It is considered a category of no-till, as long as it leaves the necessary amount of surface residue after planting.

Ridge-till: Ridge-till is also known as ridge-plant or till-plant. With ridge-till, the soil is left undisturbed from harvest to planting except for possible fertilizer application. Crops are planted and grown on ridges formed in the previous growing season. Typically, ridges are built and reformed annually during row cultivation. A planter equipped with sweeps, disk row cleaners, coulters, or horizontal disks is used in most ridge-till systems. These row-cleaning attachments remove 0.5 to 2 inches of soil, surface residue, and weed seeds from the row area. Ideally, this process leaves a residue-free strip of moist soil on top of the ridges into which the seed is planted. The use of ridge-till has decreased considerably in the past decade, and it is currently practiced on small acreage. Reasons for its decline include the inconvenience related to driving across ridges during harvest, the difficulty in forming and maintaining ridges, especially on slopes, and the requirements for specialized equipment and row cultivation during the season.

Mulch-till: Mulch-till includes any conservation tillage system other than no-till and ridge-till. Deep tillage might be performed with a subsoiler or chisel plow; tillage before planting might include one or more passes with a disk harrow, field cultivator, or combination tool. Herbicides and row cultivation control weeds. The tillage tools must be equipped, adjusted, and operated to ensure that adequate residue cover remains for erosion control, and the number of operations must also be limited. At least 30% of the soil surface must be covered with plant residue after planting.

Studies show that only around 35 % of the maize residue is available in conventional tillage. In the case of reduced tillage, farming might allow an increased removal rates and higher availability of straw for other uses. In case of no till farming, 68–82 % of the maize residue can be available. (Iqbal et al., 2016)

3.3.2.7. Harvesting technologies

Improved harvesting methods, logistics and technologies in future will lead to increased mobilization of biomass resources – both because of increased collection efficiency and reduction of harvesting costs. The harvesting procedure varies from crop to crop and availability of machinery. Most residue recovery operations pick up residue left on the ground after primary crops have been harvested. (Iqbal et al., 2016)

Harvesting of straw, stalk, stubble and stover of cereals, maize and oil crops

In case of straw, harvesting is performed by cutting the straw from 5-20 cm stubble height depending on machine being used. The straw is harvested and left on the field in the form of ridges, therefore it is still collectable. (Iqbal et al., 2016)

Collection of residues from primary crops involves multiple passes of equipment over fields and results in no more than 40 % removal of stover or straw on average. This low recovery amount is due to a combination of collection equipment limitations, contour ridge farming, economics, and conservation requirements. It is possible under some conditions to remove as much as 60-70 % of corn stover with currently available equipment. However, this level of residue collection is economically or environmentally viable only where land is under no-till cultivation and crop yields are very high.

Future residue collection technology with the potential of collecting up to 75 % of the residue is envisioned. These systems are likely to be single-pass systems that would reduce costs by collecting the grain and residue together. Single-pass systems will also address concerns about soil compaction from multiple pieces of residue collection equipment unless the single pass system is heavier than the current grain harvesters. Further, one-pass systems for corn and grain will need to have selective harvesting capability so that some portions of the residue stream can be reapplied to the field to meet conservation requirements. (Iqbal et al., 2016)

For example, the US maize ethanol producer POET is attempting to retrofit its combine harvesters to simultaneously collect maize stover and maize cobs, which it will then convert into next-generation ethanol. (BNEF, 2010)

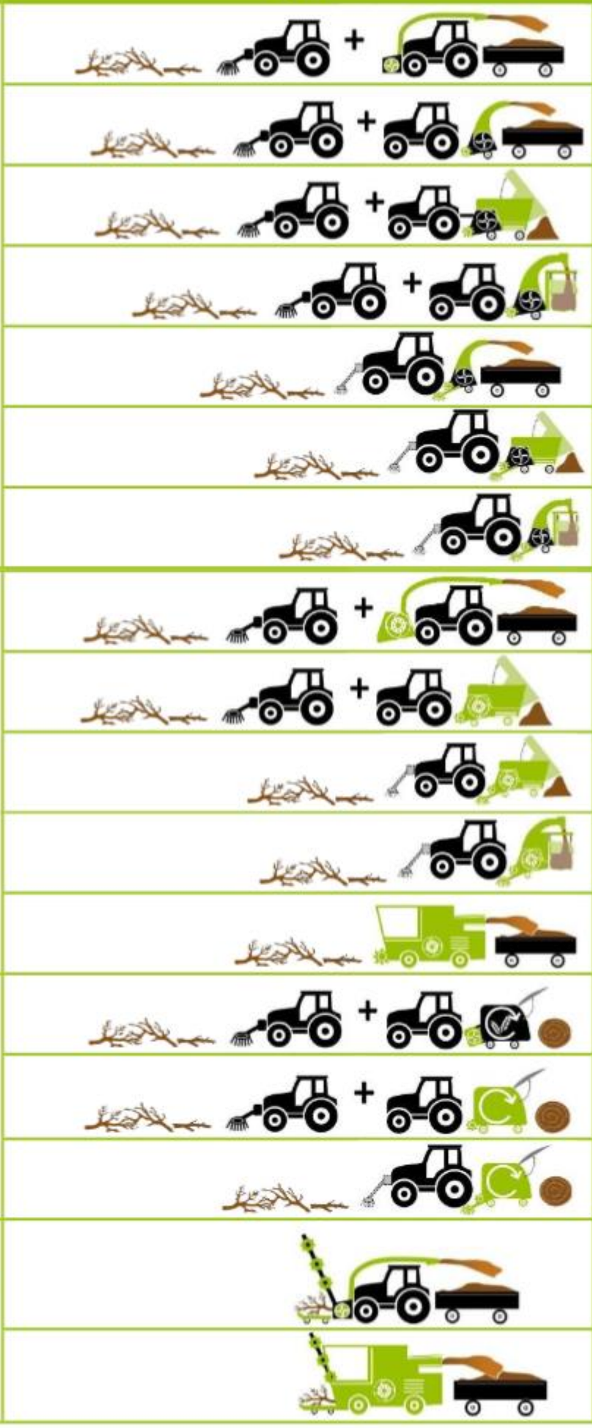
In case of cereals and oil crops cutting height during harvesting of crop plays a key role. Currently, the cutting height for cereals and oil crops is more than 20 cm depending on crop variety. The main issue with residue harvesting is lack of specific machinery at farmer level which leads to greater losses. There are no efforts to harvest residue, it is simply chopped and mixed in soil to improve soil fertility or in some cases collected to use it for livestock. (Iqbal et al., 2016)

Although there is machinery available especially in case of straw, farmers are rarely using it because there is no stable market of straw and also machinery is very expensive. Iqbal et al. (2016) suggested **reducing cutting height** up to 5 cm for cereals and oil crops. For example in case of wheat, the height of wheat varieties in Europe varies from 53 cm to 124 cm depending on location, with the mean height of 76 cm. If the stubble height is assumed 5 cm, then theoretically the rest of the straw can be harvested, if there is appropriate machinery available. Contrary to it, currently 20-30 cm unharvested straw is left on field, which is almost half of the total straw height in case of short varieties. Therefore, through appropriate use of machinery, the unharvested straw can be exploited. Iqbal et al. (2016) point out that there is already existing residue specific machinery for harvesting and collection of main agricultural residues – at least it is available on the pilot scale. In case of **using residue specific machinery**, the residue harvest can be increased theoretically up to 50% in case of straw from cereals and oil crops.

Harvesting and collection of prunings

Results of the harvesting machinery market analysis carried out in the EuroPruning project show that there are more than 70 technologies available in the market for the collection of prunings (see Figure 3.16).

Figure 3.16 Summary of existing pruning technologies in Europe



Techn.	Code	Nr observed	
Shredders and mulchers	[M1]	3	55
	[M2]	12	
	[M3]	37	
	[M4]	2	
	[M5]	1	
	[M6]	1	
	[M7]	0	
CHIPPERS	[CH1]	1	5
	[CH2]	3	
	[CH3]	1	
	[CH4]	1*	
	[CH5]	0	
BALERS	[BL1]	1	9
	[BL2]	4	
	[BL3]	4	
Integrated pruning and harvest	[PP1]	0	1
	[PP2]	1	
	TOTAL	71	

CIRCE, 2016.

As it can be observed, 55 of the technologies in market are related to adaptations of conventional mulchers, with different degrees of innovations and integration for improving the pruning biomass harvesting. Commercial prunings balers are also available in the market as well as machinery that integrate the pruning and harvesting in one step. (CIRCE, 2016)

Harvesting of energy crops and potential cost reduction

Biomass harvesting, achieved through a combination of mowing and baling operations, constitutes a significant portion of biomass provision costs. The spatial variations in biomass yield lead to the challenge of achieving high harvesting efficiency (Lin et al., 2016). Improvements of harvesting machinery will contribute to decrease of the costs of the biomass, especially related to future energy crops. For collection and harvesting of energy crops in contrary to food crops, dedicated harvesting machinery is not yet commercially available. Harvesting efficiency and cost reduction will be achieve as well thanks to the adoption of real-time sensing and control technologies, which are part of the precision farming approaches and are described in the next chapter.

Results of some studies show that it is realistic to assume that cost reduction of 10-30 % of biomass can be achieved through improvements of harvesting technologies and operations. Based on the results reported by Lin et al. (2016), ~10 % cost reduction of provision of Miscanthus biomass have been achieved in a farm in Illinois (USA) due to maximized harvesting (mowing and baling) machinery output rate. Another study (Male, 2015) reports that new improved harvesting machinery allowed up to 34 % of biomass cost reduction compared to conventional harvesting systems.

3.3.2.8. Precision farming

Precision Agriculture is a whole-farm management approach using information technology, satellite positioning data, remote sensing and proximal data gathering. These technologies have the goal of optimising returns on inputs whilst potentially reducing environmental impacts. (Zarco-Tejada et al., 2014)

The simple definition of precision agriculture is a way to “apply the right treatment in the right place at the right time”. (Zarco-Tejada et al., 2014)

The implementation of precision agriculture has become possible thanks to the development of sensor technologies combined with procedures to link mapped variables to appropriate farming practices such as tillage, seeding, fertilization, herbicide & pesticide application, harvesting and animal husbandry. The key feature of precision agriculture comes from positioning systems, principally Global Navigation Satellite Systems (GNSS) that are a major enabler of 'precision'. Precision agriculture is most advanced amongst arable farmers, particularly with large farms and field sizes in the main grain growing areas of Europe, USA and Australia, and where a business model to maximise profitability is the main driver. Controlled Traffic Farming (CTF) and auto-guiding systems are the most successful applications on arable land showing clear benefits in nearly all cases. For Variable Rate Application (VRA) methods, such as optimizing fertilizer or pesticide use to areas of need, the success varies greatly according to the specific factors of the application. (Zarco-Tejada et al., 2014)

For fruit & vegetables and viticulture, machine vision methods have brought benefits to products which are typically of high value and where quality is a key to obtaining a high price. Additionally, for such crops and also for arable areas, irrigation is under increased scrutiny since water shortages are more frequently occurring whilst availability on intensive agricultural areas requires precise management. Hence, precision agriculture technologies that use accurate indicators of water stress are employed to maximise the water use efficiency. An overview of precision agriculture technology and applications is provided in Figure 3.17. (Zarco-Tejada et al., 2014).

Moreover, extended applications of drones in agriculture are reported in the recent years. For example, drones are used to monitor the health of crops in the mid-season, to monitor the performance of irrigation systems, to identify weeds in inner parts of fields and to generate VRA maps to determine the strength of nutrient uptake within a single field for optimized fertilization. (Grassi, 2014).

Figure 3.17 An overview of precision agriculture technology and applications

Technology	Objective of development	State of Technology
Human-Machine-Interface instruments	Terminal suitable for all PA applications	Stand-alone terminals for every single application
Ownership of data	Facilitate the exchange of information between farmers, between farmers and contractors or suppliers and between the government and farmers	Data should be the property of the machine owner, but machine manufacturers use them for internal evaluation
Machine Guidance	Avoid overlapping following same tracks automatically for every field operation, driver relief, reduce chemicals and fuel	Driver assistance, steering support, automatic driving
Controlled Traffic Farming	Using the same tracks to minimise soil compaction.	Driver assistance, steering support, automatic driving
Recording of farm machinery movement	Machine surveillance, operators safety, optimization of processes	Data needed to measure and store machinery operations
Sampling location	Offline determination of soil quality, status of ground swell (pH-value, phosphor, potash, magnesium), soil composition	Detailed information about the soil fertility and transmitted diseases for optimal management and to fulfil legislation
Biomass monitoring	Mapping the state of plant growth and amount of nitrogen needed	Location-specific continuous or discrete crop phenology observations, optical sensors for canopy status and nitrogen content
Sensor and sensor fusion development	Automated data fusion of different sensor information for real-time decisions based on multi-layer datasets	Sensors for measurement of several parameters that are later integrated into products.
Machine Vision Systems	Guaranteeing the safety and security of food. Combining this data with producers' operation records (for example, when, where, and what kind of chemicals were sprayed, what kind of fertilizers were conducted)	Monitoring and classifying/grading fruit or vegetables.
Remote sensing (RS) techniques	Relating these images to yield potential, nutrient deficiencies and stresses	Recent aerial or satellite imagery
Variable rate application / technology	Application of seeding, fertilizing and spraying according to accurate mapping of soil and plant information	Enables specific treatment of areas within a crop parcel with variable levels of production.
Harvest monitoring	Localised harvesting information about crops and machine status to improve yield	Harvesting information (instant wet and dry readings, crop density, cutting and harvesting and information about yield)
Individual livestock tracking in a small scale	Information about animal health status and grazing behaviour, virtual fencing, understanding grazing pressure	Monitoring systems for the animals through GNSS receivers, storing position data at regular intervals
Tracking livestock transporting	Complying with legal regulations of animal welfare	Record the movement of vehicles
Electronic submission of area aid applications	Compliance of legal regulations	GNSS receivers allow the measurement of an area, the perimeter of a parcel or changed portions of a boundary
Farm Management and Decision Support	Software solution for farmers for automatic documentation, telemetry, decision support, machine control	Data management and decision support solutions existing from machine manufacturers and from providers of precision farming services

Zarco-Tejada et al., 2014.

Precision farming is a farming management concept based on observing, measuring and responding to inter and intra field variability observed in crops. The precision farming system can lead to increase in crop production with minimum environmental implications. (Iqbal et al., 2016)

There are many aspects in precision farming but the most important ones are site specific crop management and climate smart agriculture. By exploiting the variation in field through use of technology and application of appropriate amount of inputs, a substantial increase in actual crop yield can be achieved. These variations are not only limited to on field but also cover seasonal variations. Therefore, precision farming offers an opportunity to increase actual crop yield through precise crop management practices such as irrigation, fertilisation, seeding, crop protection and harvesting. For example increase in water use efficiency was achieved through different strategies such as regulated deficit irrigation. In south-west Europe due to climate change and variability in rainfall pattern, precision farming can play a key role in achieving high actual yields. Another important aspect in site specific crop management is nitrogen use efficiency. Studies were carried out in Germany where it was found that 10-15 % nitrogen use efficiency can be improved through precision farming. (Iqbal et al., 2016)

There is a need to carry out pilot research studies to convince farmers and also to explain the benefits of precision farming in terms of economic output but also environmental benefits. It will also help the farmers to see the environmental benefits beyond farm level. Considering the current technological developments in agriculture to realise high yields, the introduction of new machines which are able to provide high resolution information and with the capability of site specific agriculture management will not be that far. It definitely needs time to come up but it is certainly the future of agriculture. (Zarco-Tejada et al., 2014)

3.3.3 Agroforestry and SRC

Development of agroforestry and short rotation coppice will increase yields and carbon stock and will contribute to recycling of nutrients, increasing soil fertility, increasing biodiversity and will have positive impact on the water cycle. As described in previous chapters, the domestication of new crops and breeding efforts will play important role in the future to increase the availability of biomass for energy and biofuel production processes. It concerns also woody short rotation crops, where much research and innovation efforts are related to finding appropriate species for different climate areas and to make the plants more robust to be able to grow them in less suitable areas (e.g., on marginal, low value lands).

Short Rotation Coppice (SRC) are among the most promising dedicated energy crops for bioenergy production and mitigation of climate change impacts. SRC plantations result in more biomass and have larger GHG emission reduction potential than herbaceous perennial crops. (Jaradat, 2010)

Several fast-growing tree species are used as biomass feedstock for energy purposes in Europe. The most interest and research in Europe is done for willow and poplar SRC. Other SRC species which are cultivated in Europe are robinia, eucalyptus, alder, ash, and birch.

Willow

Willows, sallows, and osiers are from the genus *Salix*. This genus includes around 400 species of deciduous trees and shrubs and is found naturally primarily on moist soils in cold and temperate regions of the northern hemisphere. Willow is the species most commonly used in SRC plantations for energy in Europe. (Dimitriou and Rutz, 2015)

Willow species have been widely used in SRC plantations due to a range of suitable characteristics such as fast growth and high yields, ability to grow well under a variety of soils (e.g. ideally for pH 5-7.5, but also outside this range) and environments (from heavy clays to lighter soils), good ability to coppice (thus without needing replanting after harvest), roots that can stand highly anoxic conditions (thus can be planted in waterlogged conditions), ability to tolerate elevated nutrient and heavy metal concentrations (thus can be planted in harsh environments e.g. for phytoremediation). Willows have also another advantage that made them the most common species in SRC plantations for energy: their wide genetic variation with many different species offer different physiological characteristics that can be used in the field. Furthermore, willow is a species which can be easily bred. Thus, several crossings of different willow clones can be produced, which provide improved plant material with combinations of the different clones crossed. (Dimitriou and Rutz, 2015)

Willow genetic improvement programmes in Sweden and the UK have made significant progress in breeding willow for short rotation coppice used for bioenergy. To expand production, cultivars suited to a wider range of European environments and future climates are needed and have been developed during the last years. The primary aims of the above mentioned breeding programmes were to produce high yielding disease and pest-resistant varieties with a growth habit that facilitates mechanical harvesting. The majority of the cross breeds made by the Swedish breeding programme at Svalöf-Weibull AB (SW) have involved *S. viminalis*, *S. dasyclados* and *S. schwerinii*. The original parental material was based on Swedish and central European collections, later supplemented by collecting expeditions to central Russia and Siberia. The UK breeding programme based at IACR-Long Ashton (funded by the European Willow Breeding Partnership-EWBP) utilised over twenty different species held at the UK National Willows Collection. These included exotic equivalents of *S. viminalis* and *S. caprea* such as *S. rehderiana*, *S. udensis*, *S. schwerinii*, *S. discolour* and *S. aegyptica*. (Dimitriou and Rutz, 2015)

As a result of this work, all new willow SRC plantations now involve newly bred varieties/clones, which are more productive and have greater resistance against pests and diseases, which provides more stable yield levels. The choice of varieties/clones depends on the specific need of the grower and the climatic conditions of the site. It also depends on the availability of cuttings from the producers. Cutting producers need at least one year in order to be able to provide sufficient cuttings of each variety. Once they know which varieties/clones are required they can cut back their plantations to produce one-year old shoots for cutting production the following winter. There are presently about 25 certified EU varieties available, of which about ten are in mainstream commercial use today. Approximately one or two new varieties are developed annually. (Dimitriou and Rutz, 2015)

Poplar

Poplar belongs to the genus *Populus* of the *Salicaceae* family, and it is, together with willow, the most common species in SRC plantations for bioenergy in Europe. The natural distribution of poplar extends from the tropics to the latitudinal and altitudinal limits of tree growth in the Northern hemisphere. Species of the genus *Populus* are deciduous or (rarely) semi-evergreen and divided into six sections: *Abaso* (Mexican poplar), *Aigeiros* (Cottonwoods and black poplar), *Leucoides* (swamp poplars), *Populus* (white poplars and aspens), *Tacamahaca* (balsam poplars), and *Turanga* (arid and tropical poplars). (Dimitriou and Rutz, 2015)

For the plantation of SRC, usually poplar clones are used. Crossbreeds are made between *Populus trichocarpa*, *Populus maximowiczii*, *Populus deltoides*, *Populus tremula*, *Populus nigra*, *Populus koreana*, and *Populus tremuloides*.

Populus species are dioecious (i.e. individual trees are either male or female), and can be regenerated by coppicing and from cuttings. Various species of the genus have been widely planted around the globe, both within and outside its natural distribution. In Europe, larger trees from mature poplar stands are commercially used as saw timber, veneer and reconstituted wood products, but also for pulp. During the last years, the interest in establishing poplars in SRC systems to be harvested and used for bioenergy and fuelwood has increased, and several countries in northern Europe (e.g. Sweden), central Europe (e.g. Germany, France, Belgium, and others), and southern Europe (e.g. Italy and others) have developed plant material suitable for SRC. Several varieties/clones have been available in the market, and the grower needs to consult the nurseries and the variety/clone producers for further information that would enable an appropriate choice of plant material based on the site-specific characteristics. (Dimitriou and Rutz, 2015)

In comparison to willow, poplars grown for bioenergy in Europe are commonly considered to grow mostly in areas with: i) milder climates than for willow, thus central and south Europe are the areas that the interest for poplar is higher, although there are poplar plantations that produce satisfactory yields in northern Europe as well; ii) in sandier and drier soils than willow, which is probably related to lower water needs of poplar than willow, although poplars can grow and produce high yields even in clay soils; iii) less dense plantations as for the willow SRC systems (e.g. distances of 2-3 meters between the trees and harvest in longer rotations > 10-15 years), although there are poplars planted in coppice systems having the same densities and in general management as for willow SRC; iv) smaller surface of stands since poplar SRC can perform very well in plantation schemes that are not as intensive as willow SRC and do not need special equipment for e.g. planting and harvest if longer rotation periods are chosen (in such cases forest equipment or manual work will be needed for planting and harvest). (Dimitriou and Rutz, 2015)

Black locust

Black locust (*Robinia pseudoacacia L.*) is a foreign tree species for Europe, originating from eastern United States. It was introduced to Europe during the 17th century. Since then, a rapid spreading occurred in Europe, first as ornamental tree, and later by extensive plantations for timber production and by natural propagation. Nowadays, large areas covered with black locust can be found in central and in south-eastern parts of Europe. The species is comparatively drought-resistant, and is nitrogen fixing. For these reasons, black locust has been proved to be a suitable tree species for soil regeneration and reclaiming former mining sites. (Dimitriou and Rutz, 2015)

Robinia is characterised by its ability to grow on bare soils under extreme conditions, the fact that it is fast-growing with good coppice ability after harvest, and its high wood density. Hence, it proved to be very useful as SRC for bioenergy production. Large areas of forest stands were established with black locust in central Europe (mainly Hungary but also in other countries such as in Italy and Poland), but the interest in growing Robinia for SRC on agricultural land is lately also increasing, especially in areas where land reclamation is aimed. It has to be mentioned, however, that black locust is considered in some cases as invasive species and needs to be controlled with care. (Dimitriou and Rutz, 2015)

When referring to the production on agricultural soils, black locust grows on a broad range of soils in comparison to other SRC species, but not on very dry or heavy soils. It prefers sites with loose structural soils, especially silty and sandy loams and is resistant to environmental stresses such as drought, high and low temperatures, and air pollutants. For good black locust growth, soil aeration and water regime are the most important soil characteristics. (Dimitriou and Rutz, 2015)

Eucalyptus

Eucalyptus is a genus of fast-growing tree species originated from Australia that have been used for many years in southern Europe for pulp and paper production. During the last years, the use of wood biomass from eucalyptus for energy is gaining interest not only in southern Europe, but also in higher latitudes (e.g. in the UK and Ireland). The genus *Eucalyptus* contains more than 700 species. The most common species used in large plantations for biomass production in southern Europe are *E. globulus* and *E. camaldulensis*, and in northern Europe *E. gunnii* and *E. nitens* which are more tolerant to colder climates. (Dimitriou and Rutz, 2015)

Eucalyptus SRC plantations are traditionally planted in single-stem plantations in 3x3 m distances (or similar) and harvested after 7-12 years for pulp production. However, depending on the market situation, the wood has in some case been used in the energy market as well. Recently, interest in coppice plantations with eucalyptus for bioenergy has increased, testing and introducing more intensive production systems. In Europe most of such agricultural SRC systems are currently in the testing phase, in contrast to other parts of the world (e.g. Brazil, Australia) where SRC with eucalyptus have been implemented in a larger scale. (Dimitriou and Rutz, 2015)

Alder

Alder is the common name of a genus (*Alnus*) of flowering trees belonging to the family *Betulaceae*. The genus comprises about 30 species of monoecious trees and shrubs. They are distributed throughout the northern temperate zone with a few species extending into Central America and the northern Andes. (Dimitriou and Rutz, 2015)

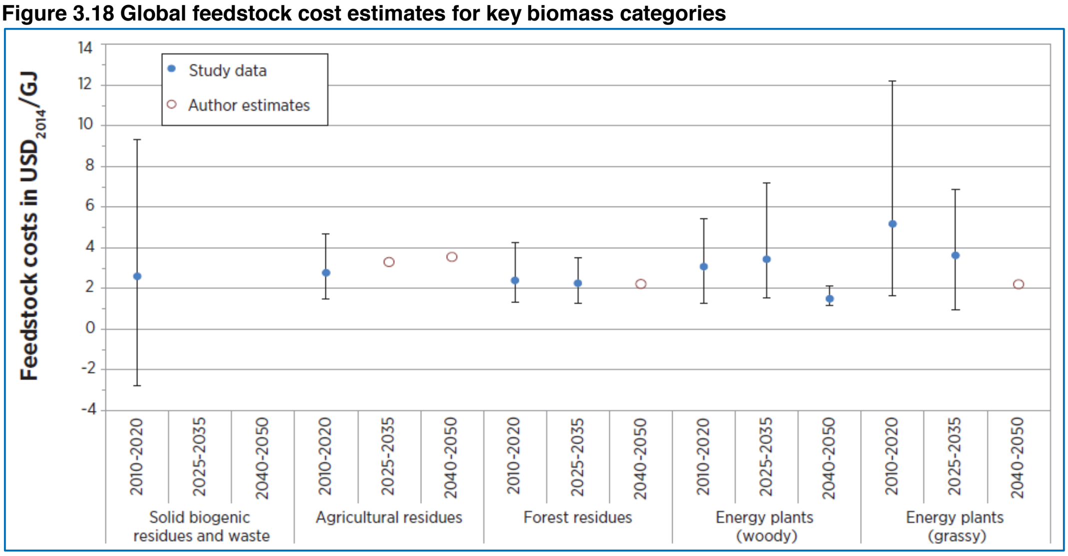
In general, the experience with alder for the SRC cultivation is still small. Some trials and plantations were just established. Alder has high light, nutrient and water demand, but can tolerate temporary innovation. The grey alder (*Alnus incana*) grows up to altitudes of 1 500 m and prefers limy soils and temperate cold climate. The black alder (*Alnus glutinosa*) prefers humid locations with high water availability and temperate climate. (Dimitriou and Rutz, 2015)

Other species

There is a large number of other species that have been candidates for SRC for biomass production for energy in Europe, such as *Acacia saligna*, *Ulmus sp*, *Platanus sp*., *Acer sp*., *Corylus avellana*, *Paulownia sp*., and others. Their introduction has been with lower success than the previous-mentioned species. Some are exotic and/or invasive species and have not been thoroughly tested and environmental concerns over potential invasiveness have been raised, while others seem to be adapted better in certain climates. (Dimitriou and Rutz, 2015)

Concerning the development of costs of SRC biomass, recent report of IRENA (2016) concluded that supply chains for dedicated non-food energy crops are at an early stage of development and therefore major deviations in cost estimates are present due to differences in yields between crops and regions. Significant data are available for SRC poplar and willow, which have a cost range of USD 2.4-4.3/GJ. Forecasts of energy crops show **costs decreasing in all regions** down to USD 1-1.6/GJ **in the next three decades**. Costs are estimated to fall to around USD 3/GJ (by ~60 %) in the next three decades (see Figure 3.18). (IRENA, 2016)

Figure 3.18 Global feedstock cost estimates for key biomass categories



IRENA, 2016.

3.3.4 *Marginal, degraded and unusable land for energy crops*

Large potential for development of energy crops in Europe is related to the use of marginal, degraded and unusable (for agriculture) land. Energy crops – both perennial grasses and SRC can be cultivated on soils of varying qualities. In addition to harvested biomass, both on marginal lands and productive lands, SRC and fast-growing grasses cultivation systems can provide multiple benefits (ecosystem services). However, marginal lands generally provide moderate yields and require optimised logistics, soil amendment and strict sustainability criteria, but there are options to improve their status. (IEA, 2016)

Yield potential for crops grown on marginal land is reduced below the optimal by stresses and therefore in future plant traits shall be identified which either **allow avoidance or increase tolerance of these stresses**. Breeding new varieties which possess these traits depends on identifying measurable physiological traits which can be used as selection criteria. The aim is to select appropriate species and genotypes which are adapted to local soil and climatic conditions. Selection criteria need to be based on the triple goals of maximizing productivity, minimizing inputs and maximizing utilization for energy production. Some of the traits of particular interest in recently instigated breeding programmes are drought tolerance, frost tolerance, maintenance of growth at low temperature, chemical composition, resistance to pests and diseases, altering plant architectural features such as dwarf structure and erect leaves and differences in photosynthetic capacity. (Barth et al., 2014)

3.3.5 *Mobilization of biomass from agriculture*

Many of the barriers facing the mobilisation of agricultural residues, and straw in particular, for use in the production of energy and advanced biofuels, are the result of the nascent nature of the market in this area and the lack of certainty about its long term future. (Kretschmer et al., 2012)

The main challenges for the mobilization of agricultural biomass resources are fuel quality, dispersion and low energy density. Fuel quality is particularly an issue for thermal conversion to electricity production, and the more general heterogeneity of the feedstock is challenging. The resource is dispersed and has a low energy density. Sufficient political support and economic incentives are required to build up and develop sustainable business cases for agricultural crop residues. (IEA, 2016)

Dispersion of biomass resources can be tackled by **optimization of supply chain logistics**. The quality of the fuel and low energy density can be improved by **developing better energy carriers** through densification and (pre-) treatment operations.

3.3.5.1. Optimized supply chain logistics

Critical to supporting the mobilization of sustainable bioenergy supply chains is **continued research and development in supply chain optimization**, particularly developing cleaner, more efficient, and more cost-effective technologies. Expanded funding for research programs and demonstration plants would support necessary technological innovation and supply chain optimization. (IEA, 2015)

Streamlining biomass supply chains with existing silvicultural and agricultural practices (e.g., timing of operations, use of machinery) is another opportunity to increase efficiencies and cost effectiveness, while at the same time increasing the overall productivity of existing practices. (IEA, 2015)

Improved agricultural logistics can help to reduce post-harvest losses and to improve transportation, storage and infrastructure, thus contributing to the mobilization of biomass resources for energy and biofuels. A recent IEA Bioenergy analysis of five globally significant supply chains (boreal and temperate forests, agricultural crop residues, biogas, lignocellulosic crops, and cultivated grasslands and pastures in Brazil), has concluded that feedstocks produced via **logistically efficient production systems** can be mobilized to make significant contributions to achieving global targets for bioenergy by 2050. (IEA-Bioenergy, 2015)

The cost of collecting and transporting the feedstock can be significant. Some progress is being made in establishing advanced biofuels feedstock supply chains as part of existing demonstration and early commercial projects. However, **significant efforts are still required to improve the efficiency of these chains, establish effective business models and prove their sustainability**. This could be achieved by monitoring the impact of extracting residues from the field on crop yields, for instance. Demonstrating viable advanced biofuels feedstock supply chains at scale is critical to the development of the sector, generating learning and replication. With performance monitoring, further development of the most attractive biomass supply chains will lead to increasing knowledge of their potential, particularly in the case of energy crops. **This could improve future estimates of global and regional bioenergy potential**. (IRENA, 2016)

3.3.5.2 Improved biomass carriers

Agricultural crop residues and energy crop biomass can be improved by mechanical and thermo-chemical (pre-) treatment operations. These operations are aimed at improving energy to weight ratio, on optimizing versatility of resources and their tradability.

Lamers et al. (2016) indicated that there is an opportunity to leverage existing infrastructure and technologies of biomass handling by using high-capacity, economic transport and handling equipment developed through other industries, such as grain and petroleum. However, this infrastructure is developed to move dense, flowable, consistent material (whether solid or liquid), characteristics which raw biomass often does not have under current agricultural supply systems. Therefore one of the future challenges is how to **transform raw, unstable, bulky biomass into a flowable commodity** like grain or petroleum. Raw biomass, currently not a commodity, will require significant investment to transition from the current supply system of the agricultural industry and markets to a commodity-type multiple market system. (Lamers et al., 2016)

Also currently used technologies are expected to be made more efficient, e.g. biomass torrefaction, steam explosion, mechanical conditioning (e.g., crushing, washing) and densification technologies (pelletising, briquetting). One of the future technological challenges is to develop technologies, which are mobile, small scale and can be applied in field operations (when dealing with primary agricultural residues). The last point relates to the technology transfer which is described in the next chapter.

3.3.6 Technology transfer

Technology transfer (from regions with well-developed supply chains to regions with minimal bioenergy deployment) and learning-through-doing provides opportunities to further increase supply chain efficiencies. Technical learning and putting entrepreneurs to work to increase profits and reduce costs is critical to advancing the efficiency and economic competitiveness of bioenergy systems. Transferring best practices and technologies from more experienced regions while accounting for regional differences, optimizing local conditions, and making use of existing infrastructure can be effective in getting supply chains off the ground. (IEA, 2015).

Using small-scale, niche applications as a platform for scaling up may be another effective approach to testing and improving supply chain technologies, gaining experience and increasing stakeholder and investor confidence. Improved financing opportunities for bioenergy would make entry into the market more attainable for smaller companies and enable the development of scalable enterprises such as these. (IEA, 2015).

Moreover, the transfer between technologies shall also be promoted. For example, biogas can fit well into a platform of technologies and agricultural practices to bring positive synergies and ecosystem services into the overall bioenergy system. When applied in synergy, biogas is able to store additional carbon, increase soil fertility and the net primary production at the farm, mitigate emissions from the farming sector, increase the organic matter of the soil and contribute to the fight against climate change at the local level while improving food security. According to IEE report (2016), this approach is promoted by the Italian Biogas Council as ‘BiogasDoneRight’. The primary feedstocks for biogas are livestock effluents (manure), agro-residues and agro-wastes, cover crops before or after cash crops, and food or perennial crops that are used to revegetate abandoned lands.

According to IPCC publication about methodological and technological issues in technology transfer (IPCC, 2000) there are several challenges related to technology transfer in biomass technology. First of all, biomass technology is still evolving, which makes it difficult to decide what exactly should be transferred in terms of knowledge and techniques. Secondly, biomass technology requires an interconnecting series of difficult technological choices concerning biomass sources and production, biomass handling and transportation, and biomass conversion and end use. These choices are to a large degree area-specific and cannot realistically be addressed on a generic level. Finally, there are a multitude of actors who potentially could become crucial players in global markets. Nevertheless, at least for some developing countries in Latin America, Asia and Africa, biomass energy may become the most important opportunity on a community level for economic development in an environmentally conscious world. Biomass technology transfer under current conditions is mostly dependent on government driven pathways, such as active involvement in R&D activities, demonstration projects financed locally or internationally, and government sponsored programmes to determine the resource availability. (IPCC, 2000)

Regarding technology transfer in agriculture sector and development in the future, IPCC (2000) report that, because of the rise of private sector plant breeding, new seed varieties (so crucial to yield growth across the world) will increasingly come from private companies demanding greater levels of IPR protection. Developing countries will have to interact with an increasingly concentrated private agricultural (primarily seed) biotechnology industry. **The private sector will thus become a more important vehicle for transferring modern crop varieties in the future**. In addition, many of the new innovations in plant breeding will come in the form of **transgenic crops**. While transgenic crops have already been widely adopted in the United States, many institutional barriers and controversies may limit their transfer to other countries (industrialised and developing). (IPCC, 2000)

3.4 Identification of major players in R&I

Identification of major players in R&I related to agriculture have been done using publication and scholarly output analysis with Elsevier SciVal (SciVal, 2017). Several data sets of customized research areas have been prepared and analysed (see Table 3.18). The analysis was made for Europe and worldwide, assessing publications of last 5 years.

Table 3.18 Customized research areas and data sets used for identification of major players in R&I in agriculture biomass fields

	Research area	Keywords	Size of retrieved publication set
1	**Feedstocks: energy crops**	energy AND crops AND agriculture	7 598
2	**Feedstocks: crop residues**	crop AND residues AND energy	7 002
3	**Feedstocks: straw**	straw AND energy	1 900
4	**Feedstocks: grassland biomass**	grassland AND biomass AND energy	171
5	**R&I: energy crop breeding**	energy crop AND breeding	388
6	**R&I: crops with high residue yields**	crop variety AND residue yield AND high	68
7	**R&I: optimized cropping systems**	cropping system AND optimal AND cover crops OR catch crops OR multiple cropping	2 676
8	**R&I: harvesting and collection of crop residues for energy**	crop residues energy AND harvesting OR collection	1 121
9	**R&I: precision farming**	precision AND farming OR agriculture AND energy	410
10	**R&I: SRC breeding and harvesting**	short rotation coppice AND breeding OR harvesting	564
11	**R&I: energy crops on marginal land**	energy crops AND marginal land	284
12	**R&I: agricultural biomass supply chain logistics**	agriculture AND biomass residue AND supply chain OR logistics	1 820
13	**R&I: Improved biomass carriers**	agriculture waste biomass AND treatment OR densification OR torrefaction	1 750

For each R&I area two types of information have been analysed:

- A **key phrase analysis** which shows the most relevant key words (phrases/terms) used in the respective set of publications and the research trends during the last five years, namely, which phrases have been increasingly researched, and on contrary, which topics experienced decreasing popularity among the scientific community;
- **Leading countries and organizations** based on the evaluation of their scholarly output in **Europe and Worldwide**.

Resulting graphs for each investigated R&I area are provided in Annex 4 and a short summary of the main findings are provided in the two following subchapters.

3.4.1 Key phrase analysis

Key phrases from the sets of publications in 2011-2015 have been identified and analysed. The most relevant key phrases and their research trends are summarized in Table 3.19.

Table 3.19 Trends of the research efforts of various areas from key phrase analysis

Areas with increasing research efforts	Areas with continuous research efforts	Areas with decreasing research efforts
Agricultural machinery	Bioconversion	Agricultural management
Agricultural wastes	Bioenergy	Alternative agriculture
Anaerobic digestion	Biofuels	Bioconversion
Arundo donax	Biomass burning	Biodiesel
Belowground biomass	Coppicing	Bioethanol

Areas with increasing research efforts	Areas with continuous research efforts	Areas with decreasing research efforts
Biogas	Crop residue(s)	Biomass power
Biomass	Delignification	Biomass silage
China	Energy crop(s)	Breeding
Coppice	Energy harvesting	Cellulose
Corn	Enzymatic hydrolysis	Conservation tillage
Cropping systems	Feedstocks	Corn stover
Crop rotation	Fermentation	Cover crops
Crops	Genomics	Energy utilization
Cultivation	Grass	Ethanol
Droughts	Greenhouse gases	Food supply
Gasification	Hydrogen production	Greenhouses
Grasslands	Intercropping	India
Irrigation	Jatropha	Land use change
Miscanthus	Life cycle analysis	Lignin
Optimization	Nitrogen	Moisture determination
Panicum virgatum	*Phalaris arundinacea*	Pelletizing
Populus	Routing protocols	Phytomass
Rice	Saccharification	Plantation forestry
Robinia pseudoacacia	Solid wastes	Pruning
Salix	Sorghum	Sensor networks
Sensor nodes	Stubble	Synthesis gas
Straw		Tree planting
Unmanned aerial vehicles (UAV)		Waste utilization
Yields		Wheat straw
Wheat		Zero tillage
Wireless sensor networks		

During the last five years the research efforts have been increasing for agricultural residues (including straw), crop rotation and cropping systems. It can be noticed that increasing research has been done on particular cellulosic energy crops, e.g., miscanthus, giant reed, switchgrass, poplar, robinia and willow. Possibly because of the ILUC and energy vs food debate, research efforts have decreased regarding biofuels – bioethanol, biodiesel as well as for biomass to power.

3.4.2 Major players in R&I in agriculture in Europe and Worldwide

For each of the 13 customised research areas (given in Table 3.18) countries and research organisations on Europan and Global level have been ranked according to the scholarly output. In order to be able to identify overall leading countries and leading organisations, they have been ranked by assigning 5 points to the entry (country or organisation) on the leading position, 4 – to the second leading, 3 – to the third leading, 2 – to the forth strongest and 1 point – to the fifth strongest player in the respective research area.

Country level analysis:

Table 3.20 Evaluation of major countries in R&I in agriculture in Europe

	1	2	3	4	5	6	7	8	9	10	11	12	13	Total
Germany	**5**	**5**	**5**	**5**	4		**5**	4	**5**	**5**	3	3	2	**51**
Italy	4	4	1		3	3	4	**5**	4	3	**5**	**5**	**5**	**46**
Spain	3	3			2	**5**	3	3	3		1	4	3	**30**

	1	2	3	4	5	6	7	8	9	10	11	12	13	Total
UK	2	1	3	4	**5**	4	1	2	1	4	4	1	4	**36**
France	1	2	2				2		2	1		2	1	**13**
Denmark			4											**4**
Ireland				3										**3**
Austria				2		2								**4**
Netherlands				1	1			1			2			**5**
Belgium						1								**1**
Sweden										2				**2**

On European level in majority of identified research areas the leading country is Germany. Germany is strong in research of feedstocks – energy crops, crop resideues, straw and grassland biomass and is leading research regarding cropping systems, precision agiculture and SRC breeding and harvesting. Italy is strong in development of new harvesting and crop residue collection technologies, researching energy crops on marginal land, biomass supply chain logistics and improved biomass carriers. UK is leading the research on energy crop breeding and Spain is the leader in developing crops with higher residue yields. Denmark is relatively strong player in research of straw and Ireland – for grassland biomass.

Table 3.21 Evaluation of major countries in R&I in agriculture Worldwide

	1	2	3	4	5	6	7	8	9	10	11	12	13	Total
USA	**5**	**5**	4	**5**	**5**	2	**5**	**5**	4		**5**	**5**	4	**54**
China	4	4	**5**	3	4	3	4	3	**5**		4	4	**5**	**48**
India	3	3	3		2	**5**	3	4	3			3	3	**32**
Germany	2		1	4	1		2	1	2	**5**	1			**19**
Italy	1						1	2		3	3	2	1	**13**
Brazil		2							1					**3**
Australia		1				4								**5**
Canada			2									1		**3**
UK				2	3					4	2			**11**
Ireland				1										**1**
Spain						1								**1**
Sweden										2				**2**
France										1				**1**
Malaysia													2	**2**

On global level USA and China are the leading countries. From all investigated categories SRC breeding and harvesting is the only research area where Europe is leading. USA is the strongest country for research on energy crops, crop resudes and grassland biomass, while China is leading in straw research. China is also leading in precision farming science and development of improved biomass carriers. India is leading the research on crops with high residue yields and also Australia is relatively strong in this field.

Overall it can be concluded that the most active research related to biomass from agriculture on European level takes place in Germany, Italy, UK, Spain and France. On global level the leading countries (before Germany, Italy and UK) are USA, China and India. Other important third countries are Australia, Brazil and Canada. However, there the research activity is lower than in the best European countries.

Organisation level analysis:

Table 3.22 Evaluation of major organisations in R&I in agriculture in Europe

	1	2	3	4	5	6	7	8	9	10	11	12	13	Total
Wageningen University and Research (Netherlands)	**5**	4		3	1		4	**5**	4		2	**5**		**33**
INRA (France)	4	**5**	4		3		**5**	3			4	4		**32**
SLU (Sweden)	3	2			2			4		**5**	3			**19**
Aarhus University (Denmark)	2		3					1	**5**					**11**
University of Hohenheim (Germany)	1			2							1			**4**
CSIC (Spain)		3							3			3	**5**	**14**
CIRAD (France)		1										2		**3**
Technical University of Denmark (Denmark)			**5**					2						**7**
University of Copenhagen (Denmark)			2											**2**
Vienna University of Technology (Austria)			1											**1**
University of Kassel (Germany)				**5**										**5**
Aberystwyth University (UK)				4	**5**									**9**
Estonian University of Life Sciences (Estonia)				1										**1**
Rothamsted Research (UK)					4					1				**5**
Universidad Politecnica de Valencia (Spain)						**5**								**5**
Ghent University (Belgium)						4								**4**
University of Natural Resources and Applied Life Sciences (Austria)						3			2					**5**
Agricultural Research Council of Italy (Italy)						2								**2**
Agricultural Univeresity of Plovdiv (Bulgaria)						1								**1**
ETH Zurich (Switzerland)							3							**3**
CNR (Italy)							2				**5**			**7**
University of Bonn (Germany)							1							**1**
Karlsruhe Institute of Technology KIT (Germany)									1					**1**
University of Gottingen (Germany)										4				**4**
University of Antwerp (Belgium)										3				**3**
Technische Universitat Dresden (Germany)										2				**2**
Aristotle University of Thessaloniki (Greece)												1	2	**3**
University of Naples Federico II (Italy)													4	**4**
CNRS (France)													3	**3**
University of Granada (Spain)													1	**1**

Two leading organisations in Europe are Wageningen University from the Netherlands and INRA from France. Wageningen is leading the research on energy crops, harvesting and collection of crop residues and biomass supply chain logistics. INRA leads the research on crop residues and optimisation of cropping systems. SLU in Sweden is the leader of research in SRC, Aarhus

University in Denmark is the top organisation in research of precision agriculture. CSIC (Spain) is the strongest organisation in research regarding improvement of biomass carriers, Technical University of Denmark leads the research on straw and University of Kassel (Germany) is the leader for grassland biomass research. Aberystwyth University in UK is leading research on energy crop breeding, Universidad Politecnica de Valencia (Spain) – research on crops with higher residue yields and CNR in Italy is the leader of research of growing energy crops on marginal land.

Table 3.23 Evaluation of major organisations in R&I in agriculture Worldwide

	1	2	3	4	5	6	7	8	9	10	11	12	13	Total
U.S. Department of Agriculture (USA)	**5**	**5**			**5**		4	**5**	4			**5**	4	**37**
Wageningen University and Research (the Netherlands)	4			3			1	1						**9**
Chinese Academy of Sciences (China)	3	3	1	2	2						4	4		**19**
INRA (France)	2						2					1		**5**
University of Illinois at Urbana-Champaign (USA)	1								1		2			**4**
AgriFood Canada (Canada)		4				4						2		**10**
Indian Agricultural Research Institute (India)		2						4						**6**
China Agricultural University (China)		1	**5**			3	**5**	3	**5**			3	3	**28**
Technical University of Denmark (Denmark)			4											**4**
Ministry of Agriculture of the People's Republic of China (China)			3											**3**
University of Saskatchewan (Canada)			2											**2**
University of Kassel (Germany)				**5**										**5**
Aberystwyth University (UK)				4	4									**8**
University of Hohenheim (Germany)				1										**1**
International Crops Research Institute for the Semi-Arid Tropics (India)					3									**3**
Rothamsted Research (UK)					1					1				**2**
Universidad Politecnica de Valencia (Spain)						**5**								**5**
Colorado State University (USA)						2								**2**
Ghent University (Belgium)						1								**1**
Chinese Academy of Agricultural Sciences (China)							3							**3**
University of Nebraska (USA)								2						**2**
Universidade de Sao Paulo (Brazil)									3					**3**
Northeast Agricultural University (China)									2					**2**
SLU (Sweden)										**5**				**5**
University of Gottingen (Germany)										4				**4**
University of Antwerp (Belgium)										3				**3**
Technische Universitat Dresden (Germany)										2				**2**
Michigan State University (USA)											**5**			**5**
Institute of Botany chinese Academy of Sciences (China)											3			**3**
Purdue University (USA)											1			**1**
Universiti Sains Malaysia													**5**	**5**
University Putra Malaysia													2	**2**
University Teknologi Malaysia													1	**1**

Globally the leading research organisation is U.S. Department of Agriculture in USA. This organisation is the leader of research in energy crops, crop residues, energy crop breeding and harvesting and collection as well as in agricultural biomass supply chain logistics. On the second and third position are two organisations from China - China Agricultural University and Chinese Academy of Sciences. China agricultural university is leading the research on straw, optimisation of cropping systems and precision agriculture. Chinese Academy of Sciences is the second best research organisation for growing energy crops on marginal lands and agricultural biomass supply chain logistics. From European organisations the leaders on global scale are University of Kassel (Germany) in grassland biomass research, Universidad Politecnica de Valencia (Spain) for research on crops with higher residue yields and SLU (Sweden) for SRC breeding and harvesting. Another university from USA - Michigan State University is the global leader in the research of energy crops on marginal land. Unversities from Malaysia, in particular Universiti Sains Malaysia, is leading research on improved biomass carriers. AgriFood Canada is realively strong in crop residue research and in development of crops with higher residue yields.

It can be concluded that on the level of organisations, in Europe the leading research organizations are Wageningen University and Research (the Netherlands), INRA (France), SLU (Sweden), CSIC (Spain) and Aarhus University (Denmark). On the global level the leading research organisations are U.S. Department of Agriculture (USA), China Agricultural University (China), Chinese Academy of Sciences (China) and AgriFood Canada (Canada). Only then follows the best European organisation – Wageningen University and Research (the Netherlands).

3.5 Definition of scenario elements for selected R&I fields

Based on the comprehensive review of agricultural biomass resources and the most relevant R&I fields in the sector, a definition of elements to be included in feedstock availability modelling scenarios have been made. At this stage it has been important to put the R&I field activities on a time line – identifying strategies and research activities in short, medium (until 2030) and long term (until 2050).

Regarding agricultural resources the priority was given to measures which do not impose high risks of ILUC. A feedback received during the expert workshop organized in this study, suggested that first priority should be to close the yield gap of conventional crop production between the European countries and afterwards – to focus on growing lignocellulosic energy crops on marginal land. Similar order of priorities is mentioned by Chen and Zhang (2015), saying that to provide feedstock for next generation bio-refineries, current agricultural and forest residues can be utilized before dedicated perennial plants are cultivated on a large scale.

Sustainable agriculture will start with the cultivation of perennial plants on margin and low-yield agricultural lands. Numerous perennial crops will be selected based on local climate conditions, such as sunshine, rainfall, temperature, soil quality and their nitrogen fixation ability. Furthermore, to decrease biomass recalcitrance, the discovery of genetic variants in native populations of bioenergy plants and direct manipulation of biosynthesis pathways have produced less recalcitrant feedstocks with favourable properties for biomass pre-treatment and down- stream conversion. Also, to decrease protein production costs, plants can be modified for low-cost production of recombinant proteins. (Chen and Zhang, 2015)

Further proposal for implementation of R&I activities related to agricultural management practices has been made by Iqbal et al. (2016) – see Table 3.24. According to this study in **short term**

strategies, selection of better adopted crop varieties from already developed ones will be made and this can contribute 5-10 % in yield increase. This increase can be multiplied through right combination of management practices such as fertilisation, irrigation, tillage system etc. Therefore, high yield potential of a specific variety can only be realised through combination of aforementioned factors. (Iqbal et al., 2016)

The **medium term strategies** for crops involve improved management practices, appropriate selection of crop variety and precision farming. For grasslands – optimisation of grassland mixtures along with improved management practices to increase productivity of grassland are proposed. (Iqbal et al., 2016)

The **long term strategies** include choice of variety from already available crop varieties and development of new varieties and improved management practices through precision agriculture practices. For grassland, the long term strategies involve improved management practices, optimal grassland mixtures and use of modern breeding techniques to develop better growing grassland species. (Iqbal et al., 2016)

Table 3.24 Categorisation of best practice strategies based on time duration required for implementation

Timeline	Best practice strategies	
	For agricultural crops	For grassland
Short term strategies (0-5 years)	Improved management practices + selection of appropriate crop varieties	Improved management practices (cutting frequency, irrigation, fertilisation)
Mid-term strategies (5-10 years)	Improved management practices + selection of appropriate crop varieties + precision farming	Improved management practices + optimal grassland mixtures (woody biomass + grassland)
Long-term strategies (10-20 years)	Improved management practices + precision farming + development of new varieties for a specific crop	Improved management practices + optimal grassland mixtures + modern breeding techniques

Made after (Iqbal et al., 2016.

Proposal for the timing of the R&I activities (scenario elements) for this study is provided below.

3.5.1 *Short-term activities:*

Improvement of conventional crops:

- Improved yields of food crops through breeding activities;
- **Increased stress tolerance by modifying plants through understanding of the mechanistic basis of plant drought, salt and cold tolerance** (e.g., transferring C4 photosynthetic machinery to C3 plants).

Improvement of conventional cropping practices:

- **Developing agronomics to effectively and efficiently plant, grow, and harvest** (the yield increase effect due to best practice strategies adds up to 16% for straw residues):
  - Selection of high residue yielding varieties;
  - Adjusting of N fertilization rates to increase residue yield;
  - Application of fungicides (straw yields were increased by more than 20 % in winter wheat);
  - Varying sowing time and rate;

- Optimized cropping systems with crop rotation, multi-cropping, catch and cover crops use;
- Selection of tillage system (studies show that only around 35 % of the maize residue is available in conventional tillage. In the case of reduced tillage, farming might allow an increased removal rates and higher availability of straw for other uses. In case of no till farming, 68–82 % of the maize residue can be available).

➔ Improvement in farming practices should simultaneously drive **the development of additional equipment to collect agricultural residues from the field;**

➔ **Improved harvesting:**
- Collection of residues from primary crops results in no more than 40 % removal of stover or straw on average. Future residue collection technology with the potential of collecting up to 75 % of the residue is envisioned. These systems are likely to be single-pass systems that would reduce costs by collecting the grain and residue together (Iqbal et al., 2016);
- Currently, the cutting height for cereals and oil crops is more than 20 cm depending on crop variety. Reducing cutting height up to 5 cm for cereals and oil crops is suggested. In case of using residue specific machinery, the residue harvest can be increased theoretically up to 50% in case of straw from cereals and oil crops (Iqbal et al., 2016).

Optimization of supply chains:

➔ Continued research and development in supply chain optimization, particularly developing cleaner, more efficient, and more cost-effective technologies. Expanded funding for research programs and demonstration plants would support necessary technological innovation and supply chain optimization;

➔ There is a potential to increase supply chain efficiencies through technology transfer (from regions with well-developed supply chains to regions with minimal bioenergy deployment) and learning-through-doing. Technical learning and putting entrepreneurs to work to increase profits and reduce costs is critical to advancing the efficiency and economic competitiveness of bioenergy systems;

➔ Streamlining biomass supply chains with existing silvicultural and agricultural practices (e.g., timing of operations, use of machinery) is another opportunity to increase efficiencies and cost effectiveness, while at the same time increasing the overall productivity of existing practices;

➔ Supply chains for dedicated non-food energy crops are at an early stage of development so there are major deviations in cost estimates due to differences in yields between crops and regions. Forecasts of energy crops show costs decreasing in all regions. Costs are estimated to fall to around USD 3/GJ in the next three decades.

Development of new biomass carriers:

➔ pre-treatment;

➔ densification;

➔ improved properties for conversion to energy.

3.5.2 *Mid-term activities*

Breeding of conventional crops:

➔ **Genetic improvement of conventional crops** for potential use in biofuel production can result in rapid progress based on pre-existing knowledge and germplasm collections.

Breeding of energy crops:

➔ **Development of hybrids** of specific crops dedicated to energy are feasible in the mid- to long-term and will undoubtedly improve biomass and the mitigation of global climate change;

- **Development of stress resistant/tolerant energy crops**, by:
  - Understanding of mechanisms by which plants survive drought and other abiotic stresses and adapting this knowledge to improving biomass energy crops. - > opening more opportunities for growing SRC on marginal lands and expanding suitable cultivation areas;
  - Improving physiological knowledge of the processes of abiotic stress tolerance (especially in perennial grasses) by investing significantly more effort to complement and guide breeding and genetic programs.
- **Development of energy crops with a higher biomass yields**, by:
  - breeding of new crop varieties:
    - Screening large populations to identify useful genetic variants to be used as sources for breeding is a slow and time-consuming process. Development of markers or DNA polymorphism indicative of desired traits will facilitate this process.
- **Development of energy crops with improved properties for conversion to energy**, by:
  - Altering cell-wall composition to increase cellulose and decrease lignin;
  - Other improvements in the composition and biochemical structure of energy crops.

Growing SRC on marginal lands:

- Crop varieties appropriate for marginal lands (more stress tolerant) are developed.

Development of precision agriculture practices:

- **Increased actual crop yields through precise crop management practices such as irrigation, fertilisation, seeding, crop protection and harvesting.** In south-west Europe due to climate change and variability in rainfall pattern, precision farming can play a key role in achieving high actual yields. Another important aspect in site specific crop management is nitrogen use efficiency. Studies were carried out in Germany where it was found that 10-15 % nitrogen use efficiency can be improved through precision farming (Iqbal et al., 2016);
- **Introduction of new machines** which are able to provide high resolution information and with the capability of site specific agriculture management.

Sustainable intensification of agriculture:

- Introduction of economic and social changes in agricultural management practices and re-direction of research to address more complex set of goals than just increasing yield;
- Simultaneously raising yields, increasing the efficiency with which inputs are used and reducing the negative environmental effects of food production.

3.5.3 Long term activities

Development of new generation of energy crops by advanced breeding:

- **Understanding the mechanisms that regulate net photosynthetic CO_2 fixation in the plants;**
- **Maximizing photosynthetic CO_2 fixation to support carbon accumulation in plants**, by:
  - increased photosynthesis;
  - optimized photoperiod response;
  - optimized plant architecture;
  - biotic resistance, abiotic tolerance;
  - floral sterility (if flowering can be delayed or prevented, this energy may be transferred into increasing the overall plant biomass);
  - regulated dormancy;
  - delayed leaf senescence;
  - greater carbon allocation to stem diameter instead of height growth;

- optimal nitrogen acquisition and nutrient use efficiency; and
- less extensive root system to maximize aboveground biomass.

➔ **Identifying factors that regulate plant growth and duration;**

➔ **Genetic modification of bioenergy crops to increase biomass and bioenergy yields:**
- Application of genomics to the discovery and manipulation of genes to create optimally designed energy plants;
- Comparative genomic studies, using modern biotechnological tools, will improve knowledge and allow logical inferences that may lead to the transfer of genes to distantly related cereal species.

➔ **Improved genetic material and management of dedicated energy crops is expected due to rapid developing breeding experiences in the future**, by:
- Better understanding of gene regulation and control of plant metabolic pathways;
- Improving gene modification through functional genomics;
- Developing new screening systems;
- Improving biotechnological method for gene stacking, organelle transformation and molecular evolution;
- Expanding knowledge of carbon flow at the molecular level;
- Carbon partitioning in higher plants to direct more carbon to storage tissues for increasing yield or carbon partitioning between different components (e.g., changing of biomass from one form to another (starch-to-oil for biodiesel));
- Identifying mechanisms of gene switching;
- Developing broad bioinformatics.

➔ **Breeding of crops specifically for biofuel production** which are:
- based on perennials from selected appropriate species and genotypes;
- grown by application of optimal water, fertilisation, disease and weed control practices and harvesting times and methods;
- Plants and production practices are adapted to each agro-ecological zone and are improved over time.

Improved stress tolerance:

➔ The actual production of transgenic plants with demonstrably improved abiotic stress tolerance has been slow, more progress can be gained by **exploiting further the synergies of interfacing of physiological and molecular genetic research.**

Agricultural practices

Large and wide application of precision agriculture with highly developed ICT tools.

3.5.4 Quantification of expected yield increases due to R&I activities in agriculture

This subchapter summarizes findings from the literature regarding the expected yield increase due to implementation of different R&I measures in agriculture.

According to Iqbal et al., 2016, there are two main factors affecting yields: i) low yields caused by poor management practices and ii) low yields because of site conditions and limitations. Improved management practices can theroretically increase ceral yields by 45-75% in high yielding and low yielding areas respectively and application of tailored management practices to the regions with site specific limitations can increase cereal yields by 30% (theoretical yield increase for wheat). For oil crops (rapeseed and sunflower) improved management practices can contribute to 30-65% yield increases and up to 20% yield increase under difficult site conditions. An overview about about theoretical yield increases for different crop types as modelled in the study of Iqbal et al (2016) is given in Table 3.25.

Table 3.25 Theoretical yield increase (%) of agricultural crops based on improved management practices and optimal varieties

Crop	Measures					Total yield increase
	Better selection of variety	Optimised fertilisation	Improved crop protection (use of fungicides, herbicides, weeding)	Improved cultivation practices (soil preparation, seed priming, irrigation)	Improved management of soil fertility (catch crops, crop rotation)	
Wheat	5-10%	15-20%	10-20%	10-15%	5-10%	45-75%
Barley						20-50%
Maize						15-40%
Oat						20-50%
Rapeseed	5-10%	10-20%	10-15%	5-15%	0-5%	30-65%
Sunflower						10-30%
	Optimisation of grassland mixtures	Optimised fertilisation (NPK)	Improved crop protection (use of herbicides)	Irrigation	Optimised cutting frequency	
Grasslands	5-15%	10-15%	0-5%	5-15%	5-10%	25-60%

Made after Iqbal et al., 2016.

As mentioned before in this study, there is a correlation between crop yields and the yields of crop residues. To increase the amount of collectable crop residues, several residue specific measures can be applied. These measures include improved harvesting procedures and technologies (e.g reducing cutting height, development of resiude specific machinery for harvesting and collection), increased residue removal rate (e.g by compensating residues with surplus manure, compost, ash or digestate) and by improved transport, storage and handling operations (e.g by application of densification technologies and by using single pass machinery to cover several processing steps in one). Through use of modern machinery the residue yield for cereals and oil crops can be increased by 10-15% and by 20% for vine prunings. Theoretical yield increase of residues is summarized in Table 3.26.

Table 3.26 Theoretical yield increase (%) of agricultural residues based on residue specific measures

Crop	Residue	Theoretical yield increase of residues
Whaet	Straw	20-40%
Barley	Straw	20-40%
Oat	Straw	20-40%
Rye	Straw	20-40%
Maize	Stover, cobs	30-40%
Rapeseed	Straw	30-40%
Sunflower	Straw	30-40%
Wine	Prunings	40-50%

Made after Iqbal et al., 2016.

Crop residue yield increase figures presented in the table above are theoretical and in practice the achievable realistic residue yield increase will be reduced because of sustainability constraints (e.g sustainable residue removal rate) and technical constraints along the biomass supply chain (e.g harvest, collection, transport, storage and handling). Estimated yield increase (Iqbal et al., 2016) taking into account sustainability and technical constraints is presented in Table 3.27.

Table 3.27 Technical sustainable yield increase (%) of agricultural residues based on crop and residue specific measures

Crop	Yield increase through crop specific measures	Yield increase through residue specific measures
Whaet	2-8%	5-10%
Barley	5-10%	5-10%
Oat	5-10%	5-10%
Rye	5-10%	5-10%
Maize	2-8%	10-15%
Rapeseed	2-8%	10-15%
Sunflower	2-8%	10-15%
Wine	1-4%	15-20%

Made after Iqbal et al., 2016.

There is less information available in the literature regarding potential yield increase of dedicated energy crops (e.g. due to advanced breeding efforts, including domestication of new plant species, optimised plant architecture or GM). Some studies revealed that GM plants produced 58 – 101 % more biomass yield compared with the non-transgenic control and increased ethanol yield by up to 38 % in conventional biomass fermentation processes.

3.5.5 Scenario elements on the time line

Scenario elements for agricultural biomass are summarized in Figure 3.19.

Figure 3.19 Scenario elements of R&I activities for increased availability of biomass feedstocks from agriculture

The timeline shows, when the considered R&I activities are expected to result in actual increase of biomass availability.

3.5.6 Scenario elements for modelling production and delivery of biomass feedstock from agriculture

In order to facilitate the development of scenario storylines for modelling the production and delivery of biomass feedstock, scenario elements have been identified for promising R&I activities in the field of agriculture. Specifically, these scenario elements were grouped into R&I measures targeting either (a) increased supply of biomass through **enhanced production** or (b) **improved biomass supply** through innovative harvesting, supply chain logistics and mobilization of potentials.

The following table presents an overview of R&I scenario elements for enhanced production and improved biomass supply for the field of agriculture.

Table 3.28 R&I scenario elements for enhanced production and improved biomass supply from agriculture

	R&I scenario elements for enhanced production	R&I scenario elements for improved biomass supply
Biomass from agriculture	• Yield increase of conventional (food/feed) crops due to breeding efforts. Breeding efforts to build up the resistance to biotic and abiotic stresses (drought, pests and diseases) as well as to increase residue to crop ratios (straw/grain ratio) are included. It will result in absolute increase of main crop biomass and crop residues and potentially providing more space for growing energy crops (if demand for food/feed can be satisfied with less land); • Enhanced production by growing dedicated energy crops on un-used agricultural lands. Further expansion of energy crops on non-agricultural areas (marginal lands) is anticipated in the future. Expansion on marginal lands will be possible because of breeding efforts targeted to developing more robust plants, which are able to grow in less suitable conditions; • Improved agricultural management practices (e.g. selection of varieties, crop rotation and intercropping, fertilization, water management, adoption of precision agriculture practices) to bridge the current gaps of yields among EU member states.	• Improved harvesting practices and machinery (development of new equipment for both – conventional and dedicated energy crop harvesting, improving harvesting practices, development of precision farming); • Increased mobilisation of agricultural biomass by optimised supply chain logistics (mobilization of so far unexploited biomass by using cleaner, more efficient and more cost-effective technologies, technology transfer, streamlining biomass supply chains with existing practices, development of new supply chains for dedicated energy crops); • Increased awareness and capacity of various actors involved in the biomass supply chain.

The above described scenario elements were further used for the development of agricultural feedstock scenario narratives and assumptions to be used for the modelling with CAPRI. Scenario narratives and assumptions used in modelling are further described in the report D1.2.

4 Assessment of the R&I potential in the field of forestry

This review study gives an overview about research and innovation activities related to forestry feedstocks to increase their potential use for the production of bioenergy, including advanced biofuels.

The main feedstock categories included in this chapter are presented in Table 4.1.

Table 4.1 Main forestry feedstock categories covered by the study

	Biomass Category	Biomass Type	Biomass Subtype
Biomass from forestry	Round-wood production	Stemwood	Roundwood from final fellings
			Roundwood from thinnings
	Primary forestry residues	Logging residues	Tops, branches
			Stumps
			Early thinnings
	Secondary forestry residues	Woodchips and pellets	Woodchips
			Pellets
		Sawdust	
		Black liquor	

4.1 Brief overview of current market situation and existing forest biomass potential assessments

4.1.1 Current market situation based on facts from EUROSTAT, Forest Europe and Joint Wood Energy Enquiry

According to EUROSTAT figures, bioenergy generated from woody biomass is currently the largest renewable energy source in the EU. Although its relative share is slowly declining, woody biomass was still contributing 44% to overall renewable energy production in 2014 (EUROSTAT 2016)[3]. The latest State of Europe's forest report indicated for the EU-28 a net annual increment of 720 million m3 and total fellings of 522 million m3 in 2010. Felling rates, i.e. the proportion of increment that is utilized by fellings, vary regionally between 42% in Southeast Europe and 79% in Northern Europe.

European wide statistics about the current production of woody biomass are only available for stemwood production from forests areas available for wood supply (Table 4.1.1). The data suggest that roundwood removals have generally increased from 1990 to 2010, with the highest removals either in the year 2005 or in 2010.

[3] Eurostat statistics explained: Energy from renewable sources. http://ec.europa.eu/eurostat/statistics-explained/index.php/Energy_from_renewable_sources; accessed 10th September 2016. The statistics refer to "wood and other solid biofuels (excluding charcoal)".

Table 4.2 Quantity of roundwood removals in total and per ha of forest area available for wood supply (FAWS) in EU countries from 1990 – 2010

Country	Forest area [1,000 ha]	Total Roundwood Volume							
		Volume [1000 m3]				Volume [m3/ha FAWS]			
	2010	1990	2000	2005	2010	1990	2000	2005	2010
Austria	3,860	13,214.40	13,941.12	18,092.30	18,614.03	3.99	4.17	5.41	5.57
Belgium	681.2	3,816.45	3,347.80	4.082,91	3.690,94	5.67	5.05	6.14	5.53
Bulgaria	3,737	3,785.00	4,238.27	5,784.67	5,863.60	1.6	1.88	2.26	2.46
Croatia	1,920	-	-	-	5,714.00	-	-	-	3.28
Cyprus	172.8	-	-	-	-	-	-	-	-
Czech Republic	2,657.40	11,773.60	14,310.00	16,487.40	15,773.40	4.57	5.59	6.55	6.83
Denmark	587.1	1,948.93	2,099.38	2,307.06	2,621.46	3.62	3.71	4.32	4.75
Estonia	2,233.90	2,758.23	9,619.84	5,531.70	5,888.95	1.33	4.58	2.67	2.93
Finland	22,218	41,726.60	53,431.48	53,662.54	48,801.77	2.04	2.63	2.68	2.51
France	16,424	61,420.00	58,760.00	52,880.00	54,020.00	4.46	4.06	3.48	3.46
Germany	11,409	48,575.00	42,451.80	60,330.00	53,267.67	4.63	3.92	5.55	4.89
Greece	3,903	2,590.40	1,931.55	1,638.83	1,238.58	0.85	0.58	0.47	0.34
Hungary	2,046.40	5,505.41	5,022.10	5,251.31	5,709.48	3.6	3.1	3.12	3.3
Ireland	725.6	1,626.40	2,524.84	2,654.87	2,476.45	-	-	4.58	4.07
Italy	9,028	-	-	-	-	-	-	-	-
Latvia	3,354	2,471.00	12,929.78	12,705.98	11,428.99	0.88	4.28	4.11	3.63
Lithuania	2,170	3,160.00	5,423.60	6,101.00	6,415.20	1.86	3.09	3.32	3.46
Luxembourg	86.8	-	261.32	268.31	284.88	-	3.01	3.12	3.31
Malta	0.3	-	-	-	-	-	-	-	-
Netherlands	373.5	1,286.20	962	1,061.80	1,030.20	4.66	3.34	3.62	3.45
Poland	9,329	22,448.20	27,495.20	33,504.40	36,746.60	2.7	3.3	3.98	4.52
Portugal	3,239.10	10,367.20	9,209.00	10,583.15	10,210.68	4.56	4.13	4.8	4.76
Romania	6,515	14,221.20	13,015.74	15,012.20	13,922.95	2.53	2.59	2.97	2.71
Slovakia	1,938.90	4,584.33	5,809.38	7,779.40	9,073.84	2.59	3.29	4.44	5.1
Slovenia	1,247	1,671.00	2,198.80	2,787.12	3,063.40	1.5	1.9	2.39	-
Spain	18,247.20	15,471.00	14,995.00	15,634.00	15,610.28	-	-	1.13	1.07
Sweden	28,073	53,580.00	62,500.00	75,680.00	69,700.00	2.35	3.01	3.74	3.48
United Kingdom	3,059	6,343.20	7,766.20	8,470.60	9,379.60	2.28	2.63	2.8	3.07

Forest Europe, 2015.

The Joint Wood Energy Enquiry compiled by UNECE/FAO[4] provides additional information about sources of biomass and use in different sectors, including also other biomass compartments besides stemwood, but the information is not complete for all EU countries. For the reporting European countries a domestic production of 250 million m3 of industrial roundwood and 106 million m3 fuelwood was recorded in 2013. Industrial residues amounted to 107 million m3 plus 44 million tons of black liquor and talloil.

4 https://www.unece.org/forests/jwee.html.

Table 4.3 Energy wood production from wood in 2011

Country	Forest [1000 ha]	Total energy supply from wood	Energy from direct wood fibre sources			Energy from co-products and residues of the wood processing industries		Energy from processed wood - based fuels		Energy from post consumer recovered wood	Energy from unknown/ unspecified sources
			Total	Forests & other wooded land	Other land	Total	Solid residues	Total	Imported		
Austria	3,860	106,655	32,742	27,093	2,913	68,861	48,271	5,052	12,545	-	0
Belgium	681.2	0	-	-	-	-	-	-	916	-	-
Bulgaria	3,737	19,932	14,502	14,502	-	5,380	3,176	50	4	-	-
Croatia	1,920	-	-	-	-	17,000	-	1,642	-	-	-
Cyprus	172.8	166	43	4	39	13	13	110	110	-	-
Czech Republic	2,657.40	41,480	23,490	9,190	7,300	16,670	7,870	1,320	728		-
Denmark	587.1	63,683	26,403	16,971	9,432	6,353	6,353	24,274	22,332	6,652	0
Estonia	2,233.90	19,955	10,750	10,438	313	8,327	7,127	524	212	354	-
Finland	22,218	188,276	53,806	53,806	0	131,784	34,514	660	169	2,025	-
France	16,424	196,279	142,734	73,166	26,131	40,111	22,692	6,057	1,048	7,377	-
Germany	11,409	282,768	142,406	120,615	21,791	56,605	47,056	19,098	4,455	57,711	6,949
Greece	3,903	-	-	-	-	-	-	-	-	-	-
Hungary	2,046.40	24,854,297	20,056,715	-	-	2,398,566	2,398,566	450	204	-	-
Ireland	725.6	3,033	991	951	40	1,472	1,472	570	316	0	0
Italy	9,028	50,405	34,222	-	-	11,000	11,000	-	676	5,183	-
Latvia	3,354	0	-	-	-	-	-	-	22	-	-
Lithuania	2,170	20,590	8,460	7,540	910	6,250	3,620	4,570	-	1,310	0
Luxembourg	86.8	1,427	873	-	-	542	542	12	37	0	-
Malta	0.3	-	-	-	-	-	-	-	-	-	-
Netherlands	373.5	22,558	4,115	1,340	2,775	1,910	1,910	11,240	10,570	3,600	0
Poland	9,329	41,686	-	-	-	-	-	-	740	-	41,686
Portugal	3,239.10	-	-	-	-	-	-	-	-	-	-
Romania	6,515	75,010	16,520	-	-	-	-	-	38	-	58,490

Country	Forest [1000 ha]	Total energy supply from wood	Energy from direct wood fibre sources			Energy from co-products and residues of the wood processing industries		Energy from processed wood - based fuels		Energy from post consumer recovered wood	Energy from unknown/ unspecified sources
			Total	Forests & other wooded land	Other land	Total	Solid residues	Total	Imported		
Slovakia	1,938.90	22,962	9,515	8,666	849	13,094	7,324	270	21	353	0
Slovenia	1,247	11,765	9,126	7,614	1,512	2,315	2,315	60	510	84	180
Spain	18,247.20	-	-	-	-	-	-	-	-	-	-
Sweden	28,073	243,340	68,980	-	420	147,550	34,130	22,380	6,875	4,430	-
United Kingdom	3,059	43,160	17,120	13,530	3,590	11,590	10,660	13,320	10,770	1,130	0

Forest Europe et al., 2011.

4.1.2 Existing assessments of current and future forest biomass potentials

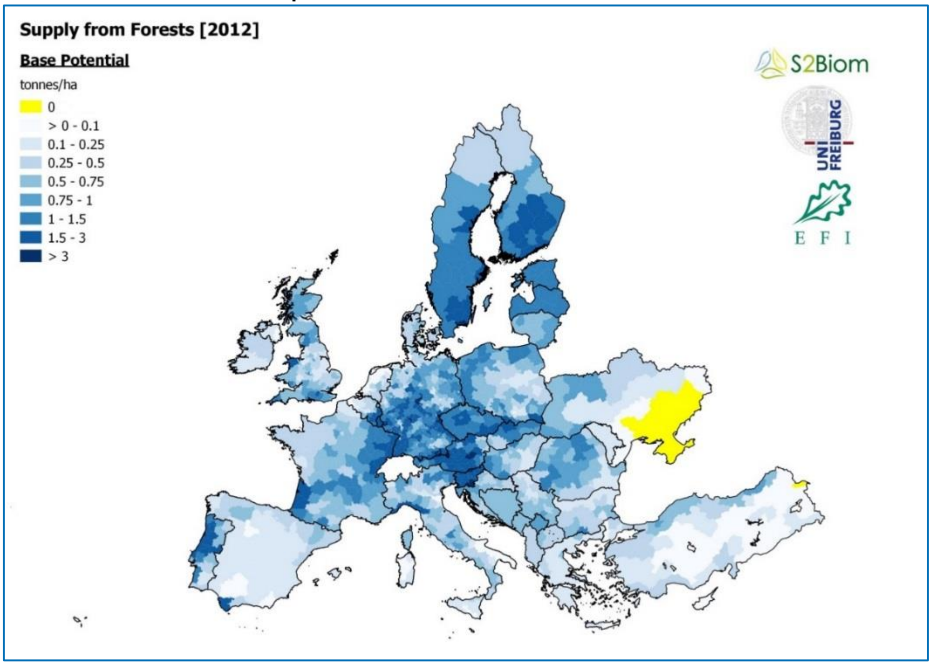
Many studies have quantified (woody) biomass potentials for the EU (Elbersen et al., 2012; Mantau et al., 2010; Mola-Yudego et al., 2017; Verkerk et al., 2011). Large differences in results have been found between studies (Rettenmaier et al., 2010), which reflects a wide range of methodologies and assumptions in the assessments. This variability makes it challenging to compare results across studies. The most comprehensive assessment to date was conducted in the S2BIOM project (Dees et al., 2017a; Dees et al., 2017b), including up-to-date data on forest resources from the EU28 and 9 neighbouring countries and an explicit distinction between several alternative types of potentials.

Within S2BIOM biomass potentials were estimated for the following types:

- A **Technical potential,** representing the absolute maximum amount of lignocellulosic biomass potentially available for material and energy use assuming the absolute minimum of technical constraints;
- A **Base potential,** defined as the potential most closely aligned to current guidelines of sustainable forest management. This also covers legal restrictions such as restrictions from management plans in protected areas such as Natura 2000;
- A **High potential** with less constraints compared to the base potential, assuming a strong focus on the use of wood for producing energy. It includes a strong mechanisation of harvesting across Europe. Biomass harvesting guidelines are less restrictive, e.g. stumps are included in this potential for all S2Biom countries;
- Additional **User-defined potentials** can be derived from the Base Potential with varying types and number of considerations per biomass assortment:
    a. User defined potentials 1-4 vary in consideration of environmental constraints, as compared to the Base potential;
    b. User defined potentials 5 and 7 allow the determination of the potential available for energy and new bio-based materials production. Wood production dedicated for material use is deducted and considered as a constraint;
    c. User defined potentials 6 and 8 allow the determination of the utilisation for pulp and paper, particle board, energy and new biobased materials production. In comparison with User defined potentials 5 and 7 wood dedicated for pulp and paper and for particle board production is not deducted as a constraint.

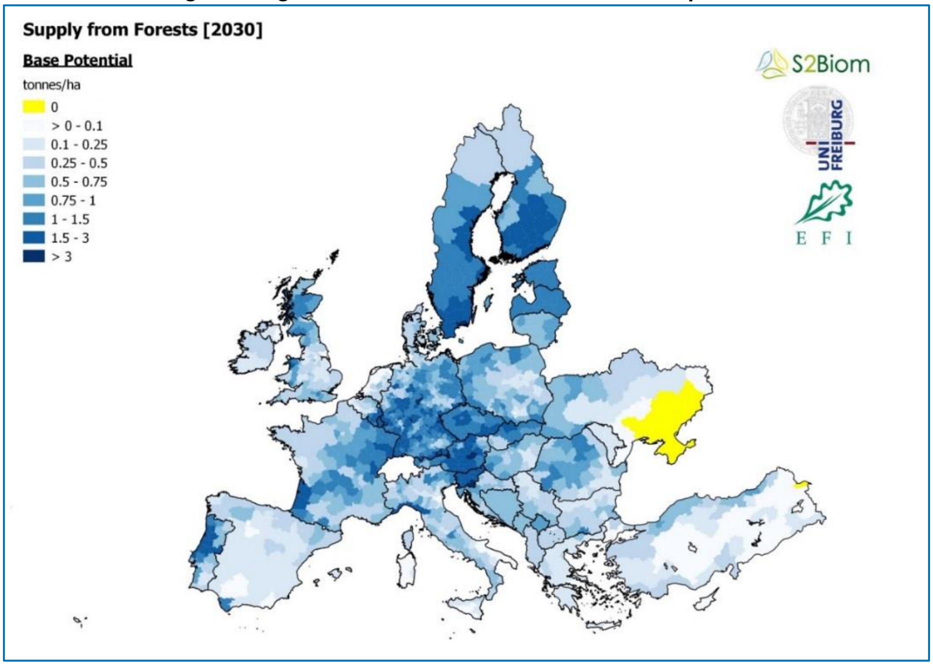
For illustration we present here the results on the spatial distribution of the Base Potential in 2012 and 2030 (Fig x and y) and country level results for three potentials (Table 4.4): Base Potential, High Potential, and Potential with enhanced biodiversity protection (S2BIOM User-defined potential 4). All data sets are accessible through the S2BIOM toolset at http://biomass-tools.eu.

Figure 4.1 Total forestry supply potential (round-wood production and primary residues) per ha of land at NUTS-3 level for the Base potential in 2012



Dees et al., 2017b.

Figure 4.2 Total forestry potential (round-wood production and primary residues) per ha of land for EU28 and nine neighbouring countries at NUTS-3 level for the Base potential in 2030



Dees et al., 2017b.

Table 4.4 Total forestry potential (round-wood production from forests and primary forestry residues) in EU28 and 9 neighbour countries [1000 t] for the Base Potential (BP), the High Potential (HP) and the User-defined potential with enhanced biodiversity protection (UP4) in 2012, 2020 and 2030

		2012			2020			2030		
Country	**ID**	**BP**	**HP**	**UP4**	**BP**	**HP**	**UP4**	**BP**	**HP**	**UP4**
Austria	**AT**	14222	17731	12800	14380	17897	12942	14003	17329	12603
Belgium	**BE**	2071	2318	1864	2266	2537	2040	2239	2516	2015
Bulgaria	**BG**	4002	4607	3601	4000	4609	3600	4016	4600	3615
Cyprus	**CY**	16	19	15	18	20	16	18	20	16
Czech Republic	**CZ**	11246	12775	10122	11302	12854	10171	11364	12991	10228
Germany	**DE**	43216	46679	38895	44438	47984	39994	44828	48393	40345
Denmark	**DK**	1976	2427	1779	1884	2315	1696	1850	2242	1665
Estonia	**EE**	6222	6944	5600	6072	6784	5464	5691	6366	5122
Greece	**EL**	2288	2604	2059	2340	2663	2106	2136	2431	1923
Spain	**ES**	11873	14493	10686	12086	14736	10878	11992	14651	10793
Finland	**FI**	34269	43256	29257	34746	43954	29629	34322	43610	29165
France	**FR**	44749	51174	40274	44253	50487	39828	42152	48163	37936
Croatia	**HR**	3426	3790	3083	3395	3760	3056	3264	3606	2938
Hungary	**HU**	5796	6624	5216	5739	6578	5165	5555	6370	4999
Ireland	**IE**	1740	2004	1566	1787	2066	1608	2101	2450	1891
Italy	**IT**	14970	17591	13473	14484	17018	13036	13489	15840	12140
Lithuania	**LT**	4757	5900	4281	4650	5779	4185	4469	5558	4022
Luxembourg	**LU**	559	640	503	535	613	481	480	550	432
Latvia	**LV**	8680	10591	7812	8899	10863	8009	8748	10696	7874
Malta	**MT**	0	0	0	0	0	0	0	0	0
Netherlands	**NL**	811	920	730	780	887	702	758	861	683
Poland	**PL**	22105	26167	19894	21648	25610	19483	20492	24243	18443
Portugal	**PT**	10278	13139	9250	9913	12675	8921	9542	12198	8588
Romania	**RO**	16395	18480	14756	16019	18103	14417	15240	17153	13716
Sweden	**SE**	46962	57171	39747	48573	59174	41078	49604	60471	41855
Slovenia	**SI**	4870	5399	4383	4824	5349	4342	4580	5083	4122
Slovakia	**SK**	5024	5515	4522	4913	5392	4422	4859	5368	4373
United Kingdom	**UK**	14566	16239	12547	14300	15917	12352	14111	15665	12239
EU 28		**337089**	**395198**	**298714**	**338242**	**396624**	**299622**	**331907**	**389424**	**293742**
Albania	**AL**	1082	1308	974	1046	1264	942	949	1139	854
Bosnia and Herzegovina	**BA**	3114	3360	2803	3090	3333	2781	2685	2897	2417
Kosovo	**KS**	874	947	787	937	1015	843	885	959	797
Moldova	**MD**	572	652	515	487	554	438	602	686	542
Montenegro	**ME**	1028	1128	925	1003	1101	903	828	909	745
Macedonia	**MK**	1155	1263	1039	1102	1205	992	850	929	765
Serbia	**RS**	3798	4047	3418	3695	3938	3326	3211	3422	2890
Turkey	**TR**	14691	19308	13222	14353	18859	12918	13319	17552	11987
Ukraine	**UA**	15199	18308	13679	15333	18414	13800	15236	18281	13712
Non EU countries		**41513**	**50321**	**37362**	**41047**	**49684**	**36942**	**38566**	**46774**	**34709**
EU 28 & Non EU countries		**378603**	**445519**	**336076**	**379289**	**446308**	**336564**	**370472**	**436198**	**328451**

Dees et al., 2017b.

4.2 Definition of investigated feedstock categories and R&I fields

4.2.1 Forestry feedstock categories

Biomass from forestry consists of three categories: round-wood production, primary forestry residues, and secondary forestry residues. They can be further divided into biomass types and subtypes as indicated in the table below:

Table 4.5 Forestry feedstock categories covered by the study (cf. Dees et al. 2017b)

<table>
<tr><th></th><th>Biomass Category</th><th>Biomass Type</th><th>Biomass Subtype</th></tr>
<tr><td rowspan="9">Biomass from forestry</td><td rowspan="2">Round-wood production</td><td rowspan="2">Stemwood</td><td>Roundwood from final fellings</td></tr>
<tr><td>Roundwood from thinnings</td></tr>
<tr><td rowspan="3">Primary forestry residues</td><td rowspan="3">Logging residues</td><td>Tops, branches</td></tr>
<tr><td>Stumps</td></tr>
<tr><td>Early thinnings</td></tr>
<tr><td rowspan="4">Secondary forestry residues</td><td rowspan="2">Woodchips and pellets</td><td>Woodchips</td></tr>
<tr><td>Pellets</td></tr>
<tr><td>Sawdust</td><td></td></tr>
<tr><td>Black liquor</td><td></td></tr>
</table>

In some data bases biomass subtypes are further divided, for example into stemwood from conifer and non-conifer species. Secondary forestry residues comprise residues from saw mills, other wood processing industry residues and residues from pulp and paper industry. Depending on the data source, residues from saw mills can include sawdust and other residues besides sawdust.

4.2.2 Identification of R&I fields

The large differences between forest biomass supply potentials reported in different studies documented in the literature and between types of potentials quantified in the most recent S2BIOM project can be attributed to a number of key biological, technical, environmental, and socio-economic factors:

Table 4.6 Factors affecting forest biomass supply potentials

<table>
<tr><th>Type of factor</th><th>Examples</th><th>Constraints used in the S2BIOM resource assessment</th></tr>
<tr><td>Biological</td><td>Growth and productivity vary between biological species and provenances</td><td>EFISCEN model uses species specific growth functions and management regimes.</td></tr>
<tr><td rowspan="2">Technical</td><td rowspan="2">Harvest residue extraction rate that can be achieved with available technology</td><td>Recovery rate.</td></tr>
<tr><td>Slope / Terrain ruggedness.</td></tr>
<tr><td rowspan="2">Environmental</td><td>Resource potential not available to prevent soil degradation or compaction</td><td>• Site productivity;
• Soil and water protection: soil depth/soil surface texture/soil bearing capacity/soil compaction risk.</td></tr>
<tr><td>Resource potential not available due to biodiversity protection measures</td><td>Biodiversity: protected forest areas.</td></tr>
<tr><td rowspan="2">Socio-economic</td><td>Part of potential cannot be used cost-efficiently</td><td>Cost-supply curves.</td></tr>
<tr><td>Land-owner not willing to mobilize biomass potential</td><td>Fraction of potential from fragmented private forest holdings not available.</td></tr>
</table>

It is important to underline that already the Biomass Base Potential quantified for 2012 (section 4.1.2) is much higher than what is utilized in reality. An important reason behind this discrepancy are too high supply chain costs which limit the uptake of biomass feedstock in production and use of energy. Cost-efficiency of supply chain logistics is therefore an important target of R&I. Many other factors listed in Table 4.6 can be affected by changes in forest management and harvest operations and are thus also potential targets for R&I. For example, tree breeding affects growth and productivity and can enhance the amount of biomass produced per ha. Innovative technology could decrease soil compaction risk, which would consequently allow relaxing the environmental constraints on biomass utilization on soft soils. Another potential target of R&I could be social innovations as establishing forest cooperations would contribute to enhanced mobilization of biomass. Table 4.7 provides a listing of candidate R&I measures for the further analysis.

Table 4.7 Measures affecting forest biomass supply which could be targeted by R&I to achieve enhanced biomass production (P+), higher biomass utilization rates (U+) or reduced costs of biomass supply (C-)

Measure	How it affects biomass production and use	
Planting improved forest genetic resources	Selection of high quality genetic reproductive material and tree breeding can improve forest productivity.	**P+**
Introduction of non-native tree species, optimised provenance selection and site-species matching	Exotic plantation species such as Sitka spruce or Eucalypts have significantly higher growth rates compared to native tree species. Also within and between natural species there are considerable site specific differences in productivity.	**P+**
Tree species composition and mixture	Mixing species with complementary ecological niches enhances total stand biomass production compared to mono-specific stands.	**P+**
Water management – drainage	Waterlogged peatland soils limit tree growths. Draining such sites enhances forest productivity.	**P+**
Soil improvement – fertilisation	Fertilizing poor soils enhances forest productivity	**P+**
Optimised silviculture and management regimes	Stand management regimes are rarely optimized for biomass production and stand productively can be enhanced with improved silviculture.	**P+**
Coppice management	Many traditional coppice forests have been taken out of regular management and can be brought back into production.	**P+**
Optimised harvesting techniques affecting enhanced biomass extraction	Mechanized harvesting enables more efficient extraction of small dimension stem wood and harvest residues.	**U+**
Optimised harvesting techniques	Substantial cost savings are possible through improved harvesting and forwarding of biomass.	**C-**
Reduced moisture content through Improved biomass storage and chipping chain	Energy conversion of biomass gets more efficient with lower moisture content, i.e. more energy is generated at lower cost per unit of energy.	**C-**
Optimised transport logistics	More efficient transport can reduce supply chain costs.	**C-**
Establish forest management cooperative	Fragmented forest holdings can be managed more effectively through management cooperatives.	**U+, C-**
Use of previously unexploited tree compartments	Stumps contain substantial biomass amounts that are rarely utilized.	**U+**

In the following section we review these candidate measures and group them into R&I fields that increase forest biomass production (in section 4.3.1; measures classified with P+ in Table 4.7) or improve biomass mobilization (in section 4.3.2; measures classified with U+ and C- in Table 4.7).

4.3 Assessment of R&I potential (in Europe and third countries)

4.3.1 *Increased forest biomass production through improved genetic plant materials, fertilization, improved silviculture*

Sustainable forest management (SFM) is a key concept in European forestry, which recognises the need to balance the social, ecological, and economic outputs from forests. The sustainability of forest management depends on the decisions made by forest managers on the type of silvicultural measures to employ at the various phases of the development of a stand or group of trees (Duncker et al. 2012). The combined set of silvicultural measures forms a silvicultural system, which may be defined as “the process by which the crops constituting a forest are tended, removed, and replaced by new crops, resulting in the production of stands of distinctive form” (Matthews 1989). Duncker et al (2012) characterize forest management in a set of major forest management decisions that need to be made and which are linked to silvicultural measures (Table 4.8).

Table 4.8 Major decisions involved in forest management and the associated silvicultural measures (modified from Duncker et al. 2012)

Decision	Silvicultural measures
Naturalness of tree species composition	Selection of tree species
Tree improvement	Selection of tree genotypes
Type of regeneration	Stand establishment
Successional elements	Stand establishment, Tending, Thinning
Machine operation	Fertilizing, Liming, Soil preparation, Thinning, Final harvest
Soil cultivation	Soil preparation, Drainage
Fertilization / Liming	Fertilization, Liming
Application of chemical agents	Pest control
Integration of nature protection	Thinning, Final harvest
Wood removals (stem, residues, stumps)	Thinning (stem), Final harvest (stem), residue removal, stump removal
Final harvest system	Final harvest
Maturity	Final harvest

The silvicultural measures listed in Table 4.8 influence the increment or growth of trees and forests and several of these could be modified to increase biomass production.

Intensive forest management has large potentials to increase forest biomass production. Productivity increases over several plantation cycles are well documented from the Southern US, where yield/ha has more than quadrupled since 1940. The largest factors contributing to the yield improvement were fertilization, weed control, tree improvement and advanced genetic biotechnologies (Fox et al., 2004). Scenarios for intensified management in Swedish forests suggested that growth enhancements of up to 122 % could be realised at site level (Nilsson et al., 2011) and that forest production at larger scale could increase by up to 26%. (Poudel et al., 2012)

Selection gains through tree breeding are documented for several species. In Norway spruce, volume production gains per unit area over a rotation from seed orchards with plus trees compared to unimproved trees amounted to 10%; the second generation of improved seed orchards established after 1980 showed gains up to 25% in the case of intense selection from tested plus trees; next generation seed orchards could reach 35% gains compared to unimproved trees (Jansson et al., 2013). However, pollen contamination from natural stands is likely to lower the potential gains in practice. Breeding Sitka spruce for high biomass yield indicated potential gains up to 100% for a clone in Denmark (Lee et al., 2013). The improvements in end of rotation gains in the UK were 21-29% compared to unimproved material (in the case of 35-50 year rotations). The breeding gains in Scots pine were quantified for seed orchards established between 1950 and 1980 with 5-20% volume growth gains (Krakau et al., 2013). Genetic gain trials in Finland indicated after 10-20 years improvements with 15-20% faster growth, with individual plus trees growing 50% faster than control seed lots. In Sweden the gains were around 10% in the first generation and are expected to increase to 20-25% in the third round of seed orchards. Douglas fir breeding in France generated 25% volume growth gain in seed orchards (Bastien et al., 2013), seed orchards in Germany showed volume growth gains of 80%.

Fertilization to increase biomass yields is mainly relevant in Northern boreal forests, where it should only be carried out in stands without high nature values, avoiding shallow soils, soils with high fertility, peatlands and areas with high N deposition (Rytter et al., 2016). In Scandinavian countries on areas with a low deposition of anthropogenic nitrogen, a single application of 150 kg N ha^{-1} increases the growth of stem wood by approximately 30% in mature Norway spruce and Scots pine stands during a 10-year period (Hedwall et al., 2014). Even larger effects are expected from regular fertilization in young conifer stands in Scandinavia, where rotation lengths could be shortened by 10 to 30 years in the South an up to 60 years in the North. (Bergh et al., 2005)

Increased productivity through improved silviculture is more difficult to quantify, but several measures such as improved species mixture management, spacing and tending are considered to have some potential for yield improvement as well. (Iqbal et al., 2016)

Irrigation has no relevance in practical forestry (Iqbal et al., 2016), although experiments demonstrated significant theoretical potentials for productivity increases. (Bergh et al., 1999; Linder and Flower-Ellis, 1992)

Expert evaluation of the measures to increase biomass production

The literature review reported above presented a range of measures that may contribute to increased biomass production. A recent study by Iqbal et al. (2016) made a similar literature review, which they complemented with an expert consultation to assess the potential yield effect, the time needed that a measure could be implemented and where a measure could be applied. The summary of their analysis is presented in Table 4.9.

The measures listed in Table 4.9 are not equally relevant across Europe. Iqbal et al. considered this by assessing the realistic potential to increase yield for each of these measures for major forest types in Europe (EU28, Belarus and Ukraine). These realistic potentials consider, for example, that fertilisation may not lead to yield increases in forests on fertile soils. The estimated, realistic potentials for yield increases are shown in Table 4.10.

Table 4.9 Summary of measures to increase forest biomass production as identified by Iqbal et al. (2016)

Level	Yield measure	Yield increase effect per ha	Time needed for measure to come into effect	Regional applicability
Species	Tree breeding	10-25%	>20 years (long-term)	Entire study area
Species	Introduction of non-native tree species	10-30%	>10 years (medium-term)	On nearly all sites of entire study area
Site	Optimised site-species matching	2-3%	>20 years (long-term)	Entire study area
Site	Water management – drainage	2-10%	>5 years (short to medium-term)	Floodplain forests, swamp and mires (in the boreal and hemiboreal zone)
Site	Soil improvement – fertilisation	5-25%	>5 years (short to medium-term)	Boreal zone
Site	Soil improvement – restoration	5-10%	>10 years (medium-term)	Mainly mountainous areas of Southern Europe
Site	Soil improvement – melioration	2-5%	>5 years (short to medium-term)	Entire study area
Stand	Tree species composition and mixture	20-30%	>15-20 years (medium to long-term)	Entire study area where monocultures or stands with only single-storey and only 1-2 species occur
Stand	Optimised management regime (spacing, tending, thinning, final harvest and regeneration)	10-20%	>15-20 years (medium to long-term)	Entire study area, mainly focused on deficit areas in private and community forests
Stand	Coppice management	10-30%	>15-20 years (medium to long-term)	Mainly south-western and south-eastern Europe
Stand	Improving degraded forests	15-40%	>15-20 years (medium to long-term)	Eastern Europe (western Russia, Ukraine) and conifer forests in south-eastern Europe (Romania, Bulgaria)
Forest management	Preventing biotic and abiotic disturbances (pest, game, grazing)	10%	>5 years (short to medium-term)	Entire study region for pest prevention and game damages, south-eastern Europe and Ukraine for grazing damages
Forest management	Fire management	~3% for south-eastern Europe	>5 years (short to medium-term)	South-eastern Europe and western Russia

Table 4.10 Estimated realistic potential for yield increase (% per ha) per European forest type (EFT) for each measure (Iqbal et al. 2016)

Level	Measure	EFT 1	EFT 2	EFT 3	EFT 5	EFT6	EFT 7	EFT 8	EFT10	EFT14
Species	Tree breeding	10	10	10	15	10	10	15	10	5
Species	Introduction of non-native tree species		5	5	4		5	4	2.5	0
Site	Optimised site-species matching	0								
Site	Water management – drainage	1		0.4					0	0
Site	Soil improvement – fertilisation	6								2
Site	Soil improvement – restoration							1	1	
Site	Soil improvement – melioration					2	1			
Stand	Tree species composition and mixture	4	8	5	6	4		11	6	5
Stand	Optimised management regime (spacing, tending, thinning, final harvest and regeneration)	10	6		4	6	8		12	
Stand	Coppice management				5	0.2-0.7		8		
Stand	Improving degraded forests	0			0		2	3	3	0.8
Forest management	Preventing biotic and abiotic disturbances - pest	0	0.1	1	1.9		6		2	6
Forest management	Preventing biotic and abiotic disturbances - game		0.9	6	1.4	4	2			
Forest management	Preventing biotic and abiotic disturbances - grazing			1	1.2	2	5			
Forest management	Fire management	0		0.3					1	0.5
Improved yield		**31**	**30**	**28.7**	**38.5**	**28.9**	**39**	**42**		**19.3**

EFT1: Boreal forests; EFT 2: Hemiboreal Forests; EFT 3: Alpine Forests; EFT 5: Mesophytic Deciduous Forests; EFT 6: Beech Forests; EFT 7: Mountainous Beech Forests; EFT 8: Thermophilous deciduous Forests; EFT 10: Coniferous forests of the Mediterranean; EFT 14: Introduced tree species Forests.

4.3.2 *Improved biomass mobilization*

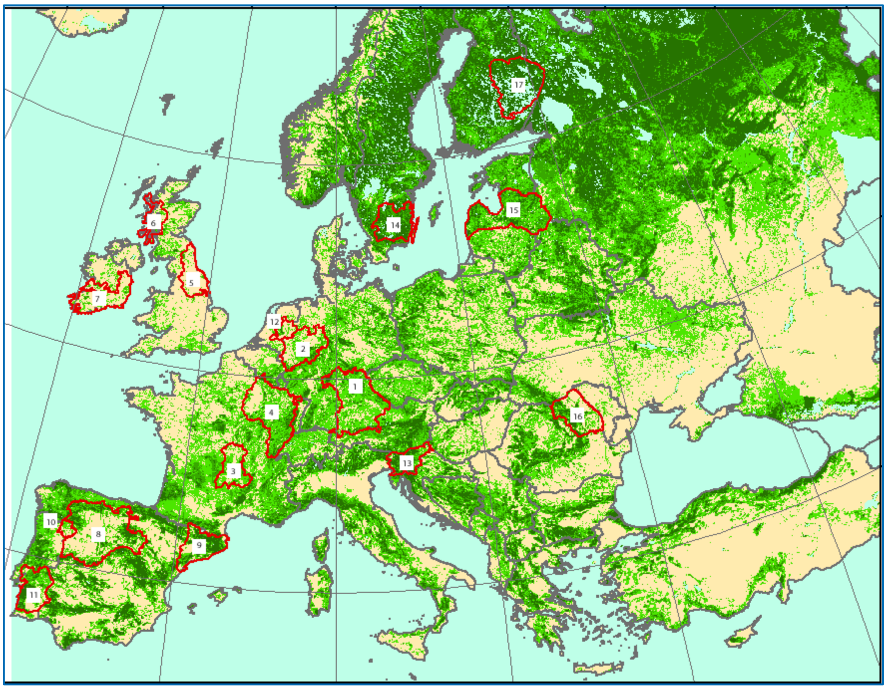
The Bioeconomy Strategy of the European Union, launched in 2012, addressed the need for development of “a more innovative, resource efficient and competitive society that reconciles food security with the sustainable use of renewable resources for industrial purposes, while ensuring environmental protection” (Innovating for Sustainable Growth: A Bioeconomy for Europe: EU 2012). The renewable energy directive (2009/28/EC) established the overall policy for the production and promotion of energy from renewable sources in the EU. Both policies call for greater mobilization of existing biomass potentials. The last major European Forest Sector Outlook study indicated that there could be a significant shortage in biomass supply to meet the projected increases in biomass demand for material and energy use (UNECE and FAO, 2011). While some studies questioned the reliability of demand projections (Hetemäki, 2014; Hurmekoski and Hetemäki, 2013), it is evident that a major utilization of biomass for advanced biofuels would require successful strategies for improved forest biomass utilization. Without this, there would likely be a shortage of wood supply and competition between the wood industry and the energy sector for the scarce biomass resources would increase.

A substantial part of existing biomass potentials is not utilized for a variety of reasons. Possible reasons for not mobilizing existing biomass potentials could be owners who are not willing to harvest or small fragmented forest holdings that are too small to manage effectively. R&I approaches addressing these issues would have to focus on social innovations such as establishment of forestry cooperations or development of new marketing models that reduce the effort needed to sell biomass. Another major factor that is limiting the mobilization of biomass potentials are low market prices and high costs of biomass supply chains. R&I investments in supply chain logistics could make biomass supply more cost-efficient and thereby enhance mobilization of potentials as well.

Mobilizing unused resource potentials

The ongoing Horizon2020 project SIMWOOD aims to identify strategies how to mobilise the unused potential of European forests in a sustainable way, by activating forest owners and promoting collaborative forest management. SIMWOOD works on 17 model regions (Figure 4.3). The regions were selected on the basis that there is a potential to increase wood mobilisation and to represent a broad range of European forest types and also a range of experience in forest governance and wood mobilisation.

Figure 4.3 SIMWOOD model regions. 1. Bavaria (Germany); 2. North Rhine-Westphalia (Germany); 3. Auvergne (France); 4. Grand Est (France); 5. Yorkshire and North East England (UK); 6. Lochaber, Scotland (UK); 7. Southern/Eastern Region Ireland; 8. Castile and León (Spain); 9. Catalonia (Spain); 10. Nordeste Transmontano (Portugal); 11. Alentejo (Portugal); 12. Overijssel & Gelderland (the Netherlands); 13. Slovenia; 14. Småland (Sweden); 15. Latvia; 16. Northeast Romania; 17. Eastern Finland



Background: Forest map of Europe; EFI (Gunia et al., 2011).

The regional case studies first described the specific context for wood mobilisation in each of the regions, identified knowledge gaps, barriers to wood mobilisation, and potential solutions to overcome the barriers. Next, the cases carried out a series of pilot projects to explore novel solutions addressing governance and ownership questions, forest functions, or forest management and harvesting practices in order to contribute to an increased and sustainable wood mobilisation.

<u>Forest owners as key actors in wood mobilisation:</u> The key to mobilizing wood potentials is the willingness of a large number of public and private forest owners to engage in or permit an increase in biomass harvesting. The majority of woody biomass in Europe is sourced from private forest owners, the majority of whom are individuals and families. Because their forests are often under-utilised, they account for a significant, increasing portion of the wood potential. The number of ‘traditional’ forest owners, who recognise the economic potential of their forest holding and are actively involved in timber harvesting, is declining as a result of structural changes in agriculture and forestry and the transfer of ownership through inheritance. The number of urban forest owners who are living at considerable distance from their property is gaining in importance. The changing ownership pattern is also leading to an increased fragmentation of forest holdings: almost two-thirds of European private forest holdings occupy less than one hectare (Schmithüsen and Hirsch, 2010). Many of these owners have little knowledge of forest management and wood production. R&I targeting the mobilisation of wood resources hence requires a ‘mobilisation of forest owners’, building on a good understanding of the motivations and objectives of the different types of owners. These owners are less likely to use the forest as a source of income, and other objectives and motivations such as using their forest for recreation or for nature conservation could be more important. Thus there is a need for social innovations such as the establishment of cooperatives, knowledge exchange events or trainings targeting small forest owners, which allow the mobilization of biomass potentials from unter-utilized private forests (unpublished SIMWOOD project results).

Another issue is to ensure that the wood from these forests reaches the desired market. Therefore, a larger group of regional actors in the wood supply chain has to be involved. Professional foresters, forest entrepreneurs, wood industries and members of local authorities and communities all have important roles to play in mobilization of the wood resources. Their collective expert knowledge of drivers in wood mobilisation and their input into identifying suitable solutions is essential.

Optimized supply chain logistics

Innovations in forest wood supply were recently studied in the FP7 project INFRES (Alakangas et al., 2015). A number of novel technologies and methods for the utilization of residual forest biomass are available to enhance the performance of woody biomass supply chains. Innovations in supply chain logistics are generally described as either a) Radical innovations that change the operating principle of a system and lead to a technology leap, or b) Incremental innovations that improve the existing systems by enhancing their resource efficiency or reducing their costs in gradual steps. In wood harvesting, radical innovations have been the introduction of the chain saw in the 1950s and 1960s and mechanization of the felling, delimbing and cross cutting by using the single grip harvester principle in the 1980s. Once introduced, these technologies have been gradually improved so that their performance levels have risen and e.g. fuel consumption has been markedly reduced.

Novel technologies such as sensor technology, automation, electric drives, hybrid technology, and machine vision were assessed in the INFRES project concerning their applicability in energy wood supply. From a total of 51 reviewed innovations, five promising ones were selected for further investigation in the project:

1) The “High Capacity Transport (HCT) Truck” with either 74 tonne or 90 tonne truck load is 25 or 30 m long, respectively. Employing a 90 tonnes truck reduces fuel consumption, GHG emissions and transportation costs per transported tonne by 20% (74 tonnes truck: 10% to 12%). Furthermore, every third truck could be removed from the roads and the number of bypasses for neighbourhood residents reduced;
2) “Open forest street map” is a concept of building OpenStreetMap, an open database for planning harvesting and transportation processes. It allows storing data from GPS-units on forest machinery and handhelds as well as forest road network data and their attributes, including storage places and average speed for different classes;
3) The Bracke “MAMA” head is a harvester head dedicated for thinning operations in dense first thinning stands with heights of between 8 m and 15 m. Biomass is cut-to-length and compressed before piling at strip-road side. Harvested biomass density increases by approximately 45% to 70%, whereas, due to leaving nutrients rich needles and small twigs in the stand, harvesting yield decreases 10% to 23%. Due to handling of compressed biomasses, the forwarder pay-loads increased by 20% and the forwarding productivity increased by 46% at 300 m driving distance (one-way);
4) “Increased Chip Size in the Production Chain” is a concept based on the experience that productivity and fuel consumption per produced tonne decreases when the target chip size is increased. A Bruks 605 chipper increased productivity by 50%, while fuel consumption decreased by 33%, as a result of increasing chip target length from 15 mm to 40 mm;
5) “Hultdins Supergrip II A” is a grapple optimized for easier log picking. With conventional knives, there is always a risk that a piece of wood is clamped between the cross-members and obstructs the closing motion of the grapple. The angled cross members of the A-Grapple feed everything that the tips can grab into the grapple and the rest is fed out. Thus, nothing can get stuck between the grapple arms, and the closing motion of the grapple is uninterrupted.

Considering their high development potential, these innovations might become winning technologies in a few years, as there might be steep learning curves in the adoption of a new technology or method.

Figure 4.4 High Capacity Transport Trucks with a length of 25 to 30 m could reduce fuel consumption, GHG emissions and transportation costs per transported tonne by 10-20%

Cost and fuel savings through efficient processing of forest residues

The INFRES project studied innovative residue handling technology with forwarders that have larger loading space. When residues are chipped to a roadside landing, their high bulk density affects the extraction process only, which is not enough to justify proper compaction performed by a bundler. A cheaper and cruder densification method is the use of forwarders with compressing sides, allowing reduced fuel use and maintenance costs. The demonstrations furthermore included new chipper systems to minimize machinery damage in the presence of contaminants. Compared with a conventional system, the innovative system allowed a 13% saving on financial costs and a 35% saving on fuel costs.

An even larger reduction in fuel consumption was achieved by a compact chipper-truck equipped with a new generation diesel-electric hybrid power pack. With improved chipping logistics into pre-arranged roll-on containers the system resulted in a drastic reduction of interaction delays, increasing the machine utilization to almost 90%, from a traditional benchmark of around 70%.

Harvesting of small trees for energy is often inefficient. INFRES demonstrations with innovative small-tree harvesting machines (fellerbuncher, multi-tree harvester, feller-forwarder, harwarder and feller-bundler) improved handling and compacting of biomass, resulting in about 15% increased forwarder productivity. Similar gains are expected for chipping or transportation, due to the better handling qualities of unitized loads. Integrated felling and extraction offered cost savings of between 15% and 20% compared to other mechanized options. Yet, these benefits cannot be achieved without re-designing the whole supply chain. Similarly, introduction of the most promising automatic multi-tree harvester head (i.e. MAMA harvester) requires abandoning single-tree selection and shifting to boom-corridor thinning, which does represent a big change in silvicultural practice.

Managing moisture content of biomass from harvest residues is key to optimize energy conversion efficiency e.g. in combined heat and power plants. Temporary storage of residues at the roadside reduces moisture content of biomass and thereby increases the energy yield. (Hakkila, 2006). Innovative supply chain management with automatized moisture measurement and optimized resource planning has significant potentials to reduce costs per unit energy produced. However, this R&I field is outside of the scope of the forestry models employed in this study and therefore not further considered in this section.

Forest governance and the role of regional initiatives
Today's increasing societal concern for the environment has led to criticism that forest management is too strongly focused on economic production. Multifunctional must incorporate ecological and social functions, balance the impacts of forest use, and ensure provisioning of other ecosystem services. It is increasingly important to integrate through participatory approaches other stakeholders from outside the forestry sector into forest resource use decision making (e.g. environment or recreation interest groups). Therefore, novel wood mobilisation approaches require inevitably a wider inclusion of stakeholders' opinions in forest policy making. Embedding wood mobilisation in wider regional initiatives driven by the local economy beyond the forest sector has so far not been explored on a wider scale, but this clearly deserves more attention. Future R&I efforts should therefore aim to be more cross-disciplinary to capture social innovation potentials that are critical for the mobilization of forest biomass.

Expert evaluation of the measures to mobilize biomass potentials
The study of Iqbal et al. (2016) that combined literature reviews with expert consultations also addressed measures related to the mobilization of biomass potentials. These are presented in the Table 4.11 with estimated yield increases shown in Table 4.12. Iqbal et al. (2016) targeted the mobilization measures mainly to Eastern and South-Eastern Europe. As documented by the SIMWOOD case studies and INFRES demonstrations of innovative technologies, substantial potentials exist to improve biomass mobilization also in regions with already high mechanization level. It is, however, difficult to evaluate how realistic the up-scaling of such measures is when it comes to convincing forest owners to increase the utilization of their forests.

Table 4.11 Summary of measures related to increased biomass mobilization identified by Iqbal et al. (2016)

Biomass mobilization measure	Yield increase effect per ha	Time needed for measure to come into effect	Regional applicability
Improving forest accessibility	10-15%	>1 year (short-term)	Eastern and south-eastern Europe
Optimised harvesting techniques	5-20%	>1 year (short-term)	Eastern and south-eastern Europe
Use of previously unexploited tree compartments	10-50%, depending on the previously harvested assortments and whether all species are harvested	>1 year (short-term)	Central, south-eastern and eastern Europe (western Russia, Belarus and Ukraine)

Table 4.12 Potential for yield increase from improved biomass mobilization (% per ha) per European forest type (EFT) for each measure (Iqbal et al. 2016)

Measure	EFT1	EFT2	EFT3	EFT5	EFT6	EFT7	EFT8	EFT10	EFT14
Improving forest accessibility			3			6	2	0.9	
Optimised harvesting techniques			3			12		0.9	
Use of previously unexploited tree compartments		4	3	23	4	6	1		
Improved utilisation		**4**	**9**	**23**	**4**	**24**	**3**	**1.8**	

EFT1: Boreal forests; EFT 2: Hemiboreal Forests; EFT 3: Alpine Forests; EFT 5: Mesophytic Deciduous Forests; EFT 6: Beech Forests; EFT 7: Mountainous Beech Forests; EFT 8: Thermophilous deciduous Forests; EFT 10: Coniferous forests of the Mediterranean; EFT 14: Introduced tree species Forests.

4.4 Identification of major players in R&I

4.4.1 Methodology

Identification of major players in R&I related to forest biomass, enhanced biomass production, improved biomass mobilization, forest supply chain logistics, bioenergy, advanced biofuels

Major players were identified in EC's FP6, FP7 and H2020 framework programmes from the CORDIS data base (https://data.europa.eu/euodp/data/publisher/publ) within the 'forestry-related' projects. Organizations were identified by their Participant Identification Code (PIC). 'Forestry-related' projects were identified as projects matching the definition of forestry as stated by Society of American Foresters (http://dictionaryofforestry.org/dict/term/forestry), which is:

> The profession embracing the science, art, and practice of creating, managing, using, and conserving forests and associated resources for human benefit and in a sustainable manner to meet desired goals, needs, and values —note the broad field of forestry consists of those biological, quantitative, managerial, and social sciences that are applied to forest management and conservation; it includes specialized fields such as agroforestry, urban forestry, industrial forestry, nonindustrial forestry, and wilderness and recreation forestry.

We used the list of forestry-related projects within Framework programmes (matching the above stated definition of forestry) as identified by the Technology Platform of the Forest-based Sector (www.forestplatform.net) to define the initial data frame for the analysis ('core' forestry projects'). The project summaries of all the core forestry projects have been summarized into a single text, together with their titles. This text was cleaned from 'stop-words' (e.g. "the", "and", "will", "for", "from", "this", "are", "that"), and then transformed into lemmatized strings (roots of words, e.g. manage for management, manager, etc.) i.e. 'key words' (only nouns and verbs). We then analysed the complete CORDIS data base with all project summaries and goals of projects funded by the framework programmes. A distance matrix (i.e. Multi-dimensional scaling) was constructed between the modified description of core forestry projects and all the others – which provides a figure that represents 'distance' of a project's description to the core forestry projects. A count of 'key words' in the core forestry projects was carried out, and all words with frequency higher than 20 were used in the subsequent analysis. All CORDIS projects were then compared to the core forestry projects by weighted frequency of key words (e.g. the forest string had a weight of 504 whereas the weight for pathogen was 20). As an example, for FP7, a total of 188 key words was used, and nine sets of key words with varying group size were used in the analysis.

Above analysis produced a total of ten numerical measures of 'proximity' to the core forestry projects. All the projects in the data base have been ordered from the most 'similar' one to the least 'similar' one successively for each of these measures. In each of these ordered sets of 'proximity', project descriptions have been compared to the definition of forestry; and if they were matching to the definition, they were added to the 'forestry data set'. If 30 successive projects did not match the definition, the analysis moved to the following measure of proximity.

The same procedure was followed for the topic of 'biomass/biofuels'. A half-page description of the topic was extracted from the Tender specifications. Next, a list of key words was compiled and four recent projects that are very relevant to the topic were identified:

- List of key words: (1) Biomass; (2) Bioenergy; (3) Advanced biofuels; (4) Supply chain logistics; (5) Biomass production and (6) Biomass mobilization;
- Recent reference projects: S2BIOM, INFRES, Biomass policies, SimWood.

The description of the reference projects, together with key words and the half page summary of the tender specifications was compared against all the projects that have been identified in the 'forestry data set' through a set of numerical measures, and then compared individually by reading the project's description and comparing it against the topic description. This procedure produced the 'biomass/biofuels' list of projects – and from this list of projects their participants have been identified.

It has to be noted that the search for 'biomass/biofuels' related projects was confined to the context of forestry – and as such, did not entail a vast majority of projects that have been funded in the framework programmes.

4.4.2 Results

A total number of 34 projects (Table 4.13) matched the search criteria with 341 organizations participating in at least one project. The table below shows the 66 organizations that are partner in at least two of the target projects. The most active Research and Innovation Actors are EFI (international), LUKE and VTT (Finland), The University of Freiburg and Fachagentur Nachwachsende Rohstoffe (Germany), FCBA and INRA (France), BTG and Wageningen University (The Netherlands), and BOKU University in Vienna (Austria).

Table 4.13 List of projects that matched all search criteria

Acronym	Title	Programme
ACCENT	Acceleration of the Cost-Competitive Biomass Use for Energy Purposes in the Western Balkan Countries.	FP6
BIOSAFOR	Biosaline agroforestry: remediation of saline wastelands through the production of biosaline biomass (for bioenergy, fodder and biomaterials).	FP6
PRO-BIOBALKAN	Promotion of cost competitive biomass technologies in the Western Balkan countries.	FP6
DOMOHEAT	Tertiary heating systems using agro, forest and wood residues.	FP6
NILE	New Improvements for Ligno-cellulosic Ethanol.	FP6
INDISPUTABLE KEY	Intelligent distributed process utilisation and blazing environmental key.	FP6
INNOVAWOOD SSA	An innovation strategy to integrate industry needs and research capability in the European forestry-wood chain.	FP6
NANOFOREST	A nanotechnology roadmap for the forest products industry.	FP6
BIOPOL	Assessment of biorefinery concepts and the implications for agricultural and forestry policy.	FP6
WOODWISDO M-NET	Networking and Integration of National Programmes in the Area of Wood Material Science and Engineering.	FP6
EFORWOOD	Tools for Sustainability Impact Assessment of the Forestry-Wood Chain.	FP6
WOODISM	WOODISM - Improving competitiveness of the forest-wood-chain by supporting SME participation in FP6 projects.	FP6
MICROFUEL	Mobile Microwave Pyrolysis Plant turns Biomass into Fuel Locally.	FP7
SIMWOOD	Sustainable Innovative Mobilisation of Wood.	FP7
INFRES	Innovative and effective technology and logistics for forest residual biomass supply in the EU.	FP7
FOCUS	Advances in FOrestry Control and aUtomation Systems in Europe.	FP7
WOODWISDO M-NET+	WoodWisdom-Net+ Pacing Innovation in the Forest-Based Sector.	FP7
FORBIOPLAST	Forest Resource Sustainability through Bio-Based-Composite Development.	FP7

Acronym	Title	Programme
FLEXWOOD	Flexible Wood Supply Chain.	FP7
ROK-FOR	Sustainable forest management providing renewable energy, sustainable construction and bio-based products.	FP7
WOODWISDOM-NET 2	Networking and Integration of National Programmes in the Area of Wood Material Science and Engineering in the Forest-based Value Chains.	FP7
BEE	Biomass Energy Europe.	FP7
KNOWLEDGE2 INNOVATION	Promoting the exploitation of scientific knowledge through academia–industry cooperation in the Knowledge-Based Bio-Economy in Europe and beyond.	FP7
AQUATERRE	Integrated European Network for biomass and waste reutilisation for Bioproducts.	FP7
ROKWOOD	European regions fostering innovation for sustainable production and efficient use of woody biomass.	FP7
S2BIOM	Delivery of sustainable supply of non-food biomass to support a “resource-efficient” Bioeconomy in Europe.	FP7
BioSTEP	Promoting stakeholder engagement and public awareness for a participative governance of the European bioeconomy.	H2020
BioRES	Sustainable Regional Supply Chains for Woody Bioenergy.	H2020
greenGain	Supporting Sustainable Energy Production from Biomass from Landscape Conservation and Maintenance Work.	H2020
SECURECHAIN	Securing future-proof environmentally compatible bioenergy chains.	H2020
Bioenergy4Business	Uptake of Solid Bioenergy in European Commercial Sectors (Industry, Trade, Agricultural and Service Sectors) – Bioenergy for Business.	H2020
BIOSURF	BIOmethane as SUstainable and Renewable Fuel.	H2020
Bin2Grid	Turning unexploited food waste into biomethane supplied through local filling stations network.	H2020
Biomass policies	Biomass policies.	Intelligent Energy Europe

Table 4.14 List of organizations with at least two participations in target projects

Organization	No. of projects	Internet site
European Forest Institute	7	http://www.efi.int/portal/
Luonnonvarakeskus	7	https://www.luke.fi/
Teknologian tutkimuskeskus VTT	7	http://www.vtt.fi/
Albert-Ludwigs-Universitaet Freiburg	6	http://www.uni-freiburg.de/universitaet-en
Institut Technologique FCBA	6	http://www.fcba.fr/
B.t.g. Biomass Technology Group bv	5	http://www.btgworld.com/en
Fachagentur Nachwachsende Rohstoffe e.v.	5	http://www.fnr.de/
Institut national de la recherche agronomique INRA	5	http://www.inra.fr/en/Scientists-Students
Stichting dienst landbouwkundig onderzoek Alterra/Wageningen University	5	http://www.wur.nl/
Universitaet fuer Bodenkultur Wien BOKU	5	https://www.boku.ac.at/en/
Centre tecnologic forestal de Catalunya CTFC	4	http://www.ctfc.cat/?lang=en
Energetski institut hrvoje pozar	4	http://www.eihp.hr/
Imperial college of science, technology and medicine	4	https://www.imperial.ac.uk/
Stiftelsen skogsbrukets forskningsinstitut - Skogforsk	4	http://www.skogforsk.se/
Centre for renewable energy sources and saving foundation	3	http://www.cres.gr/kape/index_eng.htm
Confederation europeenne des proprietaires forestiers CEPF	3	http://www.cepf-eu.org/
Forestry commission	3	http://www.forestry.gov.uk/
Gozdarski institut slovenije	3	http://www.gozdis.si/domov/
Ifer - ustav pro vyzkum lesnich ekosystemu	3	http://www.ifer.cz/page/index.php
Instytut badawczy lesnictwa	3	https://www.ibles.pl/
Internationales Institut fuer angewandte Systemanalyse	3	http://www.iiasa.ac.at/
Ministry of agriculture and forestry	3	http://mmm.fi/en/frontpage
Wirtschaft und Infrastruktur gmbh & co Planungs kg	3	http://www.wip-munich.de/
Agency for new technology, energy and the environment	2	http://old.enea.it/com/ingl/
Agenzia per la promozione della ricerca europea	2	http://www.apre.it/
Aidima - asociacion de investigacion y desarrollo en la industria del mueble y afines	2	http://www.aidima.es/
Association europeenne pour la biomasse	2	http://www.aebiom.org/
Association foret cellulose	2	http://agriculture.gouv.fr/afocel-association-foret-cellulose
Bundesforschungsanstalt für Forst- und Holzwirtschaft (Federal research centre	2	https://www.thuenen.de/en/about-us/history/bfh-forestry-and-forest-

Organization	No. of projects	Internet site
for forestry and forest products)		products/
Centro ricerche fiat s.c.p.a.	2	https://www.crf.it/EN
DBFZ Deutsches Biomasseforschungszentrum gemeinnuetzige gmbh	2	https://www.dbfz.de/en/news.html
Department of agriculture, food and the marine	2	https://www.agriculture.gov.ie/
Energikontor sydost ab	2	http://www.energikontorsydost.se/en
Energy research centre of the Netherlands (ECN)	2	https://www.ecn.nl/
European biomass industry association	2	http://www.eubia.org/
Forstliche Versuchs- und Forschungsanstalt Baden-Wuerttemberg	2	http://www.fva-bw.de/
Fundacion circe centro de investigacion de recursos y consumos energeticos	2	http://www.fcirce.es/
Innovaatiorahoituskeskus Tekes	2	http://www.tekes.fi/tekes/
Innovawood ltd	2	https://ec.europa.eu/energy/intelligent/projects/en/partners/innovawood-ltd
Instituto Superior de Agronomia	2	https://www.isa.ulisboa.pt/en
Internationales Institut für Wald und Holz nrw e.v.	2	http://www.wald-institut.de/
Istituto di studi per l'integrazione dei sistemi	2	http://www.isis-it.com/
Itä-suomen yliopisto	2	http://www.uef.fi/fi/etusivu
Johann heinrich von Thünen Institut, Bundesforschungsinstitut für ländlichen Raum, Wald und Fischerei	2	https://www.thuenen.de/
JRC -Joint Research Centre- European Commission	2	https://ec.europa.eu/jrc/en
Kungliga Tekniska Hogskolan	2	https://www.kth.se/en
Latvian valsts koksnes kimijas instituts (Latvian state institute of wood chemistry)	2	http://www.kki.lv/
Latvijas Zinatnu Akademija	2	http://www.lza.lv/index.php?mylang=english
Lunds Universitet	2	http://www.lu.se/
Macedonian geothermal association	2	http://www.maga.con.mk/?i=1
Ministere de l agriculture de l agroalimentaire et de la foret	2	http://agriculture.gouv.fr/
Ministerie van economische zaken	2	https://www.rijksoverheid.nl/ministeries/ministerie-van-economische-zaken
Ministrstvo za izobrazevanje, znanost in sport	2	http://www.mizs.gov.si/en/
Ministry of Agriculture Republic of Latvia	2	https://www.zm.gov.lv/en/
Nacionalna asociacia po biomasa	2	
Norges Forskningsrad	2	http://www.forskningsradet.no/no/Forsiden/1173185591033
Scientific engineering centre biomass ltd	2	http://biomass.kiev.ua/en/

Organization	No. of projects	Internet site
Slovenska inovacna a energeticka agentura	2	http://en.siea.sk/
SP Sveriges Tekniska Forskningsinstitut ab	2	https://www.sp.se/en/Sidor/default.aspx
Suomen Akatemia	2	http://www.aka.fi/
Sveriges Lantbruksuniversitet	2	http://www.slu.se/en/
Syncom Forschungs- und Entwicklungsberatung gmbh	2	http://en.syn-com.com/company/company.php
Technicka univerzita vo Zvolene	2	https://www.tuzvo.sk/en/
The University of Nottingham	2	https://www.nottingham.ac.uk/
Universiteit Utrecht	2	http://www.uu.nl/en
Verket för Innovationssystem	2	http://www.vinnova.se/sv/

Project participation is unbalanced across regions, with dominance of participation of institutions from Central and Northern Europe. Eastern European participants are clearly under-represented.

Figure 4.5 Distribution of participating organizations of target projects across regions in Europe

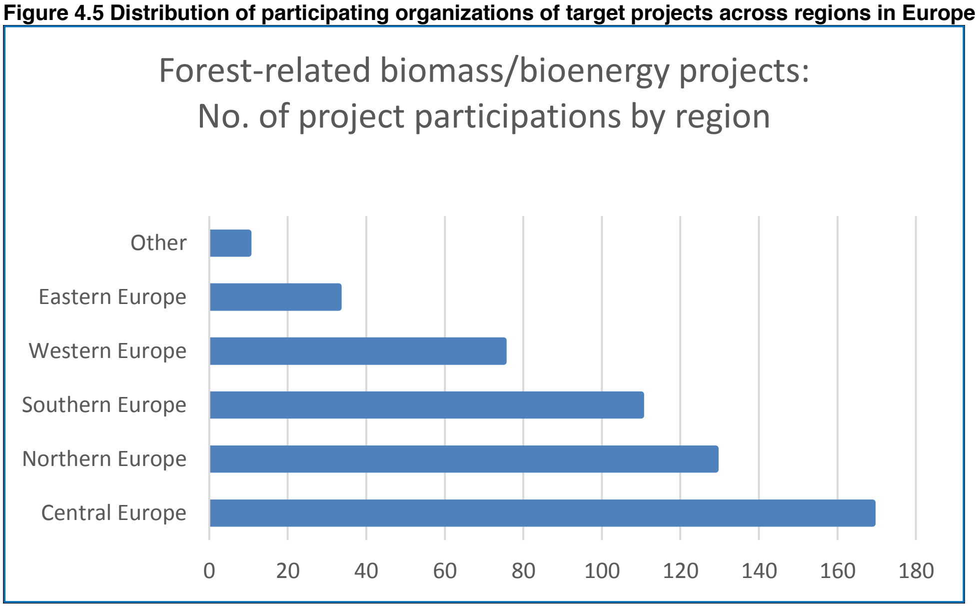
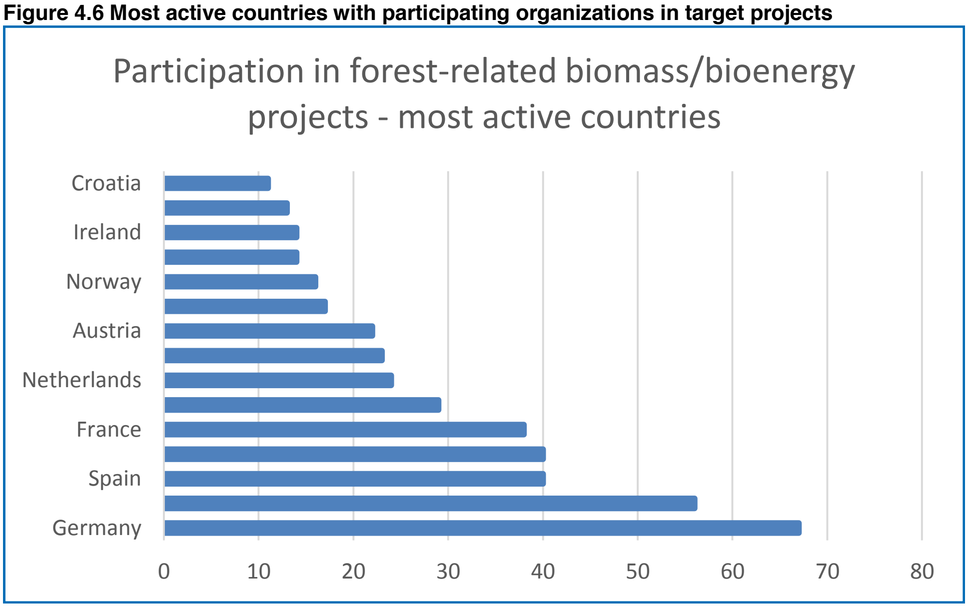


Figure 4.6 Most active countries with participating organizations in target projects



4.5 Definition of scenario elements for selected R&I fields

The review of R&I potentials to increase forest biomass resource utilization indicated that there are two distinct lines of R&I fields in the sector: a) R&I targeting measures for increased production of forest biomass and b) R&I targeting measures for increased mobilization of forest biomass potentials.

Several measures have been identified that could increase forest biomass production.

As forest management is characterized by very long production cycles that last several decades to more than a century – much longer than in other sectors covered in this study – it is generally so that changes in forest resource management take time to result in significantly increased biomass potentials. Major measures such as planting improved genetic material (different species or genetically improved seeds) can only be implemented at the end of the current management cycle, and consequently there are only small shares of the total forest area on which new technology can be implemented each year. The common rotation length in European forests varies from 25-40 years in plantation forestry to 60-180 years in other management regimes. Considering that the average rotation length in Europe is probably around 80 years it follows that over the next 10 years less than 15 % of the total forest area is harvested and subject to forest regeneration and initiation of a new forest management cycle. Hence, it takes long lag times before changes in forest productivity result in enhanced biomass potentials.

In contrary, measures that target enhanced mobilization of existing biomass potentials may be implemented faster. However, as many of these measures depend largely on social processes and changes in societal preferences, it is more uncertain to what extend they can be realised.

Table 4.15 presents the main measures as identified in the literature review for consideration in the R&I scenario analysis targeting enhanced utilization of forest biomass potentials. However, not all measures could be implemented due to data limitations or because of the approach used to quantify biomass potentials in the different scenarios.

Table 4.15 Main measures to increase forest biomass production and/or enhance mobilization of forest biomass in the scenario analysis

Measure	Implementation in the scenario modelling
Tree breeding	Regenerate forests dominated by Scots pine, Maritime pine, Norway spruce, Sitka spruce, Douglas fir and poplar forests with new varieties from the same species that grow 25% faster as compared to current genotypes. It is assumed that 50% of the area to be regenerated annually will be restocked with these new varieties.
Introduction of non-native tree species	Replacing Norway spruce with Douglas fir on 25% of the area.
Fertilisation	Fertilisation of forests growing on poor soils, excluding forests on peatlands. Fertilisation is implemented 20 years before the start of final fellings for conifers and long-lived broadleaves and 10 years in the case of short-living broadleaves. The expected growth increase is 10% 5 years after fertilisation and 5% 10 years after fertilisation.
Tree species composition and mixture	This measure is difficult to implement because of complex assumptions on regionally varying species compositions and the lack of suitable growth equations.
Optimised management regime	Due to increased growth rates, rotation lengths could be shortened by 20 years for conifers and long-lived broadleaved species and 10 years for other tree species. However, already in the reference scenario we calculate a much larger potential than what is currently utilized. If management would implement the full potential, the realised rotation length would already be shortened as indicated.
Coppice management	The estimation of forest biomass potentials assumes that all forests available for wood supply will be managed to provide biomass; this includes coppice forests, but the assumption is already considered also for the reference scenario biomass potentials.
Optimised harvesting techniques affecting enhanced biomass extraction	Optimized harvesting techniques correspond to a high mobilisation scenario for residue extraction. Furthermore, the ratio between removals and fellings is increased by 5%-points, i.e. there will be less harvest losses. This will result in more stemwood, but less

Measure	Implementation in the scenario modelling
	stemwood residues.
Cost savings through optimised harvesting techniques	Improved supply chain cost efficiency is considered in the quantification of cost-supply in EFI-GTM.
Use of previously unexploited tree compartments	The estimation of forest biomass potentials considers all biomass compartments (stems, branches, stumps and coarse roots) are potentially available, taking into account technical, environmental and socio-economic constraints that may affect their mobilisation.

In order to facilitate the development of scenario storylines for modelling the production and delivery of biomass feedstock, scenario elements have been identified for promising R&I activities in the field of forestry. Specifically, these scenario elements were grouped into R&I measures targeting either (a) increased supply of biomass through **enhanced production** or (b) **improved biomass supply** through innovative harvesting, supply chain logistics and mobilization of potentials.

The following table presents an overview of R&I scenario elements for enhanced production and improved biomass supply for the field of forestry.

Table 4.16 R&I scenario elements for enhanced production and improved biomass supply from forestry

	R&I scenario elements for enhanced production	R&I scenario elements for improved biomass supply
Biomass from forestry	• Use of more appropriate breeding material for main production tree species; • Use of new, more productive varieties for main production tree species through tree breeding; • Introduction of Douglas fir on sites when Norway spruce dominated stands are felled; • Fertilisation of forests growing on poor soils.	• Successful translation of recommendations on wood mobilisation and increased awareness of owners lead to an increased mobilisation of wood from forests. New forest owner associations or co-operations are established throughout Europe. Together with existing associations, these new associations lead to improved access of wood to markets; • Strong mechanisation is taking place across Europe; existing and new technologies are effectively shared between countries through improved information exchange, enhancing also the extraction of biomass from rugged terrain and water logged sites; • Trees are harvested more efficiently, which results in a reduction of harvest losses and thereby logging residues; • Biomass harvesting guidelines become less restricting, because technologies are developed that are less harmful for the environment. As a result, biomass from all tree compartments (stems, logging residues and stumps) are extracted; • Improved harvest machinery is applied, which reduces environmental impacts and thereby allows for increased forest biomass extraction; • Innovative harvesting, supply-chain logistics

	R&I scenario elements for enhanced production	R&I scenario elements for improved biomass supply
		and mobilisation is available resulting in more efficient felling, extraction and transport of woody biomass; • Application of fertilizer is permitted to limit detrimental effects of logging residue and stump extraction on the soil.

5 Assessment of the R&I potential in the field of waste

Eurostat defines waste briefly as “any substance or object which the holder disposes of or is required to dispose of pursuant to the provisions of national law in force”. (Eurostat, 2014)

A more comprehensive definition is provided by the United Nations Department of Economic and Social Affairs, which defines waste as “...materials that are not prime products (that is, products produced for the market) for which the generator has no further use in terms of his/her own purposes of production, transformation or consumption, and of which he/she wants to dispose. Wastes may be generated during the extraction of raw materials, the processing of raw materials into intermediate and final products, the consumption of final products, and other human activities. Residuals recycled or reused at the place of generation are excluded. The different categories include biological waste, solid waste, industrial wastes and household waste”. (United Nations Statistics Division n. d.).

This chapter focuses on the potential of feedstock for bioenergy production which can be recovered from the waste streams. Thus, waste streams with high organic fraction content are given a closer look in the following chapters. The need to act in this sector can also be taken from the recent JRC report “Towards a better exploitation of the technical potential of waste-to-energy” (Saveyn et al., 2016), which revealed that 2/3 of the energy contained in all the waste sent for incineration is comprised by household and similar waste as well as sorting residues and also wood waste. This information alone highlights the big potential within the single waste streams.

The main feedstock categories included in this chapter are presented in Table 5.1.

Table 5.1 Main waste feedstock categories covered by the study

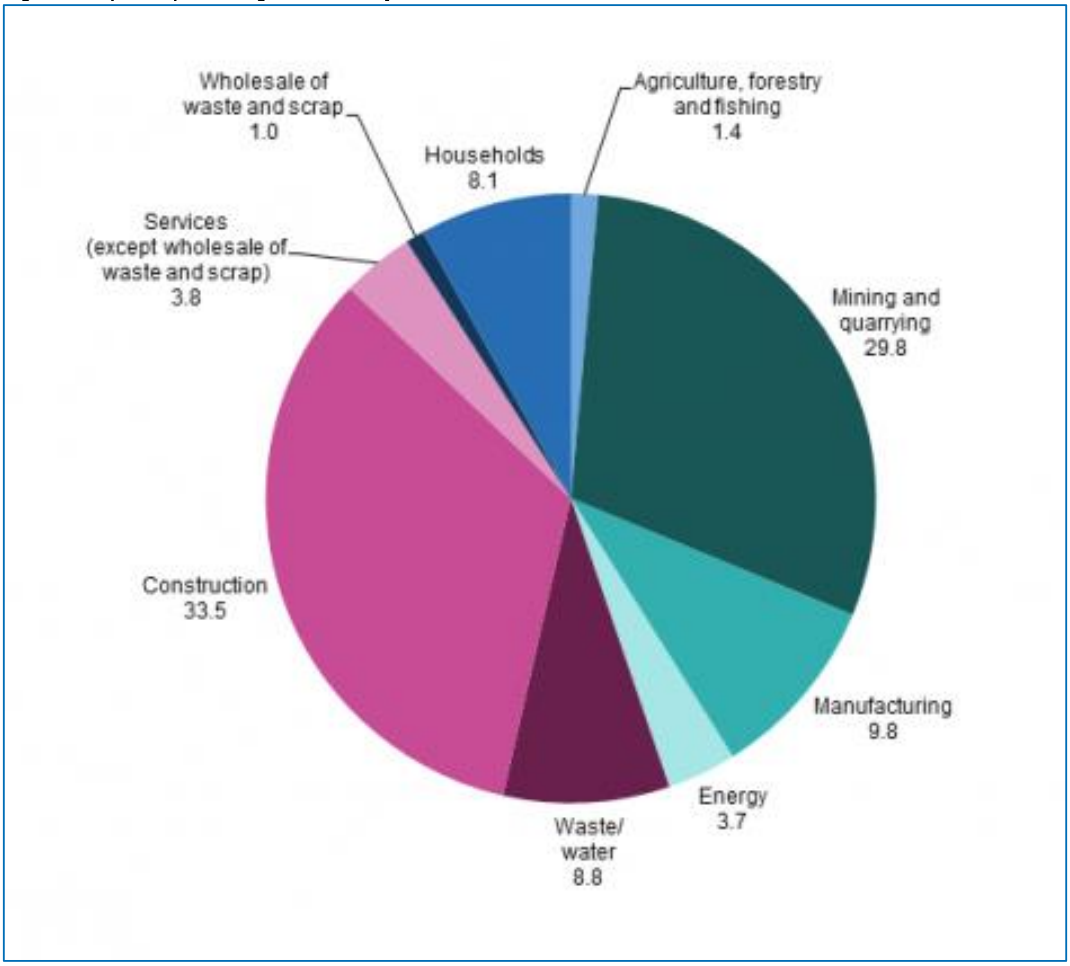
	Biomass Category	Biomass Type	Biomass Subtype
Biomass from waste	Household and similar wastes (EUROSTAT)	Municipal Solid Waste (MSW)	Organic fraction of municipal solid waste (OFMSW)
	Animal and mixed food waste (EUROSTAT)	Mixed wastes of food preparation	Used Cooking Oil
	Wood wastes (EUROSTAT)	Post-consumer wood	Packaging waste
	Vegetal wastes (EUROSTAT)		
	Paper and cardboard waste (EUROSTAT)		
	Sludges and liquid wastes from waste treatment (EUROSTAT)	Sewage sludge	

5.1 Brief overview of current market situation and waste potential for bioenergy production

Before giving an overview of the current market situation and the potential for bioenergy production from waste, it is important to know that statistical data about the waste sector are available in many different classifications, and are often defined in a too broad and general way. Thus additional input is required.

According to Eurostat (data from 2014), in the European Union the total waste generated by all activities amounted to 2,598 million tonnes. The main share of this amount originates from the construction sector (33.5 %), followed by mining and quarrying (29.8 %) and manufacturing (9.8 %). The next big shares originate from households (8.1 %) and energy (3.7 %). The remaining 15 % came from other economic activities and included mainly waste and water services (8.8 %) and other services (3.8 %). Figure 5.1 shows the share of the different sectors contributing to the total European waste at a glance.

Figure 5.1 (EU 28) Waste generation by economic activities and households



Eurostat 2016.

The present study analyses the bioenergy potential by using the PRIMES model. In this model, a category called “Wastes and Residues” is included, besides the categories “Energy Crops”, “Forestry”, and “Aquatic Biomass” (E3M-Lab, 2016). Under Wastes and Residues, the following sub-categories apply in PRIMES:

- Agricultural Residues;
- **Wood Waste;**
- Waste Industrial Solid;

- Black Liquor;
- **Used oils and fats;**
- **Municipal Waste;**
- Sewage Sludge;
- Landfill Gas;
- Manure;
- Animal Waste.

Based on the findings of the before mentioned JRC study, for the scenario development in the waste sector, the PRIMES categories wood waste, used oils and fats, and municipal waste are further used for modelling.

In order to implement the modelling, statistical data from Eurostat are used. These data are collected from EU countries on the basis of the Regulation on waste statistics (2150/2002/EC) and published every two years in line with common methodological recommendations. Although not all of the Eurostat categories are used for modelling with PRIMES, they are still shown below in order to illustrate the whole scope of potential bioenergy production out of waste. Thus the relevant Eurostat categories for the bioenergy sector are shown in Table 5.2. (Eurostat, 2010)

Table 5.2 Eurostat categories of waste and their definitions which are related to biomass/bioenergy

Eurostat waste category	Definition / Kind of waste
Sludges and liquid wastes from waste treatment (Items 9 and 10)	• Sludges/liquids from physico/chemical treatment; • Digestate and liquor from anaerobic treatment of organic waste.
Paper and cardboard waste (Item 18)	• Paper and cardboard; • Paper and cardboard waste from sorting and separate collection.
Wood wastes (Items 21 and 22)	• Wooden packaging; • Sawdust, shavings, cuttings; • Waste bark, cork and wood from production of pulp and paper; • Wood from construction and demolition of buildings; • Separately collected wood waste.
Animal and mixed food waste (Item 31)	• Animal waste of food preparation and products, incl. sludges from washing and cleaning; • Mixed wastes of food preparation and products incl. biodegradable kitchen / canteen wastes, and edible oils and fats.
Vegetal wastes (Item 32)	Vegetal waste from food preparation and products, including sludges from washing and cleaning.
Household and similar wastes (Item 34)	• Mixed municipal waste (MSW), bulky waste, street cleaning waste, kitchen waste, household equipment; • Except separately collected fractions.
Sorting residues (Items 37 and 38)	• Sorting residues from mechanical sorting processes for waste, like screening, fluff-light fraction combustible waste (refuse derived fuel); • non composted fractions of biodegradable waste.
Common sludges (Item 39)	Waste water treatment sludges from municipal sewerage water and organic sludges from food preparation and processing.

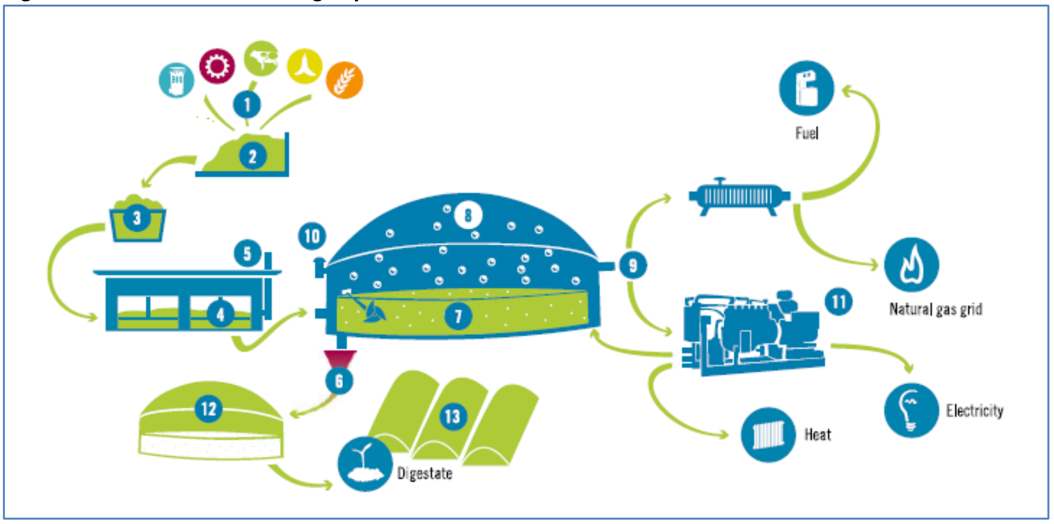
Eurostat, 2010.

The three different waste streams which are modelled are providing a major share for potential energy production. For the modelling, the organic fraction of MSW (OFMSW) is used for anaerobic digestion (AD) in biogas plants, used cooking oils for biodiesel production and wood waste (only tertiary wood waste, no forestry wood waste) for CHP or 2nd generation biofuels. A brief description of the corresponding markets shall emphasize the impact potential which can be achieved if the feedstock supply is increased.

OFMSW for anaerobic digestion (AD) in biogas plants

The European biogas sector is already playing an important role in Europe. At the end of 2015, 17,376 biogas plants were being operated in the EU which marked the highest number of biogas plants ever. Although the market growth in the biogas sector slowed down, the potential for biogas plants using biodegradable waste as feedstock is still considerably high as the numbers in this chapter will show. According to the Annual Statistical Report of the European Biogas Association for 2016, biogas plants are classified into agricultural, sewage, landfill, and other (including biowaste). Figure 5.2 shows a typical scheme on how organic waste can be converted into sustainable bioenergy for different purposes.

Figure 5.2 Waste treatment biogas plant



Strippel, Findeisen, Hofmann, Wagner and Wilken, 2016: 8.

In a first step the feedstock is brought to the facility and stored there (in bunkers, tanks, vessels, silos – 1-2). Then (3) the feedstock is prepared, sorted and processed and transferred into an enclosed building (4) for the acceptance, storage and preparation for the input into the digester. Bio-filters (5) reduce smells and organic compounds which is also important for acceptance from neighbouring citizens. A sanitary unit (6), either during the digestion at thermophilic temperatures (>55°C) or while post-composting, ensures that the digestate has no hazardous effect. In the digester (7) the feedstock is processed into biogas which is stored on top of the digester. Before being further used the biogas has to pass a gas cleaning system (desulphurisation and dewatering). Pressure relief devices, safety valves gas flares and instrumentation and control equipment are part of the safety equipment (10). The energy production takes place in a combined heat and power unit (CHP) were power and heat are produced (11) or where the biogas is upgraded for feed into the national gas grid or used as fuel for vehicles. The digestate storage (12) is needed to store the digestate safely in times when it cannot be applied (e. g. winter). The digestate can be upgraded (13) through separation, drying, pelletizing, or post composting. (Strippel, Findeisen, Hofmann, Wagner and Wilken, 2016: 8)

The following Table 5.3 provides the most actual data about the European biogas market:

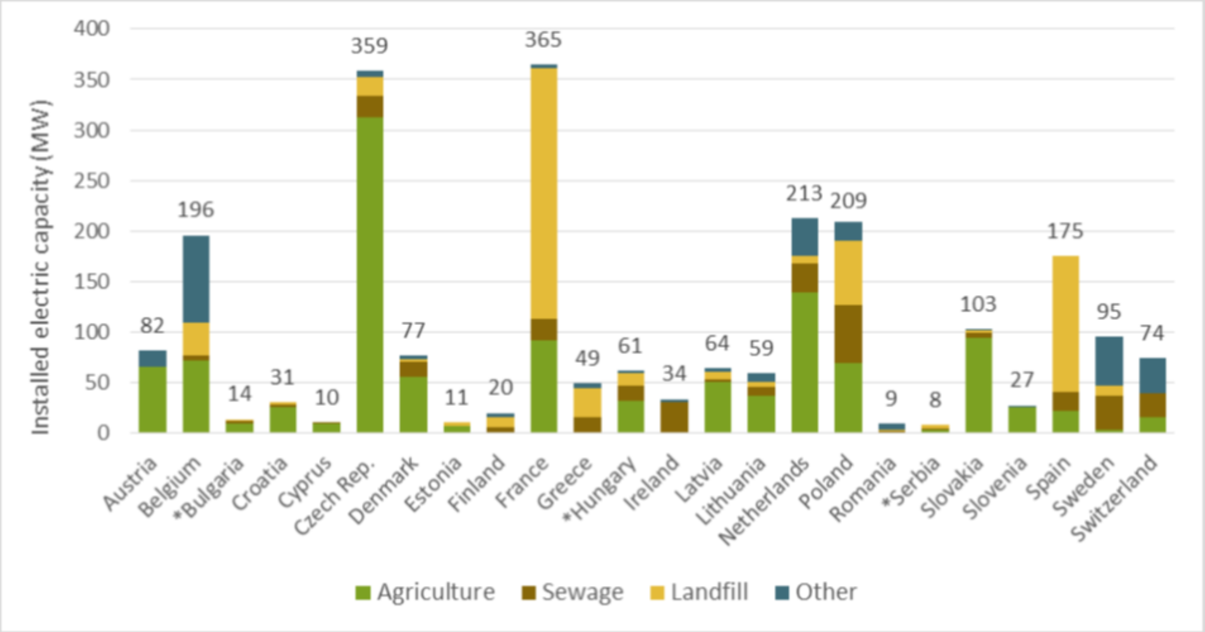
Table 5.3 Biogas production (from agriculture, sewage, landfill and other, i.e. biowaste), installed electric capacity, heat used and electricity generated in Europe in 2015

Country	Biogas production (TJ)	Installed electric capacity (MW)	Heat used (TJ)	Electricity generated (GWh)
Austria	5,702	82	1,116	560
Belgium	7,880*	196	4,310	948
Bulgaria	4*	14*	n/a*	1*
Croatia	695*	31	579*	78*
Cyprus	500*	10	n/a	37
Czech Rep.	23,911*	359	2,336	2,614
Denmark	5,533	77	n/a	401*
Estonia	302*	11	180	43
Finland	3,359*	20	1,739	159
France	18,284*	365	7,884	2,738
Germany	221,400*	3,723	65,048	31,890
Greece	829	49	688	230
Hungary	4,410*	61*	873	194
Ireland	2,020*	34	108*	183
Italy	95,602*	1,171	50,587	9,368
Latvia	3,279	64	1,457	375
Lithuania	648*	59	27*	n/a
Luxembourg	536*	n/a	n/a	334*
Malta	n/a	n/a	n/a	33*
The Netherlands	13,833	213	6,705	1,148
Norway	n/a	n/a	252	35
Poland	3,758	209	n/a	690
Portugal	2,732	n/a	9	248
Romania	1,256	9	n/a	26
Serbia	n/a	8*	n/a	19*
Slovakia	2,786*	103	n/a	493
Slovenia	1,451	27	n/a	141
Spain	2,632	175	11	n/a
Sweden	6,872	95	1,392	62
Switzerland	3,760	74	1,594	316
United Kingdom	64,048	1,491	n/a	7,280
Total	498,023	8,728	146,895	60,644

Stambasky et al., 2017: 14.

In order to associate the numbers from Table 5.3 with the bioenergy potential from waste it is necessary to know the different feedstocks that were used in in the biogas plants.

Figure 5.3 Installed electric capacity below 1,000 MW in some European countries in 2015, by feedstock type



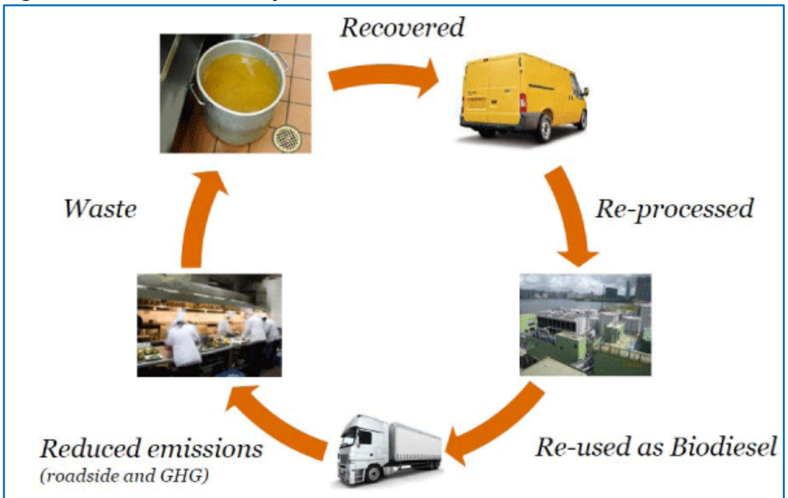
Stambasky et al., 2017: 9.

Figure 5.3 shows the installed electric capacity below 1,000 MW in some European countries. There are many countries where the majority of installed electric capacity originates from sewage, landfill or other waste. Information on Germany (installed electric capacity: 3,723 MW), Italy (1,171 MW) and the UK (1,492 MW), is not shown in Figure 5.3 as the numbers for these countries are much higher and difficult to illustrate in the same figure. It is still interesting to know that in the UK the majority of biogas is being produced at landfills (70 % or more than 1,000 MW installed electric capacity). In Germany (95 % agriculture) and Italy (74 % agriculture, 19 % landfill, 7 % sewage and other) the majority of biogas plants are using agricultural feedstock (Stambasky et al., 2017: 11).

Used cooking oils for biodiesel production

Used cooking oil (UCO) is a sustainable feedstock for the generation of biodiesel. The challenge to increase the UCO supply is directly connected with effective collection measures. UCO can be separately collected which increases the potential use for sustainable biodiesel production. Figure 5.4 shows a typical waste-to-biofuel-cycle for UCO.

Figure 5.4 UCO biodiesel cycle



Vazquez, 2015: 22.

After a considerable development of the production and use of biodiesel (most common form - Fatty Acid Methyl Esters) in Europe from 2005 to 2010, changing policies, framework conditions and support schemes have led to stagnation in the market. According to the European Biodiesel Board (2017) the main producers are Germany (2,516,000 t/year), France (1,885,000 t/year) and the Netherlands (1,248,000 t/year). In Europe, biodiesel is mainly based on rapeseed oil, whereas plant oil imports to Europe also include soybean oil and palm oil. Only a small fraction of the biodiesel production in Europe originates from used cooking oils (UCO). Compared to the total amount of generated biodiesel in Europe (2013) of altogether 10,367,000 tonnes the collected amount of household UCO of 47,736 tonnes represents not even 0.5 %. The market potential which lies in the collection of UCO can be seen in Table 5.4 which is a result of the study “Analysis of the current development of household UCO collection systems in the EU” led by Greenea ((ed.) 2016). The numbers show that a significant share of UCO from households is not collected yet and thus, if suited collection measures would be implemented, the production of sustainable UCO biodiesel can be increased significantly.

Table 5.4 UCO collection and resources from households (in tonnes) (Greenea (ed.), 2016: 53)

Country	UCO collectable household resources	Collected UCO	% collected
Italy	156,000	15,000*	9.60%
Germany	65,000	1,209	1.90%
France	52,000	0	0.00%
Spain	232,000	5,000	2.20%
Romania	49,000	0	0.00%
Poland	47,000	0	0.00%
United Kingdom	42,000	8,600*	20.50%
Hungary	29,000	400	1.40%
Bulgaria	27,000	0	0.00%
Portugal	30,000	1,000	3.30%
Czech Republic	16,000	500	3.10%
Croatia	12,000	0	0.00%
Belgium	13,000	8,300	63.80%
Slovakia	10,000	360	3.60%
Netherlands	12,000	3,600	30.00%
Austria	7,000	2,352	33.60%
Greece	20,000	14	0.10%
Lithuania	6,000	0	0.00%
Latvia	4,000	0	0.00%
Estonia	4,000	0	0.00%
Slovenia	4,000	0	0.00%
Finland	3,000	0	0.00%
Sweden	3,000	1,400	46.70%
Denmark	2,000	1	0.10%
Ireland	2,000	0	0.00%
Cyprus - modelled	4,000	0	0.00%
Malta - modelled	2,000	0	0.00%
Luxembourg - modelled	1,000	0	0.00%
TOTAL	**854,000**	**47,736**	**5.60%**

Wood waste

The third waste stream that is modelled in this study is wood waste.

Wood waste is classified as part of solid biomass. In a briefing called "Biomass for electricity and heating - Opportunities and challenges" which was published by the European Parliamentary Research Service in September 2015 the role of wood for renewable energy production was emphasized. In 2015, 46 % of renewable energy in the EU came from solid biomass (almost only wood). The wood waste which is covered in the study is so called post-consumer wood which means all kinds of wooden material that is available at the end of its use as a wooden product (e.g. pallets or demolition wood) (Dees et al., 2017: 62). The market potential for this wood waste can be seen when comparing the expected amounts of more than 10 million tonnes per year of post-consumer wood available in the EU (see more detailed below in chapter 5.3.3) with the 18.3 million tonnes of wood pellets used in 2013 (according to Vis et al. (eds.) 30 % of the post-consumer wood is still being landfilled). Of these18.3 million tonnes only 12.2 million tonnes were produced in Europe (Eurobserv'er (ed.), 2015: 3). So the amount of wood waste corresponds to almost the whole amount of wood used for the EU pellet production. This comparison is only quantitative, as wood waste usually is not suitable for pellet production because of possible impurities (e.g. paint on window frames). Thus the wood waste is used in CHP plants with adequate filter systems for bioenergy production.

5.2 Definition of investigated feedstock categories and R&I fields

Depending on the model which is used or on the collected and processed data, different feedstock categories can be applied for the production of bioenergy from waste.

Most of the data originate from Eurostat, so the definition of the feedstock categories that are modelled are taken from the official Eurostat categories of waste.

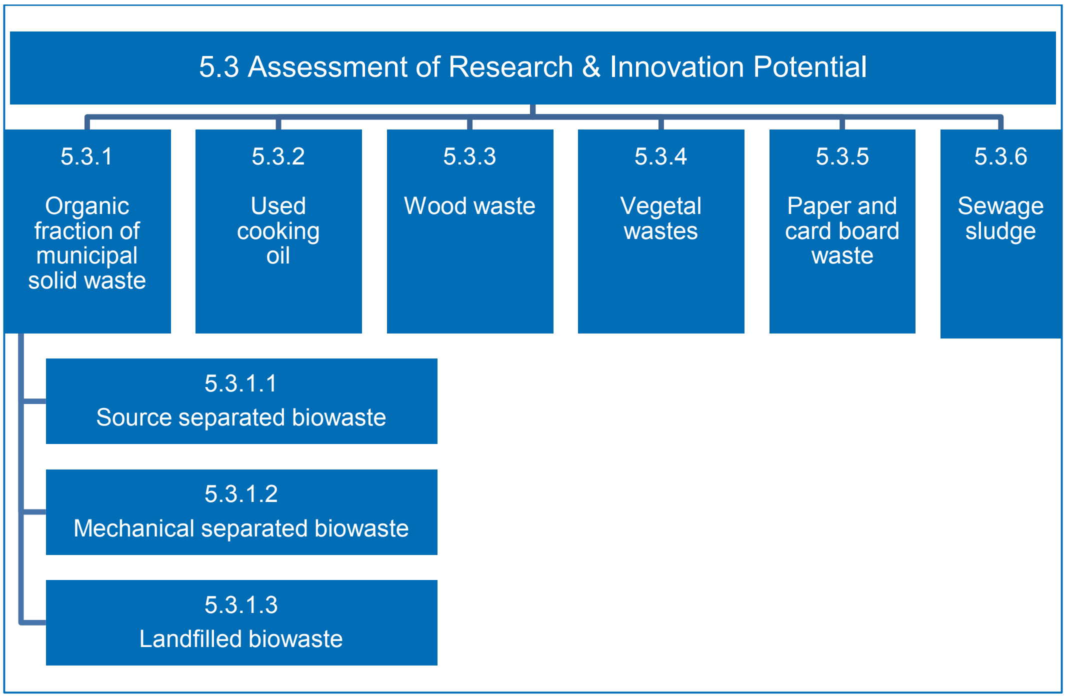
Biowaste originates mainly from the category “Household and similar wastes” (Item 34), which is comprised of mixed municipal waste, bulky waste, street cleaning waste, kitchen waste and household equipment.

Used cooking oils fall under the classification “Animal and mixed food waste” (Item 31) and is comprised of Animal waste of food preparation and products, incl. sludges from washing and cleaning as well as of Mixed wastes of food preparation and products incl. biodegradable kitchen / canteen wastes, and edible oils and fats.

“Wood wastes” (Eurostat items 21 and 22) include wooden packaging, sawdust, shavings and cuttings, waste bark, cork and wood from production of pulp and paper as well as wood from construction and demolition of buildings and also separately collected wood waste.

5.3 Assessment of R&I potential (in Europe and third countries)

Chapter 5.3 presents an assessment of the Research & Innovation potential in the field of waste. The structure of chapter 5.3 is displayed in the schematic below.



The mobilisation and use of biowaste as feedstock material for bioenergy or biofuel production is very different to the mobilisation of agricultural or forestry feedstock. The aim is to generally avoid or reduce waste, whereas the mobilisation of agricultural or forestry feedstock is usually related to the objective to increase the production. The use of waste for bioenergy per se is characterized by the following aspects that are of high relevance for agricultural or forestry feedstock:

- It is a secure feedstock source;
- It has a low Indirect Land Use Change (ILUC) risk;
- It does not lead to increase the overall agricultural land;
- It does not interfere with food production.

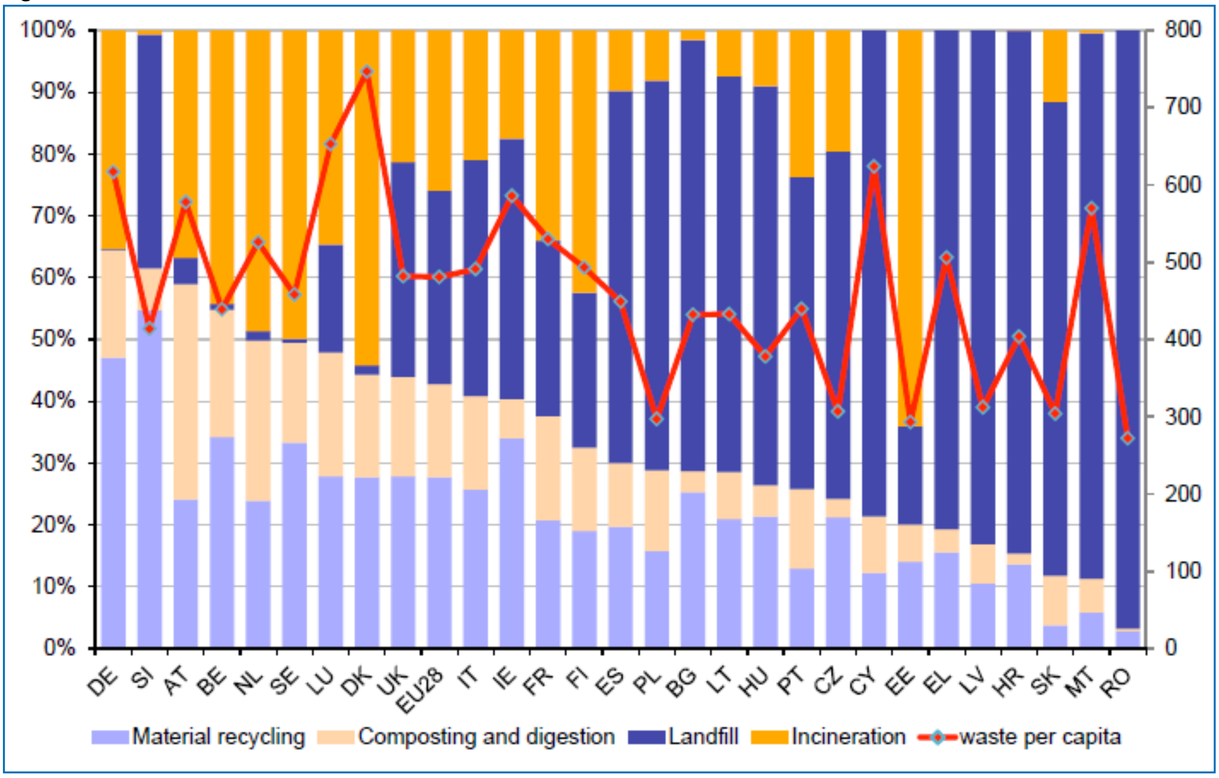
In the next chapters the feedstock potential of biowaste for bioenergy is examined for the categories that promise to have the highest impact on energy production, namely the organic fraction of MSW (OFMSW), Used cooking oil (UCO) and wood waste.

Moreover a qualitative look is given to the categories “Vegetal waste”, “Paper and cardboard waste” and “Sewage sludge” to find out whether the production of bioenergy from these feedstocks is advisably.

5.3.1 Organic fraction of municipal solid waste

The main amount of biowaste appears as organic fraction of municipal solid waste (OFMSW). Municipal solid waste (MSW) is the waste discarded by the public consisting of everyday items. The composition of MSW varies greatly from municipality to municipality and changes significantly with time. The collection system of MSW is highly responsible for the quality of the individual waste streams that are collected. Today, in the EU there are different existing approaches to MSW treatment.

Figure 5.5 Overview about waste treatment in the EU-28 in 2013



Source: Members' Research Service, Understanding waste management, 2015.

Figure 5.5 provides an overview about waste treatment in the EU-28. It shows that in many MS a large fraction of the waste is landfilled. The very large potential for the generation of bioenergy out of the waste streams is visible when Figure 5.5 and Figure 5.3 are compared. For example Croatia, Romania and Slovakia are still sending a lot of their waste to landfills. At the same time in these Member States no landfill gas usage is reported.

Concerning the theoretical potential amounts of biowaste in MSW, there are several studies which have addressed the issue.

The study “Bio waste potential in household waste” from the Witzenhausen-Institut (Kern, Siepenkothen, 2014: 360) revealed that in the German residual waste still million tons of organic waste (4.7 million tonnes in 2012) can be found, i.e. 39 % of the total quantity of domestic residual waste (without business waste, so 100 % would account for 12.1 million tonnes).

Other studies published higher rates of 46 % of organic fraction (Baxter and Al Seadi, 2013: 5) or even of rates between 50 and over 60 %. (Dehoust, Vogt, 2015: 22).

For estimating the theoretical potential conservatively, the lowest factor (39 %) has been chosen. The results can be seen in Table 5.5.

Table 5.5 Biogenic amount calculation using Eurostat data (year 2013)

GEO/Parameter	Total amount MSW in thousand tonnes (year 2013)	Factor	Biogenic amount in thousand tonnes
European Union (28 countries)	242,051	0.39	94,400
European Union (27 countries)	240,330	0.39	93,729
European Union (25 countries)	4,892	0.39	1,908
European Union (15 countries)	3,135	0.39	1,223
Belgium	3,228	0.39	1,259
Bulgaria	4,223	0.39	1,647
Czech Republic	49,570	0.39	19,332
Denmark	386	0.39	151
Germany	2,693	0.39	1,050
Estonia	5,585	0.39	2,178
Ireland	21,184	0.39	8,262
Greece	33,996	0.39	13,258
Spain	1,721	0.39	671
France	29,573	0.39	11,533
Croatia	533	0.39	208
Italy	627	0.39	245
Cyprus	1,280	0.39	499
Latvia	335	0.39	131
Lithuania	3,738	0.39	1,458
Luxembourg	246	0.39	96
Hungary	8,842	0.39	3,448
Malta	4,905	0.39	1,913
Netherlands	11,295	0.39	4,405
Austria	4,598	0.39	1,793
Poland	5,070	0.39	1,977
Portugal	853	0.39	333
Romania	1,645	0.39	642
Slovenia	2,682	0.39	1,046
Slovakia	4,326	0.39	1,687
Finland	30,890	0.39	12,047
Sweden	5,078,172	0.39	1,980,487
United Kingdom	41,613,383	0.39	16,229,219

The potential for increasing the amount of OFMSW is investigated in the subchapters “Source separated biowaste”, “Mechanical separated biowaste” and “Landfilled biowaste”. This order has been chosen to lead from the best feedstock supply (quantity and quality wise) and feedstock conversion to the worst one.

5.3.1.1 Source separated biowaste

Source separated biowaste is usually provided by the waste producer using separation devices and is, from the environmental viewpoint, usually the best solution as this allows good subsequent treatment (AD or composting) which results in a high-quality output, namely digestate or compost. Digestate or compost can substitute fossil fertilizers and re-cycle limited phosphor, a key advantage that can be only achieved with high-quality biowaste as input material and thus, source separation.

According to Seyring et al. (2015), the collection of the source separated biowaste depends on many factors, including the climate or settlement density. In rural areas, home-composting may be advantageous with regards to more expensive collection logistics, whereas in areas with higher population densities, the collection of source separated biowaste with subsequent anaerobic digestion is the best solution. The implementation of separate biowaste collection in Europe depends on the national legislations of the Member States, which are based on the European legislation.

Results of Seyring et al. (2015) also showed that biggest amounts of source separated biowaste could be recovered using the method of door-to-door collection (of single fractions). The quality of biowaste and the collection systems are correlated with the living conditions. Door-to-door systems seem to be better suited for residential areas with single houses and the like, rather than in multi-store houses, where it is challenging to encourage and organize MSW separate collection for people living there. Centralized bring-systems are often used then, yet lack in efficiency as the inhabitants would need to carry several times several kinds of waste repositories to the collection point.

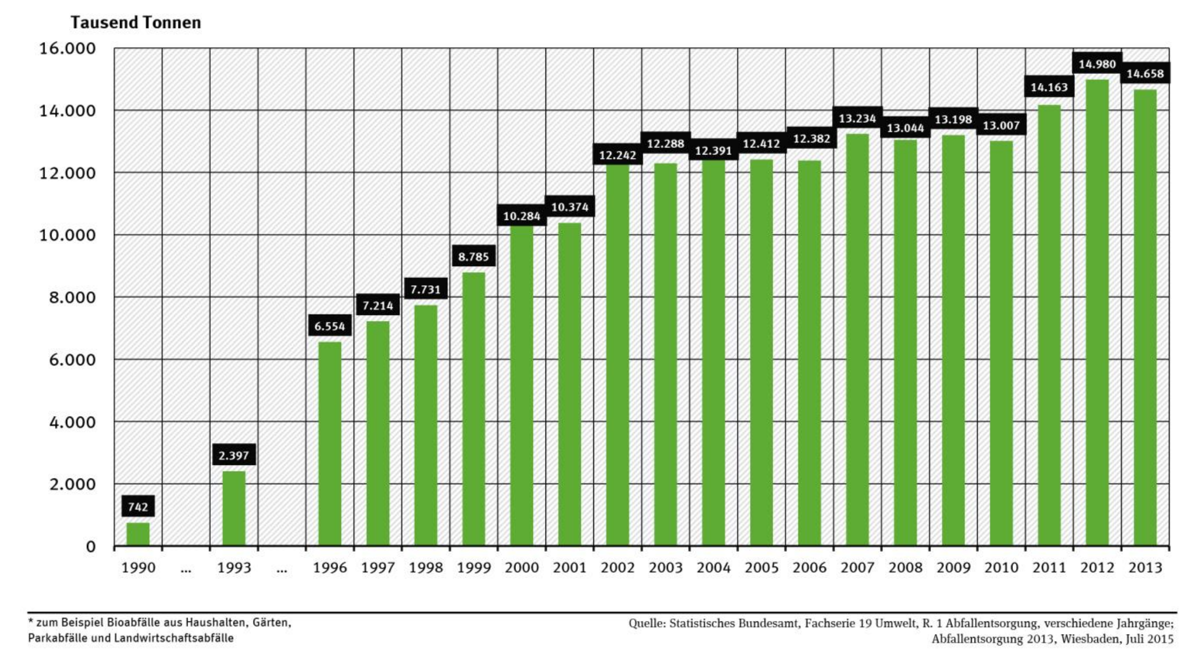
In some Member States approaches have been already made to collect as much as possible separated biowaste for a later conversion (either compost or anaerobic digestion). In Germany for example, at source separation of waste is seen as best way for the mobilisation of the organic waste fraction. It is mandatory to collect biowaste from households source separated in dedicated biowaste bins since the beginning of 2015. The development of collected amounts in Germany is shown in Figure 5.6, in order to give an impression which growth rates are achievable if suited measures are implemented. Germany began in 1985 with the collection of at source separated organic waste and used the collected biowaste at first in composting plants. Today, the collected waste is treated at facilities where it is either composted or anaerobically digested.

After the introduction of several collection schemes in Germany, a significant increase of the collected amounts of biogenic waste could be seen until 2002. From then on the increase happened only slowly. According to the statistics in 2013 the amount of 14.7 Mio tonnes of biogenic waste was treated biologically. (Umweltbundesamt, 2016)

The numbers can be seen as possible development scenarios for countries that have not introduced separate collection schemes yet.

In 2015 in Germany around 400 biogas plants (out of a total of around 8,050 biogas plants) were using biowaste as feedstock. Already 2 million tonnes of source separated organic waste were used in these plants (Strippel, Findeisen, Hofmann, Wagner and Wilken, 2016: 5-39). That means that in Germany 5 % of the biogas plants are using the feedstock biowaste.

Figure 5.6 Development of biogenic waste collection in Germany



Umweltbundesamt, 2016.

Another implementation example comes from Ireland and shows the potential for increasing the amount of biowaste after the implementation of regulations which address the topic.

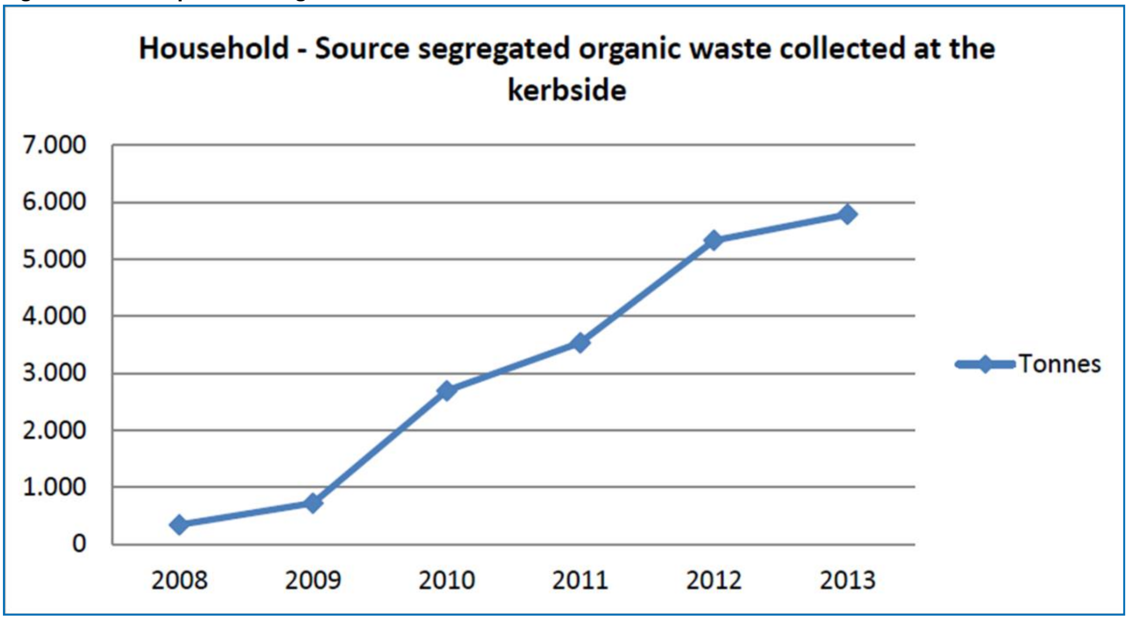
In Ireland, the Waste Management (Food Waste) Regulations 2009 came as legislative framework into force on 1 July 2010. The law obliges major producers of food waste, such as shops, supermarkets, public houses, state buildings, restaurants, cafés, bistros, wine bars, hot food outlets, canteens in office buildings, hotels, B&Bs, guest houses, hospitals, nursing homes, schools, colleges, train stations, marinas and airports, to separate theses wastes. Non-compliance with the Food Waste Regulations is an offence. Consequences of offences relating to the Food Waste Regulations usually involve that offenders are required to appear at the District Court. The relevant maximum penalties are a 3,000 € fine per offence or 12 months imprisonment, or both. (Cre, 2010: 1)

There is also a showcase of the private sector in Ireland. The process of the successful introduction of a household organic bin in the Southern Region of Ireland showed the following findings:

- The National Legislation to ensure the same requirements is applicable throughout the country – therefore there is no competitive advantage for operators operating in areas where less strict requirements exist;
- Public consultation has been done before the implementation of the measure. For example the commercial and household food waste regulations were subject to public consultation before they were implemented;
- Certainty in the market must be guaranteed. The collectors require assurance that the household collection market is not going to change in the short-to-medium term. There was a period in Ireland between 2011-2012 where the possibility of franchise bidding/competitive tendering was undergoing consultation and this led to stagnation in the market in relation to the roll-out of the brown bin;
- Education and awareness need to be conducted at national and local level to ensure that all relevant parties are aware of their requirements;
- The evidence of enforcement of the legislative is paramount to ensuring successful implementation across all sectors;

- Feedback gathering and the publication of relevant data need to be done in order to demonstrate the effectiveness of the measure.

Figure 5.7 Development of organic waste collection in Southern Ireland



King and Sweetnam, 2014: 13.

The efficiency of the undertaken measures in Ireland is presented in Figure 5.7, which shows the development of organic waste collection in Southern Ireland. Since 2008 there has been a significant increase year by year on the total quantity of commercial biodegradable waste collected for recovery within the Region with the largest increase between 2011 and 2012 (i.e. 43 % increase) indicating the effectiveness of the sustained enforcement and awareness programmes implemented in 2011.

While the numbers shown seem promising, still the challenge remains that despite the awareness campaigns of government bodies and the private waste collectors there was a significant number of commercial and householders unaware of the requirement to source segregate food waste when enforcement was undertaken. Motivating people to change their behaviour seemed very difficult, particularly in relation to waste management, unless there is an actual monetary gain. A lack of enforcement of both, the collectors and producers of the waste leads to a slow roll out of the bins and their subsequent use. There is a need for consistent enforcement across all local authorities to ensure that specific collectors or businesses in areas where the requirements are not enforced yet do not have a competitive advantage over regions with stricter rules.

The issue of collection frequency was also identified to play an important role. For example, the collection of household food waste and some food waste from the retail sector every 2 weeks has raised the issue of the quality of the material presented for composting, particularly during the summer months. It has also been seen as a barrier to participation as householders/commercial premises do not have adequate capacity for the storage of 2 weeks food waste. That resulted in food waste being disposed of again in the residual bin. (King and Sweetnam, 2014: 10-16)

Another example from Slovenia shows that it is not only the implementation of strict regulations that facilitates the collection of higher biowaste amounts.

In Ljubljana in Slovenia it was shown that improvements in collection measures are possible without the need to invest large amounts of money. This was achieved by the use of modern IT solutions. A specialised software for designing optimised waste collection routes is used there to reduce the frequency of waste collection. This has proven as a measure to encourage people to separate waste at source and to reduce waste management costs for households. By applying this solution the local provider Snaga managed to reduce the time necessary to collect waste from the same number of consumers by 10 % and to shorten the route length by 17 %. This resulted in lowering the monthly cost per household to 7.96 € in 2014. (Seyring et al., 2015: 112)

It can be stated that, if available measures would be applied in all places that still lack of an efficient waste management system, the availability of a biogenic feedstock would be increased tremendously. However, it is difficult to give a reliable prediction what can be really achieved, because there is a strong dependence between the support of the feedstock providers (here the waste producers) and the processing industry.

Regarding source separated biowaste, as mentioned before, the challenge is to receive an as clean as possible organic feedstock. Therefore, in Germany a project has started in May 2016 which addresses the identified set of problems. The Federal Environmental Agency (UBA) commissioned three German research institutions to conduct a study on high quality recovery of biowaste for energetic use. The study shall also find out which challenges such a feedstock means for the converting plants. One part of the study is the development of quality criteria for the recovery of biowaste. Furthermore, the state-of-the-arts methods shall be assessed using the new criteria. Another central field of the study is the preparation of the biowaste with regards to impurities, with a special focus on enclosed plastic parts. Next to this the status quo of the use of high quality biowaste recovery in the existing plants will be assessed and thus gaps shall be identified. Finally, ways and measures shall be elaborated on how to achieve a high quality biowaste recovery (including legal regulations or support measures) by adapting existing plants. The project results are expected in the second half of 2017. (Kern, 2016)

5.3.1.2 Mechanical separated biowaste

Although source separated waste collection is considered as the best waste management practice for biowaste, still large amounts of waste are collected as mixed waste today. Considering the waste hierarchy and the general European objective to recycle biowaste, only the separation of the biowaste at source is sustainable.

Nevertheless, there exist initiatives and companies that promote the collection of mixed waste which is mechanically separated in centralized treatment facilities. The advantage is that the current waste collection system does not have to be changed which is comfortable for the consumers as they need only one bin instead of two. However, the big disadvantage is the loss of nutrients, as the resulting material (digestate-like-output or compost-like-output) still has many contaminants (plastic, glass, heavy metals, etc.) so that it cannot be used on agricultural land.

For the centralized mechanical separation of the biowaste, two concepts are implemented today:

Mechanical Biological Treatment (MBT): A MBT facility incorporates a central sorting facility alongside a form of biological treatment, such as composting or anaerobic digestion. MBT plants produce various outputs, such as recyclates and compost-like outputs.

Materials Recovery Facility (MRF): Actually there are two concepts of MRF. Either a clean MRF, which accepts recyclable commingled materials that have already been source separated from waste generated; or a dirty MRF, which accepts a mixed waste stream and then separates out recyclable materials through a combination of manual and mechanical sorting.

MBT plants can be used for the generation of bioenergy as they can process large amounts and as they separate the biogenic fraction. The capacity of MBT plants can range from 10,000 tonnes per annum (tpa) to large scale facilities of 250,000 t/a. Most MBT technologies have been developed in Germany, but Austria, Switzerland and the Netherlands provide also technologies. In 2011 more than 330 MBT plants were operating in Europe while at the same time more MBT plants (the study expected about 450 MBT plants in 2016) were planned (Ecoprog (ed.), 2011: 2).

There exist many mature and applied technologies for centralized mechanical separation of biowaste. Two rather innovative examples are briefly presented below.

The Danish energy provider “Dong Energy” started construction works for a new approach of treating unsorted MSW in spring 2016. According to Dong Energy, a new bio resource facility in Northwich, England, will recover resources from waste and generate renewable electricity through treatment with enzymes (enzymatic hydrolysis), mechanical sorting and anaerobic digestion. The plant will treat up to 120,000 tonnes of waste per year (corresponding to the waste of 110,000 UK households) and is expected to be fully operational by early 2017 (Dongenergy 2016). The separation efficiency ratio of the organic fraction shall be 95 % and the reclaimed biogenic sludge is foreseen to undergo AD in a biogas plant with a capacity of 5 MW. When being in final use the plant shall have 24 full-time employees. The enzymes for the plant are provided by “Novozymes A/S”, who together with Dong Energy also agreed to further develop the enzymes for the technology together (Renewable Energy World 2016). The completion of the so called Renescience plant is foreseen in 2017.

Another approach to get as much biogenic content as possible out of a waste stream is the so called 3D MSW Separation. Again it was a Danish company that came up with a new approach. The company “IBUS Innovation A/S” has developed the IBUS 3D MSW Separation process which separates waste based on density characteristics and on how waste floats (and sinks) in water. By combining air flows, water flows and mechanical transportation, this system shall separate household waste into multiple fractions without damaging recyclable materials (e.g. bottles, jars, metals, plastic) or hazardous materials (batteries). The system is constructed of mass produced components (tank, pumps, blowers, transporters etc.) and thus expected not to be as expensive as tailor-made plants. The plant capacity of such a treatment plant is 15,000 t/year (corresponding to 50,000 inhabitants in Northern Europe; NB: different assumptions on waste per capita in different EU countries). According to the producer this solution is suitable for smaller cities, one module being able to process 3 t/day. The separation efficiency ratio is expected to be 90 % (assumption). The prefeasibility study revealed an investment of 2.1 Mio € for the plant and according to the producer, savings of 34-36 % compared to conventional separation methods are possible. Therefore the company declared the solution to be suitable for less densely populated regions where an expensive construction of a waste treatment plant would not be economical feasible. (Ibusinnovation 2016).

In the following example, real data on an existing MBT plant is given (the used weight unit Mg corresponds to metric tonnes – ed. Note).

A performance study of an existing MBT plant (MBA Südniedersachsen - MBT Southern Lower Saxony) in Lower Saxony, Germany, found that out of an input of 96,000 Mg/a roughly 31,300 Mg (corresponding to 32.5 % of the input) could be separated and sent to further treatment. The gas generation of the derived organic input material in this case reached only 70 Nm³/Mg. It was assumed that this could be improved when the organic fraction would consist of smaller particles. When realising these measures a gas generation of 130 Nm³/Mg was seen as a realistic result.

Two independent studies published gas generation rates of 126–132 Nm³/Mg with a methane content of 60 %, so taking 130 Nm³/Mg as parameter can be seen realistic.

The energetic efficiency ratio of the studied MBT plant was 39.7 % and is classified lower than the average ratio of 45 % which is given for German incineration plants.

The economic result of the plant was calculated and it was concluded that the plant showed very high specific operation costs of 170 €/Mg. This was due to the low utilisation rate (e.g. the plant has a capacity of 133,000 Mg/a, yet the input was only 96,000 Mg). When using the full capacity of the plant, the operation costs were estimated to be 142 €/Mg. (Fricke and Kugelstadt, 2010: 11-45)

Although MBT plants per se do not mean an increase of biowaste for bioenergy production, in cases where no other measures have been implemented yet, the use of MBT plants would mean an increase of biogenic feedstock.

5.3.1.3 Landfilled biowaste

According to the European Commission, "unquestionably, landfilling is the worst waste management option for biowaste" and according to the Landfill Directive, landfilling of biowaste shall be phased out. Thus, there is no need to put efforts in research and innovation for new landfills. However, the existing landfill sites in Europe need to be managed in a best way so that the environmental impacts are reduced. This means that the landfills are converted into sanitary landfills. According to the Landfill Directive this includes water and leachate control which are achieved by geological barriers on top of the landfill together with a leachate collection and sealing system (bottom lining) at the bottom. The occurring landfill gas must be collected, treated and used. If an energetic use is not possible, then the collected gas must be flared.

Still, there are approximately 150,000 landfills in Europe which are covering about 300,000 hectares, and of which most of them are closed and many times having inadequate environmental management systems in place. Thus, these landfills are posing risks to the environment and public health. Until national governments implemented the European Landfill Directive and other relevant measures, unlicensed or poorly engineered landfill sites often considered only few environmental protection measures, such as the mentioned bottom lining and draining systems for leachate and landfill gas.

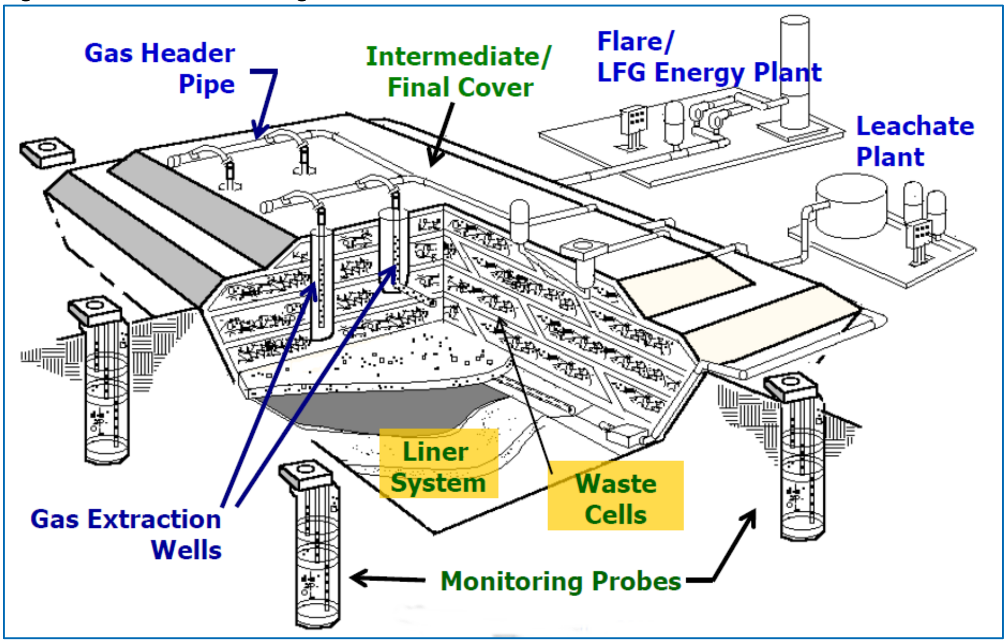
These uncontrolled landfills, which mostly operated decades ago, often combined a wide variety of wastes, some of them possibly hazardous. To protect against the impacts of former and abandoned landfills, the risks associated with these sites need to be assessed and managed. Furthermore, closed landfills often take up a considerable amount of space. Many locations are situated near the edge of cities, towns and villages, where developers, local authorities and residents might otherwise show significant interest in the available land (The SufalNET Project (ed.), 2007: 4).

A concrete negative example about the long term consequences can be seen in Getlini, Latvia. Although the Getlini dump has been converted into a sanitary landfill, now the citizens living around the landfill are being warned not to operate self-installed wells because of contamination of the shallow groundwater within the territory of the waste disposal site. (Getlini 2017)

In case of mixed waste that is or was dumped on landfill sites, the decomposition of the biowaste in the landfill is the largest environmental threat. During the uncontrolled decomposition, methane is produced which acts as greenhouse gas if released to the atmosphere. About 3% of the total greenhouse gas emissions in the EU-15 in 1995 originated from landfills. (European Commission 2016)

For the existing landfill sites in Europe, these methane emissions should be collected as landfill gas and converted to energy, and thus increasing the amount of bioenergy out of waste. Landfill gas is a mix of different gases and normally contains 40 to 60 % of methane. It can be directly used to generate combined heat and power, heat only, or power only. Furthermore, it could be theoretically upgraded to natural gas quality and then used, e.g. for transport. However, upgrading technologies are expensive and may not be economically feasible for the uncontrolled landfill gas production in a covered landfill site. Figure 5.8 gives an overview about a sanitary landfill with landfill gas use.

Figure 5.8 Scheme of landfill gas use



U.S. Environmental Protection Agency, 2013.

The most actual data provided by Eurostat show that in the EU a considerable potential still remains untapped as landfilling is still ongoing. The Implementation report of the EU waste legislation of 2013 for the period 2007 – 2009 showed that the treatment methods for municipal waste varied significantly between Member States, ranging from extremely high reliance on landfilling (Bulgaria, Romania, Malta, Lithuania, and Latvia landfilling over 90 % of their waste) to below 5 % of landfilling (Belgium, Denmark, Germany, the Netherlands, Austria, and Sweden). The Eurostat table below shows the development of landfilling in the EU from 2005 until 2014.

Table 5.6 Eurostat 2016 data on development of landfilling in the Member States [thousand tonnes]

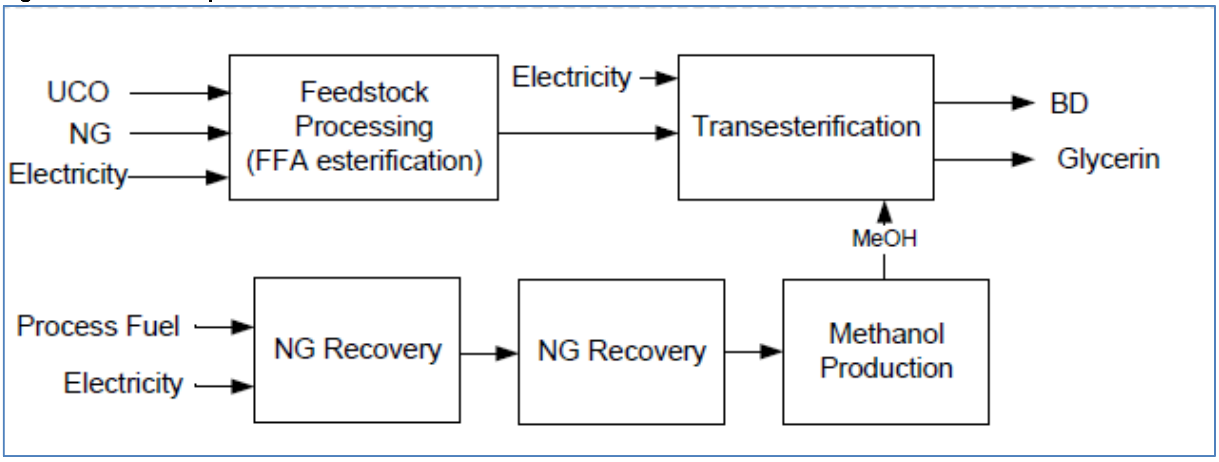
GEO/TIME	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
European Union (28	:	:	107,442	101,083	97,834	93,361	85,403	77,610	72,413	67,113
European Union (27	108,651	108,435	105,793	99,353	96,143	91,824	83,907	76,230	71,000	65,803
Belgium	583	492	499	371	348	84	69	51	46	47
Bulgaria	3,144	2,751	2,980	3,359	3,421	3,041	2,568	2,323	2,167	2,217
Czech Republic	1,934	2,043	2,121	2,057	2,114	2,162	2,167	1,828	1,815	1,827
Denmark	207	203	204	175	130	130	111	89	71	57
Germany	3,980	307	299	286	176	206	247	107	684	691
Estonia	369	373	390	333	287	267	243	129	53	30
Ireland	1,833	1,981	2,015	1,939	1,724	1,496	1,344	1,028	1,028	:
Greece	4,295	4,295	3,999	4,181	4,181	4,903	4,578	4,507	4,507	:
Spain	12,584	15,657	15,569	13,091	14,540	14,789	14,276	13,263	11,801	11,138
France	11,465	12,318	12,372	10,995	10,802	10,745	9,677	9,120	8,777	8,691
Croatia	:	1,221	1,649	1,731	1,691	1,537	1,496	1,380	1,413	1,310
Italy	17,117	17,462	16,912	16,069	15,538	15,015	13,206	11,720	10,914	9,332
Cyprus	489	499	512	531	540	490	461	451	423	398
Latvia	561	670	735	705	694	617	531	516	521	515
Lithuania	1,174	1,211	1,245	1,237	1,093	1,079	1,034	971	798	748
Luxembourg	60	61	60	60	61	62	62	61	61	61
Hungary	3,859	3,792	3,429	3,341	3,212	2,838	2,563	2,609	2,415	2,181
Malta	229	219	255	266	257	226	205	203	196	204
Netherlands	168	232	199	154	152	145	151	138	131	128
Austria	535	485	427	373	302	153	230	207	199	194
Poland	8,623	8,987	9,098	8,716	7,915	7,428	7,659	7,158	5,979	5,437
Portugal	2,969	3,143	3,170	3,530	3,342	3,381	3,048	2,593	2,320	2,307
Romania	6,413	6,294	6,122	6,486	6,164	4,813	4,057	3,427	3,503	3,558
Slovenia	659	725	688	685	628	571	481	316	224	208
Slovakia	1,144	1,169	1,210	1,276	1,264	1,325	1,240	1,211	1,152	1,158
Finland	1,478	1,504	1,411	1,406	1,180	1,136	1,093	901	672	458
Sweden	210	226	186	140	58	38	33	27	28	27
United Kingdom	22,569	21,335	19,685	17,590	16,020	14,686	12,574	11,277	10,516	8,656

5.3.2 Used Cooking Oil

Used cooking oil can be used for biodiesel production and is seen as sustainable feedstock. UCO has a high free fatty acid (FFA) content that has to be reduced. Therefore, a pre-processing step is necessary before the UCO is esterified to biodiesel. This can be processed via acid esterification using sodium hydroxide to neutralize sulfuric acid, or with a continuous, non-acid esterification (California Environmental Protection Agency, 2003).

Figure 5.9 shows the typical conversion of UCO into Biodiesel (BD).

Figure 5.9 Biodiesel production



California Environmental Protection Agency, 2003.

According to findings in the report “Wasted” the amount of sustainable available Used cooking oil (UCO) is 1 million tonnes per year in Europe (Harrison, 2014: 7). While recycling of UCO from the professional sector, e.g. larger restaurants or hotels, is already well developed in most of the Member States, the collection from individual households or smaller catering services is only in its early developmental stage (Greenea (ed.), 2016: 7). Currently, only three countries in the EU have a household UCO collection system organized on a country level (Austria, Belgium and the Netherlands). Also Sweden has a functioning system which is organized decentral by local authorities. The study found that crucial points for success are the country support of a national household collection system, then the willingness and awareness of the participating people (information campaign for citizens), especially education at schools and, further the use of appropriate logistics that have proven to work (collection scheme).

It was also revealed that organisation and functioning of the systems are, to a large part, culture specific and have to be adjusted depending on the country or region of application. Therefore, it is necessary to make a thorough local research on the habits and customs of people in a given area before deciding on the household collection strategy. An important aspect when introducing UCO collection schemes is the provision of hygienic UCO collection containers for participating households. The containers need to be temperature-resistant (up to 80°C) and easy to handle (easy to open and to seal, preventing the emission of unpleasant smell). Figure 5.10 shows a UCO container model (3 litre volume) which is used at the moment in Austria and in parts of Italy and Germany.

Figure 5.10 UCO collection container

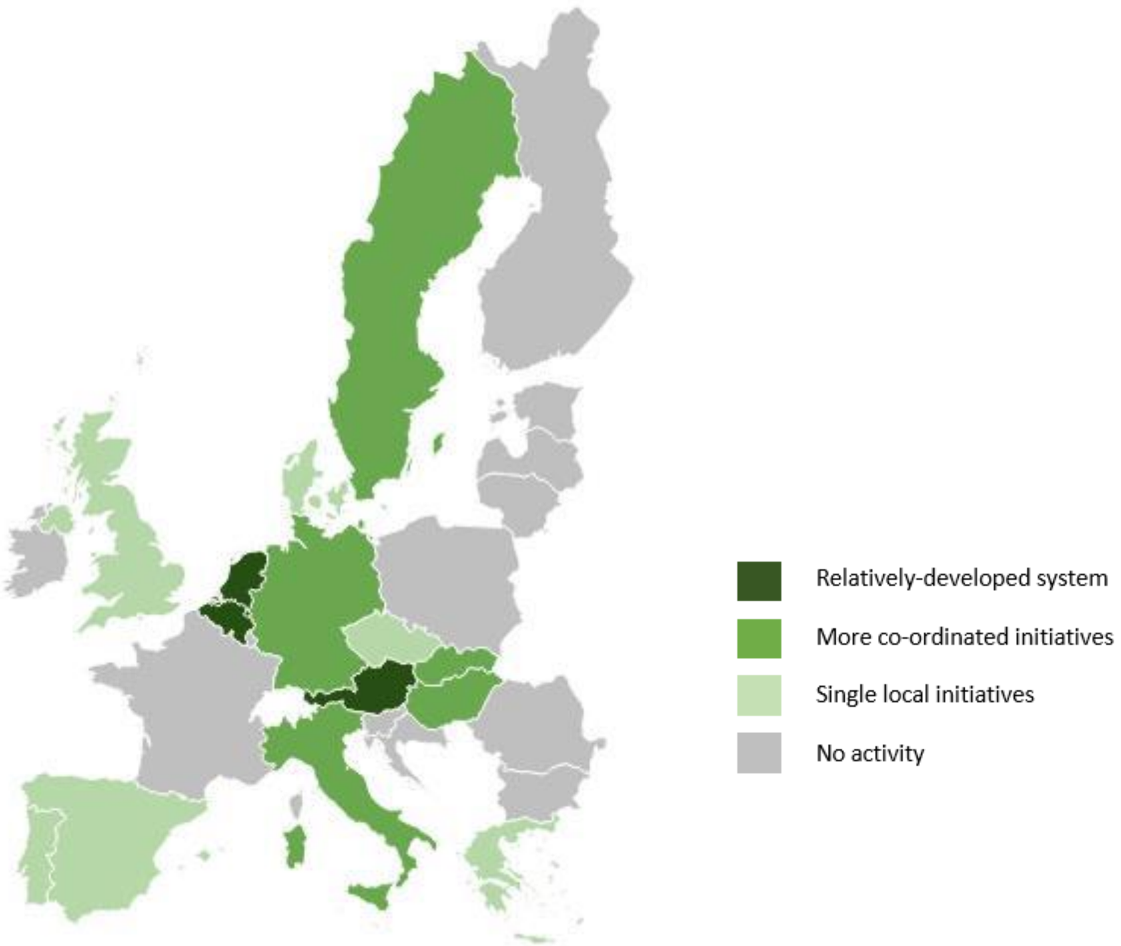
Greenea (ed.), 2016: 22.

Depending on the conditions (densely populated cities or rural regions) the collection of the UCO containers is either performed by door-to-door collection or by the implementation of collection points (Greenea (ed.), 2016: 13, 64).

Another crucial success factor is the support by authorities, as it is known that comprehensive promotional campaigns are important to convince individuals to recycle their UCO.

Figure 5.11 below shows, that for the household sector in the EU, the potential of the UCO collection to be achieved has not been reached by far and thus needs support (Greenea (ed.), 2016: 32).

Figure 5.11 Status of UCO collection systems in the EU



Greenea (ed.), 2016: 12.

Figure 5.11 already showed the amount of UCO which is collected from households for the production of biodiesel. The following Table 5.7 gives an overview about the UCO collection from the professional sector as of now in order to show the complete potential for UCO collection.

Table 5.7 Professional sector UCO collection and resources across the EU (in tonnes)

Country	UCO collected	Estimated possible growth potential	Total resource
Italy	59,000	20%	71,000
Germany	140,000	15%	161,000
France	44,000	20%	53,000
Spain	65,000	20%	78,000
Romania	19,000	40%	27,000
Poland	32,000	30%	42,000
United Kingdom	100,000	15%	115,000
Hungary	4,000	30%	5,000
Bulgaria	n.a.	n.a.	8,000
Portugal	22,000	20%	26,000
Czech Republic	10,000	30%	13,000
Croatia	3,000	30%	4,000
Belgium	29,000	15%	33,000
Slovakia	4,000	30%	5,000
Netherlands	60,000	15%	69,000
Austria	15,000	20%	18,000
Greece	21,600	20%	26,000
Lithuania	3,000	20%	4,000
Latvia	2,000	30%	3,000
Estonia	1,500	30%	2,000
Slovenia	3,000	30%	4,000
Finland	4,000	30%	5,000
Sweden	8,000	20%	10,000
Denmark	5,000	20%	6,000
Ireland	12,000	20%	14,000
Cyprus - modelled	1,000	40%	1,000
Malta - modelled	500	40%	1,000
Luxembourg - modelled	2,000	20%	2,000
TOTAL	**675,600**		**806,000**

Greenea (ed.), 2016: 53.

The potentially available amounts of FOG/UCO as feedstock in the EU countries, taken from Table 5.4 and Table 5.7, give information about the theoretical potential. However, the study “Analysis of the current development of household UCO collection systems in the EU” predicts that, while the collection of UCO from the household sector in the EU will need a lot of efforts, it is estimated that until 2030, out of 850,000 tonnes of available UCO, maximum 200,000 tonnes per year (around 24 %) could be collected.

The professional sector, however, is able to collect around 70 % of the produced UCO. The potential to capture more UCO from this sector is estimated to be around 130,000 tonnes per year.

For Europe, according to the study, that would mean further 330,000 tonnes per year of UCO available for generating sustainable biodiesel.

Reaching the full potential of almost 1 million tonnes per year can only be achieved if tailor-made solutions for the Member States will be elaborated and put in place.

Regarding the efficiency of household collection systems, the measures that have already proven high effectiveness in the best performing countries shall be taken as objectives for other Member States (best performers of Table 5.7).

Besides UCO, also other Fats, Oils and Greases (FOG) could be used for biodiesel production. The category FOG includes all types of biological lipids, thus, also UCO.

Potentials for a wider use of FOG exist all over the world. For example, according to the University of Minnesota, the U.S. produces roughly 2.7 billion pounds (which corresponds to 1,224,699 tonnes) of yellow and brown grease (grease that was caught in fat traps) a year, which are the by-products of restaurant kitchens and various industrial processes. (Varrasi, 2012)

5.3.3 Wood waste

As already mentioned at the beginning of the chapter, there are still huge amounts of wood that are disposed without benefitting from its energetic potential. Wood waste can be energetically used in cogeneration or combined heat and power (CHP) plants. By using CHP plants, efficiency rates of over 80 % can be reached if all heat is used. (EBTP, n.d.)

In the EU, efforts have been made to move attention towards bioenergy feedstocks that are genuine and unavoidable wastes, rather than processing residues or primary biomass that could have other uses and markets. Therefore, care needs to be taken to follow the same logic within any efforts to promote the resource efficient use of wood for material purposes (cascading) and not lead to further conflicts within the current policy framework.

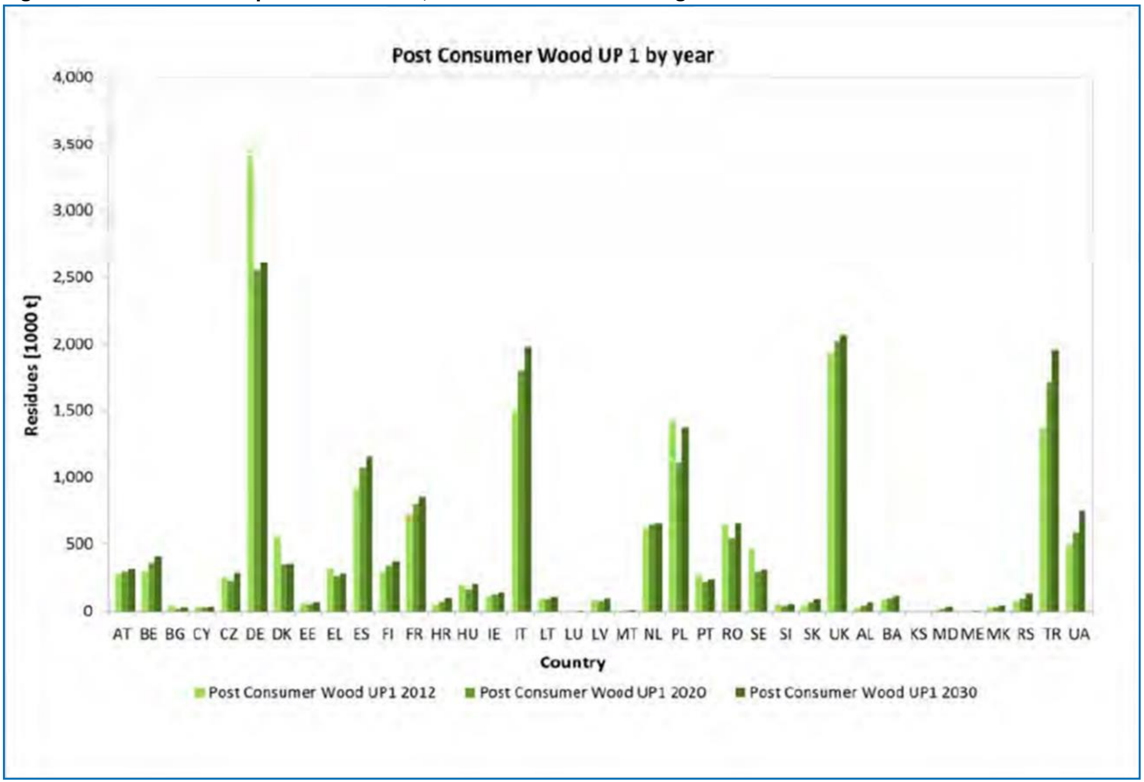
A study from Vis et al. (2016) identified governance barriers that obstruct the cascading use of wood and thus, the availability of woody waste for the production of bioenergy. For the source separation of recyclable wood materials there is no EU wide obligation, other than for glass, plastics, metals and paper (Vis et al. (eds.), 2016: 16).

That's why the biggest R&I potential for woody waste can be identified in political steering processes in the Member States in order to maximise the amount of available woody waste while at the same time assuring that the resource is used in a sustainable cascading approach, in line with the Strategic Research Agenda of the European forest-based sector (Strategic Theme 2: Responsible management of forest resource). Vis et al. (2016) have identified the need to improve the data around wood/wood waste use and flows through improved reporting and traceability of wood assortments as well to enable and support research activities to overcome specific technical barriers to cascading use. They recommend moreover that research should be commissioned in certain strategic areas in order to further improve understanding and to develop new initiatives (e.g. in situ sorting and separation techniques; supply chain development between disparate actors; technological developments in utilising hardwood streams more effectively; scanning and separation technologies; product labelling and tracing). So a main point is that the general understanding of wood flows in Europe has to be improved (for example, it is unknown at the moment what happens to 2/3 of the wood inflow material).

Actual data show that of the total yearly amount of used wood in the EU (52.3 Mm^3), on average 36.4 Mm^3 is recovered by collection systems. 16.8 Mm^3 (32 %) of this are used for material applications; 19.6 Mm^3 (37 %) for energy; **and 15.9 Mm^3 (30 %) are still disposed without recovery** (in some countries the amounts of organic waste landfilled are still higher than allowed according to the Landfill Directive). The total provision of wood processing residues is 178.7 Mm^3 (2010) and consists of three main assortments. Sawmill residues (82.3 Mm^3) are an untreated and clean wood resource that can be used materially in the pulp and panel industry. Black liquor (59.6 Mm³) is currently used energetically in the pulp and paper industry and to regain chemical substances as part of a circular production process. However, it can also be used as a resource for new bio-based products in biorefineries. Other residues (36.8 Mm³) occur mainly in the finished products production processing sector and are of varying quality, depending on the combination with other substances (materials). The total volume of residues is linked to the overall use of wood products, because they occur within the production process (Vis et al. (eds.), 2016: 3).

The available potential of wood waste for bioenergy production is dependent on the cascading use of the wood resource. In the S2Biom Project this fact was taken into account and led to the following potentials:

Figure 5.12 User-defined potential in 2012, 2020 and 2030 according to S2Biom



Dees et al., 2016: 65.

The user-defined potential shows how much wood would remain available for energy production if increased cascading use in 2020 and 2030 is considered. The Circular Economy Package proposes a target of 75 % of material recycling of packaging wood in 2030. This will be a challenge, but the quality of packaging waste (mostly clean sawn wood) is suitable for recycling. The other waste wood fractions are more difficult to recycle (e.g. not many options to recycle used panels like particle board, MDF, OSB, plywood). The recycling rates of other wood (besides packaging) are not expected to exceed 50 %. This results in an overall material application of non-hazardous post-consumer wood of 49.2% in 2020 and 61.5% in 2030. Moreover, all hazardous waste wood is assumed to be available for energy generation. The difference between the user defined scenario of increased cascading use of wood and the base scenario potential depends on the historical shares of energy, material and disposal of postconsumer wood on country level (Dees et al., 2017: 61-63). The country level data for modelling is given in the following subchapters Base Scenario and Advanced Scenario.

5.3.4 Vegetal wastes

According to the Eurostat classification, “Vegetal wastes (Item 32)” originate from food preparation and from vegetal products processing, including sludges from washing and cleaning. The category includes wastes from solvent extraction, wastes from spirit distillation and green waste.

In many cases these wastes are already used in different ways. Brewery wastes for example are still used as fodder or are converted into biogas using AD. Wastes from the dairy industry can be applied on the land.

However, it is difficult to concretely assess the feedstock increase potential for “Vegetal waste” as this category includes many different input sources and as it is so far unknown to which collection/disposal scheme each of these are connected. In order to find out in detail about the real bioenergy potential, research needs to be done, that addresses all the different fractions which altogether form the category “Vegetal wastes”.

The following table shows the Eurostat data on vegetal wastes in order to visualize the huge potential within this category.

Table 5.8 Eurostat data (for 2012) on generation of vegetal wastes [tonnes]

GEO/WASTE	Vegetal wastes
European Union (28 countries)	56,730,000
European Union (27 countries)	56,670,000
European Union (25 countries)	52,580,000
European Union (15 countries)	48,450,000
Belgium	3,713,681
Bulgaria	510,853
Czech Republic	371,047
Denmark	781,623
Germany	11,003,734
Estonia	22,495
Ireland	242,812
Greece	143,033
Spain	2,182,421
France	6,880,974
Croatia	60,370
Italy	4,738,605
Cyprus	55,265
Latvia	92,231
Lithuania	356,275
Luxembourg	48,925
Hungary	256,412
Malta	7,721
Netherlands	9,131,100
Austria	1,173,035
Poland	2,535,520
Portugal	76,639
Romania	3,578,668
Slovenia	101,421
Slovakia	322,947
Finland	237,828
Sweden	822,224
United Kingdom	7,277,846

5.3.5 *Paper and cardboard waste*

The common EU target of recycling 75 % of packaging waste by 2030 includes the recycling of paper waste (paper and cardboard) (European Commission 2016_a). In 2013 paper and cardboard accounted for 41 % of the total amount of packaging waste generated in the EU-28 (European Commission_b 2016). The applied Eurostat classification is “Paper and cardboard waste (Item 18)”.

There is plenty of experience about the recycling of paper and cardboard waste and impressive CO_2 reductions could already be achieved (e.g. in Germany recycling of paper and cardboard waste together with scrap wood showed the biggest reduction potential for the waste streams). (Recyclingnews 2010)

The paper sector has a much higher recycling volume compared to other parts of the wood sector. Of the total yearly recovered waste paper volume in the EU (129.8 Mm^3) on average 125.9 Mm^3 (97 %) is used in the paper industry and the remaining 3.9 Mm^3 (3 %) for energy (Vis et al. (eds.), 2016: 15).

Based on results on a study by Forum Oekologie & Papier „Papier - Wald und Klima schützen“ (Paper – protect wood and climate), instead of urging to use waste paper for energy production, the recycling potential shall be maximally exploited. The study showed that about 60 % energy savings can be made when producing recycled paper out of waste paper, thus making it obvious that recycling waste paper still is favourable compared to the incineration of paper (with energy recovery) or landfilling.

Although this would not mean a concrete increase of bioenergy production, the energy savings made when producing recycling paper should be treated similarly like generated bioenergy.

Being aware of the actual achievements of paper waste recycling (more or less depending on the Member States) it is obvious that higher recycling rates can and shall be achieved in the short-to-medium term. The following Table 5.9 presents the paper recycling rates based on Eurostat data. It shows that it is possible to achieve high recycling rates of more than 80 %. Compared to landfilling statistics (please see above) a significant difference between Western and Eastern European countries cannot be observed.

Table 5.9 Recycling rates for paper and cardboard waste in the EU (Eurostat data)

GEO/TIME	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
European Union (28 c	:	:	:	:	:	:	:	83,9%	84,6%	82,2%
European Union (27 c	73,3%	75,7%	78,4%	80,9%	83,4%	83,5%	83,0%	83,9%	84,6%	82,2%
Belgium	83,3%	89,1%	92,0%	89,4%	88,0%	89,8%	90,4%	89,8%	89,1%	90,6%
Bulgaria	81,6%	51,8%	97,8%	84,9%	67,3%	81,9%	98,1%	94,2%	88,8%	70,1%
Czech Republic	84,0%	90,8%	94,2%	93,8%	93,9%	93,5%	90,5%	85,9%	87,6%	88,6%
Denmark	60,0%	62,2%	60,5%	61,0%	93,5%	93,5%	63,8%	76,5%	85,4%	85,9%
Germany (until 1990	82,1%	80,2%	80,2%	87,7%	91,1%	90,2%	88,0%	87,6%	88,2%	87,3%
Estonia	45,1%	55,2%	57,0%	65,1%	69,1%	82,9%	79,1%	77,2%	75,5%	74,2%
Ireland	71,6%	73,7%	77,0%	78,2%	81,2%	84,0%	91,5%	83,0%	79,1%	:
Greece	72,5%	70,0%	79,5%	73,6%	83,0%	94,1%	91,9%	83,6%	79,7%	:
Spain	69,2%	71,4%	70,0%	73,4%	76,7%	76,1%	76,6%	77,8%	75,0%	78,2%
France	80,9%	84,6%	89,0%	86,9%	85,6%	91,9%	88,0%	91,8%	95,8%	94,1%
Croatia	:	:	:	:	:	:	:	96,1%	88,2%	76,9%
Italy	66,6%	66,6%	69,7%	73,8%	80,4%	78,7%	79,5%	84,5%	84,6%	78,7%
Cyprus	12,9%	38,0%	39,2%	59,9%	78,9%	83,4%	88,3%	88,9%	97,3%	:
Latvia	59,1%	58,3%	57,5%	66,1%	74,6%	74,9%	75,2%	75,3%	74,7%	81,5%
Lithuania	59,3%	59,5%	67,7%	73,0%	73,5%	83,5%	83,7%	82,4%	87,3%	89,1%
Luxembourg	69,3%	71,6%	70,6%	77,6%	76,5%	76,0%	77,8%	76,7%	74,4%	77,4%
Hungary	85,8%	94,2%	86,5%	90,6%	94,0%	94,7%	94,0%	73,0%	78,3%	66,2%
Malta	10,8%	11,2%	8,1%	29,6%	48,4%	51,4%	72,7%	77,2%	48,4%	55,5%
Netherlands	71,7%	94,0%	93,8%	96,4%	94,8%	89,9%	88,6%	88,9%	88,2%	81,8%
Austria	86,4%	87,0%	83,5%	85,4%	84,8%	84,5%	84,5%	84,9%	84,3%	84,9%
Poland	41,0%	51,0%	69,1%	67,1%	50,9%	57,1%	58,7%	53,1%	50,0%	72,8%
Portugal	59,8%	68,2%	81,8%	87,8%	79,5%	67,0%	71,3%	66,1%	73,4%	69,1%
Romania	51,1%	55,7%	61,2%	61,6%	68,7%	66,8%	65,5%	69,8%	:	:
Slovenia	77,3%	66,3%	68,5%	66,4%	71,8%	74,7%	73,5%	78,7%	78,7%	80,4%
Slovakia	20,1%	60,8%	86,1%	53,6%	84,2%	50,8%	80,2%	84,7%	79,7%	79,9%
Finland	79,1%	86,1%	87,6%	93,1%	94,7%	96,2%	96,8%	99,2%	97,6%	101,2%
Sweden	72,2%	72,0%	73,5%	74,1%	74,2%	69,6%	75,5%	76,8%	78,4%	79,3%
United Kingdom	74,2%	78,0%	79,3%	79,7%	83,9%	81,9%	84,8%	86,5%	89,4%	73,1%

Marked in yellow in Table 5.9 are recycling ratios below 70 % (or almost 70 % as in the case of Bulgaria) and marked in green are the ratios over 80 %. The Finnish example shows a recycling rate over 100 % which can only be explained by the methodological approach of accounting.

As mentioned before, rather than looking for R&I potentials to produce bioenergy, it shall first be tried to bring all EU Member States to a similar high recycling level.

In order to increase the recycling rates which are well below the (EU) average of around 82% there is nothing like a general solution. Tailor-made solutions need to be developed to achieve the best possible results in the respective countries.

5.3.6 Sewage sludge

Sewage sludge is classified in the Eurostat system as “Common sludges (Item 39)” which is defined as waste water treatment sludges from municipal sewerage water and organic sludges from food preparation and processing.

Sewage sludge is the result of sewage treatment in wastewater treatment plants and contains valuable elements such as phosphor, nitrogen, potassium, magnesium and micronutrients. However, the sludge may also contain small amounts of organic contaminants (e.g. antibiotics, hormones) as well as heavy metals. When using treated sewage sludge as fertilizer in the agricultural sector the risk remains to contaminate soils with these unwanted substances.

Because of this, bringing out treated sewage sludge on agricultural soils is scrutinized in several Member States with the result that some Member States have already implemented stricter limit values for heavy metals and set requirements for other contaminants than necessary on EU level.

The EU Sewage Sludge Directive (Directive 86/278/ EEC), which was adopted over 20 years ago, is currently in the process of revision. (European Commission 2016_c)

It is already common in many Member States nowadays to use sewage sludge as feedstock for energy production (AD) as well as source for the reclaiming of phosphate. In order to reclaim the included phosphate, it is necessary to incinerate the sewage sludge in mono-incineration plants. In Germany, the most economical operation is expected for mono-incineration plants with a capacity of more than 20,000 t dm per year. However, in order to avoid long distance logistics also plants with capacities of less than 20,000 t dm per year were put in operation in Germany. The heating value of sewage sludge depends on the moisture content of the sludge and can vary from 3,000 kJ/kg (moisture content 70 %) to 13,000 kJ/kg (moisture content 10 %). It is important to know that a mono-incineration of sewage sludge can only occur when a steady sludge input can be guaranteed. (Brand, 2011: 24-38)

In Germany, phosphate recycling shall be carried out when the phosphate content in the sludge exceeds 20 g/kg dm and when this sludge is meant to be incinerated (Wendenburg, 2013: 2-3). Although the phosphor reclaiming is not a generation of bioenergy, it would still mean that energy for mining of phosphate can be saved.

Generally, co-firing of the sludge can also take place in waste incineration plants, coal-fired power plants as well as in cement plants. In these cases, depending on the phosphate ratio in the sludge, the phosphate recovery shall be done already before the incineration, either directly out of the sewage sludge or later out of the sludge liquor.

An example from the Netherlands shows the bio-energetic potential of sewage sludge if state-of-the-art technology is used. The company “Slibverwerking Noord-Brabant (SNB)”, as of 2016, operates the biggest sewage sludge incinerator (almost 450,000 t/year in 2015) in Europe and managed to do so in an energy-neutral way. The company could achieve this by turning two of the four low-pressure steam lines into high-pressure lines. Company representatives think that the plant can be a net energy producer if the remaining low-pressure lines would also be converted into high-pressure lines (SNB, 2015: 6). Being a net energy producer is surely not the case for the majority of European sewage sludge incinerators and should be taken into account when energy efficiency measures are planned in mono-incineration plants. At the SNB plant, additionally to the energy production, phosphate reclaiming also takes place.

R&I is still needed on the development of economical smaller plant solutions. The need for this can be taken out of the information that most of the incineration plants for sewage sludge in Germany have a capacity of less than 20,000 t/year (Brand, 2011: 54). A managing director from the German engineering office “Dr. Born - Dr. Ermel GmbH” advises that mono-incineration plants shall have a minimum capacity of 4,000 t/year so that an economical operation can be achieved. (Franck, 2015: 33)

Although statistical data of sewage sludge is missing for many Member States, the existing data shows that each year in the EU around 10 Mio tonnes of sludge are generated and would be available as phosphate source.

Table 5.10 Sewage sludge generation in the EU (Eurostat data)

GEO/TIME	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014
Belgium	113.1	127.5	129.1	139.8	:	176.3	:	157.2	:	:
Bulgaria	41.7	38.0	39.9	42.9	39.4	49.8	51.4	59.3	60.3	:
Czech Republic	171.9	203.4	216.3	220.0	207.2	196.3	217.9	263.3	260.1	:
Denmark	:	:	140.0	108.0	108.0	141.0	:	141.0	:	:
Germany	2,169.6	2,099.9	2,040.0	2,052.6	1,949.9	1,911.5	1,956.6	1,848.9	1,815.5	:
Estonia	29.8	27.6	28.8	22.2	21.8	18.8	18.3	21.7	18.8	:
Ireland	59.8	77.7	86.4	103.3	106.8	90.0	85.7	72.4	64.6	:
Greece	116.8	126.0	134.0	136.1	151.5	:	147.0	118.6	:	:
Spain	1,120.6	1,065.0	1,152.6	1,156.2	1,205.1	1,205.1	:	2,756.6	:	:
France	:	:	:	1,086.7	:	966.4	:	987.2	886.5	:
Croatia	:	:	:	:	29.6	30.3	31.0	42.1	32.1	:
Italy	1,056.4	:	:	:	:	1,102.7	:	:	:	:
Cyprus	8.3	:	7.8	7.5	9.2	8.1	6.8	6.5	:	:
Latvia	28.9	23.9	23.3	19.3	22.3	21.4	19.7	20.1	22.8	:
Lithuania	:	:	:	:	:	:	:	45.1	:	:
Luxembourg	13.4	15.2	16.2	12.8	:	9.7	:	7.7	:	:
Hungary	261.0	237.6	205.0	172.2	149.3	170.3	168.3	161.7	166.5	:
Malta	0.0	0.0	0.0	0.1	0.8	1.2	6.1	10.4	9.6	:
Netherlands	359.1	372.7	353.2	353.2	350.1	351.0	350.8	346.4	:	:
Austria	:	254.6	:	253.5	:	262.8	:	266.3	:	:
Poland	486.1	501.3	533.4	567.3	563.3	526.7	519.2	533.3	540.3	:
Portugal	:	:	189.1	:	344.3	:	:	338.8	:	:
Romania	67.8	225.6	99.6	79.2	120.5	82.1	114.1	85.4	172.8	:
Slovenia	13.6	19.5	21.2	20.1	27.3	30.1	26.8	26.1	27.3	:
Slovakia	56.4	54.8	55.3	57.8	58.6	54.8	58.7	58.7	57.4	56.9
Finland	147.7	148.8	147.0	144.2	149.0	142.7	140.9	141.2	:	:
Sweden	210.0	207.1	217.1	213.8	212.4	203.5	200.1	207.5	:	:
United Kingdom	1,770.7	1,809.0	1,825.0	1,813.8	1,760.6	1,419.1	:	1,136.7	:	:

A definite trend of the sewage sludge processing for the whole EU cannot be seen until now, yet in some central European countries there is a move from agricultural use and instead, incineration has been chosen (mono- and co-incineration). The study “Trend: research 2010” assumed that until 2020 the ratio of mono- and co-incineration will increase up to 50 %. The reason for this development was seen in the low public acceptance of the use of sewage sludge in agriculture, mostly because of the uncertainty of contaminants and the interaction of those, which are in many cases unknown. (Brand, 2011: 59-81)

Furthermore, having in mind that the EC added phosphate rocks to the critical raw materials list in 2014, in order to reduce the dependence of phosphate imports in the EU, the construction of mono-incineration plants with subsequent phosphate recovery should be supported. This will only be able in a medium to long term perspective as for example the logistical framework and economical models would need to be developed first and the capacities of incineration plants are not existing yet (Brand, 2011: 82). Bearing in mind that some Member States have more experience in using this technique, dissemination programmes of existing best practices should be supported.

5.4 Identification of major players in R&I

Table 5.11 shows a selection of several companies and institutions from the sectors AD, mechanical waste separation and enzyme production, whose R&I activities can have an impact on the production of bioenergy from waste.

Large fractions of organic waste can be used for AD. As mentioned before this feedstock is not homogenous and thus needs to be treated in tailor-made plants. In the EU, according to the latest report of the European Biogas Association (EBA), more than 5,000 biogas plants are already using feedstock out of waste streams (i.e. sewage, landfill or other) as input (Stambasky et al., 2016: 7). The European biogas industry is always trying to exploit the economic and ecologic potential of suited feedstocks. Companies of the sector whose R&I activities can be directly connected with waste digestion (plants and supplies) and MBT are thus shown in Table 5.1. The information is based on an internet analysis and new publications of the European Biogas Association (EBA 2017) and a publication in cooperation with the German Biogas Association (Sunbeam GmbH (ed.) 2015).

Enzymatic treatment of waste streams is a field of research in universities in many EU countries and also of already established companies in the sector. The use of enzymes for waste treatment has been realised recently and offers promising potential in the future. A selection of European enzyme producers with R&I activities in the field of biotechnology (based on the members list of AMFEP – Association of manufacturers & formulators of enzyme products) is also shown in Table 5.11.

R&I activities in the UCO sector occur in several biodiesel producing companies and also in initiatives to increase UCO collection. A selection of companies dealing with UCO is therefore shown in Table 5.11 as well.

Table 5.11 Selected list of major players in R&I for the waste sector

Waste digestion (plants & supplies)			
Company	**Country**	**Research areas**	**Website**
agriKomp GmbH	Germany	Biogas plant producer with R&I department.	www.agrikomp.de
BDI – BioEnergy International AG	Austria	Biogas plant producer, specialised on waste digestion plants.	www.bdi-bioenergy.com
Bilgeri EnvironTec GmbH	Austria	Specialist on digestion towers, gas cleaning and gas storage.	www.environtec.at
BioConstruct GmbH	Germany	Biogas plant producer with experience in waste digestion plants and R&I department.	www.bioconstruct.de

Waste digestion (plants & supplies)			
Company	**Country**	**Research areas**	**Website**
Bioprocess Control AB	Sweden	Plant producer; research on feedstock optimisation, process optimisation and instrumentation.	www.bioprocesscontrol.com
Bioreact GmbH	Germany	Expert company on biological processing, analytics and consulting	www.bioreact.de
BOKU, IFA Tulln	Austria	Research projects, consulting. Laboratory, analytics.	www.ifa-tulln.ac.at, www.codigestion.com
BTS Biogas	Italy	Plant producer with own research department.	www. bts-biogas.com
DSM	Netherlands	R&I on feedstock optimisation, process optimisation and instrumentation.	www.dsmbiogas.com
Evonik Industries AG	Germany	Supplier of specialty chemicals, expert on gas treatment.	www.sepuran.com
Fraunhofer IWES	Germany	Investigation of the whole process chain for electricity, heat, and energy source production from biomass; Biomass usage for new energy conversion technologies.	www.iwes.fraunhofer.de
Institute for Biogas, Waste Management and Energy	Germany	Research on organic waste to energy.	www.biogasundenergie.de
Lindner-Recyclingtech GmbH	Austria	R&I activities on feedstock pretreatment processes.	www.l-rt.com
Lipp GmbH	Germany	Specialist on fermenter construction, experience with waste digestion plants.	www.lipp-system.de
NETZSCH Pumpen & Systeme GmbH	Germany	Specialist on mixing and delivery systems for biogas plants.	https://pumpen.netzsch.com
Sattler Ceno Biogas GmbH	Germany	Specialist on gas storage, R&I department for special solutions.	www.sattler-ceno-biogas.com
Sauter Biogas GmbH	Germany	Plant producer with own research department.	www.sauter-biogas.de
Schmack Biogas GmbH	Germany	Holistic biogas plant producer with R&I department and solutions for organic waste materials.	www.schmack-biogas.com
TNO Energy	Netherlands	Independent R&D institute, working on the entire biogas value chain.	www.tno.nl

Mechanical Biological Treatment - plant manufacturers

Company	Country	Research areas	Website
BTA/MAT	Germany	Specialist for the wet mechanical pre-treatment of different kinds of waste and the subsequent anaerobic digestion of the organic fraction.	http://www.bta-international.de/en/home.html
Haase	Germany	Consulting company for Mechanical-Biological Waste Treatment, Biowaste Treatment, Food waste Treatment, Agricultural Biogas Plants and landfill technology including landfill gas utilisation and leachate treatment.	http://haase-ec.de/index.php?id=3&L=1
FHF	Germany	Solutions for the recycling of lightweight packaging, cardboard packaging, household waste and bulky waste. In addition, FHF builds treatment plants for the treatment of wood and alternative fuels.	http://www.fhf.global/
Strabag	Germany	STRABAG Umwelttechnik GmbH is a full supplier of mechanical-biological waste treatment plants.	http://www.strabag-umwelttechnik.com
Nehlsen	Germany	Provider of complete range of waste and resource management services, from collection and sorting, to treatment, recycling and disposal of solid, viscose and fluid waste.	https://en.nehlsen.com/services/
Sutco	Germany	Sutco offers complete MBT solutions and has developed a new digestion technology BioPV (organic waste press water digestion).	https://www.sutco.de/en/plant-technology/
Renewi	UK	Operator of waste processing and resource management activities around the world.	http://www.renewi.com/en/
Veolia	UK	Operator of waste facilities for composting, energy recovery and materials recovery.	http://www.veolia.co.uk/
Komptech	Austria	Technology supplier of machinery and systems for the mechanical and mechanical-biological treatment of solid waste and for the treatment of biomass as a renewable energy source.	https://www.komptech.com/en/about-komptech/in-brief.html

Mechanical Biological Treatment - plant manufacturers			
Company	**Country**	**Research areas**	**Website**
SCT	Italy	Designer and manufacturer of waste recycling and treatment facilities worldwide.	http://www.sctecno.com/en/index.htm
Waste Treatment Technologies (WTT)	Netherlands	Supplier of high-tech waste treatment solutions.	http://www.wtt.nl/
Kompogas	Switzerland	Provider of dry anaerobic digestion plants of organic wastes.	http://www.axpo.com/axpo/ch/de/geschaeftskunden/biomasse.html
OWS	Belgium	Designer and operator of MBT plants.	http://www.ows.be/biogas-plants/
Valorga International	France	Designer and manufacturer of Municipal Solid Waste treatment plants including the anaerobic digestion of the organic matter.	http://www.valorgainternational.fr/en/?

Enzymes			
Company	**Country**	**Research areas**	**Website**
BASF	Germany	Global player: chemical company with enzyme production division.	https://www.basf.com/de.html
DuPont Industrial Bioscience	USA	Global player: Research on agricultural, biotechnology, chemical and material sciences.	http://biosciences.dupont.com/
Groupe Soufflet	France	Enzyme production for biotechnology	http://www.soufflet.com/
NRC Group	Germany	Producer of specialty chemicals.	http://www.nrc.de/en/home.html
Novozymes	Denmark	Enzyme production for biotechnology.	http://www.novozymes.com/en
Tegaferm	Austria	Enzyme production.	http://www.tegaferm.com/index.html
evoxx technologies	Germany	Enzyme production.	http://www.evoxx.com/
c-LEcta	Germany	Enzyme production.	http://www.c-lecta.com/
MetGen	Finland	Enzyme production for biotechnology.	http://www.metgen.com/#top
WeissBioTech GmbH	Germany	Enzyme production.	http://www.weissbiotech.com/index.html

UCO - (UCO collection, biodiesel production and/or R&I activities)			
Company	**Country**	**Research areas**	**Website**
Agroinvest	Greece	Biodiesel producer, supporting biodiesel R&I.	http://agroinvest.gr/
Argent Energy	UK	Biodiesel producer, also collecting UCO (using special treatment for UCO).	https://argentenergy.com/

UCO - (UCO collection, biodiesel production and/or R&I activities)			
Company	**Country**	**Research areas**	**Website**
Avril	France	Agroindustry company, biodiesel R&I activities.	http://www.groupeavril.com/fr/recherche-innovation/energies-renouvelables
Bioagra	Poland	Biodiesel producer, also collecting and processing UCO.	http://www.bioagra-oil.comeze.com/Home/
ecoMotion	Germany	Biodiesel producer, biodiesel R&I (UCO processing).	http://www.ecomotion.de
Evonik Industries AG	Germany	Special chemicals producer, biodiesel R&I activities.	www.evonik.de
GF Energy	Greece	Biodiesel producer, also collecting and processing UCO.	http://www.gfenergy.gr/
Green Biofuels Ireland	Ireland	Biodiesel producer, also collecting and processing UCO.	http://www.gbi.ie/
Mercuria	Germany	Global energy & commodity group, also producer of UCO biodiesel.	http://www.mercuria.com/
Muenzer	Austria	Biodiesel producer, also collecting UCO and offering logistic solutions therefore.	http://www.muenzer.at/de/altspeisefett.html
Neste	Finland	Oil industry company, also producing sustainable biodiesel (R&I).	https://www.neste.com/en/companies/products/renewable-fuels
Nord Ester	France	Biodiesel producer, also collecting and processing UCO.	http://www.nord-ester.fr/
Oeli	Austria	UCO collection scheme provider in Austria and parts of Germany and Italy.	http://www.oeli.at
Olleco	UK	Biodiesel producer, also collecting UCO and offering logistic solutions therefore.	https://www.olleco.co.uk/
Petrotec	Germany	Biodiesel producer, biodiesel R&I (UCO processing).	www.petrotec.de
Prio	Portugal	Biodiesel producer, providing collection schemes for UCO in Portugal.	https://www.prioenergy.com/

UCO - (UCO collection, biodiesel production and/or R&I activities)			
Company	**Country**	**Research areas**	**Website**
Rotie	Netherlands	Organizer of UCO collection scheme in the Netherlands.	http://www.rotie.nl/nl/oud-frituurvet-afvoeren/
Soleval	France	Producer of animal fats, dehydrated animal proteins, hydrolysed proteins and food grade bone chips, also collecting and processing FAG into biodiesel.	http://www.soleval.akiolis.com
Valorfrit	Belgium	Organizer of UCO collection scheme in Belgium.	http://www.valorfrit.be
Verbio	Germany	Biodiesel producer, R&I on biodiesel.	https://www.verbio.de/

However, the best results for the waste field can be expected when use is made of already existing separation measures, realised by the end consumers. The main identified relevant stakeholders for a maximum implementation success thus are waste collection companies, municipalities, action groups, committed citizens and lawmakers.

5.5 Definition of scenario elements for selected R&I fields

Forecasts of the development can be taken for the field of waste when assuming different developments of the realisation of EU reduction targets (e.g. impact on generation of landfill gas), as well as when assuming best separation techniques and thus maximum provision of organic waste for the generation of bioenergy.

A special focus will be given to the potential use of separated organic waste fractions, used cooking oil (out of FOG/UCO) and the available woody waste.

For each of the investigated feedstock categories, two scenarios will be set up:

- Business as usual:
  There will be no major changes in the use of organic waste fractions. The most actual data is used to show the status quo;
- Optimistic scenario:
  Considerably more organic waste feedstock will be used for energy generation. The assumptions go in line with studies conducted in this field.

For modelling the separated biogenic fraction to be treated in AD plants, the theoretical organic fraction in waste is used as modelling element as well as the possible energy generation of organic waste in waste digestion plants.

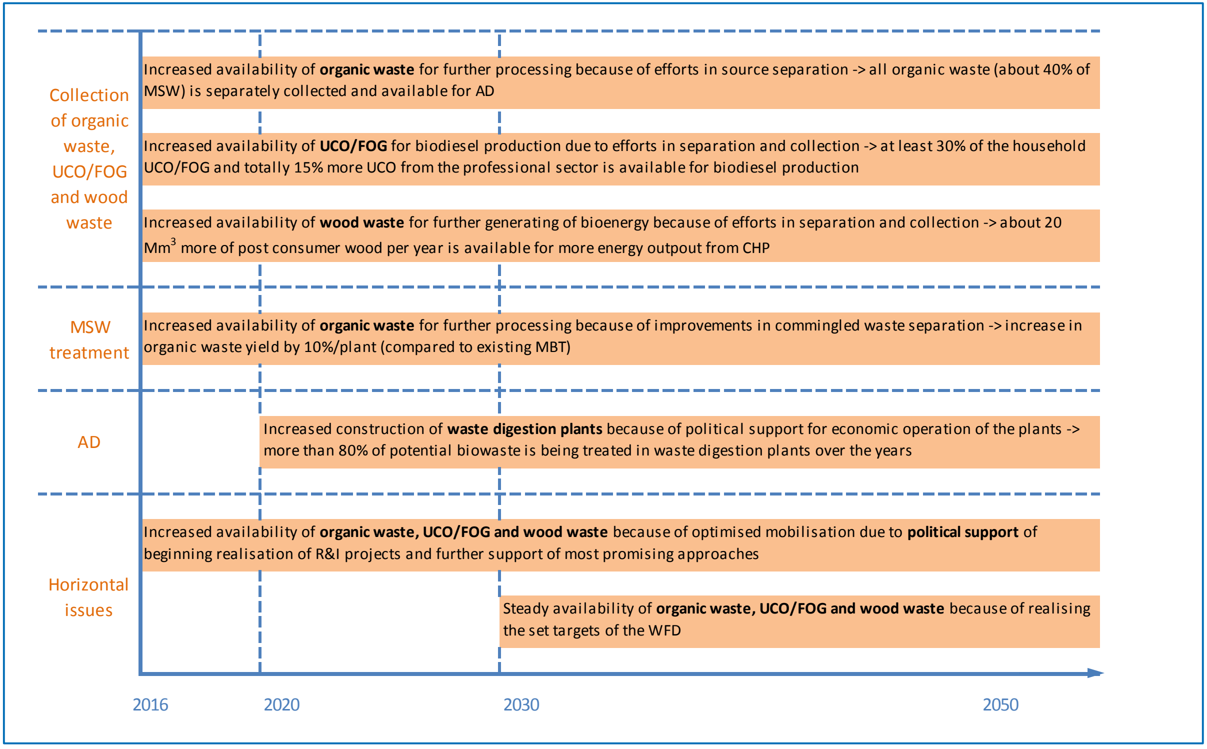
The simulation elements to be used for modelling of the FOG/UCO collection and use for biodiesel production are the actually available amounts of FOG/UCO and the potentially obtainable amounts of FOG/UCO.

The modelling elements for wood waste are the available unused amounts and the possible energy generation out of wood waste in CHP plants.

5.5.1 Scenario elements on the time line

Scenario elements for the waste sector are summarized in Figure 5.13.

Figure 5.13 Summary of Scenario elements for the waste sector



5.5.2 Scenario elements for modelling production and delivery of biomass feedstock from waste

In order to facilitate the development of scenario storylines for modelling the production and delivery of biomass feedstock, scenario elements have been identified for promising R&I activities in the field of waste. Specifically, these scenario elements addressed **improved biomass supply** through innovative supply chain logistics and mobilization of potentials.

The following table presents an overview of R&I scenario elements for improved biomass supply for the field of waste.

Table 5.12 R&I scenario elements for improved biomass supply from waste

	R&I scenario elements for improved biomass supply
Biomass from waste	• Increasing availability of UCO/FOG by increasing collection yields due to extended application of separation and collection methods (from 2017), by: - Information campaigns in all EU countries (school level as well as for adults) where that hasn't been done yet (taking into account lessons learnt from conducted studies); - Development of efficient and accepted collection infrastructures. • Increasing availability of the organic waste fraction (pre-sorted and out of commingled MSW) by mobilising at source separation, using most advanced separation technology and using suited AD plants for energy generation (from 2017), by: - Information campaigns directed at school and adult level for enhanced separation of biogenic fraction at source (i.e. home);

	R&I scenario elements for improved biomass supply
	- Using of most modern industrial separation technologies for maximising organic waste yield out of commingled waste streams; - Using of state of the art waste fermentation plants for the recovered organic fractions; - Supporting schemes for extended construction of aforementioned plants in the EU in a decentral manner; - Wider use of recent technology developments resulting in increased availability of organic waste.

6 Assessment of the R&I potential in the field of aquatic biomass

Algae constitute a large and diverse group of plant-like aquatic organisms that range from multi-cellular macroalgae (seaweeds) to unicellular microalgae. All types can be found worldwide both in freshwater and saline habitats. Like terrestrial plants, most of the 50,000 documented algae species are (photo-) autotrophic, converting solar energy into chemical forms through photosynthesis and a variety of biochemical pathways. Algae species that are cultivated at pilot and large-scale include: *Chorella vulgaris*, *Dunaliella*, *Scenedesmus obliquus*, *Selenastrum rinoi*, *Haematoccus* and *Spirulina*.

Particularly due to their high growth rate, which is believed to considerably surpass productivity rates of terrestrial energy crops, as well as their lipid accumulation capacity algae have received a lot of attention as a potential feedstock for the production of sustainable transport fuels (i.e. biofuels) in recent years.

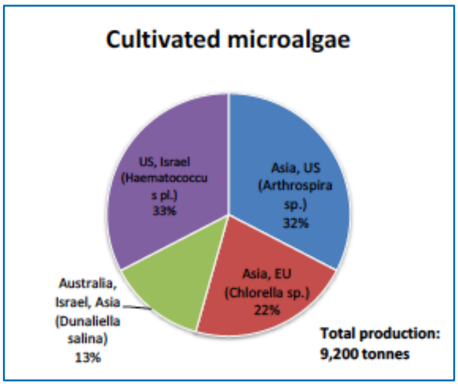
This interest resulted in research and demonstration projects focusing on algae-to-biofuels pathways. Seeing as the lipid content of macroalgae is relatively low, they are most commonly utilized for the production of biogas and bioethanol. Microalgae on the other hand, are due to their high lipid content a promising feedstock for the production of biofuels and other products of higher value such as nutritional or cosmetic products.

The following chapters will first introduce microalgae, the cultivation and harvesting techniques that currently applied as well as GHG emissions resulting from the different production steps. Special focus will be placed on the resources required for microalgae production and potential achievable yields. For the assessment of R&I potentials of algae production in Europe and selected third countries that are predestined for producing large quantities of algae-based fuels and products, a market overview featuring the most important players in the field will be given. Based on this assessment, the R&I potential of algae production will be estimated. The same approach will be applied for macroalgae.

6.1 Brief overview of current market situation and aquatic biomass potential

While there are a lot of research and innovation activities concerned with the cultivation and further processing of microalgae in Europe, particularly the production of microalgae-based biofuels is still in its infancy, meaning that they have not been commercially developed yet. In terms of commercially available production sites and systems, the market for microalgae-based food and feed products is considered to be well-established. However, a total annual production of 9.200 tonnes (Figure 6.1) worldwide puts this notion in perspective and allows for a first estimation of the market situation of microalgae production for biofuel applications.

Figure 6.1 Annual estimates (in dry wt. tonnes) of cultivated microalgae for food and feed production worldwide



Rocca et al. 2015.

In fact, microalgae cultivation is currently limited to the production of highly valuable molecules[5] such as proteins, polyunsaturated fatty acids (PUFAs) and pigments, such as carotenoids and astaxanthin (pigment / colorant), with high commercial values. (Rocca et al. 2015)

Most of the commercial microalgae production is currently carried in open ponds, also called open *raceway* ponds (OPRs). In addition, microalgae are cultivated in closed photobioreactors (PBRs), which have several advantages but also various disadvantages compared to cultivation in OPRs. A comprehensive introduction to both cultivation systems is given in Chapter 6.3.

Seeing as microalgae cultivation for the production of biofuels is not commercially developed at this point, it is very difficult to retrieve reliable information concerning actual production volumes. A considerable share of the production initiatives is additionally led by industry, which virtually does not disclose any information. Taking these framework conditions into account, a data-fed assessment of microalgae production itself as well as the surrounding R&I landscape is a complicated endeavour.

While the actual production of microalgae is currently very limited, their production potential is believed to vastly surpass the potential of terrestrial crops.

It has to be mentioned that estimations concerning the production potential of microalgae vary significantly – even more so than for terrestrial crops. Furthermore, the sufficient supply of CO_2 for optimal growth of the aquatic biomass is one of the main challenges with respect to the large-scale cultivation and the according production potential.

In an exhaustive study, Skarka (2015) assessed the theoretical potential of microalgae in Europe by developing a GIS (geographic information system)-based model in order investigate the distance of potential algae production sites to large CO_2 sources and how the spatial distribution of algae production sites and CO_2 sources affects the algae biomass costs and the related potentials. (Skarka, 2015)

Figure 6.2 shows the theoretical geographical potential in the EU-27, which is calculated by modelling yield and area available. The darker the green in the figure, the higher is the yield per area unit. Locations that partially cannot be used for microalgae installations have not been

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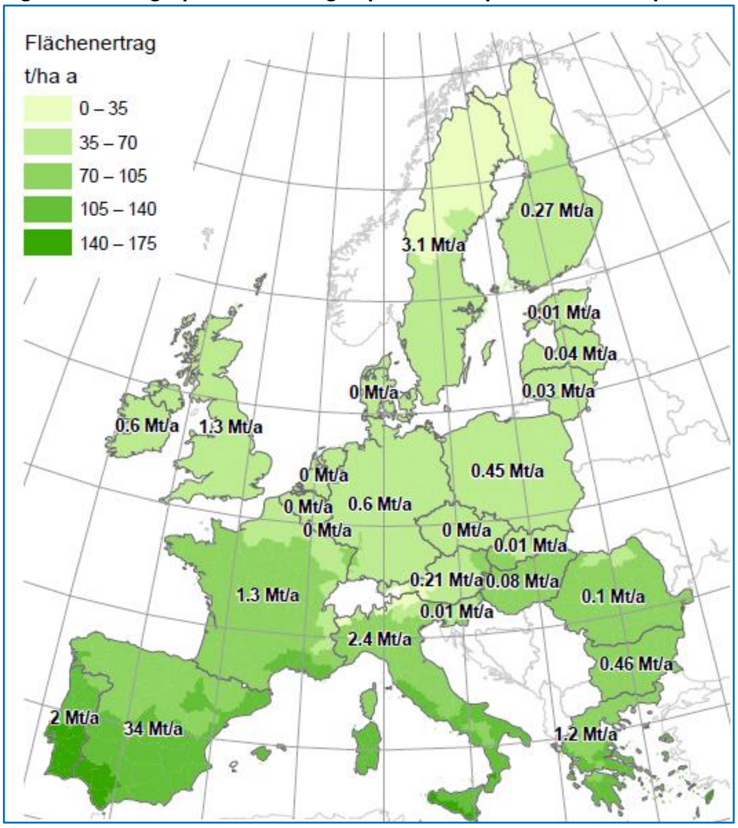
5 An exhaustive overview of the major products and producers of food and feed based on microalgae is given in:http://publications.jrc.ec.europa.eu/repository/bitstream/JRC85709/final%20version%20online%20ipts%20jrc%2085709.pdf.

identified and not included in calculating the geographic potential, which amounts according to Skarka to 49 Mt/y for the EU-27.

Figure 6.2 Geographical microalgae production potential in Europe



Skarka, 2015.

The technical potential on the other hand takes into account that at some of the identified locations, PBRs cannot be built on certain areas (of the identified location). According to Skarka, 5.502 locations have a production potential of 41 Mt/y, with averaged costs of 1.330€/t.

Although these well-founded calculations suggest that microalgae have a vast production potential if a sufficient CO_2 supply and land to build the PBRs on is available, a reminder on the actual microalgae production worldwide of 9.200 t/y food and feed puts the values stated above in perspective. In order to realize the technical production potential of 41Mt/a, considerable R&D efforts including the corresponding funding will be necessary. Although making use of waste gases from industry will benefit the GHG balance of microalgae cultivated in PBRs, their energy requirements still need to be improved. In addition, CO_2 from industrial processes may be contaminated with substances such as heavy metals, which will negatively impact algal growth and decrease the total production potential.

In addition to the geographical as well as the technical microalgae production potential, Skarka (2015) calculates the cost-based technical potential of microalgal production in Europe, as shown in Table 6.1 Cost-based (kt/y) microalgae production potential in different cost intervals (€/t) for the 10 European countries showing the highest technical production potential. The biomass production costs are given in seven intervals, ranging from < 750 €/t to 4000 €/t. Factors such as biomass costs, CO_2 capture and compression costs, costs for pipelines as well as costs emerging at the production sites are used to calculate the cost-based technical production potential of the EU-27 Member States. The 10 Member States with the highest technical production potential are shown in the table below. Depending on the factors outlined above as well as land availability, the total technical production potential of the different Member States is distributed over the cost categories / intervals.

Table 6.1 Cost-based (kt/y) microalgae production potential in different cost intervals (€/t) for the 10 European countries showing the highest technical production potential

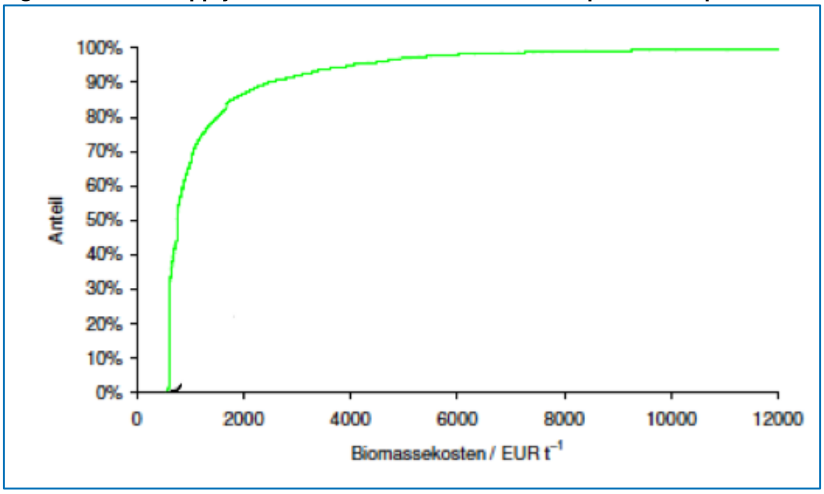
Land *Country*	min–750	750–1000	1000–1500	1500–2000	2000–3000	3000–4000	4000–max	Gesamt *Sum*
Spanien	19.047	3.975	2.272	1.044	977	398	459	28.172
Schweden	–	–	1.055	190	137	276	1.100	2.757
Italien	461	540	386	206	205	117	118	2.034
Portugal	362	883	270	74	47	23	20	1.680
UK	–	–	14	777	175	57	126	1.149
Frankreich	64	234	296	124	143	93	115	1.069
Griechenland	–	508	189	117	134	66	2	1.016
Zypern	797	78	40	2	12	–	–	930
Irland	–	–	412	39	26	9	15	500
Deutschland	–	–	344	99	34	4	5	485
EU-27	20.731	6.602	5.559	2.871	2.108	1.151	2.159	41.181

Skarka, 2015.

Spain shows according to this calculation not only the highest overall production potential in Europe, but also the highest potential at the lowest cost, i.e. in first cost interval (< 750 €/t). Although Sweden has the second highest overall technical potential in comparison to other Member States in the EU-27, the production itself is more expensive than in other countries – approximately one third of Sweden's overall technical production potential can according to Skarka be produced at costs of between 1.000 and 1.250 €/t.

The cost-based potential shown in Table 6.1 can also be graphically depicted as a sum curve in relation to biomass costs (Figure 6.3). The figure below shows that based on the calculations and underlying assumptions by Skarka (2015), 85% of the technical production potential can be produced at costs below 2.000 €/t. At costs below 1.000 €/t, approximately 65% of the technical potential can be produced in Europe.

Figure 6.3 Cost-Supply-Curve of the cost-based technical production potential



Skarka, 2015.

Information Box: Carbon Dioxide (CO_2) as a Resource

Carbon Dioxide (CO_2) utilisation covers a variety of established and innovative industrial processes that utilise CO_2 as a source of carbon by transforming it into value added products such as ***chemical feedstocks, synthetic fuels or building materials***. Thereby, CO_2 utilisation is regarded as complementary to CCS (Carbon capture and storage/sequestration) and often by definition does not include biological routes of transformation via aquatic biomass.

CO_2 for utilisation can be obtained from a range of sources such as industrial gas streams, power generators (flue gas), bio-fermentation, anaerobic digesters, and geological sources or directly from the atmosphere. Each CO_2 source has certain challenges in terms of its concentration, humidity and other chemicals present. Direct Air Capture (DAC) allows CO_2 to be directly collected from the atmosphere. DAC processes may thus be sited in any location with access to low-cost low-carbon electricity while facing drawbacks with respect to energetic requirements to harvest CO_2 at concentrations in the air that are much lower than industrial sources (400 ppm vs 140,000 ppm).

The figure below presents an overview of Carbon Dioxide (CO_2) utilisation value chains from different carbon resources via transformation processes (using further inputs such as energy and materials & wastes) to end products. Potential direct uses of CO_2 include enhanced oil recovery (EOR) and the use in drinks and greenhouses.

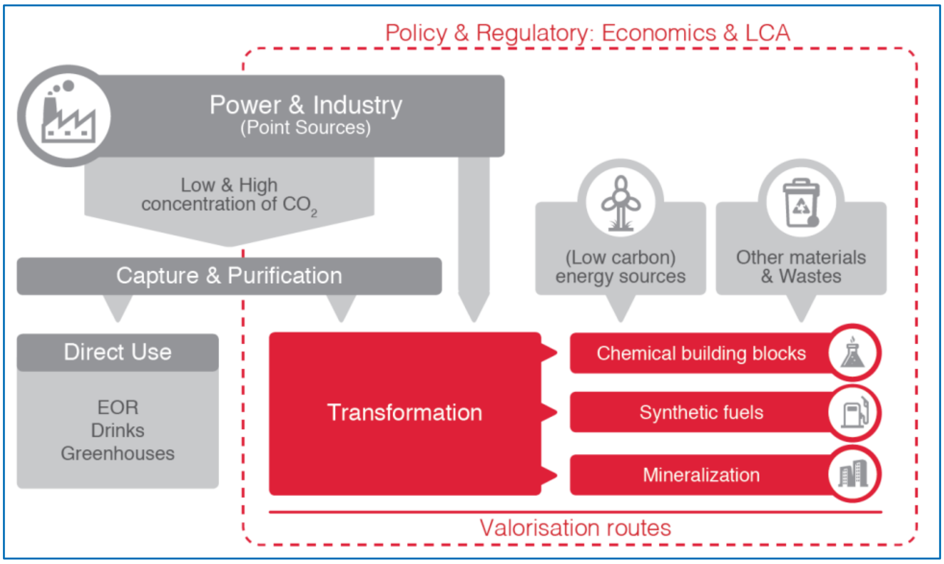


Figure: **Carbon Dioxide (CO_2) utilisation value chains (SCOT 2015).**

Synthetic fuels of non-biological origin from CO_2 are often also termed synthetic or e-fuels, power-to-gas (PtG) or power-to-liquids (PtL). They offer the potential to provide an energy buffer (storage solution) between low-carbon electrical energy sources and energy demands and may serve as drop-in replacements for liquid or gas fossil fuels with applications in the heavy vehicle and aviation sector. Thereby, the capture of CO_2 from the air or the use of biogenic/biomass sources of carbon could provide potential future carbon-neutral or negative liquid/gaseous fuels. Examples for such synthetic fuels are DME (Dimethyl Ether), methane, DMC (Dimethyl Carborate), methanol and synthetic diesel.

Information Box: Carbon Dioxide (CO_2) as a Resource (cont.)

A large number of ***chemicals*** can be produced using CO_2 as a feedstock such as methanol, polymers, urea, carboxylates, carbonates, and olefins. Many of these products are also valuable intermediates including synthesis gases and small organic molecules (e.g. formic acid). Methanol is an important product due to its use as a feedstock in many subsequent chemical processes.

Finally, materials such as industrial wastes can be carbonated leading towards the production of building materials and stabilised waste products. Industrial ***mineralisation*** has the benefit of improving certain industrial wastes to create waste streams that are less toxic and chemically stable, while at the same time sequestering CO_2.

The figure below provides an overview of the range of Technology Readiness Levels (TRLs) of promising CO_2 utilisation pathways. Some CO_2 utilisation technologies are close to the market (especially in the field of mineralisation), however many processes to transform CO_2 into products still require more research and technological development to become commercial.

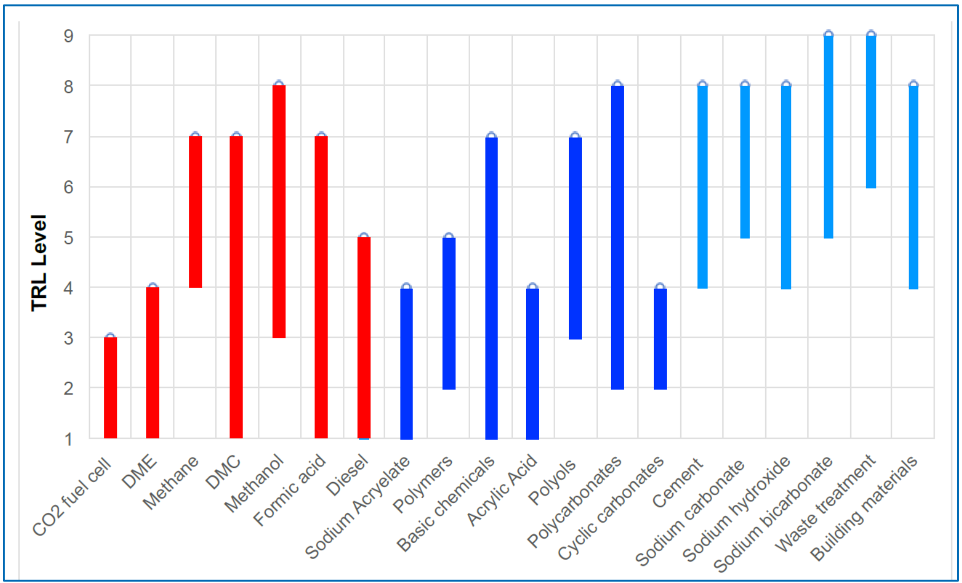


Figure: Range of TRLs of different CO_2 utilisation technologies (SCOT 2015).

As shown in the figure above, technologies for the production of synthetic fuels from CO_2 are currently in the research and demonstration stage and production volumes are negligible. However, in its final report from March 2017 the Sub Group on Advanced Biofuels (SGAB) of the Sustainable Transport Forum estimates the potential contribution to 2030 transport fuel targets of e-fuels (i.e. advanced fuels from renewable electricity via electrolysis) and Low Carbon Fossil Fuels (i.e. fuels from conversion of exhaust or waste streams via catalytic, chemical, biological or biochemical processes) to be 2 Mtoe (0.5% of total EU energy for transport) and 2-3 Mtoe (0.7%), respectively (SGAB 2017). It has to be noted that SGAB represents an industrial consultative body promoting an optimistic view of future developments of synthetic fuels from CO_2.

Information Box: Carbon Dioxide (CO_2) as a Resource (cont.)

The following main technological developments are needed to move towards future commercialisation of CO_2 utilisation technologies (SCOT 2015):

- Advances in plasma and co-electrolysis processes as competing routes to conventional Fischer-Tropsch and Sabatier processes to produce syngas and hydrocarbons;
- Advances in modular reactors to be operated under flexible part load regimes facilitating the use of variable low-carbon low-cost renewable electricity;
- Advances in carbon capture technology (including air-capture technology) to reduce costs and energy use;
- Advances in CO_2 utilisation processes based on photochemistry by mimicking photosynthesis to generate fuels and chemicals (i.e. artificial photosynthesis);
- Advances in catalyst development such as catalysts based on earth abundant materials, catalysts recovery and catalysts allowing the direct use of flue gases of varying composition.

Specifically, the table below provides an overview on important research and innovation priorities of selected synthetic fuel end products (SCOT 2016a).

Research and innovation priorities of selected end products

Methane

Methane is used in heat, power and transport sectors. It is syn-thesised by combining CO_2 (or CO) with H_2 via Sabatier reaction at high temperatures with metal catalysts. Sources of H_2 with low carbon footprint are required.

- Heat management for the Sabatier process;
- New reaction pathways such as co-electrolysis that require water (steam) as an input to the reaction rather than hydrogen;
- More efficient methane production pathways such as CO_2 & H_2O plasma in direct contact with novel catalyst;
- Photo electrochemical systems for methane production;
- Improve catalyst selectivity and stability;
- Reduce the use of noble metals and other expensive elements in the electrodes.

Methanol

Methanol is a major intermediate for the chemicals industry. CO_2 is hydrogenated in the presence of a wide range of catalysts to form methanol. Sources of H_2 with low carbon footprint are required.

- Photo electrochemical systems for methanol production;
- Direct processes (from methane) with high selectivity and yield;
- Improve catalyst yield (at low temperature), turnover rate, selectivity and stability;
- Inverse methanol fuel cells (novel electrodes and membranes);
- Process Intensification of methanol synthesis (design of more efficient reaction and separation equipment).

Higher hydrocarbons

CO_2 can be converted to hydrocarbons using either indirect routes via synthesis gas (syngas) followed by the Fischer-Tropsch process or via methanol synthesis. Use as synthetic aviation fuel (kerosene) and synthetic diesel in the aviation and heavy duty transport sectors.

- Minimising production costs via catalyst optimisation and developing new process routes;
- Efficient one reactor CO2 conversion to higher hydrocarbons;
- Efficient syngas production from CO2 as input for Fisher-Tropsch synthesis;
- Novel catalyst materials with improved selectivity in chemical synthesis from syngas to a specific hydrocarbon end-product.

Information Box: Carbon Dioxide (CO_2) as a Resource (cont.)

Today, the scale of profitable business opportunities is a major barrier for companies to further engage in the commercialisation of CO_2 utilisation technologies. However, the following innovative companies are developing processes for CO_2 utilisation and some products (chemical feedstocks, synthetic fuels or building materials) are already entering certain niche markets on a commercial basis (SCOT 2015).

AUDI, Germany: pilot-scale demonstration (TRL7-8) of Power-to-Gas technology linking renewable electricity with car mobility and the natural gas network (E-gas project).

Sunfire, Germany: pilot plant demonstration (TRL7) of Power-to-Liquid technology using renewable energy, water electrolysis, CO_2 conversion processes and Fischer Tropsch chemistry to create blue-diesel which can directly be used in cars.

Carbon Recycling International (CRI), Iceland: production of methanol from CO_2, hydrogen and geothermal power. The CRI George Olah plant in Iceland produces 4000 tons/year methanol (TRL9). A new pilot plant in Germany at the Steag Lünen coal-power plant will produce 400 tons/year (TRL7-8).

Carbon 8 Systems, UK: accelerated carbonation technology (ACT) to manufacture a high quality lightweight aggregate (C8Aggregate). The ACT process permanently captures more CO_2 than is generated during its manufacture, making the aggregate carbon-negative.

Covestro (former Bayer MaterialScience), Germany: production of CO_2-based polyols for polyeurethanes has been demonstrated at pilot scale. A production line for 5,000 tons/year (TRL9) is built in Dormagen, Germany (‘Dream Production’ project).

Novomer, USA: use of CO_2 in the co-polymerization of epoxides to produce polycarbonates (PPC polyol is available at commercial scale).

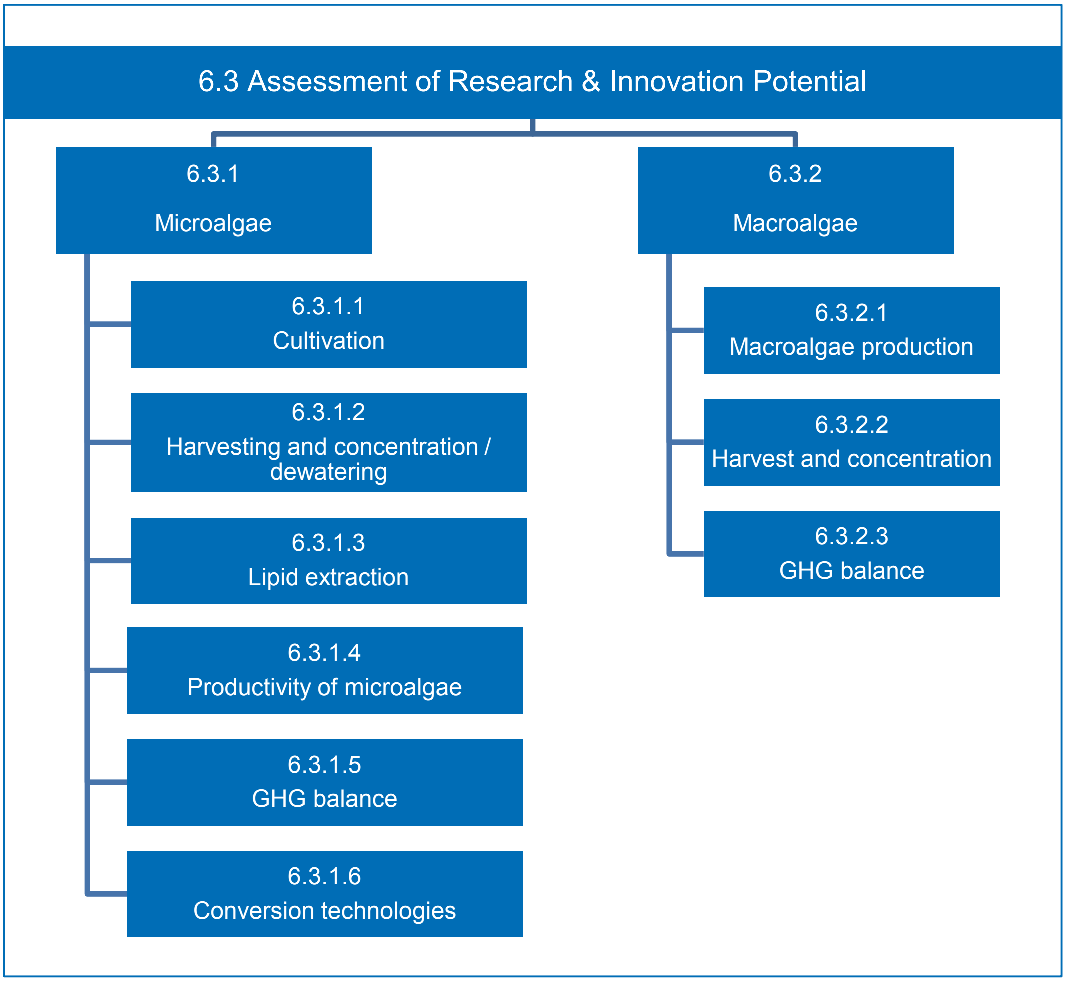
Recoval, Belgium: pilot scale demonstration of the recycling of a fine fraction of steel slags into construction materials.

6.2 Definition of investigated feedstock categories and R&I fields

As mentioned above, aquatic biomass is categorized in two main groups, i.e. micro- and macroalgae. Particularly microalgae as an overarching group are made of a vast variety of different species, ranging between 50.000 and 100.000 known species. For the purpose this chapter, those microalgae species such as Chorella vulgaris that are cultivated for a series of applications at varying maturity levels (from pilot and demo to industrial scale) are considered in this report. An overview of the most commonly cultivated algae strains is given in Table 6.2 in Chapter 6.3.1.1.

6.3 Assessment of R&I potential (in Europe and third countries)

Chapter 6.3 presents an assessment of the Research & Innovation potential in the field of aquatic biomass. The structure of chapter 6.3 is displayed in the schametic below.



6.3.1 Microalgae

6.3.1.1 Cultivation

In general, Microalgae are cultivated by applying three methods under different nutrient supply modes. These are[6]:

- phototrophic cultivation: microalgae make use of light as energy source and CO_2 as an inorganic carbon source for their photosynthetic growth;
- heterotrophic cultivation: microalgae grow without light, i.e. in a dark environment utilizing organic substrate such as glucose, acetate and glycerol as both energy and carbon source;
- mixotrophic cultivation: microalgae are able to grow either via phototrophic or heterotrophic conditions, depending on the concentration of organic carbon sources and light intensity.

The main advantage of cultivating microalgae under phototrophic conditions is that CO_2 streams can be captured from flue gases. This method, however, shows major limitations in locations where proper sunlight intensity is not always available throughout the year (Rocca et al., 2015). Heterotrophic cultures on the hand are able to overcome this problem as microalgal strains can grow in a dark environment while still attaining high lipid yields and biomass productivity (Rocca et al., 2015). Nevertheless, heterotrophic systems exhibit significant issues that need to be taken into account. These issues include the high risk of contamination by other microorganisms due to the presence of organic substrates as well as carbon sources, high energy requirements or high costs of the upstream supply. (Rocca et al., 2015)

[6] Rocca et al. (2015).

As phototrophic cultivation systems for microalgal growth are due to the presence of light most commonly utilized, the subsequent section will focus on these.

Phototrophic microalgae strains are either cultivated in open systems (Raceway Pond System) or in closed photo-bioreactors (PBR), both having several advantages and disadvantages in terms of their economic viability, environmental performance as well as with respect to specific technical parameters. Open ponds are artificial water bodies of approximately 20 cm depth, which are kept in continuous movement by paddle wheels (cf. Figure 6.4). The main drawback of open pond systems is according to Rösch (2012) their relatively low biomass yield (10-25 g/(m^{2}d) compared to closed systems (25 – 50g/ m^{2}d)). In addition, only a limited number of algae species can be cultivated in open ponds and they are very vulnerable to contamination and evaporative water loss. As shown in Figure 6.5, cultivation in PBRs takes place in pipes, tubes, plates or tanks.

Figure 6.4 Open Raceway Pond

Wikipedia, ©JanB46, CC BY-SA 3.0.

Figure 6.5 Photobioreactor

Wikipedia: ©IGV Biotech, CC BY-SA 3.0.

While the majority of commercially produced algae biomass is currently cultivated in open pond systems (advantages: easy operation and maintenance, low energy requirements), closed PBRs gained popularity amongst companies, academics and other researchers in algal biofuel R&D in recent years, as they operate at high biomass concentrations, which in turn equates to a higher oil yield and favours the production of so-called “high-value” products such as nutritional supplements, cosmetics or pharmaceuticals. In addition, atmospheric impacts, meaning the emission of climate-active gases, are believed to be significantly lower compared to open systems.

Negative characteristics of PBRs mainly concern their high energy demand as well as their limited scale-up potential. PBRs can either be orientated vertically or horizontally. A vertical PBR orientation is advantageous as it increases the surface area and therefore sunlight dilution.

The following table by Rösch (2012) gives a comprehensive overview of the advantages and disadvantages of the two different cultivation options outlined above.

Table 6.2 Comparison of the impacts between algae cultivation in open ponds and photobioreactors

Parameter	*Open ponds*	*Photobioreactors*
Land footprint	High	Low
Water footprint	High	Low
CO_2 release	High	Low
Energy requirement	Low	High
Application of waste water	Yes	Yes
Temperature control	Not needed	Required
Reactor cleaning	Not needed	Required
Risk of contamination	High	Low
Product quality	Variable	Reproducible
Microbiology safety	No	Yes
Biomass productivity	Low	High
Capital and operation costs	Low	High

Rösch, 2012.

As outlined previously and stated in the table above, PBRs have gained and are still gaining considerable attention due to their alleged advantages in productivity, water usage and GHG balance. However, as for the general environmental, economic and technical potential of algae as a biofuel feedstock, disunity prevails in the literature on “real” advantages of PBRs, particularly in terms of their large-scale production potential. This especially concerns productivity benefits, water usage as well as the efficient usage of CO_2.

Cultivating microalgae in either open ponds or PBRs is the first step of the production process. After the cultivation stage, the biomass needs to be harvested and dried, subsequently to which the lipid fraction is extracted. For microalgal biomass, a variety of different harvesting (dewatering) methods ranging from simple sedimentation, over centrifugation to filtration and flocculation can be applied.

Large microalgae species are harvested solely by sedimentation, the cheapest alternative. For the most commonly occurring small microalgae species, the preferred harvesting method is centrifugation. However, due to the low biomass concentration (< 3 g/L) that is particularly noticeable in open pond systems, large centrifuges (with the according capacity) are required, making the process energy-intensive and expensive.

High energy demand, high investment costs as well as high operation costs are also characteristics of filtration. In addition, as opposed to terrestrial crops, algae must be harvested on a daily basis.

For the production of biofuels, a feedstock’s productivity is of paramount importance. Although microalgae are naturally occurring worldwide, for them to reach optimal growth rates in artificial cultivation systems, a number of inputs are essential:
- **Sunlight**: Like all biomass, microalgae require sunlight to grow both in open systems as well as in PBRs. Areas with high incidents of solar radiation are crucial for a satisfying microalgae productivity, which is directly linked to their solar conversion efficiency. (see below);
- **Nutrients**: Nitrogen (N) and Phosphorus (P) are important fertilizers to increase the growth rate of algae. Especially nitrogen is a key nutrient as its assimilation is required for the formation of genetic material, energy transfer molecules, proteins, enzymes, chlorophylls and peptides.

(Usher, 2014) Potentially negative impacts of nitrogen fertilization will be discussed in more detail in the sustainability chapter;

- **CO_2:** Optimal algae growth occurs in a CO_2 enriched environment. Apart from sunlight, carbon is the most important nutrient for the growth of phototrophic algae, making up approximately half the dry weight of the biomass. Sources of CO_2 are threefold, namely from the atmosphere, discharge from heavy industries (e.g. power plants) and soluble carbonates. As microalgae are capable of utilizing considerable amounts of CO_2, excess, meaning additional supply of carbon may be required to ensure growth. It is, however, important to find the right amount of $CO_{2,}$ otherwise the growth is inhibited;
- **Temperature:** Although some strains of microalgae are able to withstand extreme temperatures, they generally show highest productivity rates at temperatures between 15°C and 35°C.

All of the factors outlined above are essential for reaching optimal microalgae growth as well as sufficient lipid productivity for biofuel production. The lipid content and productivity of a variety of algae strains is depicted in Table 6.3. As can be seen below, green algae show in most of the cases the highest productivity and are therefore most suitable for further processing into synthetic fuels.

Table 6.3 Lipid content (% in dry wt. tonnes) and productivity (in mg/l/day) of various microalgae strains

Microalgal strains	Lipids content % dry wt. biomass	Lipids productivity mg/l/day
Green		
Chlorella emersonii	*25-63*	*10.3-50*
Chlorella protothecoides	*14.6-57.8*	*1,214*
Chlorella sorokiniana	*19-22*	*44.7*
Chlorella vulgaris CCAP 211/11b	*19.2*	*170*
Chlorella vulgaris	*5-58*	*11.2-40*
Chlorella sp.	*10-48*	*42.1*
Chlorococcum sp. UMACC 112	*19.3*	*53.7*
Dunaliella salina	*16-44*	*46.0*
Nannochloropsis oculata NCTU-3	*30.8-50.4*	*142*
Nannochloropsis oculata	*22.7-29.7*	*84-142*
Neochloris oleoabundans	*29-65*	*90-134*
Scenedesmus quadricauda	*1.9-18.4*	*35.1*
Schizochytrium sp.	*50-57*	*35.1*
Tetraselmis suecica	*8.5-23*	*27-36.4*
Tetraselmis sp.	*12.6-14.7*	*43.4*
Diatoms		
Chaetoceros muelleri	*33.6*	*21.8*
Chaetoceros calcitrans	*14.6-39.8*	*17.6*
Phaeodactylum tricornutum	*18-57*	*44.8*
Skeletonema sp.	*13.3-31.8*	*27.3*
Skeletonema costatum	*13.5-51.3*	*17.4*
Thalassiosira pseudonana	*20.6*	*17.4*
Eustigmatophyceae		
Ellipsoidion sp.	*27.4*	*47.3*
Nannochloris sp.	*20-56*	*60.9-76.5*

Rocca et al., 2015.

Photosynthetic and Solar Conversion Efficiency

As mentioned above, the level of solar radiation and the efficiency at which microalgae are converting the energy of light into chemical energy are essential growth rate parameters and therefore the productivity of this feedstock. The main factor to evaluate the growth rate of biomass is their photosynthetic efficiency (PE), which is defined as the fraction of light that is fixed as chemical energy during photo-autotrophic growth (Bauen et al., 2009). Like terrestrial plants, to fix CO_2 most algae use the C3 pathway (otherwise known as the Calvin Cycle), where CO_2 is combined with a 5-carbon compound to yield two 3-carbon compounds (Darzins et al., 2010). The

C4 pathway is more efficient (up to twice the photosynthetic efficiency of C3 plants) and can be found in diatoms and sugar cane. (Bauen et al., 2009)

The maximum theoretical efficiency of the C3 pathways is approximately 12%. However, the maximum that can be practically achieved is 5%, which is roughly the equivalent to the photosynthetic efficiency of a leaf (Bauen et al., 2009). Other authors (Lundquist et al., 2010) observed light energy conversion into biomass with either actual or simulated full-sunlight intensities of 1% - 3% with a maximum theoretical efficiency of 10%.

Based on the understanding of the energetics of photosynthesis and CO_2 fixation, the maximum theoretical growth rate for (micro) algae can be determined. In areas of high solar insolation (>6kWh/m^2/day) the maximum theoretical growth rate for algae is approximately 100 g/m^2/day. This theoretical maximum will be accordingly lower in areas that receive less solar radiation input. In practice, the productivity of both open and closed systems is in the range of 20-30 g/m^2/day, which is more or less in line with the findings of Rösch (2012).

In summary, microalgae thrive best in warm, low-latitude regions close to the equator that exhibit little seasonal variation in sunlight levels and temperatures. Accordingly, most of commercial microalgae production is taking place in regions that show the characteristics outlined above.

6.3.1.2 Harvesting and concentration / dewatering

Cultivating microalgae in either open ponds or PBRs is the first step of the production process. After the cultivation stage, the biomass needs to be harvested and dried, subsequently to which the lipid fraction is extracted. Depending on the features of the selected microalgae strains, for example size and density but also the targeted concentration of the final slurry, harvesting requires a set of different steps and approaches. With respect to the economic viability of microalgae production, it has to be mentioned that the harvesting stage is one of the main contributors to the overall costs.

The harvesting phase generally includes two main processes, namely thickening and dewatering. In the thickening process the microalgae suspension is transformed into slurry of approximately 6-10% total suspended solids (TSS). Dewatering is performed to further increase the TSS to approximately 10-25%, which is achieved by converting the processed slurry to an algae paste.[7] For both of these processes a variety of different options exist, which show a wide range in terms of efficiency as well as energy requirements. For each of the processes a selection of options is briefly introduced.

Thickening:

- **Chemical coagulation / flocculation:** With these methods the biomass suspension is manipulated by adjusting pH value of the broth or by adding chemical coagulants or flocculants (e.g. chloride, sulphate, aluminium salts, calcium hydroxide solutions) to it. Adding these chemicals to the biomass suspension / broth promotes the agglomeration of the microscopic algal cells into large aggregates that will be settling afterwards by gravity sedimentation;
- **Autoflocculation / bioflocculation:** With this method the algal cells are bound to algae aggregates without using chemical flocculants, which ultimately positively impacts of the environmental performance of algae production. When microalgae cultures are exposed to sunlight, under limited CO_2 supply and pH conditions between 8.6 and 10.5, this process may occur naturally. Bioflocculation can also entail adding bacteria or fungi, or even higher organisms such as shrimp that may facilitate the harvesting and dewatering of microalgae. The efficiency of this method depends, however, to a large degree to the ability of microalgae to form aggregates in such an environment.

[7] Rocca et al. (2015).

Separation of microalgae from the growth medium

After the thickening process, microalgae need to be separated from the growth medium, i.e. water, by applying one of the method outlined below:

- **Gravity sedimentation:** subsequently to the process described above, sedimentation takes place, resulting in the separation of microalgae from the water stream. The advantage of this sedimentation is that it can be applied to various algae strains. However, it logically requires considerable time until the sedimentation process is fully completed;
- **Dissolved Air Floatation (DAF):** In contrast to sedimentation, algal biomass is separated from the water medium by forcing the algal cells to float on the surface, which is achieved by injecting gas bubbles into the broth. Equivalent to sedimentation, DAF is mostly implemented after the different coagulation / flocculation steps.

Dewatering

In order to further increase the concentration of the harvested biomass, i.e. the TSS, the microalgal slurry from the different thickening steps described above is subject to a dewatering process. Dewatering is achieved by applying one of the following steps:

- **Filtration:** depending on the size and density of the selected microalgae strain, this conceptually easy thickening method can be applied in combination with the previous steps or even without them. The suspension is filtrated by forcing it through a membrane with appropriate pore size. Although this method seems easy (conceptual simplicity), it is an expensive and challenging process. Challenges include declining filtration rates as a consequence microalgae depositing on the membrane, which in turn can lead to fouling. In order to counteract this issue, promising lab- and pilot scale research with vibrating membranes has been conducted, seeming to increase the overall biomass recovery. On the other hand, just like regularly cleaning the filtration membranes, vibrating ones are costly and energy-intensive;
- **Centrifugation:** Large microalgae species are harvested solely by sedimentation, the cheapest alternative. For the most commonly occurring small microalgae species, the preferred thickening method is centrifugation. However, due to the low biomass concentration (< 3 g/L) that is particularly noticeable in open pond systems, large centrifuges (with the according capacity) are required, making the process energy-intensive and expensive. High energy demand, high investment costs as well as high operation costs are also characteristics of filtration. In addition, as opposed to terrestrial crops, algae must be harvested on a daily basis.

After the steps outlined above that serve the purpose of concentrating the microalgal biomass, it is dried. The drying step is conducted in order to increase the efficiency of the downstream process, such as extracting lipids from the dried algal biomass and converting these lipids into biodiesel or microalgae-based jet fuel. The heat that is required for drying the biomass is most commonly obtained from natural gas fed drum dryers and other oven dryers. In semi-arid to arid climatic regions, solar or wind drying is a potential option to decrease energy and capital inputs in the microalgae-to-biofuels value chain. The large-scale deployment of naturally drying microalgae is, however, very limitedly feasible due to the long time and large surface required for drying algal biomass naturally. In addition, the risk of material lost is another issue to consider in this regard.

After the harvesting and dewatering steps, a microalgae stream that contains approximately 10-25% solids is obtained, meaning that 100-250 tonnes of water are removed per each tonne of microalgae (Rocca et al., 2015). In order to increase the sustainability of these steps, it is crucial to select harvesting methods that allow for water recycling to the microalgal cultivation system. It also vital that the harvesting techniques additionally preserve the quality of the aquatic biomass for its conversion into the two main microalgae applications, namely bioproducts and biofuels.

With respect to microalgae-based biofuels, a vivid scientific debate is held concerning the ideal harvesting method that shows a satisfying performance in terms of applicability, environmental sustainability as well as cost efficiency. Key factors for enhancing the sustainability of the entire microalgae production chain are, however, decreasing the harvesting costs while increasing the biomass recovery rate.

In existing commercial microalgae production chains of the food and feed industry on the other hand, the most commonly applied techniques include flocculation, sedimentation, filtration as well as centrifugation, which are commercially available. Since the design of these harvesting methods cannot be transferred one-to-one to the biofuel sector, future efforts have to focus on adapting the commercially available harvesting / separation technologies outlined above to microalgae-to-biofuel value chains.

6.3.1.3 Lipid Extraction

After the biomass has been harvested, its lipid content is extracted for further processing into biofuels. This is especially in case of microalgae challenging due to the small size of the algae cell as well as the thickness of the cell wall and cell membrane. Extraction is achieved by first disrupting the cell walls, after which the oil is extracted by either using solvents such as hexane, supercritical fluids (supercritical CO_2), heated oil, or, by applying mechanical and biological extraction methods.

Conventional Solvent Extraction

Solvents are predominantly used to extract and purify soybean seed and roils, high-value fatty acids and nutraceutical products (Darzins et al., 2010), which is why this extraction method is often used in assessing algal biofuel production because the technology is known, and at least for oil seeds, is practiced on a large scale with viable economics. A prime example of using solvents for extraction oil from a biodiesel feedstock is rapeseed.

However, solvent-based processes are most effective with dried feedstocks or those with minimal water content, which logically poses some challenges to the economic viability of applying this extraction method to algal biomass. Drying feedstock entails significant costs and is thereby adding to the overall costs and requires considerable energy inputs. Additional (environmental) costs emerge from utilizing the toxic solvent hexane.

Supercritical Fluid Extraction (SFE)

On a commercial scale, SFE is used in manufacturing to remove caffeine from coffee and to separate high-value oils from plants (Darzins, 2010). In the laboratory, this extraction method has shown viability in trans esterifying lipids into biodiesel from sewage sludge. With respect to algal biomass, supercritical CO_2 has been successfully used to extract algal lipids with the subsequent successful conversion into biofuel. Other supercritical fluids that are currently research for extracting lipids from microalgal biomass include ethylene, ethane, methanol, ethanol, benzene and toluene. Advantages of SFE, especially compared to conventional solvent extraction, mainly concern the rapidness of the process and that it can replace toxic and expensive chemicals such as hexane. In addition, it enables the sequential and selective extraction of different lipid classes (e.g. triacylglycerides, phospholipids), produces solvent-free lipids and high-quality biofuels, and increases the overall efficiency (Rösch, 2012). The required CO_2 is not released into the atmosphere, but can be recycled after extraction or fed into PBRs.

High capital costs and the large amount of energy required to compress supercritical fluids count as the major disadvantages of this extraction technique. Another major drawback of this extraction method is the low yield, which is not sufficient for energy applications.

Mechanical and Biological Extraction

Mechanical extraction processes are used to crack the cell walls of microalgae species leading to enhanced oil recovery. Examples of mechanical treatments are ultra-sonication (disruption with high frequency sound waves) and homogenization, which is carried out by rapid pressure drops (Darzins, 2010). These treatments may provide economically viable solutions for recovering the lipid fraction of algal biomass, but more research is needed. A company (Pursuit Dynamics) that manufactured devices based on steam injection and supersonic disruption filed for bankruptcy in 2013.

Biological extraction techniques potentially offer methods for recovering lipids that require little monetary input and are of simple technical design. Successful demonstrations have been undertaken in feeding microalgae to brine shrimp, which concentrate the algae, followed by harvesting, crushing and homogenizing the larger brine shrimp to recover the oil (Darzins, 2010). It is questionable though if this extraction method is in line with animal welfare, even if the shrimp are held in aquacultures.

In general, it has to be noted that lipid extraction represents another bottleneck hindering the economical industrial-scale production of algal biofuels (Rösch, 2012). So far, only laboratory-scale technologies but no methods for industrial-scale extraction have been established, which therefore serve analytical rather than biofuel production goals.

6.3.1.4 Productivity of Microalgae

For the production of biofuels, a feedstock's productivity is of paramount importance. Although microalgae are naturally occurring worldwide, for them to reach optimal growth rates in artificial cultivation systems, a number of inputs are essential:

- **Sunlight**: Like all biomass, microalgae require sunlight to grow both in open systems as well as in PBRs. Areas with high incidents of solar radiation are crucial for a satisfying microalgae productivity, which is directly linked to their solar conversion efficiency. (see below);
- **Nutrients**: Nitrogen (N) and Phosphorus (P) are important fertilizers to increase the growth rate of algae. Especially nitrogen is a key nutrient as its assimilation is required for the formation of genetic material, energy transfer molecules, proteins, enzymes, chlorophylls and peptides. (Usher, 2014) Potentially negative impacts of nitrogen fertilization will be discussed in more detail in the sustainability chapter;
- **CO_2:** Optimal algae growth occurs in a CO_2 enriched environment. Apart from sunlight, carbon is the most important nutrient for the growth of phototrophic algae, making up approximately half the dry weight of the biomass. Sources of CO_2 are threefold, namely from the atmosphere, discharge from heavy industries (e.g. power plants) and soluble carbonates. As microalgae are capable of utilizing considerable amounts of CO_2, excess, meaning additional supply of carbon may be required to ensure growth. It is, however, important to find the right amount of CO_2, otherwise the growth is inhibited;
- **Temperature:** Although some strains of microalgae are able to withstand extreme temperatures, they generally show highest productivity rates at temperatures between 15°C and 35°C.

All of the factors outlined above are essential for reaching optimal microalgae growth as well as sufficient lipid productivity for biofuel production. The lipid content and productivity of a variety of algae strains is depicted in Table 6.4. As can be seen below, green algae show in most of the cases the highest productivity and are therefore most suitable for further processing into synthetic fuels.

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Schizochytrium sp.	50-57	35.1
Tetraselmis suecica	8.5-23	27-36.4
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Diatoms		
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Chaetoceros calcitrans	14.6-39.8	17.6
Phaeodactylum tricornutum	18-57	44.8
Skeletonema sp.	13.3-31.8	27.3
Skeletonema costatum	13.5-51.3	17.4
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Eustigmatophyceae		
Ellipsoidion sp.	27.4	47.3
Nannochloris sp.	20-56	60.9-76.5

Rocca et al., 2015.

As mentioned above, the level of solar radiation and the efficiency at which microalgae are converting the energy of light into chemical energy are essential growth rate parameters and therefore the productivity of this feedstock. The main factor to evaluate the growth rate of biomass is their photosynthetic efficiency (PE), which is defined as the fraction of light that is fixed as chemical energy during photo-autotrophic growth (Bauen et al., 2009). Like terrestrial plants, to fix CO_2 most algae use the C3 pathway (otherwise known as the Calvin Cycle), where CO_2 is combined with a 5-carbon compound to yield two 3-carbon compounds (Darzins et al., 2010). The C4 pathway is more efficient (up to twice the photosynthetic efficiency of C3 plants) and can be found in diatoms and sugar cane. (Bauen et al., 2009)

The maximum theoretical efficiency of the C3 pathways is approximately 12%. However, the maximum that can be practically achieved is 5%, which is roughly the equivalent to the photosynthetic efficiency of a leaf (Bauen et al., 2009). Other authors (Lundquist et al., 2010) observed light energy conversion into biomass with either actual or simulated full-sunlight intensities of 1% - 3% with a maximum theoretical efficiency of 10%.

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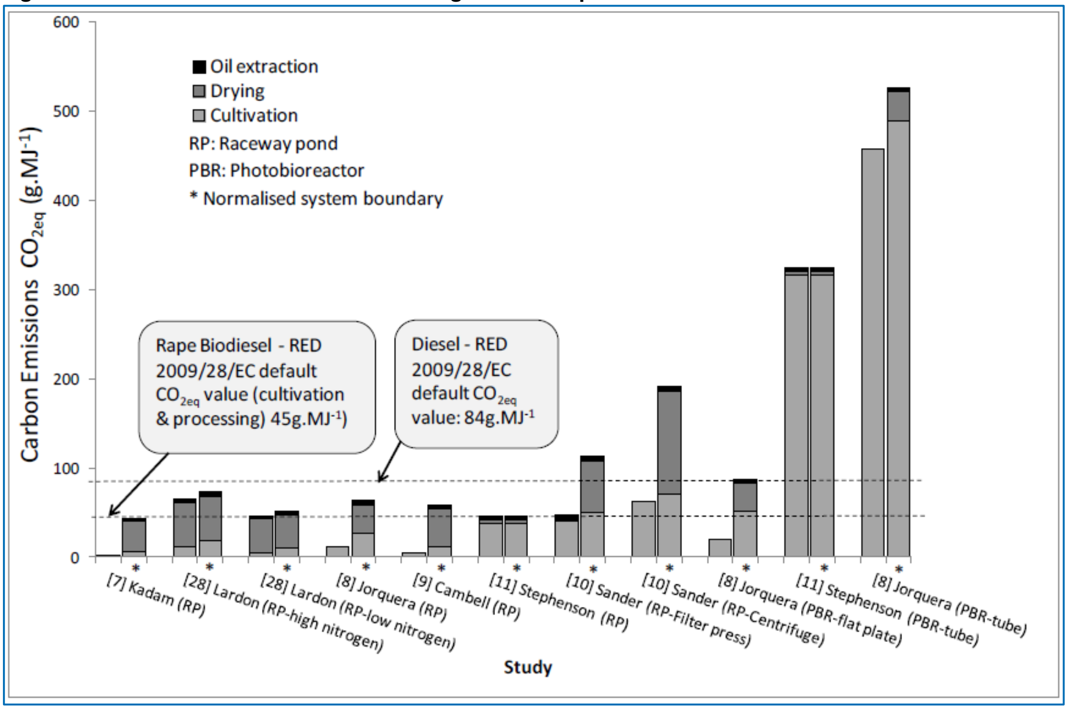
In summary, microalgae thrive best in warm, low-latitude regions close to the equator that exhibit little seasonal variation in sunlight levels and temperatures. Accordingly, most of commercial microalgae production is taking place in regions that show the characteristics outlined above.

6.3.1.5 GHG balance of microalgae production

One of the most vital characteristics an energy feedstock and the biofuel derived from it must have is its GHG reduction potential compared to fossil fuels. Apart from costs, this will be the primary determinant if a feedstock is to be cultivated on a large scale.

Slade and Bauen (2013) estimated the carbon dioxide emissions associated with algal biomass production by multiplying the external inputs to the process by the default emission factors described in the EU Renewable Energy Directive (RED). As can be seen in the figure below, the largest share of the emissions are attributable to the electricity consumption of pumping, mixing and drying microalgae. The emissions associated to cultivation in raceway ponds are roughly in the same magnitude as the cultivation and production stages of rape methyl ester diesel. The cultivation process in PBRs is in all considered LCA studies more carbon intensive than conventional fossil diesel. This picture may change if the carbon dioxide release from the cultivation system itself (not the emissions of the required energy) would have been taken into account. In this case, as suggested in Table 6.4 PBRs could show a far better performance. Slade and Bauen (2013) state conclusively that the analysis of carbon emissions strongly depends on the emission factors used for the different energy inputs into the system (particularly electricity) and that generic factors may not be appropriate in all situations.

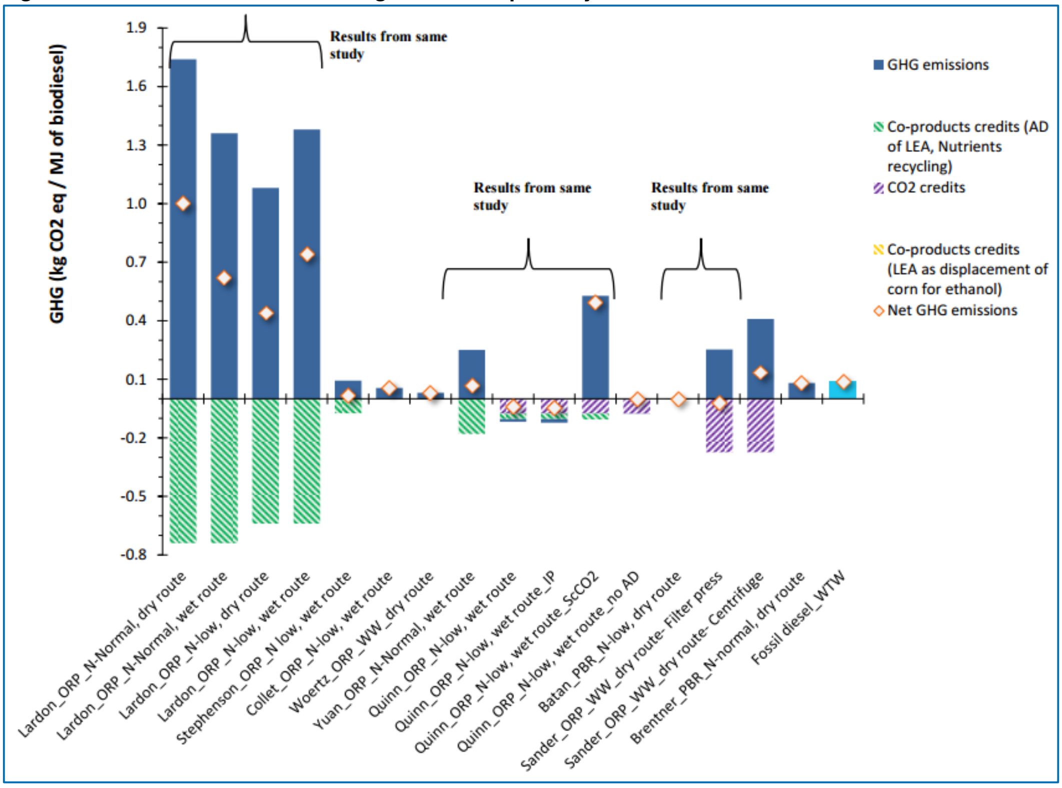
Figure 6.6 Carbon dioxide emissions from algal biomass production



Slade/Bauen, 2013.

In a more recent report from 2015, Rocca et al. compared a series of LCA studies assessing the GHG balance of microalgae-based biodiesel, also showing a considerable range in the results.

Figure 6.7 GHG emissions of microalgal biodiesel pathways



Rocca et al., 2015.

6.3.1.6 Conversion technologies for microalgal biofuel production

Biodiesel

Due to the high lipid content of microalgae, the production of biodiesel has been one of the most important and theoretically viable pathways that have been researched in the past decades. As outlined in the section on lipid extraction, particularly the thick and hard cell walls of microalgae still pose challenges with respect to making this type of aquatic biomass an economically viable and commercially available biodiesel feedstock.

Once the lipids are extracted, their conversion into biodiesel is achieved by conventional transesterification, which is defined as the as a physiochemical process that reorders the molecular structure of oils stirred at moderate temperatures (50-70°C) with a homogenous catalyst (Kröger/Müller-Langer, 2012). The transesterification process requires transglycerides as charge, which in turn are long-chained trivalent alcohols, i.e. fatty acids (FAs) of different chain length connected via a glycerine molecule. These glycerine connections are broken and the fatty acids are again esterified with methanol to a monovalent FA methyl ester, glycerine being a by-product of this process (Kröger/Müller-Langer, 2012).

Of this transesterification process several variations exist today and known to science and industry, respectively, the most widely utilized and therefore mature process is a one-step process in which potassium- or natruim-hydroxide are used as base-catalysts. Due to the relatively easily achievable process parameters, i.e. the low mixing temperatures of 50-70°C mentioned above, transesterification can be established from small- to large-scale – a clear advantage of this conversion process. An issue linked to this process is, however, that it only shows a good performance with oils and lipids that are of low free fatty acid (FFA) content, since these are converted to soap, reduce yields and may hinder the process. (Kröger/Müller-Langer, 2012)

An alternative conversion process is in-situ transesterification, the main advantage being that the chemical lipid extraction and subsequent transesterification can be performed in one step. The solvent from the chemical extraction process serves as a reactant both for lipid extraction and transesterification. In-situ transesterification is, however, a very complex process that is strongly impacted by parameters such as algal species, time, temperature, moisture, reaction mixture and the order in which the different chemicals were added to the reaction. (Kröger/Müller-Langer, 2012)

Biodiesel production from microalgae is, however, not commercial yet. The high costs of lipid extraction and conversion are hereby the main factors hindering a potential commercialization. Particularly physical extraction methods are in case of microalgae almost impossible. This is the case since their small size rapidly leads to the clogging of the filter, immediate press cake formation being the consequence. This is one of the reasons new extraction methods have to be researched and developed.

In addition, microalgae lipids consist not only of triglycerides but to a large part also membrane components, which cannot be processed in the biodiesel production chain. Microalgae can potentially be optimized in terms of an increased lipid content. This, however, translates into a lower growth rate or biologically manipulating the growth process, which in turn makes the production even more complicated.

Alternative aviation fuels

The aviation industry with its ambitious GHG emission reduction targets also shows increased interest in microalgae as a potential feedstock. The high growth rate and lipid content being the main reason for this interest. As opposed to the road transport sector, aviation has stringent rules concerning biogenic-based fuels blended with conventional kerosene. Currently five biojet production pathways are ASTM[8] certified for aviation. The only commercially available production process of renewable jet fuel is the so-called HEFA pathway, HEFA standing for hydro processed esters and fatty acids.

HEFA fuels show more favourable properties than biodiesel, which are achieved by hydroprocessing algae lipids for example. Hydroprocessing generally involves hydrotreatment, hydrocracking and hydroisomerization. It is well known from crude oil refining, the process taking place at temperatures of approximately 350 – 450 °C and an elevated partial hydrogen pressure, while standard catalysts such as CoMo (Cobalt Molybdenum) and NiMo (Nickle Molybdenum) are applied (Kröger/Müller-Langer, 2012). In the hydrotreatment phase, by adding hydrogen oxygen is removed as water and CO_2. The triglyceride are split into separate hydrocarbons and converted into three different branched chain paraffins. A Side product of the cracking process is propane, which can be fed back in the conversion process for energy recovery.

The physical and chemical properties of HEFA are similar to those of synthetic biomass-to-liquid fuels (e.g. Fischer-Tropsch diesel). HEFA fuels have in comparison to biodiesel the same components as fossil fuels, meaning better filter plugging and cold-flow properties (Kröger/Müller-Langer, 2012). The main advantages of the HEFA fuels are their high quality (comparable to fossil fuels) as well as that the HEFA process can be integrated in already existing processes. With respect to microalgae utilization, however, the same challenges as for microalgae-based biodiesel exist.

Hydrothermal Liquefaction (HTL)

A conversion process that has received considerable attention for the production of drop-in biofuels and chemicals in recent years is hydrothermal liquefaction (HTL). HTL is generally a

[8] American Society for Testing and Materials.

thermochemical process, the main difference to other processed being that water is utilized as the reaction medium. In broader terms, the HTL of biomass mimics the natural geological processes believed to be responsible for the formation of fossil fuels in a timeframe measured in minutes rather than over a geological time span. (Jazrawi et al., 2015)

The reaction itself is employed at temperatures of approximately 250 – 350 °C, and pressures high enough to maintain water as a liquid (50 – 250 bar) but close to its critical point of 374°C and 221 bar.

The main advantage of this process is that the biomass can be processed directly, without an energy-intensive drying step, since water acts as both solvent and catalyst, yielding various products such as bio-crude oil, aqueous dissolved chemicals, solid residue and gas (Jazrawi et al., 2015). The particular advantage of HTL as conversion route for microalgae is that it tolerates low cell concentrations because HTL is a wet process. This means that the feedstock preparation steps of dewatering and thickening do not have to be employed. In addition, low-lipid algae strains that often have a much higher growth rate than those optimised to accumulate high lipid levels. (Jazrawi et al., 2015)

In essence, this means that the to some extent technically immature, capital- and energy-intensive preparation steps required for converting microalgae into fuels do not have to be deployed, which clearly shows the potential of HTL as a conversion technology for microalgal biomass.

Although HTL research is currently conducted at lab scale, more and more efforts are focussing on brining this conversion technology to demonstration level.

6.3.2 Macroalgae

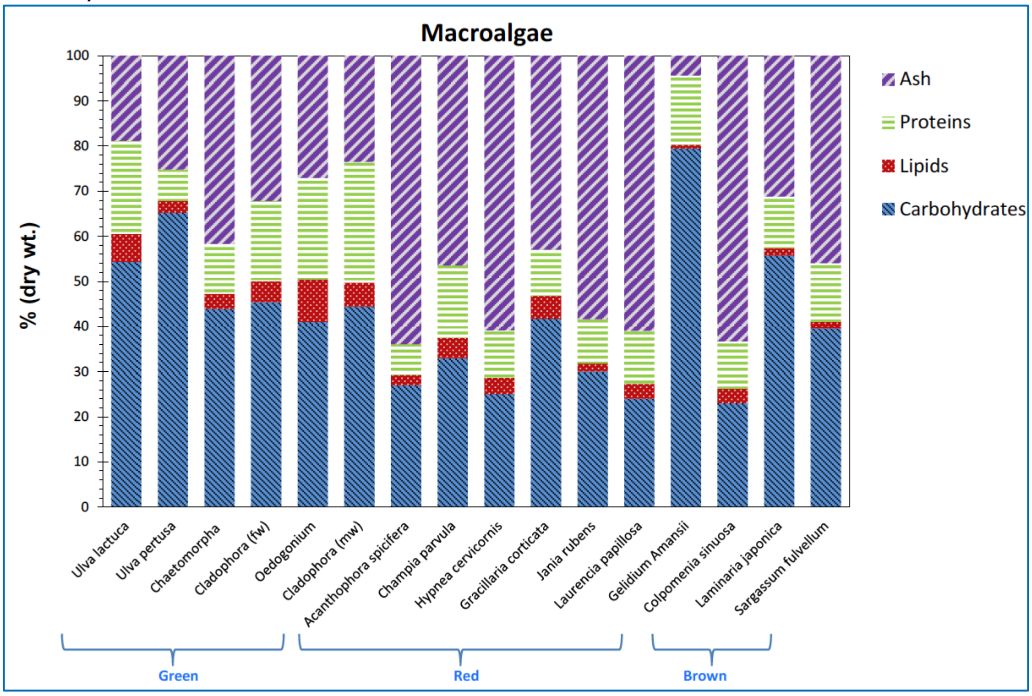
Macroalgae, or seaweeds are multicellular, fast-growing marine and saltwater plant-like organisms that can grow to considerable size, some species up to 60m in length. Macroalgae are differentiated by their dominant pigmentation, i.e. red (Rhodphyta), brown (Phaeoohyta) and green (Chlorophyta) (West et al., 2016). They mostly grow in costal (near-shore) areas attached to rocks or other suitable substrates and act as essential components for preserving the biodiversity of marine ecosystems. Other types of macroalgae float freely in oceans or drift along coastal areas.

Like microalgae, the growth rate of macroalgae considerably exceeds the rate at which terrestrial crops grow. This is due to the fact that macroalgae along coastal areas are subject to vigorous water movement and turbulent diffusion, which allows for very high levels of nutrient uptake, photosynthesis and growth (Kraan, 2013). It is for these reasons that most macroalgae do not require fertilisation. Non-cultivated types of macroalgae show average productivities of 3 to 11.3 kg (dry wt.) / m^2 per year, cultivated species reach productivities of up to 13 kg (dry wt.) / m^2 per year. (Rocca et al., 2015)

As shown in Figure 6.8 the main organic compounds of macroalgal biomass are carbohydrates, proteins and lipids in varying ratios, which primarily depend on the species as well as the growing site location. As opposed to microalgae, macroalgal biomass is characterized by low lipid contents, only accounting for less than 10% dry weight. Seasonal variations in the chemical composition may appear, depending on predominant environmental factors of the surrounding ecosystem such as light intensity, temperature as well as nutrient and CO_2 supply. Macroalgae are generally not suitable for the production of biodiesel, but show desirable properties for the production of numerous other biofuel applications, which will be shown later on in this report.

Figure 6.8 Chemical composition of various green, red and brown macroalgal species (in dry wt. biomass).

Figure 6.9 Chemical composition of various green, red and brown macroalgal species (in dry wt. biomass)

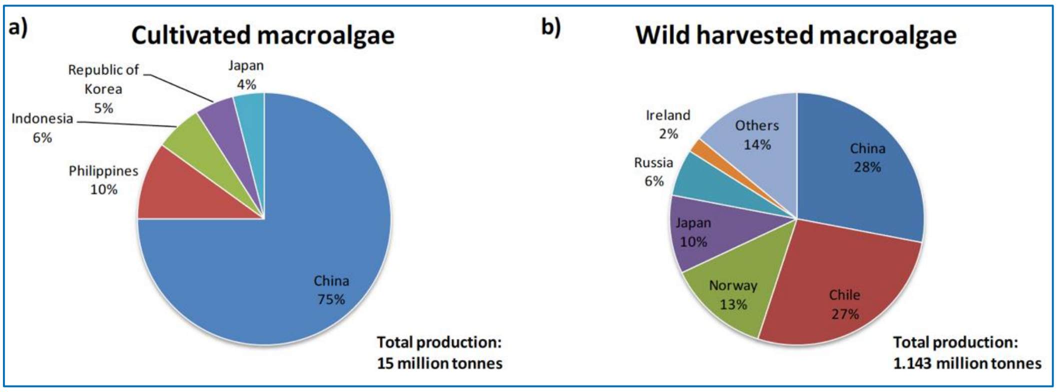


Rocca et al. 2015.

6.3.2.1 Macroalgae Production

Macroalgae are in contrast to microalgal biomass cultivated and produced at large scale, either in aquafarms (maricultures) that are located offshore, near-shore or land-based in dedicated facilities. The majority of macroalgal biomass is cultivated in Asian countries, China accounting for 75% of the global production of 15 million (wet) tonnes (2011) (Rocca et al., 2015). Other sources such as the FAO report that seaweed production volumes reached 23.8 million tonnes in 2012. Seaweeds are primarily (80% of total production) produced for direct human consumption, either eaten fresh or dried for its nutritional value or for flavouring purposes (West et al., 2016). The remaining 20% share of the total production is used as a source of the phycocolloids extracted for the use in the food, cosmetic, and medical industry as well as for animal feed additives, fertilizer, water purifier, and probiotics in aquaculture (West et al., 2016). In addition, macroalgae are also harvested from wild stocks, accounting for 1.143 million tonnes in 2011, as shown in Figure 6.10.

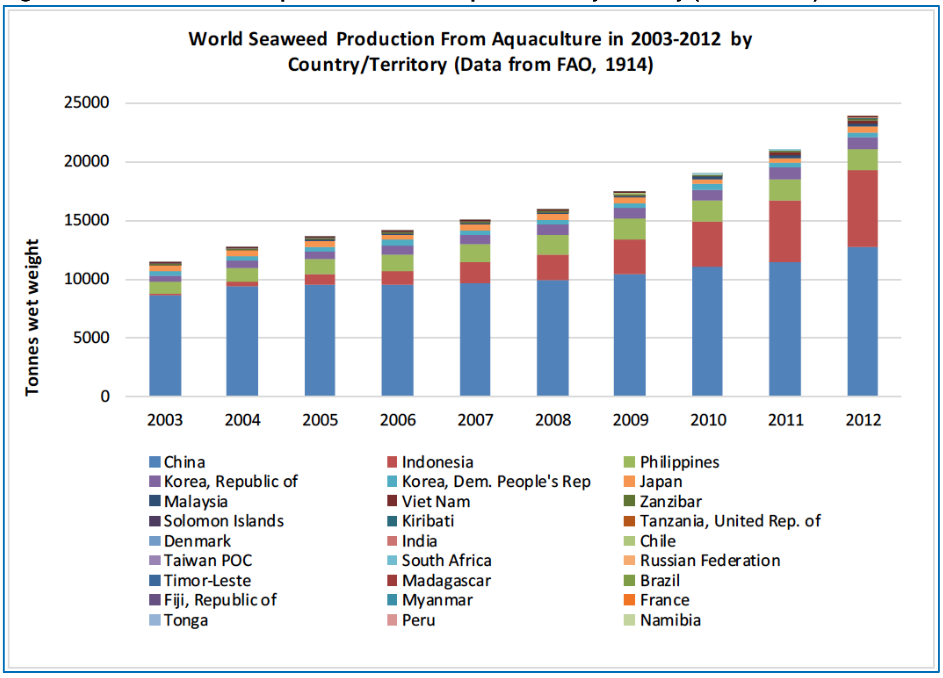
Figure 6.10 Annual estimates of annual cultivated and wild harvested microalgae by country worldwide in 2011



Rocca et al. 2015.

Macroalgae cultivation in aquacultures is at an early stage of development in Europe. Mechanical harvest of available wild seaweed stocks is, however, well-established, the most important countries being Norway, France and Italy, followed by Ireland and Scotland.
A detailed overview that depicts the development of macroalgae harvest both from aquaculture and wild stocks including the most important producing regions is given in Figure 6.11 & Figure 6.12.

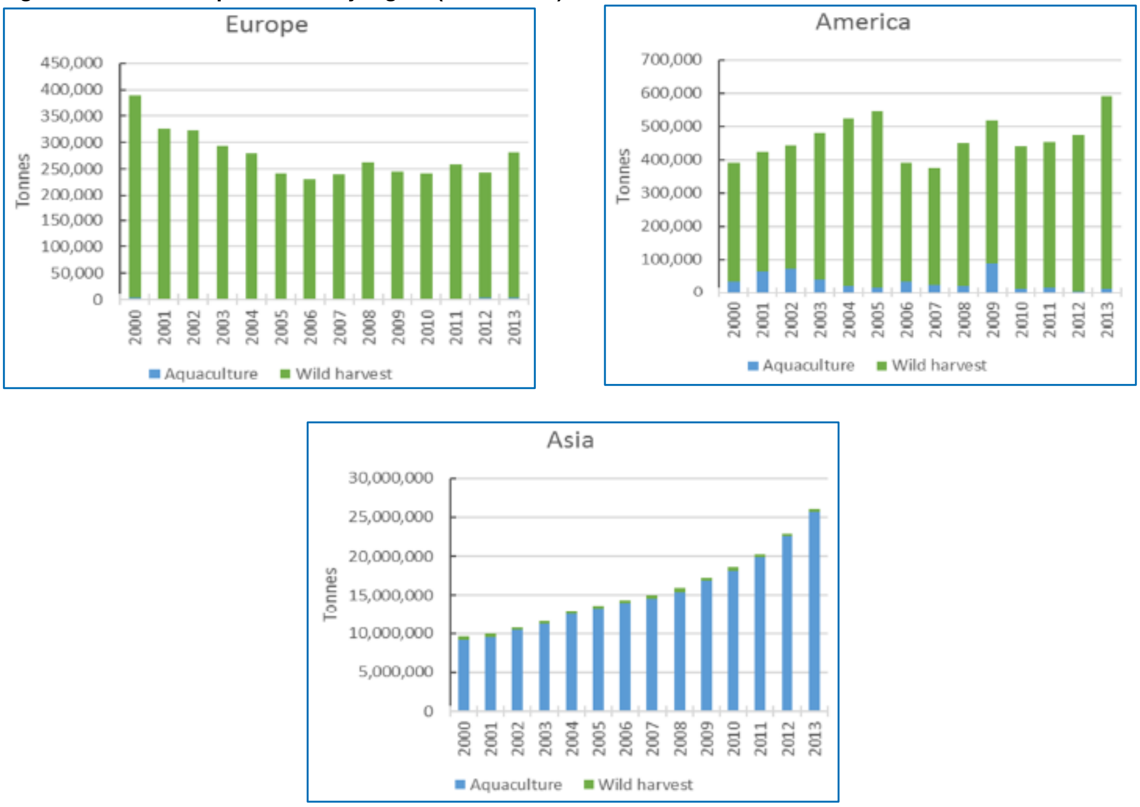
Figure 6.11 World seaweed production from aquaculture by country (2003 - 2012)



West et al., 2016.[9]

[9] Data from FAO, **2014.**

Figure 6.12 Seaweed production by region (2000 - 2013)



Capuzzo/McKie, 2016.

Cultivation systems for macroalgae range from intertidal fixed and floating bottom farms, for example in the Philippines, Vietnam and Thailand to advanced net structures and long-line systems for kelp in China, Korea and Japan (Kraan, 2013). In offshore systems, seaweeds generally require supporting structures such as anchored lines or nettings for the protection against tide and strong currents. These cultivation systems typically consist of 150 m long culture ropes that are anchored to 10 m long structural ropes, which in turn are tied to concrete blocks at the bottom of the sea. (Rocca et al., 2015)

The farming devices in near-shore cultivation systems are similar to those used in offshore systems, meaning that the seaweeds require supporting rope or net systems for optimal growth. While near-shore systems are commercially mature in Asian countries, environmental regulations as well as social resistance in Europe and the United States pose major challenges to the implementation of large-scale macroalgae cultivation systems along costal zones and rivers. It has to mentioned, however, that macroalgae cultivated in near-shore systems are able to serve as bio-filters as they are able to remove nitrates and phosphate from the water during their growing phase.

Land-based systems where macroalgae are cultivated in ponds, either as free standing farms or in combination with land-based aquaculture systems (e.g. fish culture) are not practiced at large scale at the moment. The advantage of land-based cultivation systems is, however, that macroalgae are not subject to the fluctuating conditions of the open sea, i.e. changes in temperature, salinity or currents of varying magnitude.

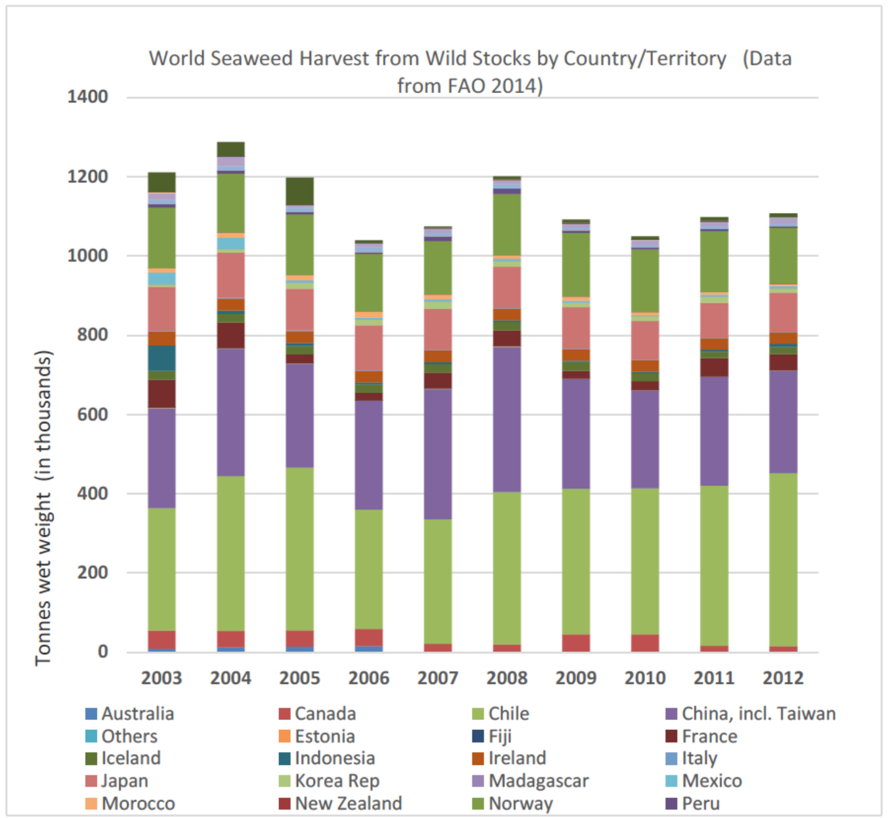
The most commonly harvested species and the corresponding harvesting techniques are given in Figure 6.13.

Figure 6.13 Macroalgae species harvested in Europe

www.netalgae.eu.

Although harvest of wild seaweeds has been practiced for centuries, reservations exist concerning the removal of large quantities due to the importance of wildly occurring macroalgal species in preserving the biodiversity of marine habitat for a wide range of organism such as fish or birds. In France for example, the heavily harvested brown kelp 'Laminaria digitata' is reported to be at the verge of local extinction. Another issue linked to the overexploitation of certain wild macroalgae species is the increased growth rate and cover of other algae that are not harvested and outcompete the desired species. (West et al., 2016)

Figure 6.14 World seaweed harvest from wild stocks by country



West et al., 2016.

Despite the importance of seaweeds for the marine ecosystem and their dispersed nature along the coastline, macroalgae harvest is practiced mostly for food in the countries shown in Figure 6.14 above.

6.3.2.2 Harvest and Concentration

When macroalgae have reached maturity, i.e. the desired length, they are harvested by either leaving a small piece that will regrow afterwards, or by removing the entire plant and cutting small pieces for further cultivation (Rocca et al., 2015). As mentioned above, manual harvest of wild seaweed species for food applications is common along the coastal areas. For large quantities to be harvested, mechanical systems that require floating vessels have to be used. The exact type hereby depends primarily on the form and growth characteristics of macroalgae. Two approaches are most commonly followed:

- rotating blades suitable for species growing attached to supporting structures;
- suction systems and subsequent cutting.

After the macroalgal biomass has been harvested, foreign objects such as stones, sand or other types of debris have to be removed manually or by washing with water. In order to increase the surface area / volume ratio for more efficient conversion of macroalgae into biofuels, the biomass is chopped or milled. (Roacca et al., 2015)

In the last step before conversion, the water content of macroalgae has to be decreased from 80% - 90% to approximately 20% - 30%. In tropical countries with sufficient solar radiation, sun-drying is the main dewatering method. This process obviously does not require fossil energy but is dependent on the weather as well as on the volume of macroalgae. In tropical climates, sun-drying takes approximately 2 – 3 days in sunny weather conditions and up to 7 days in rainy seasons. Although solar drying methods are clearly most cost-efficient, large areas are required as only around 100 g of dry matter can be produced form each square meter of sun-drier surface (Milledge et al. 2014). Centrifugation is currently the most widely applied dewatering method for macroalgae, although comparable challenges to those of centrifuging microalgae exist. Another method mechanical macroalgae dewatering method is simply pressing the biomass.

In general, it has to mentioned that unlike microalgal biomass, where production and extraction of lipids is primary goal, macroalgae have less of a demand for dewatering as part of the pre-treatment process. Anaerobic digestion, fermentation, and hydrothermal liquefaction have either a high tolerance or requirement for water (Roesijadi et al., 2010). In case of macroalgae, dewatering is more important in terms of increasing “shell life” of the biomass and decreasing its weight, which positively impacts transportation costs when distances between harvest sites and processing plants are of concern.

6.3.2.3 GHG balance of macroalgae production

LCA studies addressing the GHG balance of macroalgae production are almost non-existent. This situation is even more severe with respect to assessments evaluating the lifecycle emissions of macroalgae cultivation as a source for biofuels. This is mainly due to the fact that the production of advanced biofuels based on macroalgae is at a very early stage of development with crucial parameters such as method of cultivation, yield per hectare under varying conditions, time and method of harvest are not properly accounted for and assessed, respectively. A general advantage of macroalgae opposed to microalgal biomass is, however, that the cultivation of macroalgae does not require the supply of fertilizers such as nitrogen (N) or other nutrients like CO_2, since they draw the required nutrients from the surrounding seawater. On the other hand, significant emissions are linked to operating machinery such as vessels. In addition, drying macroalgae is very energy intensive (see below).

One study by Aitken et al. (2014), assesses the Global Warming Potential (GWP) and a series of other environmental impact parameters such as eutrophication, acidification or ozone layer depletion and Energy Return on Investment (EROI) of macroalgae cultivation and processing to biofuel applications in Chile by modelling three cultivation scenarios. These scenarios differ from each other in terms of preparation of macroalgae for cultivation (hatchery of seeds in tanks; tying previously cultivated macroalgae to ropes), cultivation method (bottom culture; long-line culture) and harvesting vessel (small vessel; barge) as well as as size of the cultivation area, based on information provided by local farmers. The assumed end-products hereby range from bioethanol, over fertilizer to biogas-based electricity.

Although the LCA study relied in parts on rather outdated data from the literature, it nevertheless concludes that macroalgae-based bioenergy production in Chile can be realized sustainably, biogas produced from the macroalgae strain ‘G. chilensis’ being the most favourable one. For the future Aitken et al. (2014) predict that with improved cultivation and processing techniques, bioethanol and biogas-based electricity from long-line cultivated ‘M. pyrifera’ will be a much more sustainable method, thereby indicating possible production pathways that should be explored in more depth in the future.

For the European context, a study by Alvarado-Morales et al. (2013) assesses GHG balances of two hypothetical macroalgal biofuels scenarios, namely:

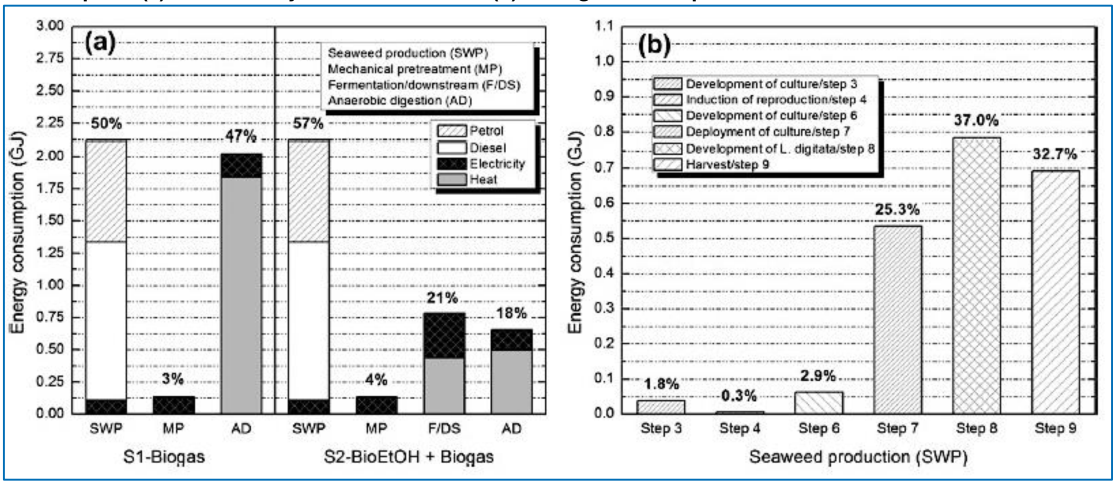
- Scenario 1: cultivation of ‘Laminara digitata’ on long-line systems in an offshore site in Denmark. In this scenario, the macroalgal biomass is harvested and mechanically pre-treated by milling and grinding, subsequently to which it is anaerobically digested for biogas production and the digestate is used as an agricultural fertilizer;

- Scenario 2: identical cultivation, harvesting and pre-treatment setup as in the scenario 1. In this scenario the biomass is converted to bioethanol via simultaneous saccharification and fermentation (SSF), the residues of this production step are used for biogas production via anaerobic digestion. The produced bioethanol is further distilled and blended with fossil gasoline.

The analysis showed that for both scenarios major energy inputs, which in turn result in the emissions of climate active gases, are required for the operation of the vessels that are used for cultivation, maintenance, harvest and transport of the macroalgae strain. This amount to approximately 30 litre of diesel per tonne of dry weight biomass. In addition, the heat requirements of approximately 1.84 MJ per kg of dry weight biomass for drying the macroalgae are the other major contributor to the GHG balances of the scenarios. The authors conclude that cultivating and harvesting macroalgae in offshore sites are the most energy and therefore emission intensive processes of the outlined biofuel pathways, accounting for more than half of the total energy demand in both scenarios. In the bioethanol scenario, the downstream processes i) fermentation and ii) bioethanol purification also contribute significantly to the overall GHG balance. Nevertheless, the authors conclude that compared to the fossil counterpart, energy production from seaweed delivers large GHG emission reductions of 603 and 616 kg CO_2-eq. per tonne of dry seaweed for scenario 1 and 2, respectively.

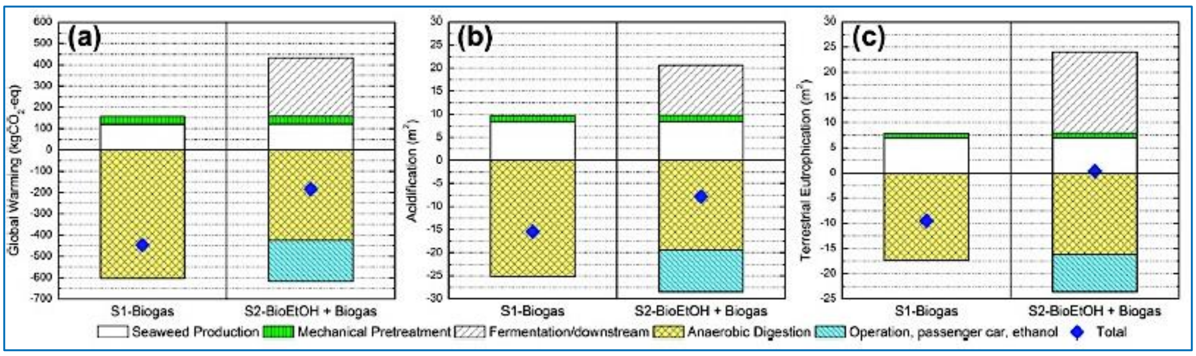
The results of the scenario assessment conducted by Alvarado-Morales et al. (2013) are graphically depicted in Figure 6.15 & Figure 6.16.

Figure 6.15 Process contribution (absolute values in GJ, relative contributions in %) to energy consumption (a) for the analysed scenarios and (b) during seaweed production



Alvarado-Morales et al., 2013.

Figure 6.16 Potential environmental impact on (a) Global Warming (kg CO2-wq.), (b) Acidification (m2) and (c) Terrestrial Eutrophication (m2) for baseline scenarios (one tonne of dry seaweed)



On the other hand, credits that can be obtained through a variety of measures in the respective production chains, e.g. for i) electricity recovery from biogas combustion delivered to the grid ii) electricity production from the AD residual biomass iii) utilization of digestate as a fertilizer in agriculture have a positive impact on the GHG balances of the two scenarios outlined above. The magnitude of these credits, however, has to be defined more clearly and therefore their impact on the overall GHG balances has to be assessed in more detail.

Apart from the unclear impact of carbon credits on the GHG balance of macroalgae production, it has to be mentioned that the accuracy of (inventory) data underlying currently existing LCA studies in this field can be questioned or regarded as speculative. This is for the simple reason that operational data for large-scale systems are not available yet. It is for this reason that more R&I efforts should be placed on generating reliable data from lab-scale cultivation set-ups.

6.4 Identification of major players in R&I

Table 6.5 Major R&I players in aquatic biomass research

Name	Industry Player (y/n)	Country	Feedstock	Research Areas	Research Specifics	Facility Type	website
Algae Tec.	Yes	Australia	Microalgae	Cultivation, Processing	Developing technology that captures waste carbon dioxide to produce commercial quantities of algae for use in the food and fuel sectors.	Commercial	http://algaetec.com.au/index.php
Algenol Biotech	yes	Germany / worldwide	Microalgae	Cultivation	Cultivation in PBRs.	Commercial	http://www.algenol.com
Algosource Group	Yes	France	Microalgae	Cultivation	Cultivation in PBRs.	Pilot	http://algosource.com
Ben Gurion University	No	Israel	Microalgae	Cultivation	Cultivation in OPS.	Pilot / Demonstration	http://in.bgu.ac.il/en/Pages/default.aspx
Ghent University	no	Belgium	Microalgae	Technology Demonstration	Treatment of real waste water streams.	Pilot	http://www.ugent.be/en
Hochschule für Technik und Wirtschaft des Saarlandes	no	Germany	Microalgae	Cultivation	Cultivation in PBRs, experimental recirculation aquaculture system as a source of nutrients.	Pilot	http://www.htwsaar.de
Indigo Rock Marine Research Station	yes	Ireland	Macroalgae	Cultivation, Filtration		Pilot	http://www.indigorock.org
Karlsruhe Institute of Technology	no	Germany	Micro- and Macroalgae	Sustainability Assessment	sustainability analysis and evaluation of different production procedures for microalgae and macroalgae.	no	http://www.kit.edu/english/
National University of Ireland	no	Ireland	Macroalgae	Cultivation	Cultivation of native species of kelp and other species with commercial value / interest.	Pilot	http://www.nui.ie
Plymouth Marine Laboratory	no	England	Microalgae	Cultivation	Provision of a strategic research capability in marine science.	Pilot	http://www.pml.ac.uk

Name	Industry Player (y/n)	Country	Feedstock	Research Areas	Research Specifics	Facility Type	website
Qingdao Institute for Bioenergy and Biotechnology	No	China	Microalgae	Cultivation, Processing	PBRs, Infrastructure.	Pilot	http://english.qibebt.cas.cn
Solix Biosystems	Yes	US	Microalgae	Cultivation, Harvest, Extraction		Commercial	http://www.solixalgredients.com,http://www.biofuelsdigest.com/bdigest/2012/08/03/solix-biosystems-to-expand-commercial-algae-production-with-31m-series-c-venture-round/
The Scottish Association for Marine Science	no	Scotland	Micro- and Macroalgae	Culture Collection	maintaining algal cultures to develop best practice methods.	Pilot	http://www.sams.ac.uk
University College Dublin	no	Ireland	Micro- and Macroalgae	Conversion and storage	Development of materials and methods for sustainable conversion of biomass to bioenergy.	Pilot	https://www.ucd.ie
University of California: California Center for Algae Biotechnology	no	US	Microalgae	Cultivation	support development of innovative, sustainable, and commercially viable algae-based biotechnology solutions for renewable energy, green chemistry, bio-products, water conservation, and CO2 abatement.	Pilot	http://algae.ucsd.edu/about/index.html
Wageningen University	No	The Netherlands	Microalgae	Cultivation	Cultivation in Open Pond System / LCA / economic viability of algae cultivation.	Pilot	http://www.wur.nl

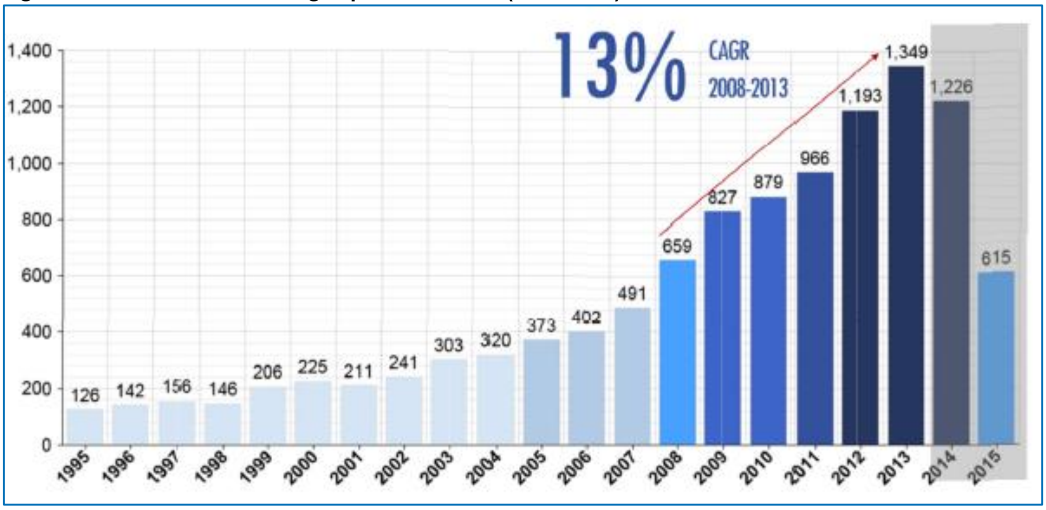
Patent Landscape of Microalgae-related Technologies and Products

A useful indicator for assessing the R&I potential of a technology or in more general terms, a sector, is the analysis of filed patents over a defined period of time, e.g. one year. A recent report[10] from 2016, prepared for the World Intellectual Property Organization (WIPO) by Questel Consulting in cooperation OMPIC[11] and MASCIR[12] analyses the patent landscape in microalgae cultivation and the subsequent processing steps of harvesting, lipid extraction and conversion for biofuel production as well as other applications.

For microalgae-related technologies, WIPO analysed a total of 11.056 patent families (patent applications relating to the same invention) for distinct microalgae geni, processing technologies, applications and end-users (WIPO, 2016). Figure 6.17 shows the patenting activity for microalgae patent families from 1995 – 2015. In the phase from 2008 – 2013, a compound annual growth rate (GACR) of 13% is shown, indicating the heightened patenting activity that is attributable to the emergence of so-called 3rd generation microalgae-based fuels.

For Figure 6.17, the date of patent filing is used instead of the patent's publication date, as this is a good indicator of the date of innovation. 18 months are usually between the date of first filing a patent and its publication. This is insofar important for the figure below (as well as the others presented in this section), as the data collection for the WIPO report referenced here took place at the end of 2015, 2013 being the last year of complete patent information.

Figure 6.17 Number of microalgae patent families (1995-2015)



The number of filed patents is insofar a good R&I indicator, as it allows for differentiation between technologies that are at an early stage of research and development, and technologies for which a potential market is sought, meaning that the technology shows a certain scale-up potential.

In practice, this differentiation is resembled by the order of patent offices in a country or region where patents are filed for, i.e. at offices of first filing (OFF) and offices for second filing (OSF). At OFFs, patent protection for a given invention is sought for by the applicants. In order to file for patents, applicants must strike a balance between the costs of filing in many different territories versus their estimate of the potential economic returns the technology could provide (WIPO, 2016).

10 http://www.wipo.int/edocs/pubdocs/en/wipo_pub_947_5.pdf.

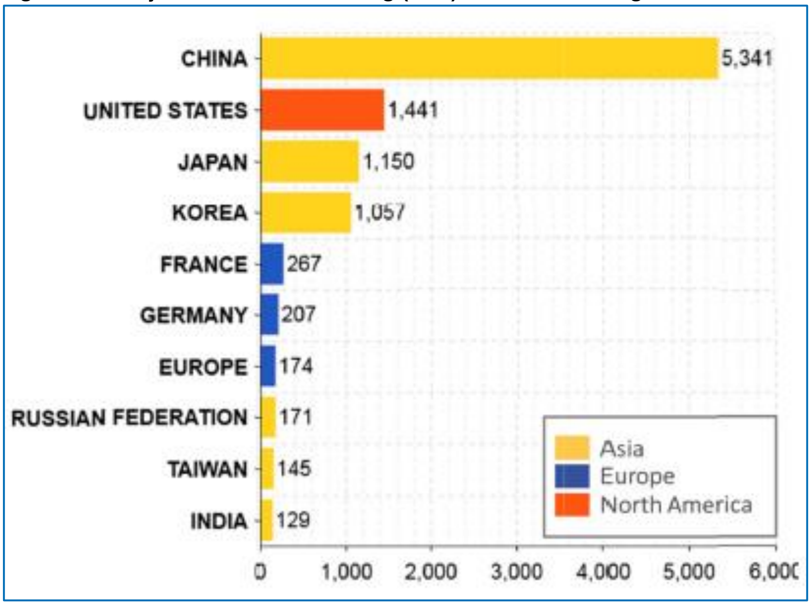
11 Macoccan Office of Industrial and Commercial Property.

12 Moroccan Foundation for Advanced Science, Innovation and Research.

It can be assumed, however, that the patent is initially filed for when the technology shows a certain maturity level, otherwise the initial application would not be filed. For an applicant, filing locally at OFFs (priority filing event) has a series of advantages such as native language, IP laws and jurisdiction etc. Apart from these advantages for applicants, the number of patents filed at OFFs also allows for an evaluation of the R&I landscape in different regions. The higher the number of OFFs in a defined region, the more R&I activities are taking place in that particular region.

As can be seen in Figure 6.18 featuring an initial filing location analysis, China has currently the highest innovation potential in microalgae-related technologies worldwide. However, this analysis shifts when the number of Offices of Second Filing (OSF) is considered.

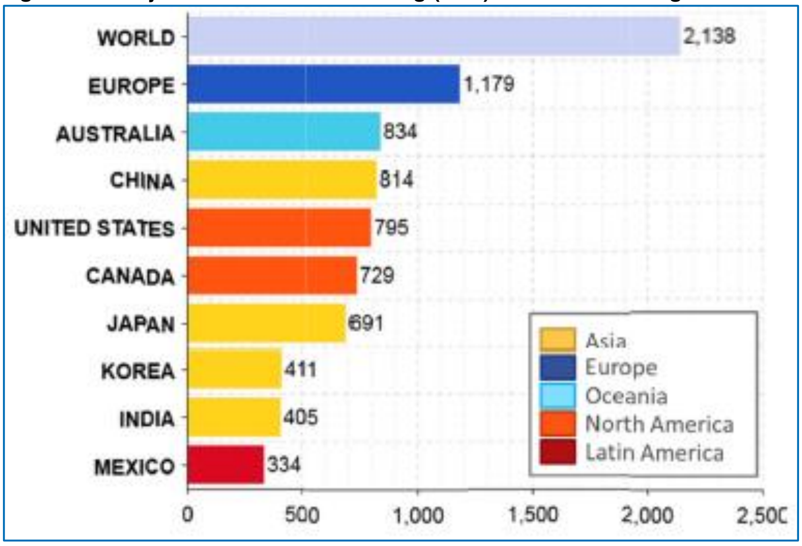
Figure 6.18 Major Offices of First Filing (OFF) linked to their region



When individual inventions are protected in multiple locations, it means that the applicant either belongs to an organization that holds businesses in multiple regions and therefore requires patent protection, or that the technology is of higher intrinsic value making a broader geographic protection necessary. As the number of different jurisdictions where an applicant seeks protection closely correlates to a large increase in the cost of protection, patent families filed in more territories could be an indication of a higher intrinsic quality, or at least likely to be used more extensively by their owner. (WIPO, 2016)

While the office of first filing indicates where a technology was developed, the office of second filing can provide an indirect market analysis, giving insight on countries which were considered by applicants as likely to represent a good market, or location for manufacturing, or the products generated from the technology. (WIPO, 2016)

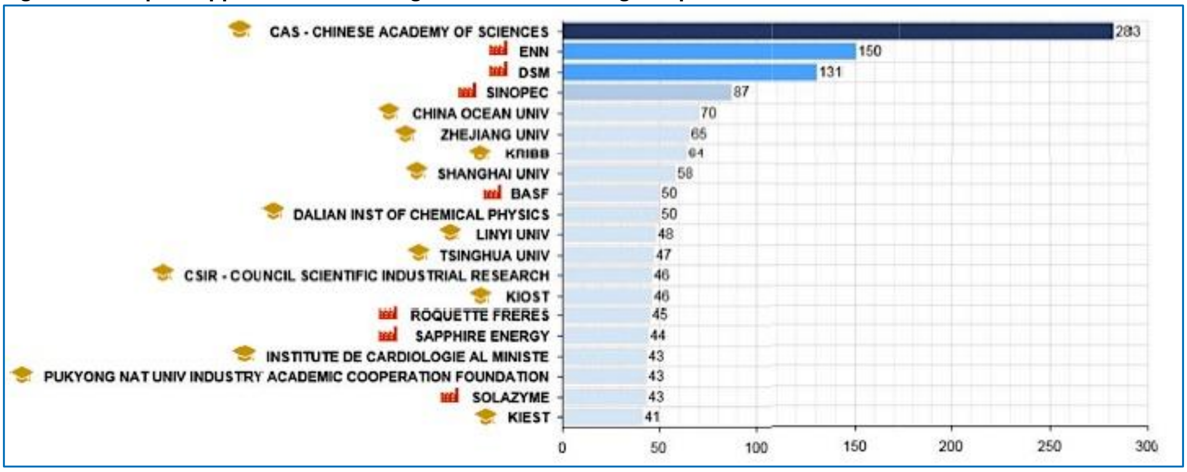
Figure 6.19 Major Offices of Second Filing (OSF) linked to their Region



Comparing Figure 6.19 and Figure 6.20 with each other, it becomes evident that although Asian countries generally show a high R&I potential for microalgae-related technologies and products, markets for these technologies / products are primarily sought for in Europe, i.e. the number of OSFs is higher. In order to put both figures in perspective, it has to be mentioned, that China (the leading Asian country with respect to microalgae patent families) is a relatively new player in this field with almost no patents filed prior to 2009. China has 'caught up' though, seeing as the majority out of the top 20 applicants in the microalgae field worldwide are Chinese organizations (Figure 6.20).

The figure below shows the size of the patent portfolios from the most active entities in microalgae R&I, based on their patenting activity, and how the number of patents is distributed among them.

Figure 6.20 Top 20 Applicants in microalgae-related technologies / products



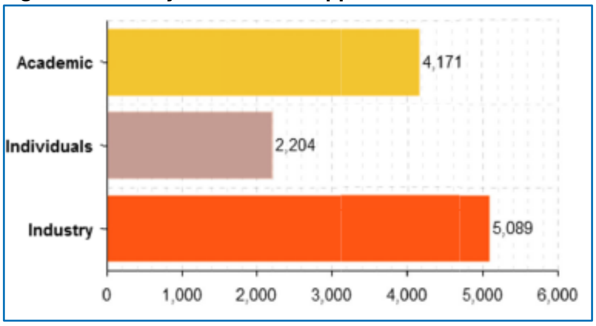
Comparing the number of the microalgae patent families worldwide to the top 10 applicants in Europe (Figure 6.22) highlights the relatively marginal activity in patent filing in Europe, at least amongst the top 3 applicants. France appears to have built a network of academic and industrial players, four French organizations being in the top 10: CNRS (academic), Roquette, L'Oréal and Fermentalg (industrial). According to the WIPO report (2016), DSM is the undisputed leader in Europe since 2010 if recent acquisitions are included. Among the top 10 in Europe, only Roquette and Fermentalg are specialized players with large business units. The other players are international chemical companies. (WIPO, 2016)

Figure 6.21 Top 10 Applicants in Europe

TOP 10 APPLICANTS - EUROPE	Total
BASF	42
ROQUETTE FRERES	42
L OREAL	29
DSM	20
CNRS	19
UMWELTTECHNIK	19
FERMENTALG	16
UNIV ALMERIA	14
BAYER AG	13
ENI	11
LONZA	10
SOLVAY	10

Another option to analyse microalgal patent activity worldwide is to review the applicants and identify whether they are academic, governmental research institutions of corporations. As shown in Figure 6.22 below, 38% of microalgal patent activity is conducted by academic or governmental entities, approximately 46% of the global patent activity is originating from industry.

Figure 6.22 Analysis of Patent Applicant Profile



Specialisation of microalgae innovation by geography

After generally analysing the microalgae patent portfolio in terms of the main players involved in the field and their geographic distribution, the figure below conclusively breaks down the microalgal patent portfolio into the main technical categories of microalgae patent activity correlated to the number of major OFFs.

	CHINA	UNITED STATES	JAPAN	KOREA	FRANCE	GERMANY	RUSSIAN FEDERATION	INDIA	TAIWAN	SPAIN	UNITED KINGDOM
Process: Bioengineering	581	413	58	59	14	25	10	8	8	2	14
Process: Conversion	236	170	38	40	14	19	17	1	6	10	2
Process: Extraction	1168	220	166	185	50	18	27	25	31	26	14
Process: Growing technologies	750	212	34	106	29	33	8	20	16	22	11
Process: Harvesting Dewatering	1468	312	96	134	57	25	12	23	20	27	15
Products: Fuels	808	517	162	188	47	44	32	16	22	27	20
Products: Lipids	535	334	72	99	54	25	3	24	10	10	13
Products: Other products	76	13	10	12	4	2	6	0	1	0	0
Products: Pigments	820	315	216	160	53	28	21	44	20	23	10
Products: Polysaccharides	518	167	98	36	62	27	3	9	13	6	8
Products: Proteins	1058	245	94	80	42	27	10	9	15	6	9
Application: Cosmetic	232	115	132	90	110	36	14	3	6	13	9
Application: Animal Nutrition - Feed	907	157	128	97	26	28	31	9	13	12	13
Application: Aquaculture	538	81	11	23	9	5	4	3	6	5	4
Application: Bioremediation	712	163	97	71	19	25	24	4	15	19	6
Application: Energy	757	511	140	182	42	38	28	21	19	27	21
Application: Human Nutrition - Food	1180	289	315	207	69	37	15	24	19	16	7
Application: Pharmaceutical	1358	474	330	181	106	57	47	36	39	16	24

The main findings that can be derived from the can be summarized as follows:

- Due to the historical use of microalgal biomass in China, entities located there predominantly focus on nutritional and medical microalgae applications;
- R&I players in the United States primarily focus microalgae-based biofuel applications with a number of large projects being funded in this area. Bioengineering is particularly developed in the US;
- The Asian players Japan and Korea focus on the extraction of pigments for applications in the food industry. Korea additionally focused strongly on pharmaceutical applications.

6.5 Definition of scenario elements for selected R&I fields

6.5.1 Scenario elements for Microalgae

Baseline Scenario:

- Microalgae production takes place worldwide for food and feed products at commercial scale with an annual production volume of 9.200 tonnes. This aquatic biomass is primarily cultivated in open pond systems in regions with sufficient solar radiation and the corresponding temperatures such as Israel, Australia, Asia, the United States and Southern Europe;
- Focus is placed on microalgae production in open pond systems (at low biomass concentration of < 3 g/L);
- Moderate cultivation of microalgal biomass in closed PBRs due to the high costs linked to cultivation, high energy requirements and generally high production costs;
- Moderate R&I efforts on improvement of algae strains, harvesting methods and conversion technologies such as HTL.

Advanced R&I Scenario:

- Increased R&I efforts for the development of Photo-Bioreactor (PBR) systems;
- Cultivation is shifted from open pond systems to closed PBRs with the aim of biofuel production;

- Increased operation of PBRs at pilot to demonstration scale (i.e. small commercial scale) in moderate temperatures and in proximity to industrial facilities with ample CO2 supply;
- Targeted R&I efforts on algae strains with high productivity rate and lipid content such as chorella vulgaris, chorella sp. or Dunaliella salina;
- Adaption of harvesting methods that are commercially available for the food and feed sector such as flocculation, sedimentation, filtration as well as centrifugation to microalgae-to-biofuel value chains;
- R&I efforts on direct conversion of microalgae to biofuels via the HTL route at pilot scale;
- Realization of microalgae technical production potential of 41 Mt/y in Europe at costs below 1.330 €/t by 2030;
- Tripling of microalgae production volume per decade;
- Decrease of production costs below 840 €/t by 2050.

6.5.2 Scenario Elements for Macroalgae

Baseline Scenario:

- 80% of the global annual macroalgae (seaweeds) production of approximately 23.8 million tonnes are used for direct human consumption. The remaining 20% are used for the production of cosmetic, nutritional or chemical supplements. Macroalgae are currently not used for the production of biofuels such bioethanol or biogas;
- Macroalgae are harvested in large quantities (23.8 Mt globally in 2012) primarily for direct human consumption. While Asian countries concentrate on cultivating macroalgae in aquaculture located along shore lines, European macroalgae almost completely relies on wild harvest, which is accompanied by a series of detrimental impacts on the marine ecosystem;
- European macroalgae production continues to rely on wild harvest, which is accompanied by a series of detrimental impacts on the marine ecosystem;
- Moderate R&I efforts in the field of aquaculture production of macroalgae;
- Moderate use of macroalgae for the production of biofuels such bioethanol or biogas.

Advanced R&I Scenario:

- Increased R&I efforts in the field of aquaculture production of macroalgae while wild harvest of seaweeds is decreased;
- Focus on making use of macroalgal biomass for the production of biofuels. 10% of the global production volume could be an initial benchmark;
- Doubling of macroalgae production volumes (mainly based on aquaculture) compared to current production volumes by 2030;
- Tripling of macroalgae production every ten years from 2030 on;
- Decrease production costs to 40 €/t (wet) by 2030, subsequently cost decrease by 20% per decade.

In order to facilitate the development of scenario storylines for modelling the production and delivery of biomass feedstock, scenario elements have been identified for promising R&I activities in the field of aquatic biomass. Specifically, these scenario elements addressed increased supply of biomass through **enhanced production**.

The following table presents an overview of R&I scenario elements for enhanced production for the field of aquatic biomass.

Table 6.6 R&I scenario elements for enhanced production from aquatic biomass

	R&I scenario elements for enhanced production
Aquatic biomass	**Microalgae:** • Increased R&I efforts for the development of Photo-Bioreactor (PBR) systems; • Cultivation is shifted from open pond systems to closed PBRs with the aim of biofuel production; • Increased operation of PBRs at pilot to demonstration scale (i.e. small commercial scale) in moderate temperatures and in proximity to industrial facilities with ample CO2 supply; • Targeted R&I efforts on algae strains with high productivity rate and lipid content such as chorella vulgaris, chorella sp. or Dunaliella salina;Adaption of harvesting methods that are commercially available for the food and feed sector such as flocculation, sedimentation, filtration as well as centrifugation to microalgae-to-biofuel value chains; • R&I efforts on direct conversion of microalgae to biofuels via the HTL route at pilot scale. **Macroalgae:** • Increased R&I efforts in the field of aquaculture production of macroalgae while wild harvest of seaweeds is decreased; • Focus on making use of macroalgal biomass for the production of biofuels. 10% of the global production volume could be an initial benchmark.

7 Summary

This report is part of the study on “Research and Innovation perspective of the mid- and long-term Potential for Advanced Biofuels in Europe” commissioned by DG Research and Innovation. It provides a detailed review and assessment of the **research and innovation (R&I) potential towards sustainable and low cost biomass availability for bioenergy** for the fields of agriculture, forestry, waste, and aquatic biomass and for the time horizons of 2030 and 2050. Table 7.1 presents an overview of the **main agriculture, forestry, waste, and aquatic biomass feedstock categories** addressed in this study.

Table 7.1 Main feedstock categories addressed

	Biomass Category	Biomass Type	Biomass Subtype
Biomass from agriculture	Energy crops	Cellulosic energy crops	Herbaceous grasses
			Short Rotation Coppice (SRC)
		New low-ILUC energy crops	
	Primary crop residues	Cereal straw	Wheat, barley, triticale, rye, oats
		Maize stover	
		Rapeseed straw	
		Sunflower stalks	
		Prunings	Wine and olive prunings
	Secondary crop residues	Cereal processing residues	Wheat and barley bran
		Sugar beet processing residues	Pulp and molasses
		Maize cobs	
		Oil crop processing residues	Rapeseed and sunflower meal
		Potato pulp and peels	
		Grape processing residues	
		Olive processing solid residues	
	Manure		
	Grassland biomass		
Biomass from forestry	Round-wood production	Stemwood	Roundwood from final fellings
			Roundwood from thinnings
	Primary forestry residues	Logging residues	Tops, branches, stumps, thinnings
	Secondary forestry residues	Woodchips and pellets	Woodchips, pellets
		Sawdust	
		Black liquor	
Biomass from waste	Household, similar wastes	Municipal Solid Waste (MSW)	OFMSW
	Animal, mixed food waste	Mixed wastes of food preparation	Used Cooking Oil
	Wood wastes	Post-consumer wood	Packaging waste
	Vegetal wastes		
	Paper and cardboard waste		
	Sludges and liquid wastes	Sewage sludge	
Aquatic	Microalgae		
	Macroalgae		

Table 7.2 presents an overview of the **main Research & Innovation fields for agriculture, forestry, waste, and aquatic biomass** covered in this report.

Table 7.2 Main R&I fields for agriculture, forestry, waste, and aquatic biomass addressed

	Concerned part of the biomass supply chain	R&I field
Biomass from agriculture	Biomass cultivation (cropping)	Breeding of food and energy cops
		Agricultural practices
		Crop rotation and intercropping
		Agroforestry & short rotation coppice
		Using marginal, degraded and unusable land for energy crops production
	Biomass harvesting, collection	Harvest of agricultural biomass
	Biomass pre-treatment and densification	Improved biomass carriers: thermo-chemically pre-treated and mechanically treated agricultural biomass
	Horizontal issues covering whole biomass supply chain	Biomass mobilization
		Agricultural logistics
		Supply chains of primary and secondary biomass
		Technology transfer
Biomass from	Increased forest biomass production	Breeding of improved genetic plant material
		Fertilisation
		Improved silviculture
	Improved biomass mobilisation	
	Optimised supply chain logistics	
Biomass from	Optimised supply chain	OFMSW – Source separated biowaste
		OFMSW – Mechanical separated biowaste
		OFMSW – Landfilled biowaste
		Used Cooking Oil, wood waste, vegetal waste, paper and cardboard waste, sewage sludge
Aquatic biomass	Cultivation (Microalgae)	Open pond systems
		Photo-Bioreactors
	Harvesting and concentration/ dewatering (Microalgae)	Thickening, Separation from growth medium, Dewatering
	Lipid extraction (Microalgae)	Solvent extraction, Supercritical fluid extraction, Mechanical and biological extraction
	Productivity(Microalgae)	
	GHG balance (Microalgae)	
	Conversion technologies (Microalgae)	Biodiesel, HEFA, Hydrothermal liquefaction
	Cultivation (Macroalgae)	Wild cultivation
		Aquafarms (maricultures)
	Harvesting and concentration (Macroalgae)	
	GHG balance (Macroalgae)	

Research & Innovation potential in the field of agriculture

Agriculture is acknowledged to be a key for genuine, large expansion of biomass supply in the future. On the other hand – there is a high uncertainty regarding how much agricultural feedstock can be mobilized for bioenergy production in a sustainable way and respecting the demand of competing sectors. Conventional biofuels have experienced strong criticism regarding their environmental impacts – primarily related to the concerns about indirect land use change (ILUC) impacts and associated emissions. Given these concerns, in the agricultural sector attention has turned to the greater use of agricultural biomass residues (both primary and secondary), and herbaceous and woody lignocellulosic energy crops, which have high biomass yields and can be grown on marginal lands without interfering with food/feed production systems.

The aim of this study was to identify research and innovation (R&I) activities in the agricultural sector which have potential to increase the availability of agricultural feedstocks for advanced biofuels production in the future (in 2030 and 2050). Based on extensive literature review and additional calculations of crop residue potentials, in the first step low ILUC, large potential agricultural biomass feedstocks have been selected as the most relevant on the EU level for the bioenergy supply in future (see overview in Table 7.2).

Many secondary crop residues have limited potential to be used for bioenergy production due to their demand in competing sectors – mostly for animal feed production industries. The focus of this study has been set to the identification of R&I potential for increasing the availability of **dedicated energy crops (cellulosic, low-input, stress-tolerant)** and **primary crop residues – straw, stalks and prunings**.

Based on the comprehensive review of agricultural biomass resources and the most relevant R&I fields in the sector (see Table 7.1 and Table 7.2), a definition of elements to be included in feedstock availability modelling scenarios have been made. At this stage it has been important to put the R&I field activities on a time line – identifying strategies and research activities in short, medium (until 2030) and long term (until 2050).

Iin **short term strategies**, selection of better adopted crop varieties from already developed ones will be made and this can contribute 5-10 % in yield increase. This increase can be multiplied through right combination of management practices such as fertilisation, irrigation, tillage system etc. Therefore, high yield potential of a specific variety can only be realised through combination of aforementioned factors.

The **medium term strategies** for crops involve improved management practices, appropriate selection of crop variety and precision farming. For grasslands – optimisation of grassland mixtures along with improved management practices to increase productivity of grassland are proposed.

The **long term strategies** include choice of variety from already available crop varieties and development of new varieties and improved management practices through precision agriculture practices. For grassland, the long term strategies involve improved management practices, optimal grassland mixtures and use of modern breeding techniques to develop better growing grassland species.

Research & Innovation potential in the field of forestry

Bioenergy generated from woody biomass is currently the largest renewable energy source in the EU. Although its relative share is slowly declining, woody biomass is expected to maintain a large role among the bioenergy feedstocks.

Felling rations in European forests vary regionally between 42% in Southeast Europe and 79% in Northern Europe. Consequently forest biomass resources are continuously expanding and in most European countries forest biomass utilization could be intensified in a sustainable way.

The S2BIOM project recently calculated up-to-date forest biomass resource potentials and indicated that high biomass mobilization could increase the base potential by 15-20%.

The review of the scientific literature and analysis of ongoing or recently completed European research projects on forest biomass utilization indicated that several potential measures exist to enhance forest biomass production beyond the currently available potentials and that the utilization of the existing potentials could be improved as well.

Measures targeting increased forest biomass production are estimated to have a realistic yield increase potential of around 30%. Impacts of measures to increase the mobilization of biomass potentials are more difficult to quantify, because there is considerable uncertainty how social processes and societal preferences can be influenced in reality.

As forest management is characterized by very long production cycles there are long time lags before changes in forest productivity result in enhanced biomass potentials. Major measures such as planting improved genetic material can only be implemented at the end of a management cycle and consequently only small shares of the total forest area are subject to possible changes each year.

Research & Innovation potential in the field of waste

Research & Innovation is going on in all parts of the European waste sector. However, it could still be considered as a real innovation potential in many Member States if only the approved measures would be implemented to make best use of the bio-energetic potential in waste. The consequent use of these measures shows the highest potential for an increase of feedstock for a sustainable production of bioenergy.

It has shown that the best feedstock for biogas production out of biowaste can be provided when the waste is source-separated. Other measures can be taken into account when at source-separation is not possible, yet will always result in lower quality feedstock for bioenergy production. The same goes for an increased collection of woody waste.

Regarding the availability of UCO for biodiesel production, the separation (provision of suitable containers) and collection measures can have the best leverage effect.

All these measures have in common that active support of the people is needed. Awareness about the topic shall be disseminated as the “human factor” is crucial for an increased availability of sustainable feedstock out of waste.

An overview of the main identified Research & Innovation activities (i.e. “scenario elements” for the R&I scenarios developed in Deliverable D1.2 of this study) for increased availability of waste feedstock is presented in the following figure. The timeline shows, when the considered R&I activities are expected to result in actual increase of feedstock availability.

Research & Innovation potential in the field of aquatic biomass

Today, ***microalgae production*** takes place worldwide for food and feed products at commercial scale with an annual production volume of 9.200 tonnes. This aquatic biomass is primarily cultivated in open pond systems in regions with sufficient solar radiation and the corresponding temperatures such as Israel, Australia, Asia, the United States and Southern Europe.

Progress in R&I could lead to a shift of cultivation from open pond systems to closed Photobioreactors (PBRs) focussing on biofuel production. Operation of PBRs at pilot to demonstration scale (i.e. small commercial scale) could first take place in moderate temperatures in proximity to industrial facilities to safeguard CO_2 supply.

Focus will be placed on the further development of algae strains with high productivity rate and lipid content such as *chorella vulgaris*, *chorella sp.* or *Dunaliella salina.*

It is anticipated that a microalgae technical production potential of 41 Mt/y in Europe at costs below 1.330 €/t can be realised by 2030, as well as a subsequent tripling of the microalgae production volume per decade and a decrease of production costs below 840 €/t by 2050.

Further R&I efforts will also lead to an adaptation of harvesting methods that are commercially available for the food and feed sector (such as flocculation, sedimentation, filtration as well as centrifugation) to microalgae-to-biofuel value chains. Lipid extraction methods and direct conversion of microalgae to biofuels via the HTL route will be economically viable at pilot scale and the production of first batches of advanced microalgae-based biofuels with a GHG emission reduction potential of 30% is expected by 2030.

Macroalgae (seaweeds) production is currently taking place on a much larger scale, with 80% of the global annual production of approximately 23.8 million tonnes used for direct human consumption. The remaining 20% are used for the production of cosmetic, nutritional or chemical supplements whereas macroalgae are currently not used for the production of biofuels such as bioethanol or biogas.

Progress in R&I could focus on making use of macroalgal biomass for the production of biofuels with about 10% of the global production volume as an initial benchmark. However, no wildly harvested macroalgae should be used for biofuel production due to sustainability constraints and all feedstock shall be produced in aquacultures.

With increased R&I efforts in the field it is anticipated that aquaculture production volumes of macroalgae could double by 2030 compared to current volumes and a further tripling of macroalgae production is achieved every ten years after 2030. Furthermore, production costs are foreseen to decrease to 40 €/t (wet) by 2030 with a subsequent cost decrease by 20% per decade until 2050 and beyond.

Research & Innovation scenario elements for the fields of agriculture, forestry, waste and aquatic biomass

In order to facilitate the development of scenario storylines for the production and delivery of biomass feedstock (Pillar A of scenarios modelled, see chapter 2.3.2), scenario elements have been identified for promising R&I activities in the fields of agriculture, forestry, waste, and aquatic biomass. Specifically, these scenario elements were grouped into R&I measures targeting either (a) increased supply of biomass through **enhanced production** or (b) **improved biomass supply** through innovative harvesting, supply chain logistics and mobilization of potentials.

The following table presents an overview of R&I scenario elements for enhanced production and improved biomass supply for the fields of agriculture, forestry, waste, and aquatic biomass.

Table 7.3 R&I scenario elements for enhanced production and improved biomass supply

	R&I scenario elements for enhanced production	R&I scenario elements for improved biomass supply
Biomass from agriculture	• Yield increase of conventional (food/feed) crops due to breeding efforts. Breeding efforts to build up the resistance to biotic and abiotic stresses (drought, pests and diseases) as well as to increase residue to crop ratios (straw/grain ratio) are included. It will result in absolute increase of main crop biomass and crop residues and potentially providing more space for growing energy crops (if demand for food/feed can be satisfied with less land); • Enhanced production by growing dedicated energy crops on un-used agricultural lands. Further expansion of energy crops on non-agricultural areas (marginal lands) is anticipated in the future. Expansion on marginal lands will be possible because of breeding efforts targeted to developing more robust plants, which are able to grow in less suitable conditions; • Improved agricultural management practices (e.g. selection of varieties, crop rotation and intercropping, fertilization, water management, adoption of precision agriculture practices) to bridge the current gaps of yields among EU member states.	• Improved harvesting practices and machinery (development of new equipment for both – conventional and dedicated energy crop harvesting, improving harvesting practices, development of precision farming); • Increased mobilisation of agricultural biomass by optimised supply chain logistics (mobilization of so far unexploited biomass by using cleaner, more efficient and more cost-effective technologies, technology transfer, streamlining biomass supply chains with existing practices, development of new supply chains for dedicated energy crops); • Increased awareness and capacity of various actors involved in the biomass supply chain.

	R&I scenario elements for enhanced production	R&I scenario elements for improved biomass supply
Biomass from forestry	• Use of more appropriate breeding material for main production tree species; • Use of new, more productive varieties for main production tree species through tree breeding; • Introduction of Douglas fir on sites when Norway spruce dominated stands are felled; • Fertilisation of forests growing on poor soils.	• Successful translation of recommendations on wood mobilisation and increased awareness of owners lead to an increased mobilisation of wood from forests. New forest owner associations or co-operations are established throughout Europe. Together with existing associations, these new associations lead to improved access of wood to markets; • Strong mechanisation is taking place across Europe; existing and new technologies are effectively shared between countries through improved information exchange, enhancing also the extraction of biomass from rugged terrain and water logged sites; • Trees are harvested more efficiently, which results in a reduction of harvest losses and thereby logging residues; • Biomass harvesting guidelines become less restricting, because technologies are developed that are less harmful for the environment. As a result, biomass from all tree compartments (stems, logging residues and stumps) are extracted; • Improved harvest machinery is applied, which reduces environmental impacts and thereby allows for increased forest biomass extraction; • Innovative harvesting, supply-chain logistics and mobilisation is available resulting in more efficient felling, extraction and transport of woody biomass; • Application of fertilizer is permitted to limit detrimental effects of logging residue and stump extraction on the soil.

	R&I scenario elements for enhanced production	R&I scenario elements for improved biomass supply
Biomass from waste	Not applicable	• Increasing availability of UCO/FOG by increasing collection yields due to extended application of separation and collection methods (from 2017), by: - Information campaigns in all EU countries (school level as well as for adults) where that hasn't been done yet (taking into account lessons learnt from conducted studies); - Development of efficient and accepted collection infrastructures. • Increasing availability of the organic waste fraction (pre-sorted and out of commingled MSW) by mobilising at source separation, using most advanced separation technology and using suited AD plants for energy generation (from 2017), by: - Information campaigns directed at school and adult level for enhanced separation of biogenic fraction at source (i.e. home); - Using of most modern industrial separation technologies for maximising organic waste yield out of commingled waste streams; - Using of state of the art waste fermentation plants for the recovered organic fractions; - Supporting schemes for extended construction of aforementioned plants in the EU in a decentral manner; - Wider use of recent technology developments resulting in increased availability of organic waste.

	R&I scenario elements for enhanced production	R&I scenario elements for improved biomass supply
Aquatic biomass	**Microalgae:** • Increased R&I efforts for the development of Photo-Bioreactor (PBR) systems; • Cultivation is shifted from open pond systems to closed PBRs with the aim of biofuel production; • Increased operation of PBRs at pilot to demonstration scale (i.e. small commercial scale) in moderate temperatures and in proximity to industrial facilities with ample CO2 supply; • Targeted R&I efforts on algae strains with high productivity rate and lipid content such as chorella vulgaris, chorella sp. or Dunaliella salina;Adaption of harvesting methods that are commercially available for the food and feed sector such as flocculation, sedimentation, filtration as well as centrifugation to microalgae-to-biofuel value chains; • R&I efforts on direct conversion of microalgae to biofuels via the HTL route at pilot scale. **Macroalgae:** • Increased R&I efforts in the field of aquaculture production of macroalgae while wild harvest of seaweeds is decreased; • Focus on making use of macroalgal biomass for the production of biofuels. 10% of the global production volume could be an initial benchmark.	Not applicable

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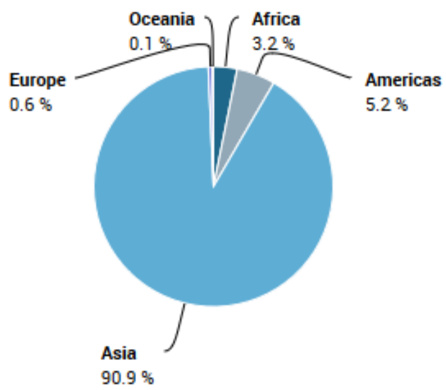
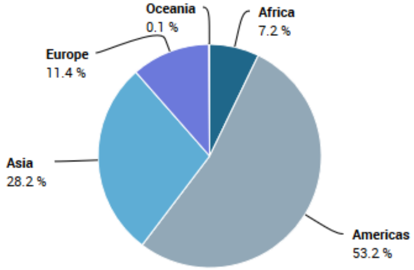
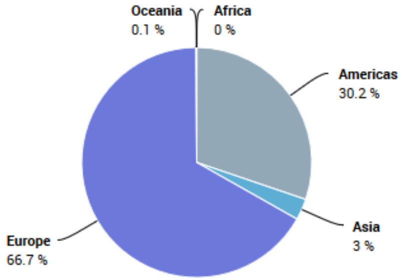
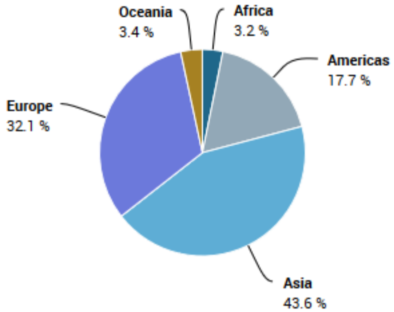
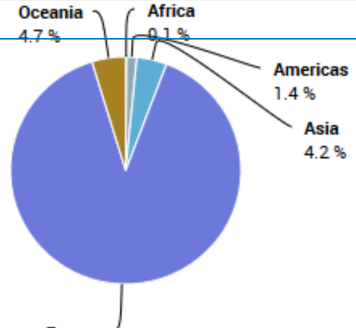
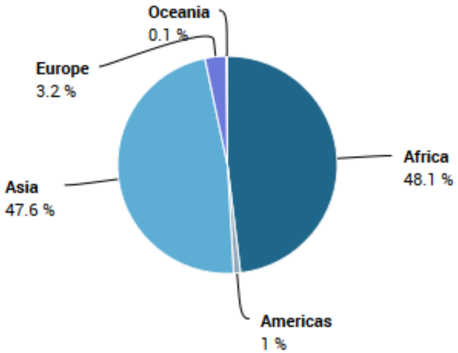
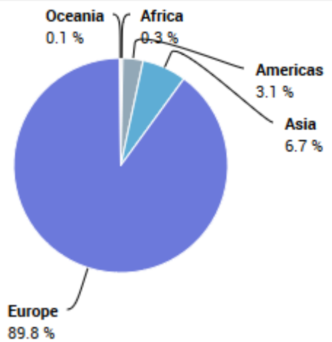
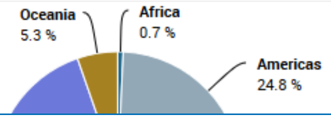
Annex 1: Main crops and generated residues

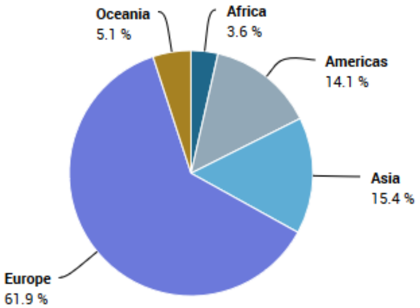
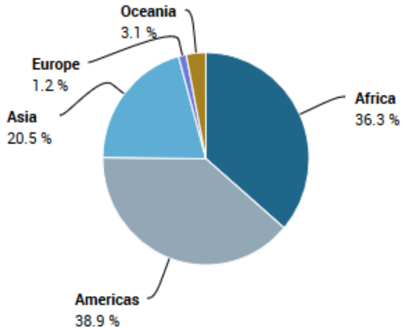
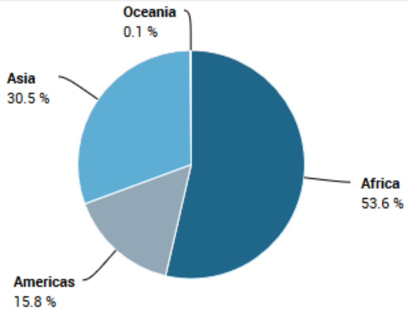
Annex 1 presents an overview about most widespread annual crops in Europe and worldwide, indicating their production shares by region, top 5 producer countries, type of generated residues, typical RSR or RPR values and moisture content.

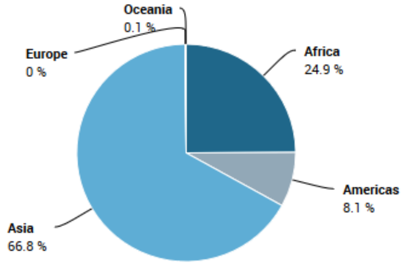
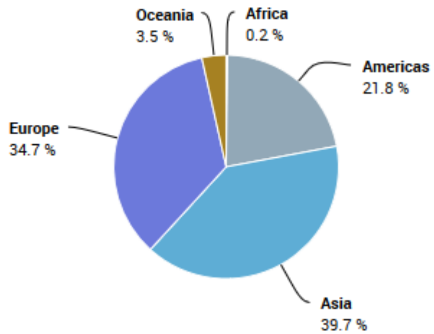
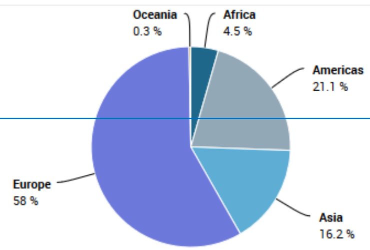
Table A.1.1 Main annual crops and generated residues

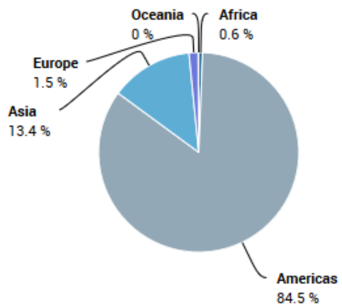
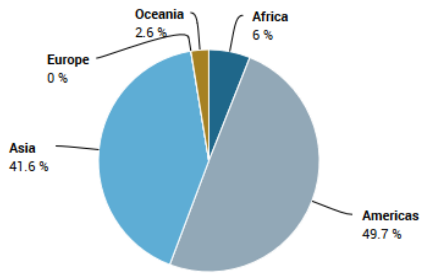
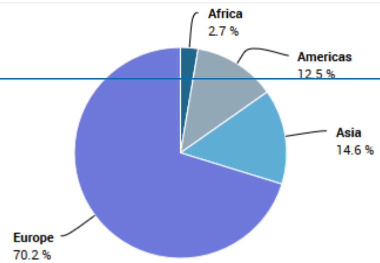
Annual crop	**Production share by region, average 1993-2013** (FAOstat, 2013)	**Top 5 producer countries, average 1993-2013** (FAOstat, 2013)	**Residues**	**RPR [kg/kg] and/or RSR [t/ha] value**	**Moisture content [%]**
Rice		China India Indonesia Bangladesh Viet Nam	Straw	1.757 kg/kg (Koopmans and Koppejan, 1997) 1.48 kg/kg (Junginger et al., 2016) 0.42-3.96 kg/kg (Mai-Moulin, Junginger et al., 2016; Mai-Moulin et al., 2016) 0.75 kg/kg (Diaz-Chavez et al., 2016) 2.35 kg/kg (Diaz-Chavez et al., 2016) 1.32 kg/kg (Searle and Malins, 2013)	12.71 % (Koopmans and Koppejan, 1997) 0 % (dry) (Junginger et al., 2016)
			Husk	0.267 kg/kg (Koopmans and Koppejan, 1997) 0.20 kg/kg (Junginger et al., 2016; Diaz-Chavez et al., 2016) 0.22-0.35 kg/kg (Mai-Moulin, Junginger et al., 2016; Mai-Moulin et al., 2016) 0.25 kg/kg (Diaz-Chavez et al., 2016) 0.27 (Searle and Malins, 2013)	2.37 % (Koopmans and Koppejan, 1997) 0 % (dry) (Junginger et al., 2016)
			Fibres	0.14-0.15 kg/kg (Mai-Moulin, Junginger et al., 2016)	
Maize	For corn:	USA China Brazil	Stalk	2.0 kg/kg (Koopmans and Koppejan, 1997) 0.78 kg/kg(Junginger et al., 2016) 0.80 kg/kg (Searle and Malins, 2013)	15 % (Koopmans and Koppejan, 1997) 0 % (dry) (Junginger et al.,

Annual crop	Production share by region, average 1993-2013 (FAOstat, 2013)	Top 5 producer countries, average 1993-2013 (FAOstat, 2013)	Residues	RPR [kg/kg] and/or RSR [t/ha] value	Moisture content [%]
		Mexico Argentina		0.9-1.2 kg/kg (Iqbal et al., 2016)	2016)
			Cob	0.273 kg/kg (Koopmans and Koppejan, 1997) 0.22 kg/kg (Junginger et al., 2016)	7.35 % (Koopmans and Koppejan, 1997) 0 % (dry) (Junginger et al., 2016)
	For forage and silage: 	USA Germany France Russia Ukraine	Husk	0.20 kg/kg (Koopmans and Koppejan, 1997) 0.20 kg/kg (Junginger et al., 2016)	11.11 % (Koopmans and Koppejan, 1997) 0 % (dry) (Junginger et al., 2016)
Wheat		China India USA Russia France	Straw	1.75 kg/kg (Koopmans and Koppejan, 1997) 0.94 kg/kg (Searle and Malins, 2013) 0.8-1.6 kg/kg (Iqbal et al., 2016)	15 % (Koopmans and Koppejan, 1997)
			Bran	0.24 kg/kg (Searle and Malins, 2013)	
Triticale		Poland	Straw	1.04 kg/kg (Searle and Malins, 2013)	

Annual crop	**Production share by region, average 1993-2013** (FAOstat, 2013)	**Top 5 producer countries, average 1993-2013** (FAOstat, 2013)	**Residues**	**RPR [kg/kg] and/or RSR [t/ha] value**	**Moisture content [%]**
		Germany France Belarus Australia	Bran	0.24 kg/kg (Searle and Malins, 2013)	
Millet	 	India Nigeria Niger China Mali	Straw	1.75 kg/kg (Koopmans and Koppejan, 1997)	15 % (Koopmans and Koppejan, 1997)
Rye	 	Russia Poland Germany Belarus Ukraine	Straw	1.75 kg/kg (Koopmans and Koppejan, 1997) 1.13 kg/kg (Searle and Malins, 2013) 0.9-1.6 kg/kg (Iqbal et al., 2016)	15 % (Koopmans and Koppejan, 1997)
			Bran	0.24 kg/kg (Searle and Malins, 2013)	
Oats	 	Russia Canada USA	Straw	1.75 kg/kg (Koopmans and Koppejan, 1997) 1.07 kg/kg (Searle and Malins, 2013) 0.9-1.4 kg/kg (Iqbal et al., 2016)	15 % (Koopmans and Koppejan, 1997)

Annual crop	Production share by region, average 1993-2013 (FAOstat, 2013)	Top 5 producer countries, average 1993-2013 (FAOstat, 2013)	Residues	RPR [kg/kg] and/or RSR [t/ha] value	Moisture content [%]
		Poland Australia	Bran	0.24 kg/kg (Searle and Malins, 2013)	
Barley		Russia Germany Canada France Ukraine	Straw	1.75 kg/kg (Koopmans and Koppejan, 1997) 0.94 kg/kg (Searle and Malins, 2013) 0.8-1.3 kg/kg (Iqbal et al., 2016)	15 % (Koopmans and Koppejan, 1997)
			Bran	0.24 kg/kg (Searle and Malins, 2013)	
Sorghum		USA India Nigeria Mexico Sudan (former)	Straw	1.25 kg/kg (Koopmans and Koppejan, 1997)	15 % (Koopmans and Koppejan, 1997)
Cassava		Nigeria Brazil Thailand Indonesia Democratic Republic of Congo	Stalks	0.167-2.0 kg/kg (Koopmans and Koppejan, 1997) 4-9 t(dry)/ha (Koopmans and Koppejan, 1997) 0.8 kg/kg (Junginger et al., 2016)	0 % (dry) (Koopmans and Koppejan, 1997) 0 % (dry) (Junginger et al., 2016)
			Peelings	1 t/ha (Koopmans and Koppejan, 1997)	50 % (Koopmans and Koppejan, 1997)
	Cassava is harvested about 12 months after planting. At harvest the plants are first topped before being uprooted. Part of the stalk is retained for replanting while part				

Annual crop	Production share by region, average 1993-2013 (FAOstat, 2013)	Top 5 producer countries, average 1993-2013 (FAOstat, 2013)	Residues	RPR [kg/kg] and/or RSR [t/ha] value	Moisture content [%]
	is discarded. Tops (leaves) and the discarded part are sometimes left in the field and sometimes used as a domestic fuel. Out of the 10-25 tons of stems and leaves per hectare, about 8 tons becomes available as fuel or about 6 tons/ha on a dry basis. Assuming a yield of about 30-45 tons of tubers per ha this would result in a residue base of about 4-9 tons per hectare. Part of the tubers is processed into starch flour and is peeled before processing. Peels represent about 2-3% of the weight of the tuber and this would yield about 1 ton of peels (moisture content 50%) generated per ha of cassava destined for starch production.				
Groundnuts (peanuts)		China India Nigeria USA Sudan	Husks/ shells*	0.477 kg/kg (Koopmans and Koppejan, 1997)	8.2 % (Koopmans and Koppejan, 1997)
			Straw	2.3 kg/kg (Koopmans and Koppejan, 1997)	15 % (Koopmans and Koppejan, 1997)
Rapeseed		China Canada India Germany France	Straw	5-8 t/ha (Kazmi, 2012) 1.08 kg/kg (Searle and Malins, 2013) 1.4-2.0 kg/kg (Iqbal et al., 2016)	10 % (Kazmi, 2012)
Sunflower seed		Russia Ukraine Argentina	Dry heads, stalks	0.3-0.7 t/ha (Díaz et al., 2011) 1.77 kg/kg (Searle and Malins, 2013) 2.2-3.2 kg/kg (Iqbal et al., 2016)	

Annual crop	Production share by region, average 1993-2013 (FAOstat, 2013)	Top 5 producer countries, average 1993-2013 (FAOstat, 2013)	Residues	RPR [kg/kg] and/or RSR [t/ha] value	Moisture content [%]
		China France	Hulls	0.2-0.3 kg/kg seeds (Feedpedia, 2016c) De-hulling efficiency 88-92% (Feedpedia, 2016c)	
Soybeans		USA Brazil Argentina China India	Straw	2.50 kg/kg (Koopmans and Koppejan, 1997; Searle and Malins, 2013) 1.40 kg/kg (Junginger et al., 2016)	15 % (Koopmans and Koppejan, 1997) 0 % (dry) (Junginger et al., 2016)
			Pods	1.0 kg/kg (Koopmans and Koppejan, 1997; Searle and Malins, 2013)	15 % (Koopmans and Koppejan, 1997)
			Meal	0.764 kg/kg (Patthanaissaranukool and Polprasert, 2016)	
Sugar cane		Brazil India China Thailand Pakistan	Bagasse	0.29 kg/kg (Koopmans and Koppejan, 1997) 0.30 kg/kg (Junginger et al., 2016) 0.10-0.33 kg/kg (Mai-Moulin, Junginger et al., 2016) 0.36-0.40 kg/kg (Mai-Moulin et al., 2016) 2.68 kg/kg (Diaz-Chavez et al., 2016)	50 % (Koopmans and Koppejan, 1997) 0 % (dry) (Junginger et al., 2016)
			Molasses	0.04 kg/kg (Mai-Moulin et al., 2016) 0.03-0.04 kg/kg (Hansa Melasse, 2016)	
			Tops/ leaves (trash)	0.30 kg/kg (Koopmans and Koppejan, 1997) 0.34 kg/kg (Junginger et al., 2016) 0.10-0.30 kg/kg (Mai-Moulin, Junginger et al., 2016) 0.10-0.33 kg/kg (Mai-Moulin et al., 2016) 3.26 kg/kg(Diaz-Chavez et al., 2016)	10 % (Koopmans and Koppejan, 1997) 0 % (dry) (Junginger et al., 2016)
Sugar beet		France USA	Leaves	0.27 kg/kg (Searle and Malins, 2013) 0.2-0.4 kg/kg (Iqbal et al., 2016)	

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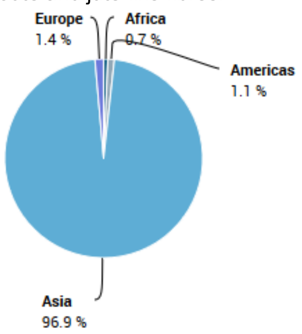
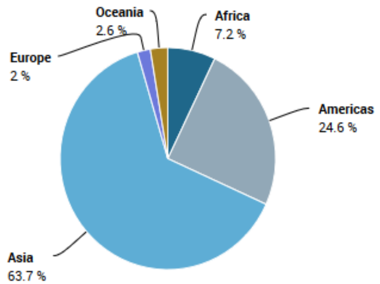
Annual crop	Production share by region, average 1993-2013 (FAOstat, 2013)	Top 5 producer countries, average 1993-2013 (FAOstat, 2013)	Residues	RPR [kg/kg] and/or RSR [t/ha] value	Moisture content [%]
		Germany Russia Ukraine		42 t (FM)/ha (Schaffner et al., 2011)	85 % (Schaffner et al., 2011)
			Pulp	0.170-0.330 kg/kg (Borowski et al., 2016)	
			Molasses	0.04-0.06 kg/kg (Hansa Melasse, 2016)	
Jute	Jute and jute-like fibres:  	India Bangladesh China Russia Thailand	Stalk Stick	2.0 kg/kg (Koopmans and Koppejan, 1997)	15 % (Koopmans and Koppejan, 1997)
Cotton	Cotton lint production:  Cottonseed production:	China USA India Pakistan Uzbekistan China India	Stalk	2.755 kg/kg (Koopmans and Koppejan, 1997)	12 % (Koopmans and Koppejan, 1997)

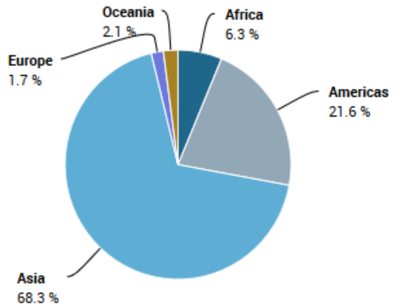
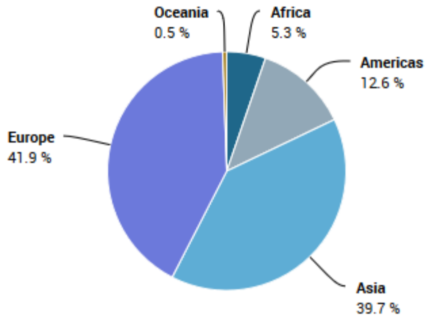
Annual crop	Production share by region, average 1993-2013 (FAOstat, 2013)	Top 5 producer countries, average 1993-2013 (FAOstat, 2013)	Residues	RPR [kg/kg] and/or RSR [t/ha] value	Moisture content [%]
		USA Pakistan Uzbekistan			
Potatoes		China Russia India USA Ukraine	Waste potato pulp	0.1 kg/kg processed potatoes (Izmirlioglu and Demirci, 2016)	
			Cull potatoes	0.05-0.2 kg/kg processed potatoes (Izmirlioglu and Demirci, 2016)	
			Peel	0.15-0.4 kg/kg processed potatoes (Izmirlioglu and Demirci, 2016)	

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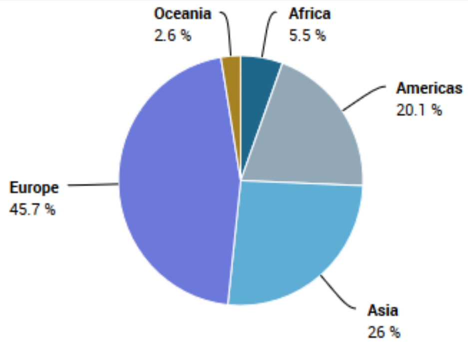
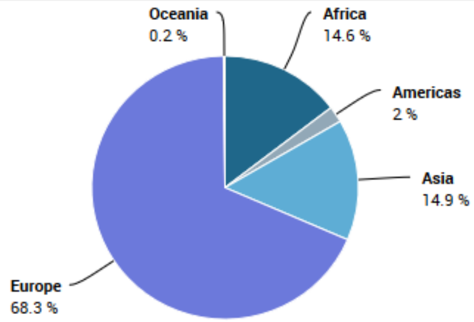
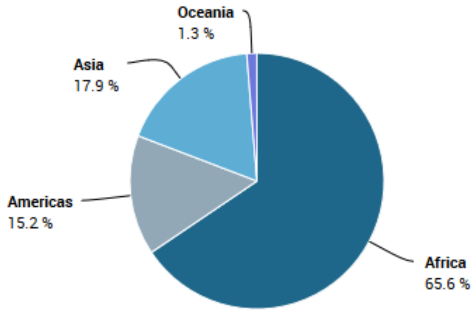
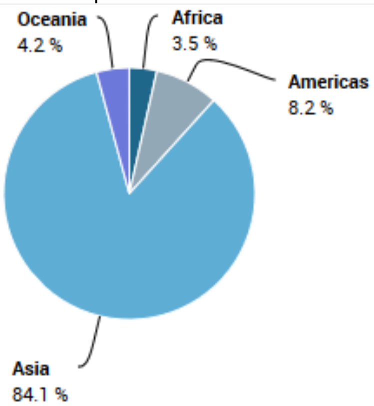
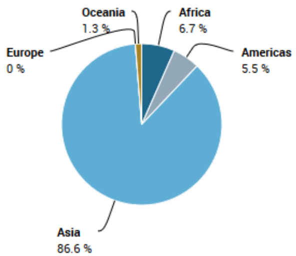
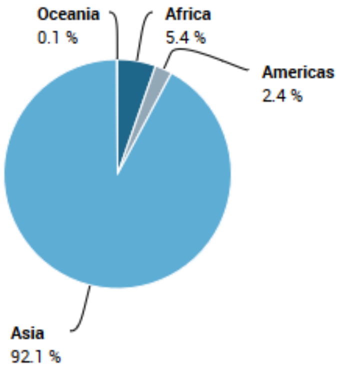
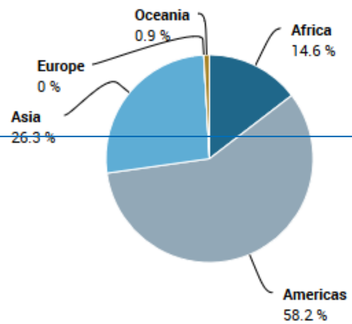
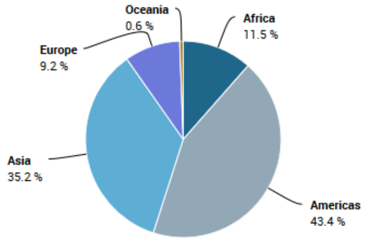
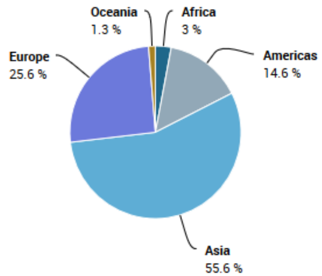
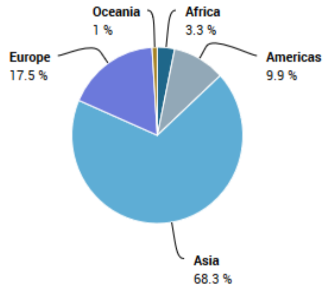
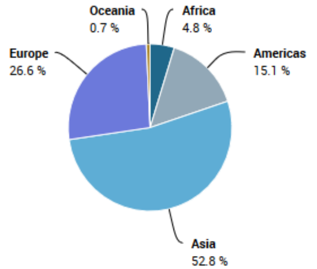
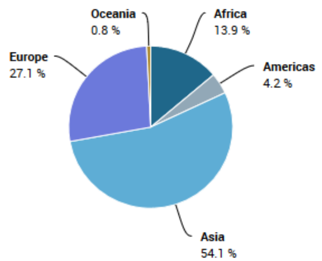
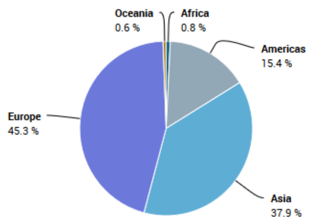
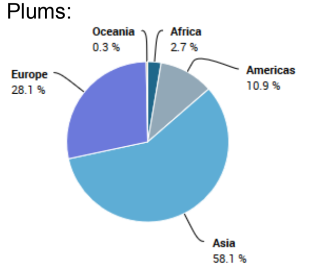
Table A.1.2 Main perennial crops and generated residues

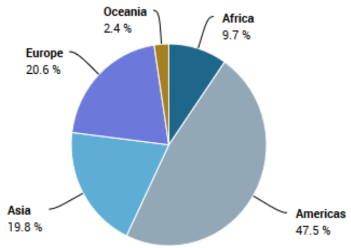
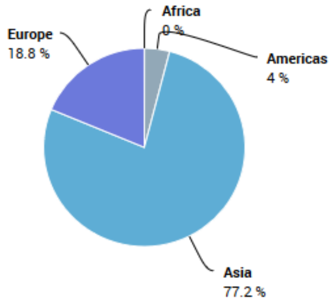
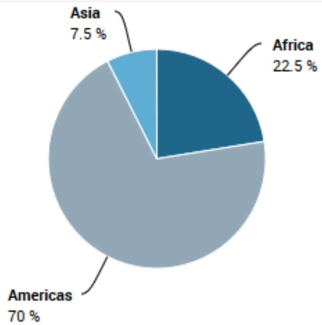
Perennial crop	Production share by region, average 1993-2013 (FAOstat, 2013)	Top 5 producer countries, average 1993-2013 (FAOstat, 2013)	Residues	RSR [t/ha] or RPR [kg/kg] and respective moisture content [%]
Vineyard, grapes		Italy France USA Spain China	Prunings	0.2-3.95 t(dry)/ha (mean 1.95) (CIRCE, 2014) 0.2-0.6 kg/kg (Iqbal et al., 2016)
			Grape marc	2.7 t/ha (M=59.3%) (Toscano et al., 2013) Grape marc components (Toscano et al., 2013): Grape skin - 1.95 t/ha (M=60.9%) Stalks – 0.3 t/ha (M=68.9%) Grape seeds – 0.45 t/ha (M=48.6%)
Olives		Spain Italy Greece Turkey Tunisia	Prunings	0.5-2.37 t(dry)/ha (average 1.38) (CIRCE, 2014) 0.12 kg/kg (Searle and Malins, 2013)
			Olive cake	Depending on the extraction method: 0.4 kg/kg olives (M=25%) (Eleftheriadis) 0.5-0.6 kg/kg olives (M=50%) (Eleftheriadis) 0.8-0.95 kg/kg olives (M=60%) (Eleftheriadis)
			Waste water	Depending on the extraction method: 0.6 kg/kg olives (12% DM) (Eleftheriadis) 1-1.2 kg/kg olives (5% DM) (Eleftheriadis)
Cocoa	Cocoa beans:	Côte d'Ivoire Indonesia Ghana Nigeria Brazil	Prunings	~21 kg dOM/tree/year = ~25 t/ha/year (Koopmans and Koppejan, 1997)
			Replacing old-trees	~48 kg dOM/tree = ~57.6 t/ha (Koopmans and Koppejan, 1997)
			Pods	150 kg (dry)/ha (Koopmans and Koppejan, 1997)

Perennial crop	Production share by region, average 1993-2013 (FAOstat, 2013)	Top 5 producer countries, average 1993-2013 (FAOstat, 2013)	Residues	RSR [t/ha] or RPR [kg/kg] and respective moisture content [%]
				
	Cocoa trees are planted and used for production for a period of about 25 years, during which they have to be pruned regularly to keep them small. After this period they are cut down and replanted. Prunings are normally left in the field. Besides wood, residues in the form of cocoa pods are generated. They are usually left in the plantation as it provides a valuable source of potash fertiliser.			
Coconut		Indonesia Philippines India Brazil Sri Lanka	Wood	n/a
			Fronds	1.5 kg (dry) wood/fond 12-14 fronds/tree/year = 2.4 t/ha (120 trees/ha) (Koopmans and Koppejan, 1997)
			Husks	0.419 kg/kg (M=10.3%) (Koopmans and Koppejan, 1997) 0.6-1.6 kg/kg (Mai-Moulin et al., 2016)
			Shells	0.12 kg/kg (M=8.7%) (Koopmans and Koppejan, 1997)
Oil palm		Malaysia Indonesia Nigeria Thailand Colombia	Tree trunks	500-600 kg stem wood/tree (Koopmans and Koppejan, 1997)
			Fronds	120 kg/tree (Koopmans and Koppejan, 1997)
			Fibre	0.14-0.15 kg/kg (M=40%) (Koopmans and Koppejan, 1997) 0.12 kg/kg (M=23%) (Mai-Moulin, Junginger et al., 2016) 0.63 kg/kg (M=35%) (Diaz-Chavez et al., 2016)
			Kernel shells	0.06-0.07 kg/kg (M=10%) (Koopmans and Koppejan, 1997; Mai-Moulin, Junginger et al., 2016)

Perennial crop	Production share by region, average 1993-2013 (FAOstat, 2013)	Top 5 producer countries, average 1993-2013 (FAOstat, 2013)	Residues	RSR [t/ha] or RPR [kg/kg] and respective moisture content [%]
				0.07 kg/kg (M=20%) (Mai-Moulin, Junginger et al., 2016) 0.22 kg/kg (M=14%) (Diaz-Chavez et al., 2016)
			Empty fruit bunches	0.23 kg/kg (M=50%) (Koopmans and Koppejan, 1997; Mai-Moulin, Junginger et al., 2016) 0.24 kg/kg (M=60%) (Mai-Moulin, Junginger et al., 2016) 1.06 kg/kg (M=65%) (Diaz-Chavez et al., 2016)
	Tree trunks and fronds become available during replanting of oil palm trees. The productive life of the trees is about 25-30 years. Trees yield ~500-600 kg stem wood and 120 kg fronds per tree. There are about 142 trees/ha but due to natural attrition at the time of replanting about 85% (120 trees) are still standing. Therefore, the average yield per ha is about 80 tons of DM. In addition fibre, shells and empty bunches are generated during processing – 1.853 t of fibre, 2.780 t of shells and 1.483 t of empty bunches per hectare as DM. Shells and fibres are normally used internally for power generation while part may be sold as fuel or used for road construction. Empty bunches are normally incinerated, after which the potash rich ash is used as fertiliser (Koopmans and Koppejan, 1997).			
Rubber trees		Thailand Indonesia Malaysia India China	Wood (when replanting)	81 t(dry)/ha (Koopmans and Koppejan, 1997)
			Leaves	1.4 t/ha (Koopmans and Koppejan, 1997)
	Rubber trees have a productive life of about 25-35 years. Trees shed their leaves every year. However, removal of the leaves may affect soil moisture and fertility, and may increase erosion.			
Coffee		Brazil Viet Nam Colombia Indonesia	Prunings	3.02 kg/kg (Diaz-Chavez et al., 2016)
			Husk	0.21 kg/kg (M=0%) (Junginger et al., 2016; Diaz-Chavez et al., 2016) 0.6-1.6 kg/kg (Mai-Moulin et al., 2016) 1-2 kg/kg(Diaz-Chavez et al., 2016)

Perennial crop	Production share by region, average 1993-2013 (FAOstat, 2013)	Top 5 producer countries, average 1993-2013 (FAOstat, 2013)	Residues	RSR [t/ha] or RPR [kg/kg] and respective moisture content [%]
		Mexico	Pulp	2.42-3.40 kg/kg (Mai-Moulin et al., 2016) 2.13 kg/kg (Diaz-Chavez et al., 2016)
Citrus fruits		Brazil China USA Mexico Spain	Prunings	1.08-4.61 t(dry)/ha (mean 4.06) (CIRCE, 2014)
			Peels	0.50 kg/kg (M=0%) for oranges (Junginger et al., 2016) 0.50-0.60 kg/kg (M=19%) for citrus in general (Negro et al., 2016)
Pome (seed) fruits	Apples:  Pears: 	China USA Turkey Italy France China Italy USA Argentina Spain	Prunings	Apple trees: 0.1-9.92 t(dry)/ha (mean 3.38) (CIRCE, 2014) Pear trees: 0.1-9.37 t(dry)/ha (mean 3.61) (CIRCE, 2014)
			Pomace	0.268 kg/kg (of processed apples) (Shalini and Gupta, 2010)
Stone fruits	Peaches and nectarines:	China Italy USA	Prunings	Peach: 0.22-3.21 t(dry)/ha (mean 2.19) (CIRCE, 2014) Apricot:

Perennial crop	Production share by region, average 1993-2013 (FAOstat, 2013)	Top 5 producer countries, average 1993-2013 (FAOstat, 2013)	Residues	RSR [t/ha] or RPR [kg/kg] and respective moisture content [%]
	 Apricots:  Cherries:  Plums: 	Spain Greece Turkey Iran Italy Pakistan Uzbekistan Turkey USA Iran Italy Spain China Serbia USA Romania Montenegro		0.1-3.21 t(dry)/ha (mean 1.45) (CIRCE, 2014) Cherries: 0.1-2.83 t(dry)/ha (mean 1.48) (CIRCE, 2014)
			Stones	Apricot: 0.063 kg/kg (calculated after (Sostaric et al., 2015))

Perennial crop	Production share by region, average 1993-2013 (FAOstat, 2013)	Top 5 producer countries, average 1993-2013 (FAOstat, 2013)	Residues	RSR [t/ha] or RPR [kg/kg] and respective moisture content [%]
Dry fruits	Almonds:  Hazelnuts: 	USA Spain Italy Iran Syria Turkey Italy USA Azerbaijan Spain	Prunings	Almonds: 0.3-3.55 t(dry)/ha (mean 1.63) (CIRCE, 2014) Hazelnuts: 0.9-1.73 t(dry)/ha (mean 1.24) (CIRCE, 2014)
			Shells	Almonds: 0.4 kg/kg (calculated from (GAIN, 2014)) (M=25%) (Hashemian et al., 2014) Hazelnuts: 0.5 kg/kg (calculated based on (Haykiri-Acma et al., 2013)) (M=12.3%) (Haykiri-Acma et al., 2013)
			Skin	Almonds: 0.04-0.08 kg/kg (shelled almonds) (Valdes et al., 2016) Hazelnuts: 0.025 kg/kg shelled hazelnut (Odabas and Koca, 2016)
Sisal		Brazil Mexico Tanzania Kenya China	Ball	3.50-4.70 kg/kg (Mai-Moulin et al., 2016)
			Bogas	15.60-24.00 kg/kg (Mai-Moulin et al., 2016)

Annex 2: Crop residue potential calculation sheet

Crops	Area harvested	Yield	Total produciton	Primary residue	RPR	RSR	Residue amount	Sustainable removal rate	Energy content	Energy potential	Primary crop residue	Secondary residue	RPR	Amount	Energy content	Energy potential	Secondary crop residue
	(FAOSTAT, 2005-2014 avg)																
	ha	t/ha	t/year		t/t	t/ha	t/year	%	GJ/t	GJ/year	PJ/year		t/t	t/year	GJ/t	GJ/year	PJ/year
Cerals:											1 800						1 205
Barley	13 145 693	4,40	57 823 867	**straw**	0,94		54 354 435	40%	15,14	329 170 457	**329**	**bran**	0,24	13 877 728	17,74	246 190 895	**246**
Maize	9 099 738	6,96	63 362 476	**stover, husk**	1,10		69 698 724	50%	15,68	546 437 994	**546**	**cobs**	0,22	13 939 745	17,49	243 806 136	**244**
Oats	2 802 415	2,92	8 177 555	**straw**	1,07		8 749 984	40%	16,02	56 069 894	**56**	**bran**	0,24	1 962 613	17,74	34 816 757	**35**
Rice	440 792	6,57	2 893 928	**straw**	1,32		3 819 984	40%	12,65	19 329 121	**19**	**husk**	0,20	578 786	12,06	6 980 153	**7**
Rye	2 454 224	3,39	8 325 375	**straw**	1,13		9 407 674	40%	15,16	57 048 136	**57**	**bran**	0,24	1 998 090	17,74	35 446 118	**35**
Triticale	2 644 689	4,07	10 754 994	**straw**	1,04		11 185 193	40%	14,00	62 637 083	**63**	**bran**	0,24	2 581 198	17,74	45 790 461	**46**
Wheat	26 028 292	5,34	138 966 955	**straw**	0,94		130 628 938	40%	13,96	729 431 988	**729**	**bran**	0,24	33 352 069	17,74	591 665 708	**592**
Tubers:																	77
Potatoes	2 034 235	29,30	59 600 436									**pulp, peel**	0,30	17 880 131	17,20	76 884 562	**77**
Oil/protein crops:											363						342
Rapeseed	6 298 430	3,10	19 510 098	**straw**	1,40		27 314 137	50%	14,86	202 944 037	**203**	**meal**	0,712	13 900 000	19,40	239 458 080	**239**
Soybean	438 141	2,69	1 179 039	**straw**	2,50		2 947 598	50%	16,48	24 288 210	**24**	**meal**	0,746	879 563	13,93	12 252 317	**12**
Sunflower	3 983 019	1,84	7 321 827	**stalks**	2,20		16 108 020	50%	16,83	135 548 989	**136**	**hulls**	0,25	1 830 457	20,2	33 536 532	**34**
												meal	0,45	3 300 000	19,40	56 977 800	**57**
Sugar crops:											30						422
Sugar beet	1 732 005	67,38	116 709 511	**leaves**	0,27		3 623 830	50%	16,70	30 258 983	**30**	**pulp**	0,20	23 341 902	17,00	353 956 605	**354**
												molasses	0,05	5 835 476	15,50	68 470 552	**68**
Perennial crops:											334						166
Oranges	307 892	20,53	6 320 790	**pruning**		4,06	1 250 042	100%	18,00	22 500 764	**23**	**peels**	0,50	790 099	18,10	14 300 788	**14**
Almonds	689 397	0,54	372 463	**pruning**		1,63	1 123 717	100%	18,00	20 226 908	**20**	**shells**	0,40	148 985	16,16	2 407 599	**2**
Hazelnuts	94 026	1,52	142 712	**pruning**		1,24	116 592	100%	18,00	2 098 658	**2**	**shells**	0,50	71 356	16,11	1 149 543	**1**
Grapes	3 494 210	7,27	25 415 815	**pruning**		1,95	6 813 709	100%	18,00	122 646 755	**123**	**marc**	2,70	9 434 366	18,90	72 571 972	**73**
Olives	4 900 329	2,45	12 019 146	**pruning**		1,38	6 762 453	100%	18,00	121 724 162	**122**	**cake**	0,50	6 009 573	20,08	60 336 111	**60**
Apples	567 268	20,27	11 500 942	**pruning**		3,38	1 917 365	100%	18,00	34 512 572	**35**	**pomace**	0,27	616 451	19,40	10 906 736	**11**
Peaches and Nectarins	249 681	16,46	4 110 151	**pruning**		2,19	546 802	100%	18,00	9 842 443	**10**	**stones**	0,063	258 939	19,47	4 718 893	**5**
											2 527						**2 213**

Ranking of the crop residues according to their energy potential:

Crop	Residue	Energy potential, PJ	% of total potential	
Wheat	straw	729	15,4	
Wheat	bran	592	12,5	
Maize	stover, husk	546	11,5	
Sugar beet	pulp	354	7,5	
Barley	straw	329	6,9	
Barley	bran	246	5,2	
Maize	cobs	244	5,1	
Rapeseed	meal	239	5,1	
Rapeseed	straw	203	4,3	
Sunflower	stalks	136	2,9	
Grapes	pruning	123	2,6	
Olives	pruning	122	2,6	
Potatoes	pulp, peel	77	1,6	
Grapes	marc	73	1,5	
Sugar beet	molasses	68	1,4	
Triticale	straw	63	1,3	
Olives	cake	60	1,3	
Rye	straw	57	1,2	
Sunflower	meal	57	1,2	
Oats	straw	56	1,2	92,3%
Triticale	bran	46	1,0	7,7%
Rye	bran	35	0,7	
Oats	bran	35	0,7	
Apples	pruning	35	0,7	
Sunflower	hulls	34	0,7	
Sugar beet	leaves	30	0,6	
Soybean	straw	24	0,5	
Oranges	pruning	23	0,5	
Almonds	pruning	20	0,4	
Rice	straw	19	0,4	
Oranges	peels	14	0,3	
Soybean	meal	12	0,3	
Apples	pomace	11	0,2	
Peaches and Nectarins	pruning	10	0,2	
Rice	husk	7	0,1	
Peaches and Nectarins	stones	5	0,1	
Almonds	shells	2	0,1	
Hazelnuts	pruning	2	0,0	
Hazelnuts	shells	1	0,0	
		4 739	**100,0**	

Selected as most important were crops with the indicative potential over 50 PJ and these represent 92.3% of the total crop residue potential.

Annex 3: Description of additional new oil crops

Macaw palm (*Acrocomia aculeata*): The neo-tropical palm species *Acrocomia aculeata* naturally occurs in a wide range of tropical and subtropical environments. In contrast to the African oil palm, it tolerates low temperatures (> -5°C) without negative impacts on yields. It grows between 30° north and south of the equator and is even found in areas with longer dry seasons up to six months such as the Chaco region of Paraguay and Cerrado region of Brazil. After five to six years 20 t/ha annually can be harvested. Since this fruit is nontoxic, all parts of it can be used. Considering the yield of perennial plants, the Acrocomia palm (2 t/ha/a of Pulp oil and 1 t/ha/a of Kernel oil) can ranked in-between the African oil palm (*Elaeis guineensis*, 3 – 6 t/ha/a of Pulp oil and 1 t/ha/a of Kernel oil) and Jatropha (*Jatropha curcas*, 1 t/ha/a).

For the past decade, the University of Hohenheim in Germany and the Catholic University of Paraguay have worked together on the domestication of *Acrocomia aculeata*, which is endemic to the Americas. There is substantial knowledge available on growth and yield performance to establish sustainable and rentable plantations.

The fruits of Macaw palm, can be used to produce food, feed, energy/fuel and raw materials for the cosmetic and chemical industry. In Paraguay ten oil mills are in operation using *Acrocomia* fruits for oil extraction.

Currently, further research to commercialise *Acrocomia* is taking place offering future potential, especially in Paraguay, Brazil, and Costa Rica where Acrocomia palm is planted and growing in various environments. (EBTP, 2015)

Dwarf saltwort / Dwarf glasswort (*Salicornia bigelovii*): A salt mash halophyte that is found on both the east and west coast of the US and Mexico. The plant is of interest as a biofuel feedstock as it grows in desert environments, it can be irrigated with seawater, and the seed contains around 30 % oil content. It is being grown extensively across the globe, for example in India. In The United Arab Emirates, the Sustainable Bioenergy Research Consortium is developing an Integrated Seawater Energy and Agriculture System (ISEAS) to cultivate the halophyte *Salicornia* as a sustainable feedstock for biofuel production. (EBTP, 2015)

Pennycress (*Thlaspi arvense*): Has been investigated in the U.S. by USDA-ARS as a potential feedstock for biodiesel. Pennycress can be grown as a winter ground cover crop and harvested in the spring, providing soy farmers with additional income. *Thlaspi arvense* varieties are being commercially developed by companies such as Arvegenix. (EBTP, 2015)

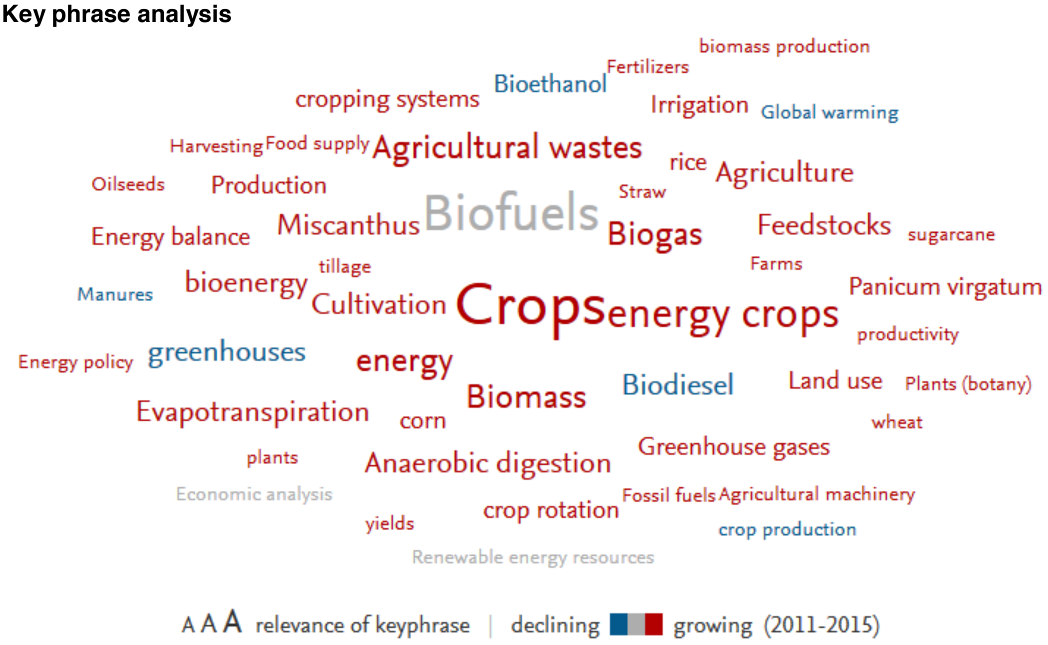
Ethiopian mustard (*Brassica carinata*): *Brassica carinata* oilseed has been developed as a biofuel feedstock (Resonance™) by Agrisoma Biosciences (Canada). It is suited to semi-arid areas and produces seed with 44 % oil content. In April 2012, Agrisoma announced that Resonance™ will be evaluated as a feedstock for Honeywell Green Jet Fuel™, and reported that the world's first civilian flight powered solely by biofuel was flown from Ottawa, Canada. (EBTP, 2015)

Indian Beech (*Millettia pinnata, Pongamia pinnata): Millettia pinnata (Pongamia pinnata*) is a leguminous tree species (15-25 m) that grows widely in Asia, including arid regions. It is pest resistant and produces seeds with 25–40 % lipid content (nearly half oleic acid). It also produces extensive root networks and can be used to prevent soil erosion (but also may cause problems as an invasive weed, if not properly managed). It has been widely investigated in India as a biodiesel. The University of Queensland is also carrying out R&D on *Pongamia pinnata* as a biofuel feedstock. (EBTP, 2015)

Annex 4: Major agriculture sector players in R&I – Output analysis with Elsevier SciVal

Feedstocks: energy crops

Key phrase analysis



Top 5 Countries (Europe):	Top 5 Institutions (Europe):
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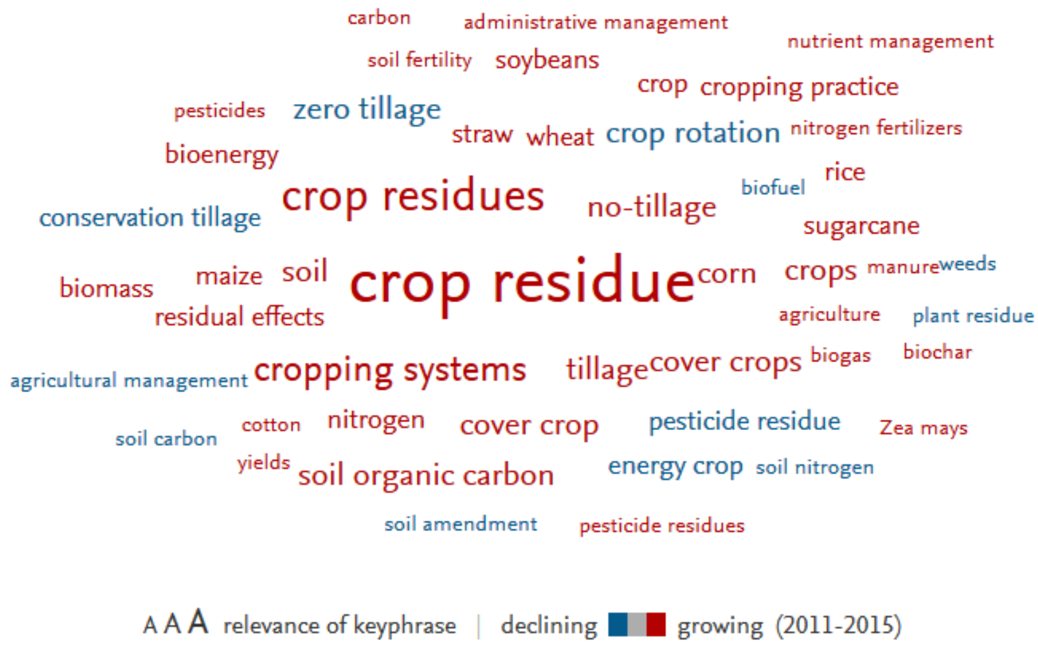
Italy	INRA Institut National de La Recherche Agronomique
United Kingdom	Swedish University of Agricultural Sciences
Spain	Aarhus University
France	University of Hohenheim

Top 5 Countries (Worldwide):	Top 5 Institutions (Worldwide):
United States	U.S. Department of Agriculture
China	Wageningen University & Research
India	Chinese Academy of Sciences
Germany	INRA Institut National de La Recherche Agronomique
Italy	University of Illinois at Urbana-Champaign

Feedstocks: crop residues

Key phrase analysis



Top 5 Countries (Europe):

- Germany
- Italy
- Spain
- France
- United Kingdom

Top 5 Institutions (Europe):

- INRA Institut National de La Recherche Agronomique
- Wageningen University & Research
- CSIC
- Swedish University of Agricultural Sciences
- CIRAD

Top 5 Countries (Worldwide):

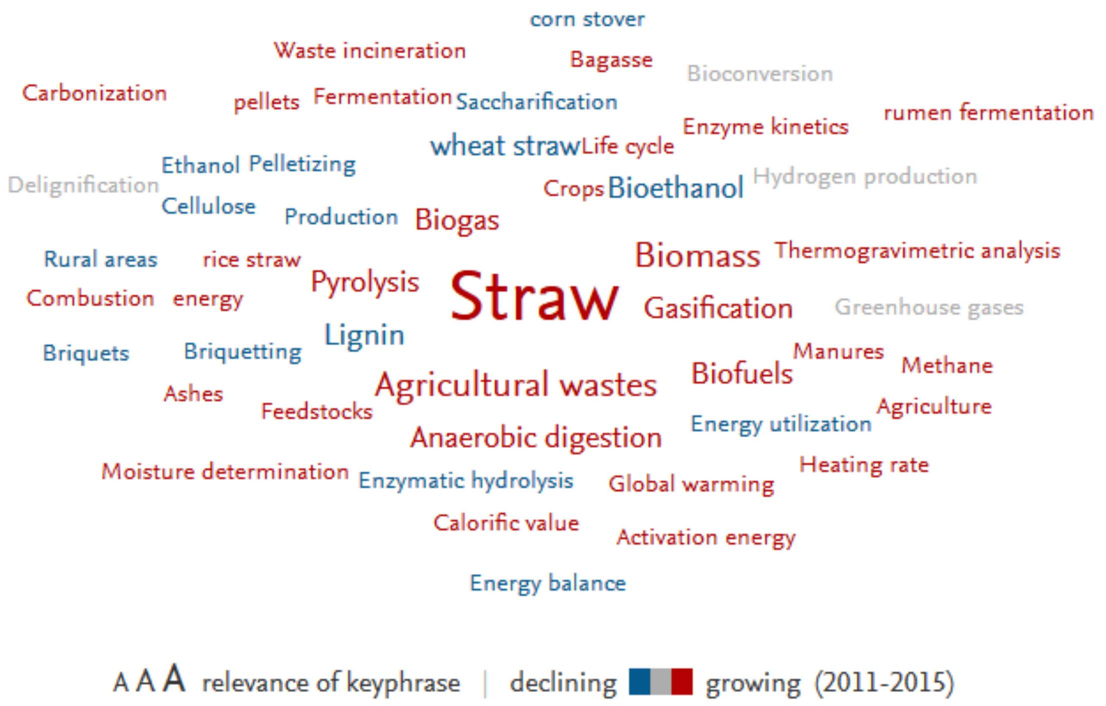
- United States
- China
- India
- Brazil
- Australia

Top 5 Institutions (Worldwide):

- U.S. Department of Agriculture
- AgriFood Canada
- Chinese Academy of Sciences
- Indian Agricultural Research Institute
- China Agricultural University

Feedstocks: straw

Key phrase analysis



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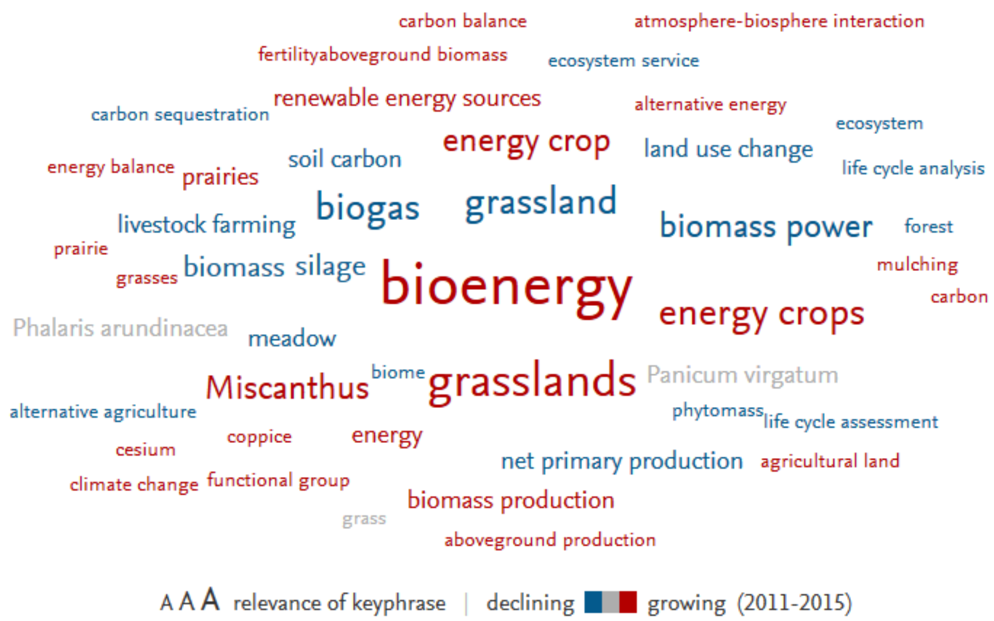
Germany	Technical University of Denmark
Denmark	INRA Institut National de La Recherche Agronomique
United Kingdom	Aarhus University
France	University of Copenhagen
Italy	Vienna University of Technology

Top 5 Countries (Worldwide):	Top 5 Institutions (Worldwide):
China	China Agricultural University
United States	Technical University of Denmark
India	Ministry of Agriculture of the People's Republic of China
Canada	University of Saskatchewan
Germany	Chinese Academy of Sciences

Feedstocks: grassland biomass

Key phrase analysis



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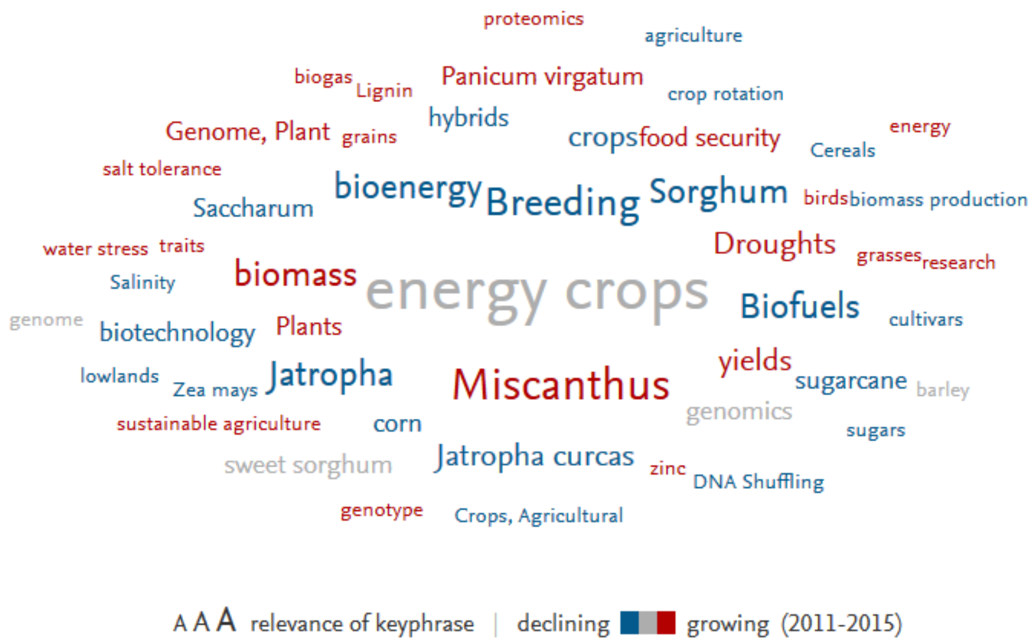
Germany	University of Kassel
United Kingdom	Aberystwyth University
Ireland	Wageningen University & Research
Austria	University of Hohenheim
Netherlands	Estonian University of Life Sciences

Top 5 Countries (Worldwide):	Top 5 Institutions (Worldwide):
United States	University of Kassel
Germany	Aberystwyth University
China	Wageningen University & Research
United Kingdom	Chinese Academy of Sciences
Ireland	University of Hohenheim

R&I: energy crop breeding

Key phrase analysis



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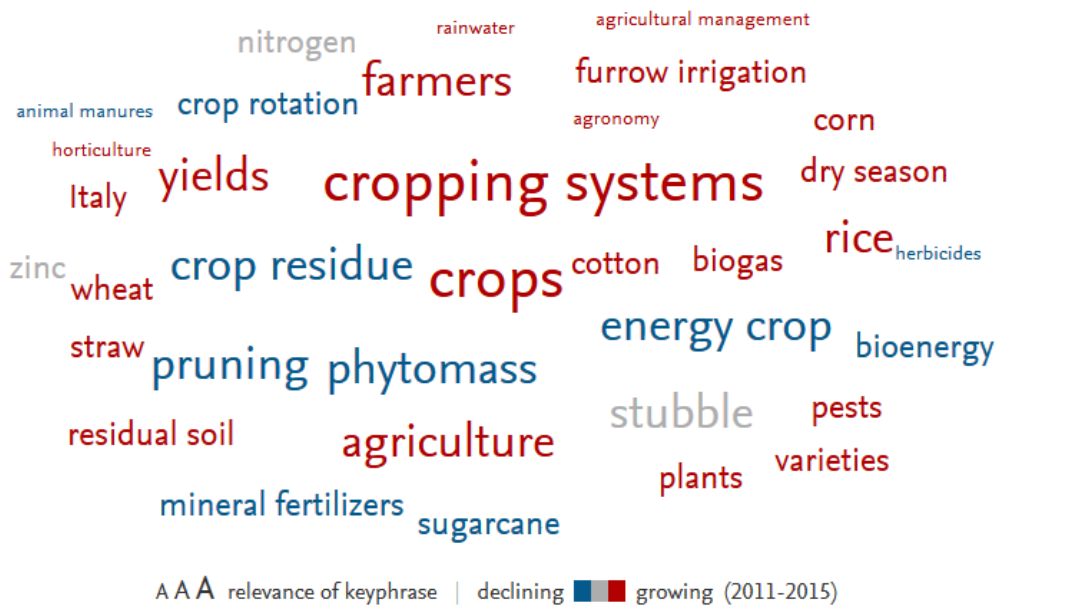
United Kingdom	Aberystwyth University
Germany	Rothamsted Research
Italy	INRA Institut National de La Recherche Agronomique
Spain	Swedish University of Agricultural Sciences
Netherlands	Wageningen University & Research

Top 5 Countries (Worldwide):	**Top 5 Institutions (Worldwide):**
United States	U.S. Department of Agriculture
China	Aberystwyth University
United Kingdom	International Crops Research Institute for the Semi-Arid Tropics
India	Chinese Academy of Sciences
Germany	Rothamsted Research

R&I: crops with high residue yields

Key phrase analysis



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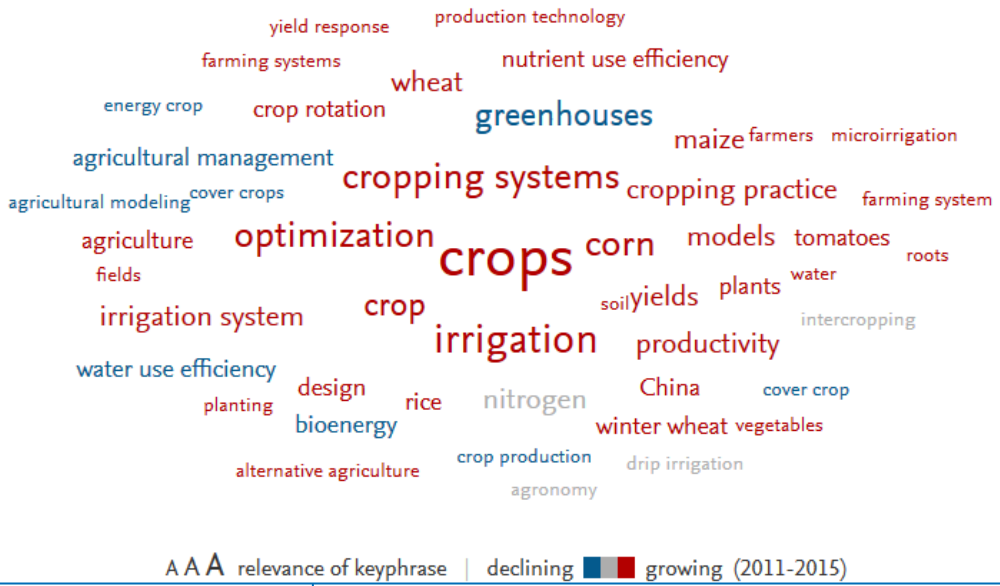
Spain	Universidad Politecnica de Valencia
United Kingdom	Ghent University
Italy	University of Natural Resources and Applied Life Sciences
Austria	Agricultural Research Council of Italy
Belgium	Agricultural University of Plovdiv

Top 5 Countries (Worldwide):	Top 5 Institutions (Worldwide):
India	Universidad Politecnica de Valencia
Australia	AgriFood Canada
China	China Agricultural University
United States	Colorado State University
Spain	Ghent University

R&I: optimized cropping systems

Key phrase analysis



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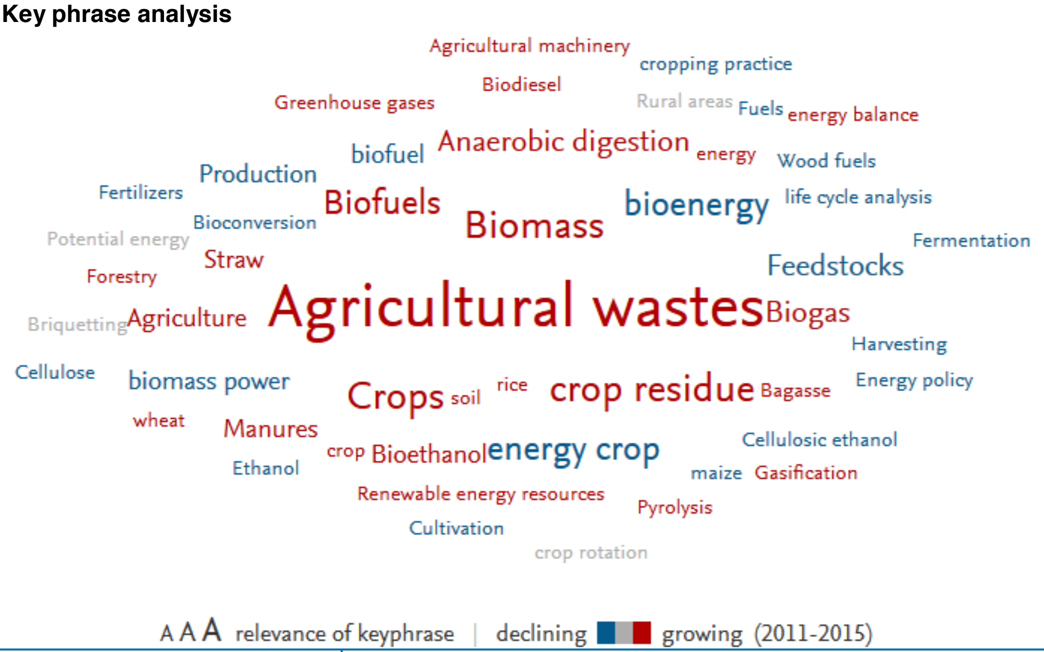
Germany	INRA Institut National de La Recherche Agronomique
Italy	Wageningen University & Research
Spain	ETH Zurich
France	CNR
United Kingdom	University of Bonn

Top 5 Countries (Worldwide):	Top 5 Institutions (Worldwide):
United States	China Agricultural University
China	U.S. Department of Agriculture
India	Chinese Academy of Agricultural Sciences
Germany	INRA Institut National de La Recherche Agronomique
Italy	Wageningen University & Research

R&I: harvesting and collection of crop residues for energy

Key phrase analysis



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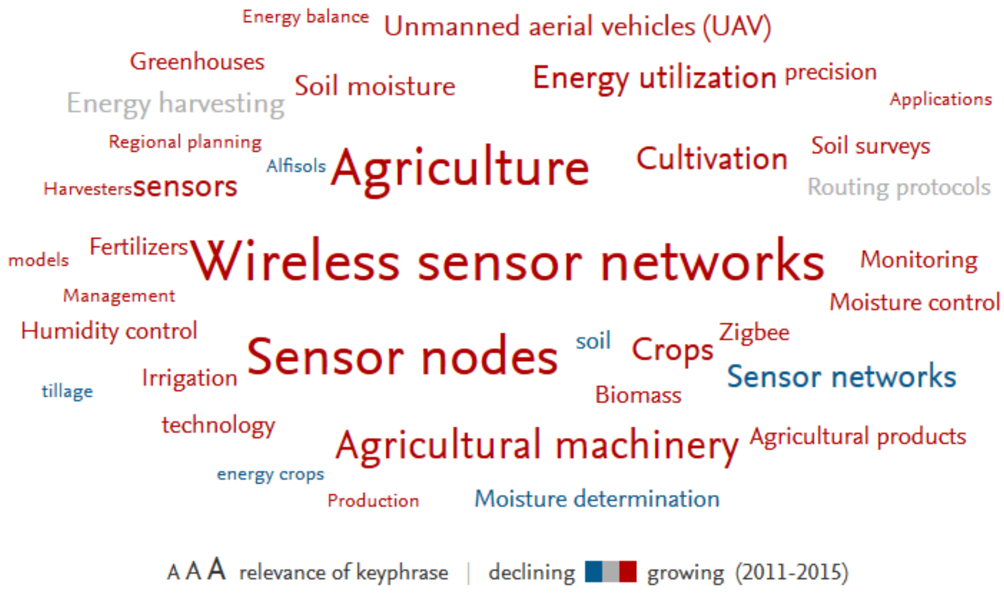
Italy	Wageningen University & Research
Germany	Swedish University of Agricultural Sciences
Spain	INRA Institut National de La Recherche Agronomique
United Kingdom	Technical University of Denmark
Netherlands	Aarhus University

Top 5 Countries (Worldwide):	Top 5 Institutions (Worldwide):
United States	U.S. Department of Agriculture
India	Indian Agricultural Research Institute
China	China Agricultural University
Italy	University of Nebraska
Germany	Wageningen University & Research

R&I: precision farming

Key phrase analysis



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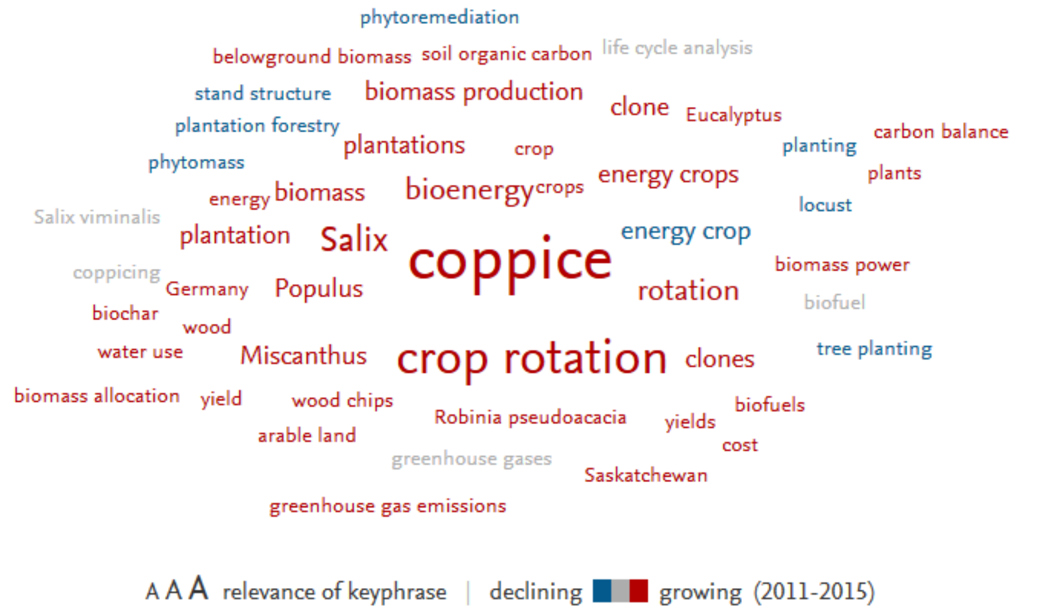
Germany	Aarhus University
Italy	Wageningen University & Research
Spain	CSIC
France	University of Natural Resources and Applied Life Sciences
United Kingdom	Karlsruhe Institute of Technology KIT

Top 5 Countries (Worldwide):	**Top 5 Institutions (Worldwide):**
China	China Agricultural University
United States	U.S. Department of Agriculture
India	Universidade de Sao Paulo
Germany	Northeast Agricultural University
Brazil	University of Illinois at Urbana-Champaign

R&I: SRC breeding and harvesting

Key phrase analysis



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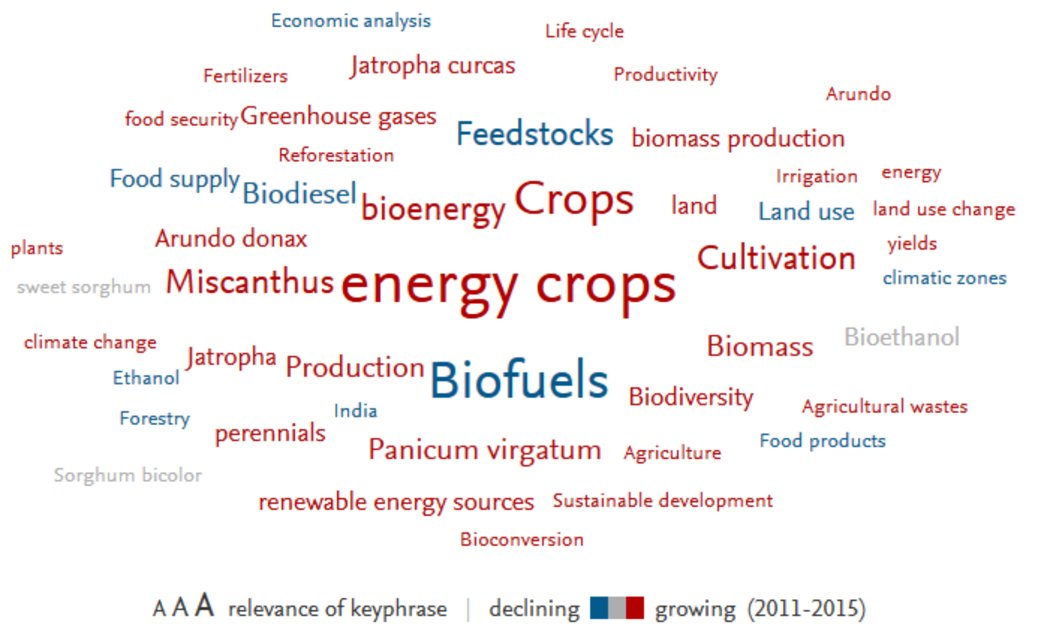
United Kingdom	University of Gottingen
Italy	University of Antwerp
Sweden	Technische Universitat Dresden
France	Rothamsted Research
Top 5 Countries (Worldwide):	**Top 5 Institutions (Worldwide):**
Germany	Swedish University of Agricultural Sciences
United Kingdom	University of Gottingen
Italy	University of Antwerp
Sweden	Technische Universitat Dresden
France	Rothamsted Research

R&I: energy crops on marginal land

Key phrase analysis



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Netherlands	Wageningen University & Research
Spain	University of Hohenheim

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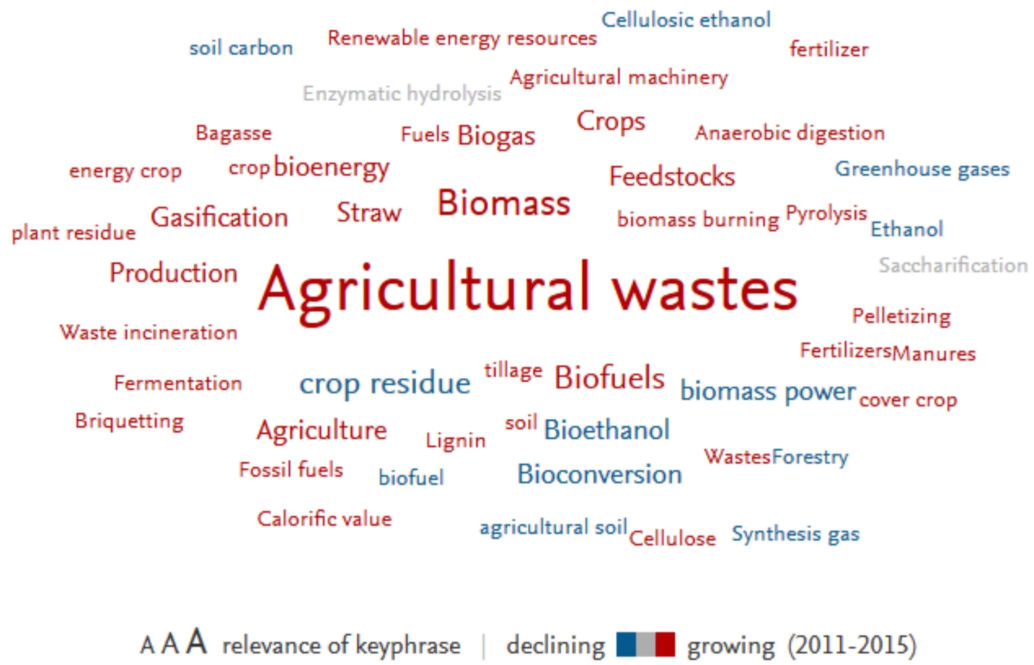
United States	Michigan State University
China	Chinese Academy of Sciences
Italy	Institute of Botany Chinese Academy of Sciences
United Kingdom	University of Illinois at Urbana-Champaign
Germany	Purdue University

R&I: agricultural biomass supply chain logistics

Key phrase analysis



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United States	U.S. Department of Agriculture
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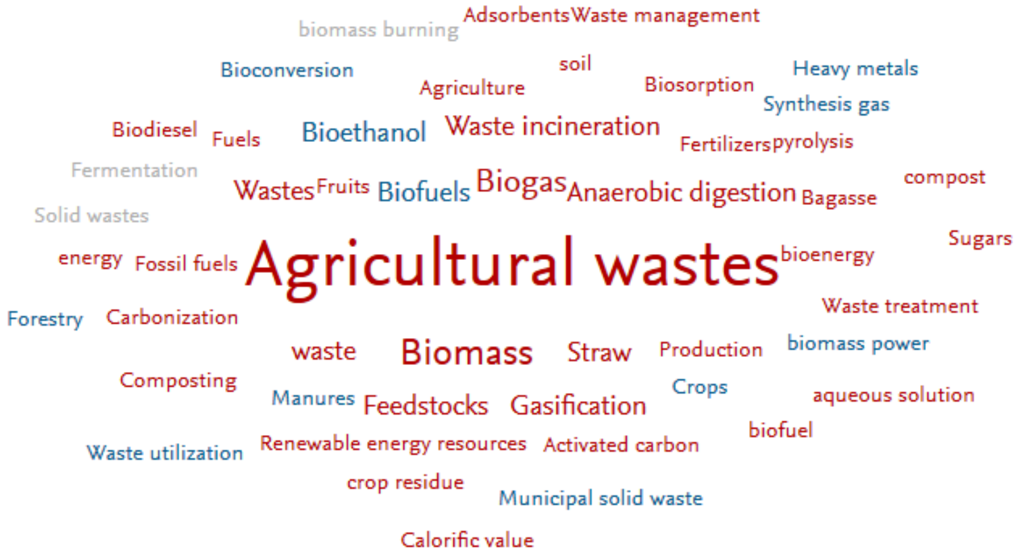
India	China Agricultural University
Italy	AgriFood Canada
Canada	INRA Institut National de La Recherche Agronomique

R&I: Improved biomass carriers

Key phrase analysis



A A A relevance of keyphrase | declining growing (2011-2015)

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India	China Agricultural University
Malaysia	Universiti Putra Malaysia
Italy	Universiti Teknologi Malaysia

Annex 5: Carbon Capture and Utilisation (CCU) Technologies

This study also estimated the potential of advanced fuel production via innovative Carbon Capture and Utilisation (CCU) technologies.

Carbon Capture and Utilisation (CCU) covers a variety of established and innovative industrial processes that utilise CO2 (or CO/CO2/H2 waste gas streams) as a source of carbon by transforming it into value added products such as synthetic fuels, chemical feedstocks or building materials. Thereby, carbon utilisation is regarded as complementary to CCS (Carbon capture and storage/sequestration) and often by definition does not include biological routes of transformation via aquatic biomass. The following CCU technologies for synthetic fuel production are addressed in this study:

- e-Fuels, Power-to-Gas (PtG), Power-to-Liquids (PtL);
- Low Carbon Fossil Fuels;
- Artificial Photosynthesis.

Carbon for utilisation can be obtained from a range of sources such as industrial gas streams, power generators (flue gas), bio-fermentation, anaerobic digesters, and geological sources or directly from the atmosphere. Each source has certain challenges in terms of its concentration, humidity and other chemicals present. Direct Air Capture (DAC) allows CO2 to be directly collected from the atmosphere. DAC processes may thus be sited in any location with access to low-cost low-carbon electricity while facing drawbacks with respect to energetic requirements to harvest CO2 at concentrations in the air that are much lower than industrial sources (400 ppm vs 140,000 ppm).

Table E.1 provides an overview of estimated global capturable CO2 emissions and capture costs for main emitting sources grouped into high purity sources (about 2% of capturable emissions), fossil-based power generation (76%) and large industrial emitters (22%). This information was adapted from a recent review paper on “Economics of carbon dioxide capture and utilization – a supply and demand perspective” by H. Naims (Naims 2016).

Table E.1: Global capturable CO_2 emissions and capture costs for main emitting sources

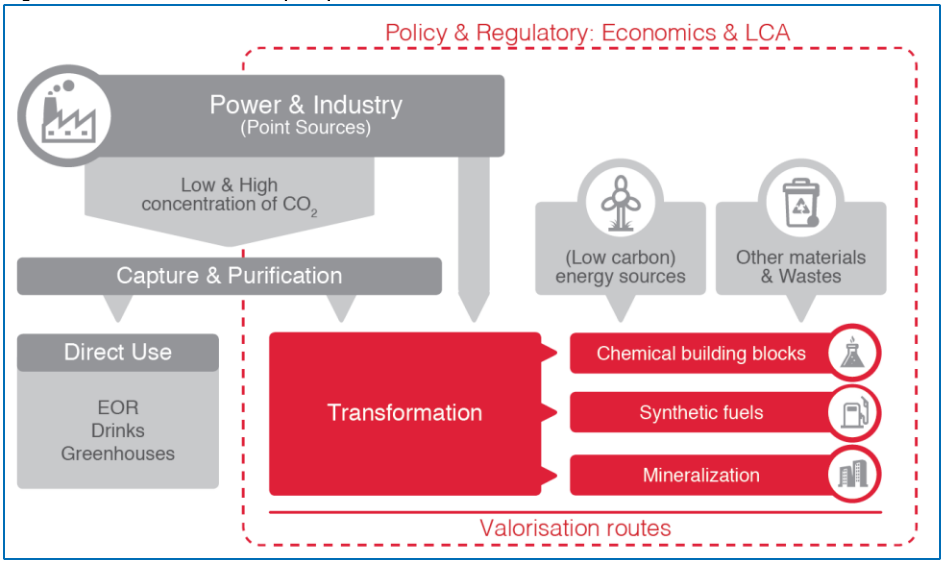
Group of emitters	Emitting source	Capturable emissions (Mt CO_2/year)	Capture costs (€/ t CO_2)
Industry high purity	Biomass fermentation	18	10
	Bioenergy	66	26
	Natural gas production	43	30
	Hydrogen production	46	30
	Ammonia production	128	33
Fossil-based power generation	Coal to power	7676	34
	Natural gas to power	1944	63
Large industrial emitters	Iron and steel production	500	40
	Cement production	1700	68
	Aluminum production	7	75
	Refineries	340	99

For certain industrial processes such as ammonia production, the CO2 emitted is very pure and capture requires only small additional efforts and thus provides CO2 at relatively low costs. Today, capture of CO2 is an established process mainly in hydrogen, ammonia and natural gas purification plants. However, CO2 capture from the largest emitting group, namely coal and natural gas power plants, currently involves significant efficiency losses and thus higher capture costs. Consequently, today coal and natural gas power plants do not represent suitable business cases for CCU. Large industrial CO2 emitting processes such as iron, steel, cement and aluminum production emit CO2 in different quantities and qualities, and thus potential business cases for CCU strongly depend on local circumstances.

For economic reasons it is expected that CCU technologies will be first implemented at industry high purity emitters and selected large industrial emitters. The present status of CO2 (or industrial waste gas) utilization for the production of synthetic fuels, chemical feedstocks or building materials is limited due to the low TRL of most existing CCU technologies, while on-going CCU-related research and innovation are covering a large variety of different utilization options and may lead to a significant production potential of CCU based advanced fuel production beyond 2030.

Figure E.1 presents an overview of Carbon Dioxide (CO2) utilisation value chains from different carbon resources via transformation processes (using further inputs such as energy and materials & wastes) to end products such as synthetic fuels, chemical feedstocks or building materials. Potential direct uses of CO2 include enhanced oil recovery (EOR) and the use in drinks and greenhouses.

Figure E.1: Carbon Dioxide (CO_2) utilisation value chains



Source: SCOT 2015

Synthetic fuels produced via CCU technologies can be broadly grouped into e-Fuels (i.e. Power-to-Gas (PtG), Power-to-Liquids (PtL)), Low Carbon Fossil Fuels, and fuels produced with Artificial Photosynthesis technologies.

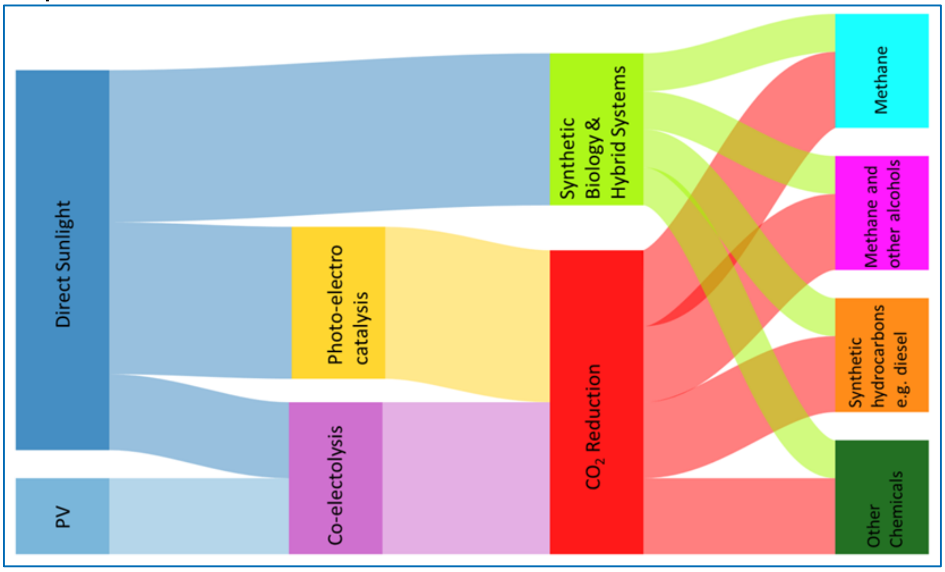
e-Fuels are advanced renewable fuels produced from renewable electricity via electrolysis. They offer the potential to provide an energy buffer (storage solution) between low-carbon electrical energy sources and energy demands and may serve as drop-in replacements for liquid or gas fossil fuels with applications in the heavy vehicle and aviation sector. Thereby, the capture of CO_2 from the air or the use of biogenic/biomass sources of carbon could even provide potential future carbon-neutral or negative liquid/gaseous fuels. Examples for such synthetic fuels are DME (Dimethyl Ether), methane, DMC (Dimethyl Carborate), methanol and synthetic diesel.

Currently, there is also considerable interest to further develop so-called **Low carbon fossil fuels** produced from gaseous streams via CCU technologies. The following definition of “Low carbon fossil fuels” was proposed by the Sub-Group on Advanced Biofuels (SGAB) initiative: Low Carbon Fossil Fuels are liquid and gaseous fuels produced by the conversion of exhaust or waste streams of fossil fuel industrial applications via catalytic, chemical, biological or biochemical processes. This definition is promoted by SGAB to facilitate incorporation of such CCU technologies in fuel decarbonisation legislation as well as their differentiation from renewable fuels unless they fulfil a similar minimum GHG saving criteria as biofuels.

Artificial Photosynthesis (AP) technologies have been recently investigated in detail in the framework of the study “Assessment of artificial photosynthesis“ performed for DG Research & Innovation (Ecorys 2016). For this study, artificial photosynthesis was understood to be a process that aims to mimic the physical chemistry of natural photosynthesis by absorbing solar energy in the form of photons and using this energy to generate fuel molecules through a synthetic system that utilises either biomimetics, nanotechnology, synthetic biology or a combination of these systems.

The main technology pathways identified and assessed in this study are co-electrolysis, photo-electro catalysis, and synthetic biology and hybrid systems as displayed in Figure E.2. Advanced fuels produced via AP pathways include methane, methanol and other alcohols as well as synthetic hydrocarbons.

Figure E.2: Technology pathways for artificial photosynthesis and indicative selection of generated compounds



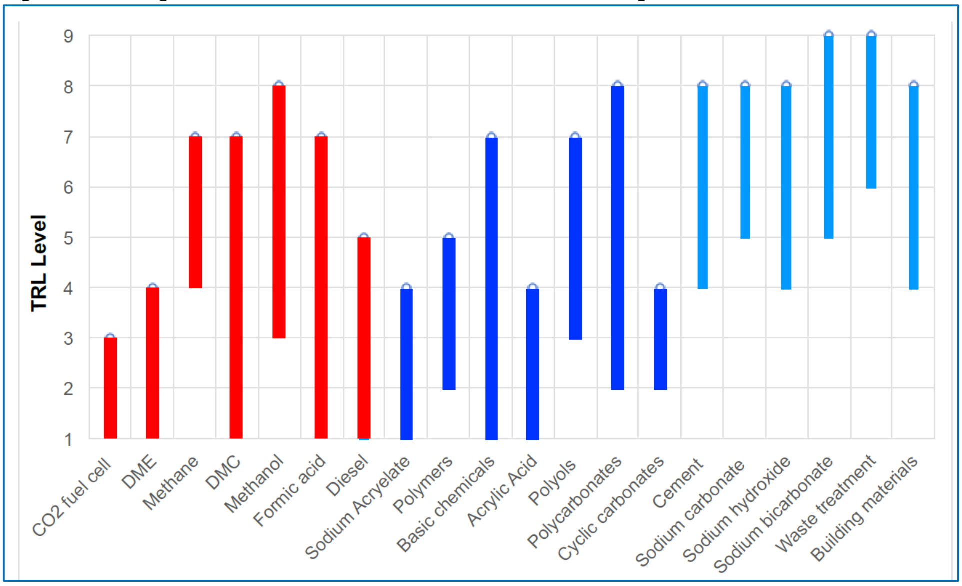
Source: Ecorys 2016.

In addition to synthetic fuels, also a large number of **chemicals** can be produced using CO_2 as a feedstock such as methanol (used as chemical building block), polymers, urea, carboxylates, carbonates, and olefins. Many of these products are also valuable intermediates including synthesis gases and small organic molecules (e.g. formic acid). Methanol is an important product due to its use as a feedstock in many subsequent chemical processes.

Finally, materials such as industrial wastes can be carbonated leading towards the production of building materials and stabilised waste products. Industrial **mineralisation** has the benefit of improving certain industrial wastes to create waste streams that are less toxic and chemically stable, while at the same time sequestering CO_2.

Figure E.3 provides an overview of the range of Technology Readiness Levels (TRLs) of promising CO_2 utilisation pathways. Some CO_2 utilisation technologies are close to the market (especially in the field of mineralisation), however many processes to transform CO_2 into products such as synthetic fuels are currently at low TRL and still require more research and technological development to become commercial.

Figure E.3: Range of TRLs of different CO2 utilisation technologies



Source: SCOT 2015.

The current TRL status of selected CCU technologies in the categories e-Fuels, Low Carbon Fossil Fuels, and Artificial Photosynthesis technologies is presented in Table E.2.

Table E.2: TRL of selected CCU technologies

	Feedstock	Technology	Type of synthetic fuels	Status
e-Fuels	H_2 via RES electricity	Catalysis	Methanol	TRL 5-6
	H_2 via RES electricity		Methane	TRL 5-6
	H_2 via RES electricity		Synthetic hydrocarbons	TRL 5-6
Low carbon fossil fuels	Steel and chemical industry (waste gases)	Fermentation	Ethanol	TRL 6-7
		Up-grading and catalytic synthesis	Methanol	TRL 5-6
			Methane	TRL 5-6
	Waste polymers, plastics, non-biodegradable fraction of MSW	Gasification, catalytic synthesis and fermentation	Synthetic hydrocarbons, alcohols from fermentation	TRL 6-8
AP	CO_2 and water	Co-electrolysis in Solid Oxide Electrolyser Cells (SOEC), catalytic synthesis	Synthetic hydrocarbons from syngas (CO/H_2)	TRL -5
	CO_2 and water	Photo-electro catalysis	H_2, methane, methanol, synthetic hydrocarbons	TRL 2-4
	CO_2 and water	Photosynthetic microbial cell factories based on cyanobacteria	Ethanol	TRL 6-8

Source: Team Analysis, adapted from SGAB 2017.

As shown in Figure E.3 and table E.2, technologies for the production of synthetic fuels from CO_2 are currently mainly in the research and demonstration stage and **production volumes are negligible**.

The following main technological developments are presently still required to move towards future commercialisation of CO_2 utilisation technologies (SCOT 2015):

- Advances in plasma and co-electrolysis processes as competing routes to conventional Fischer-Tropsch and Sabatier processes to produce syngas and hydrocarbons;
- Advances in modular reactors to be operated under flexible part load regimes facilitating the use of variable low-carbon low-cost renewable electricity;
- Advances in carbon capture technology (including air-capture technology) to reduce costs and energy use;
- Advances in CO_2 utilisation processes based on photochemistry by mimicking photosynthesis to generate fuels and chemicals (i.e. artificial photosynthesis);
- Advances in catalyst development such as catalysts based on earth abundant materials, catalysts recovery and catalysts allowing the direct use of flue gases of varying composition.

Specifically, Table E.3 provides an overview on important research and innovation priorities of selected synthetic fuel end products (SCOT 2016a).

Table E.3: Research and innovation priorities of selected end products

CO_2-derived products	Research and innovation priorities
Methane Methane is used in heat, power and transport sectors. It is synthesised by combining CO_2 (or CO) with H_2 via Sabatier reaction at high temperatures with metal catalysts. Sources of H_2 with low carbon footprint are required.	Heat management for the Sabatier process; New reaction pathways such as co-electrolysis that require water (steam) as an input to the reaction rather than hydrogen; More efficient methane production pathways such as CO_2 & H_2O plasma in direct contact with novel catalyst; Photo electrochemical systems for methane production; Improve catalyst selectivity and stability; Reduce the use of noble metals and other expensive elements in the electrodes.
Methanol Methanol is a major intermediate for the chemicals industry. CO_2 is hydrogenated in the presence of a wide range of catalysts to form methanol. Sources of H2 with low carbon footprint are required.	Photo electrochemical systems for methanol production; Direct processes (from methane) with high selectivity and yield; Improve catalyst yield (at low temperature), turnover rate, selectivity and stability; Inverse methanol fuel cells (novel electrodes and membranes); Process Intensification of methanol synthesis (design of more efficient reaction and separation equipment).
Higher hydrocarbons CO_2 can be converted to hydrocarbons using either indirect routes via synthesis gas (syngas) followed by the Fischer-Tropsch process or via methanol synthesis. Use as synthetic aviation fuel (kerosene) and synthetic diesel in the aviation and heavy duty transport sectors.	Minimising production costs via catalyst optimisation and developing new process routes; Efficient one reactor CO_2 conversion to higher hydrocarbons; Efficient syngas production from CO_2 as input for Fisher-Tropsch synthesis; Novel catalyst materials with improved selectivity in chemical synthesis from syngas to a specific hydrocarbon end-product.

Existing pilot, demonstration and pre-commercial plants

In recent years, interest in CCU technologies has grown and a number of industry-led pilot and demonstration initiatives have been launched to demonstrate technical and pre-economic viability of several different CO_2 utilisation technologies in the categories e-Fuels, Low Carbon Fossil Fuels, and Artificial Photosynthesis technologies in order to pave the way towards future commercialisation of CCU technologies (see Table E.4).

Table E.4: Pilot, demonstration and pre-commercial plants for the production of e-Fuels, Low Carbon Fossil Fuels and Artificial Photosynthesis based fuels

Technology	Industry leader	Type	Feedstock capacity	Fuel produced	Start-up year	Operation hours	Description
e-Fuels							
Power to hydrogen	E.ON	Demo, pre-commercial	RES electricity 2 MW_e	Hydrogen (intermediate fuel) 1.1 MW (360 Nm^3/h)	2013	10.000	E.ON's power-to-gas pilot unit in Falkenhagen, Germany uses renewable electricity to power electrolysis equipment that transforms water into hydrogen, which is then injected into the natural gas transmission system.
Power to gas (PtG)	Audi AG	Demo, pre-commercial	RES electricity 6.3 MW_e CO_2 from biogas plant	Methane (3.5 MW (360 Nm^3/h)	2014	12.000	This largest PtG was developed and built by Solar Fuel GmbH for Audi AG in Werlte, Germany. The produced methane is injected in the local gas grid and can be certified for Audi's Natural Gas Vehicles (NGV). The CO_2 source is stripped from a waste treatment biogas plant.
Power to gas (PtG)	Electrochaea (BioCat proj.)	Demo	RES electricity 1 MW_e 50 m^3/h CO_2 from wastewater/biogas plant	Methane 50 Nm^3/h	2016	>1.000	Electrochaea's BioCat project is located at a wastewater treatment plant in Copenhagen and demonstrates the company's biological methanisation technology. The methane will be injected in the local gas distribution grid.
Power to Methanol	Carbon Recycling International (*CRI*)	Demo	RES electricity 6 MW_e 5.600 t/a CO_2 from geothermal power plant	Methanol 10 t/day	2011	10.000	This largest Power to Methanol facility is operating since 2011 in Svartsengi, Iceland. The plant uses electricity to generate hydrogen which is converted into methanol in a catalytic reaction with carbon dioxide. The CO_2 is captured from flue gas released by a geothermal power plant located next to the CRI facility.
Power to Methanol	CRI, Steag	Demo	RES electricity 1 MW_e ~600 t/a CO_2 from fossil fuel power plant	Methanol 1 t/day	2017	N/A	This demonstration project will be implemented in the framework of the EU project MefCO2 at the Steag owned and operated hard coal fired power plant in Lünen, Germany.
Technology	Industry leader	Type	Feedstock capacity	Fuel produced	Start-up year	Operation hours	Description
Low carbon fossil fuels							
Gas	LanzaTech,	Pre-	H_2 + CO	Ethanol	2017	8,000	A consortium of ArcelorMittal, LanzaTech, Primetals

Technology	Industry leader	Type	Feedstock capacity	Fuel produced	Start-up year	Operation hours	Description
fermentation	ArcelorMittal	commercial	50,000 Nm^3/h (waste gases from steelmaking)	143 t/day			Technologies and E4tech started the construction of Europe's first-ever commercial demonstration facility at ArcelorMittal's integrated steel plant in Ghent, Belgium to create bioethanol from waste gases produced during the steelmaking process. The operation of a second gas fermentation plant is planned at the same facility in Ghent and further roll-out at ArcelorMittal sites is anticipated in the coming 10 years.
Gas fermentation	LanzaTech	Demo	H_2 + CO 15 Nm^3/h (gasified MSW)	Ethanol 0.05 t/day	2015	4,000	This demonstration plant is operated at a MSW facility in Japan using gasified MSW to produce ethanol through gas fermentation.
Gas fermentation	LanzaTech	Demo	H_2 + CO 450 Nm^3/h (waste gases from steelmaking)	Ethanol 1.4 t/day	2013	6,500	This demonstration plant is operated by Beijing Shougang LanzaTech New Energy Technology Co. in Beijing, China at Shougang Steel Mill using flue gases to produce ethanol through gas fermentation.
Artificial Photosynthesis technologies							
Electrolysis cells	Siemens Corporate Technology	Pilot	CO_2 from power station flue gases, factories and chemical plants	Methanol Chemical compounds	2015	>1,000	This pilot initiative is implemented within the project CO2toValue. Modules have been developed in which CO_2 is energetically stimulated as in plant cells. The activated CO_2 then reacts to produce methanol and other chemical compounds. The CO_2 feedstock is expected to come from power station flue gases, factories and chemical plants.
Photo-electrocatalysis	Royal Dutch Shell Bauhaus Luftfahrt	Pilot	CO_2 and water (4 kW lab set-up)	Syngas (intermediate) Synthetic kerosene	2014		In the framework of the EU project Solar-Jet an innovative process is demonstrated using concentrated sunlight to convert CO_2 and water to a synthesis gas (H_2 + CO) which is finally converted into kerosene by commercial Fischer-Tropsch technology. The follow-up project SUN-to-LIQUID was launched in 2017 and aims at up-scaling technology to a 50 kW pre-commercial plant in the field.

Estimated potential of advanced fuel production via Carbon Capture and Utilisation (CCU) technologies

Due to the current low TRL of existing Carbon Capture and Utilisation (CCU) technologies in the categories e-Fuels, Low Carbon Fossil Fuels, and Artificial Photosynthesis technologies, present production levels are negligible and will remain at a low level until 2020.

However, due to growing interest for CCU technologies among industrial players and on-going R&I initiatives such as pilot, demonstration and pre-commercial plants (mainly in Germany, Belgium, Denmark and Iceland) it is anticipated that advanced biofuels production via CCU technologies will increase in the coming decades.

At present it is difficult to predict the potential contribution of CCU technologies to the advanced (bio)fuel market in 2030 and 2050. In its final report from March 2017 the Sub Group on Advanced Biofuels (SGAB) of the Sustainable Transport Forum estimates the potential contribution to 2030 transport fuel targets of e-fuels (i.e. advanced fuels from renewable electricity via electrolysis) and Low Carbon Fossil Fuels (i.e. fuels from conversion of exhaust or waste streams via catalytic, chemical, biological or biochemical processes) to be 1.4-2 Mtoe (0.5% of total EU energy for transport) and 2-3 Mtoe (0.7%), respectively and depending on R&I ambition (SGAB 2017). The production figures for 2050 were estimated to only moderately increase for the reference and to increase about 5-fold for high R&I ambition with respect to 2030 levels as anticipated for other advanced biofuel technologies (see D2.2 of present study).

For Artificial Photosynthesis technologies the production potential was analysed in Deliverable 6: Market potential and recommendations (Ecorys 2016b) in the framework of the study “Assessment of artificial photosynthesis“ performed for DG Research & Innovation. Assessment of total produced biofuels from the AP technologies co-electrolysis and photo-electrocatalysis was done for two different scenarios, namely for moderate and high biofuel demand, and for three different level of “learning-by-doing” (corresponding to different levels of ambition in research and innovation activities). The estimated potential figures presented in Table E.5 correspond to the moderate biofuel demand scenario for two different level of research and innovation ambition. Until 2030 no contribution of advanced fuels from AP technologies are expected whereas the production potential for 2050 was estimated at 1.8 and 5.8 Mtoe depending on the level of ambition in research and innovation activities.

Table E.5: Estimated production potential of CCU technologies in 2030 and 2050

	Estimated production potential (Mtoe)			
	2030		2050	
	Reference	High R&I	Reference	High R&I
e-Fuels	1.4	2,0	2,0	10,0
Low Carbon Fossil Fuels	2.0	3.0	2.5	15,0
Artificial Photosynthesis technologies	0	0	1.8	5.8

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