Coordinating research and innovation in the field of sustainable alternative fuels for aviation

WP4 Feedstock and Sustainability, D4.2: Final Report on collection, mapping and evaluation of R&D activities in the field of feedstock production and sustainability

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EXECUTIVE SUMMARY

This “final report on collection, mapping and evaluation of R&D activities in the field of feedstock production and sustainability” introduces and evaluates a series of different types of renewable biogenic feedstock suitable for the conversion into alternative aviation fuels. The evaluation of environmental impacts connected to the cultivation and production of the feedstocks considered in this report is conducted by applying a set of sustainability indicators such as Greenhouse Gas Emission balances, the risk of inducing direct and indirect land use changes, fertilization requirements and the like. In addition, the sustainable availability of the feedstocks considered in this report in Europe is analyzed, and prominent sustainability certification schemes are introduced and compared to each other.

As examples of triglycerides (biogenic oils and fats) the feedstocks microalgae, camelina, used cooking oil (UCO) as well as rapeseed are introduced and discussed. Examples of lignocellulosic biomass include switchgrass and short rotation coppice (SRC). Agricultural and forestry residue research and development activities funded by the European Commission that have been identified as related to the production and sustainability of the selected feedstocks are listed and mapped according to their scope and relevance.

While microalgae have received a lot of attention as a promising biofuel feedstock due to their supposedly high production rates, minimal competition with food production and the like, it has been shown that particularly their cultivation is very energy intensive and therefore linked to increased Greenhouse Gas (GHG) emissions. In addition, considerable energetic inputs are required to prepare the biomass for lipid extraction, which is in turn energy and GHG intensive as well. Furthermore, water requirements particularly of open cultivation systems are high and therefore problematic from an environmental point of view.

The terrestrial crop camelina has proven to be a viable candidate for the production of alternative jet fuels with an overall GHG reduction potential of the derived HEFA-SPK of 60%, not taking into account Indirect Land Use Change (iLUC). Camelina is a low-maintenance crop, can be grown in a variety of climatic and soil conditions and requires relatively low nutrient inputs. In addition, camelina does not compete with food production and the risk of inducing land use changes is low. All of these factors make it a sustainable crop that can considerably contribute to making aviation less carbon intensive. High yields, however, are only achieved under favorable conditions. In addition, low seed weight as well as very small seed sizes can pose challenges to harvesting and transport logistics.

Rapeseed is the most widely cultivated oil crop in Europe for the production of biodiesel. However, its high fertilizer requirements, corresponding GHG emissions as well as other sustainability concerns linked to rapeseed production are seen as major obstacles for the utilization of rapeseed as bio-jet feedstock.

UCO has proven its viability as a feedstock for the production of alternative aviation fuels via the well-established HEFA pathway. UCO collection from gastronomy is well-organized but the main hindering factor is the relatively low availability. If the use of UCO as a feedstock is to contribute to making the aviation less carbon intensive in a meaningful way, solutions for collecting waste oils from households have to be found.

Lignocellulosic biomass is of special interest for the aviation industry as it does not compete with food production and can be converted into different types of fuels via a variety of conversion pathways. In addition, lignocellulosic biomass requires little agricultural inputs (N fertilization) and is of fast growing nature. Both switchgrass and SRC have low fertilization requirements, use N efficiently, show high rates of carbon sequestration and can be cultivated on a variety of different soils and in different climates. In Europe, SRC harvest is commercially mature, while switchgrass cultivation is not commercially established.

Waste and residues from agriculture and forestry have a series of sustainability advantages compared to ‘conventional’ types of feedstock and are therefore favored by the Renewable Energy Directive. Particularly straw, being residue material from wheat production for example shows a high sustainable availability and a favorable GHG balance. Competing uses for straw by other bioenergy applications as well as the agronomic on-site functions agricultural residues fulfill at farm level have to be considered when aiming at utilizing straw as a bio-jet feedstock.

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LIST OF ABBREVIATIONS

C-JF	CORE-JetFuel – Coordinating research and innovation in the field of sustainable fuels for aviation
AtJ	Alcohol to Jet
CAAFI	Commercial Aviation Alternative Fuels Initiative
CAT	Certification Assessment Tool
CoC	Chain of Custody
CO_2	Carbon Dioxide
dLUC	direct Land Use Change
dm	dry matter
e. g.	for example
FFA	Free Fatty Acid
FSC	Forest Stewardship Council
FSRL	Feedstock Readiness Level
FQD	Fuel Quality Directive
FT	Fischer-Tropsch
GIS	Geographic Information System

GHG	Greenhouse Gas
GMO	Genetically Modified Organism
GWP	Global Warming Potential
HCV	High Conservation Value
HDRD	Hydrogenation-Derived Renewable Diesel
HEFA	Hydroprocessed Esters and Fatty Acids
HTL	Hydrothermal Liquefaction
i. e.	it est
iLUC	Indirect Land Use Change
ISCC	International Sustainability & Carbon Certification
K	Potassium
LCA	Life Cycle Assessment
Mg	Magnesium
N	Nitrogen
NER	Net Energy Ratio
P	Phosphorus
PE	Photosynthetic Efficiency
PBR	Photobioreactor
R&D	Research and Development
RED	Renewable Energy Directive
RFS	Renewable Fuel Standard
RSB	Roundtable on Sustainable Biomaterials
SFE	Supercritical Fluid Extraction
SOC	Soil Organic Matter
SOM	Soil Organic Matter
SPK	Synthetic Paraffinic Kerosene
SRC	Short Rotation Coppice
WOSR	Winter OilSeed Rape
WF	Water Footprint
WHO	World Health Organization

Introduction

One of the most important challenges for the aviation sector in fulfiling its self-imposed greenhouse gas emission (GHG) reduction targets is the transformation of its energy base from fossil fuels to a secure supply of renewable, climate-protecting, sustainable and suffiently scalable alternative fuels.

In the near future, the only viable source for these alternative fuels are biogenic feedstocks that assist in making aviation less carbon intensive and therefore decrease negative impacts on the climate while increasing the sector's sustainability.

However, concerns have been voiced that certain types of feedstocks suitable for the conversion into alternative aviation fuels have detrimental environmental impacts, particularly when being cultivated and processed at large-scale. Negative effects of fertiliziation, the competition with global food production, GHG emissions emerging from altering previously unused land hereby constitute the most commonly referred to sustainability issues in this context.

This report therfore introduces a selection of different feedstocks that are suitable for the conversion into the alternative aviation fuels and discusses their sustainability performance by applying a range of sustainability indicators. First, four types of feedstocks belonging to the group of triglycerides (biogenic oils and fats) are introduced. Subsequently, two examples of lignocellulosic biomass as well as two examples of the feedstock group 'waste and residues' are discussed.

Lastly, a mapping and evaluation of European R&D activities relating to the discussed feedstocks is conducted.

Figure 1 gives a schematic overview of the technological research and development "landscape" related to the production of alternative aviation fuels considered by the CORE-JetFuel project in its assessment.

As mentioned above, the present report (D4.2) evaluates a selection of feedstocks, corresponding to three of the main feedstock groups identified on the left-hand side of the figure below. The according assessment of selected bio-jet production pathways evaluation of conversion technologies is conducted in CORE-JetFuel Deliverable 4.4.

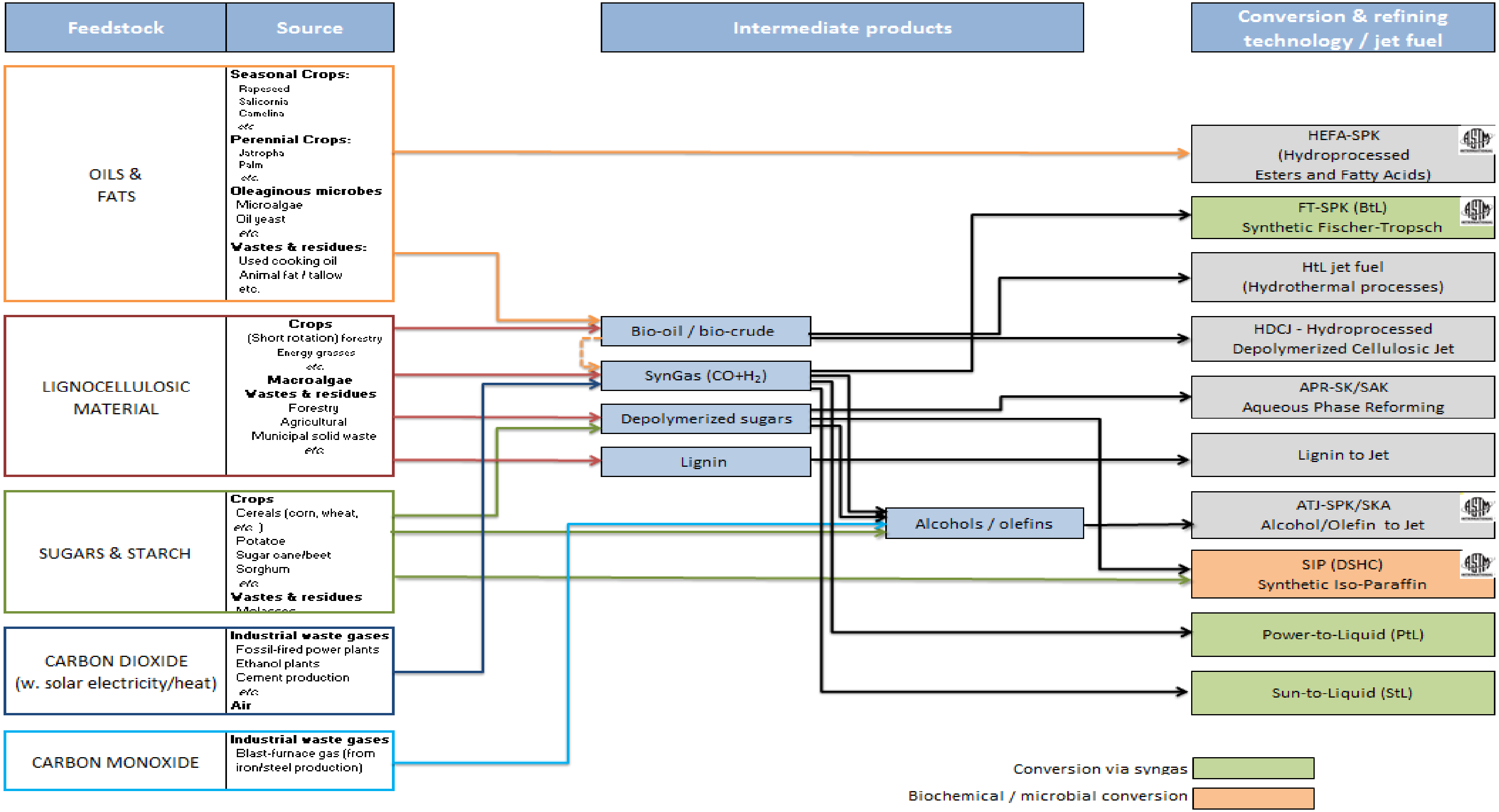

Figure 1: Schematic representation of the identified "landscape" of production pathways towards renewable jet fuel, defined by types of feedstock, conversion technologies and the feasible combinations thereof. Indication of ASTM certified pathways

BIOGENIC OILS AND FATS

1 Microalgae

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, but not for the conversion into jet fuel via the HEFA (hydroprocessed esters and fatty acids) pathway, which is analyzed and evaluated in the CORE-JetFuel Deliverable D4.4.

As stated above, macroalgae could potentially serve as a feedstock for the production of alternative jet fuels via the Alcohol-to-Jet (AtJ) pathway and Hydrothermal Liquefaction (HTL), which are also considered of D4.4. However, D4.2 will introduce and evaluate another feedstock for the AtJ conversion pathway, not macroalgae. This is also due to the fact that the cultivation of macroalgae is fundamentally different from microalgae and not very developed. The subsequent discussion and evaluation will for the reasons outlined above solely focus on microalgae.

The energy product range that can be derived from microalgae is tremendous, ranging from biofuel and jet fuel to alcohols and conventional liquid hydrocarbons, to pyrolysis oil and coke to gaseous compounds such as methane and hydrogen (Rösch, 2012). The following figure illustrates the various energy applications microalgae can be utilized for.

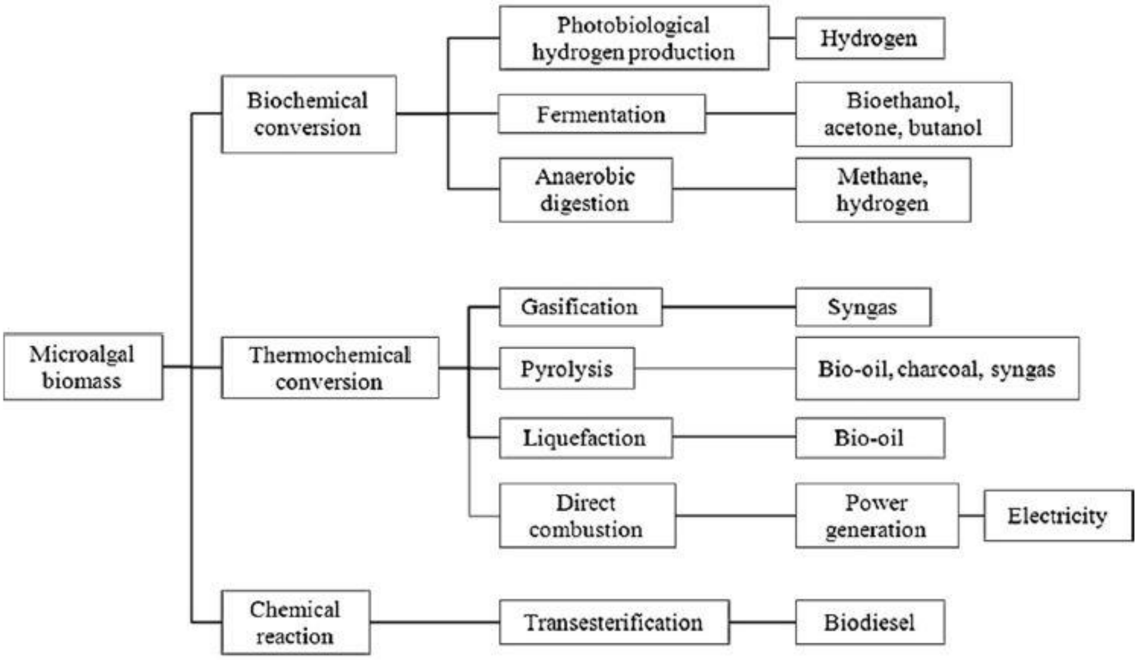

Figure 2: Alternatives of microalgae-based energy (Arnold, 2013)

Characteristics of microalgae and biodiesel produced from it are displayed in the table below. Generally, it has to be noted that most information available in the literature is calculated based on varying assumptions in terms of system boundaries, input variables and the like, with the effect that some of the values (and statements) are strongly diverging, thereby making a comparison difficult. Reliable data is also difficult to obtain, as most players involved in the production of microalgae and according biofuels do not disclose any information. This is especially true for the handful of companies worldwide that are producing on an industrial scale.

Table 1: Selected microalgae properties

Feedstock[(1)]			
	Chorella vulgaris	*Selenastrum rinoi*	*Scenedesmus obliquus*
Biomass Productivity in g/L/d	0.145 – 0.148	0.235 – 0.279	0.119 – 0.129
Lipid Content in % in dm (dry matter)	20.7 (± 0.9)	22.4 (± 2.6)	22.7 (± 0.9)
Lipid productivity in mg/L/d	12.9 (± 0.6)	18.7 (± 2.2)	9.4 (± 0.4)

[1] Petrick et al. (2013)

Table 2: Selected properties of biodiesel from microalgae

Biodiesel from algae		
	Open Pond	*PBR*
Energy Content MJ/kg (2)	35 - 41	N/A
Water Footprint m^3/GJ (3)	14-87	1-2

1.1 Cultivation of Microalgae

In general, Microalgae are cultivated by applying three methods under different nutrient supply modes. These are[4]:

- 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).

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 3). The main drawback of open pond systems is according to Rösch (2012) their relatively low biomass yield (10-25 g/(m^2d) compared to closed systems (25 – 50g/ m^2d)). 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 4, cultivation in PBRs takes place in pipes, tubes, plates or tanks.

2 Usher et al. (2014)
3 Usher et al. (2014)
4 Rocca et al. (2015)

Figure 3: Open Raceway Pond (Wikipedia, ©JanB46, CC BY-SA 3.0)

Figure 4: 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 favors 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 3: Comparison of the impacts between algae cultivation in open ponds and photobioreactors (Rösch, 2012)

Parameter	*Open ponds*	*Photobioreactors*
Land footprint	High	Low
Water footprint	High	Low
CO_2 release	High	Low
Energy re-quirement	Low	High
Application of waste water	Yes	Yes
Temperature control	Not needed	Required
Reactor clean-ing	Not needed	Required
Risk of con-tamination	High	Low
Product quality	Variable	Reproducible
Microbiology safety	No	Yes
Biomass productivity	Low	High
Capital and operation costs	Low	High

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.

Commercial scale cultures of microalgae are well-established in Asia, the United States, Israel and Australia since the 1980's. Currently, about 9,200 dry wt. tonnes of microalgae are annually produced worldwide, mainly for dietary or health food for human consumption and feed additives in aquaculture. (Rocca et al., 2015). Figure 5 shows the amounts of mass-cultivated species in different regions.

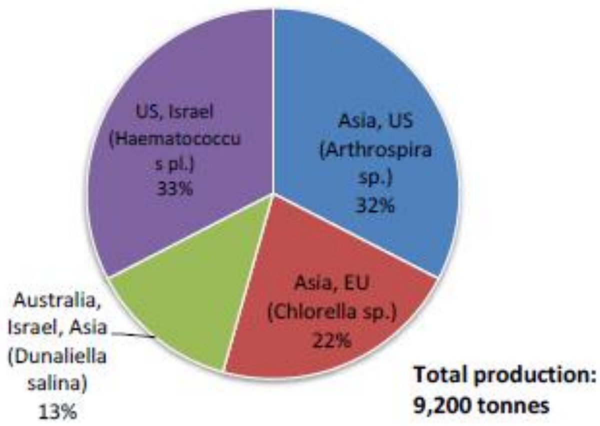

Figure 5: Annual estimates (in dry wt. tonnes) of cultivated microalgae for food feed production worldwide (Rocca et al., 2015)

1.2 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.

1.2.1 Conventional Solvent Extraction

Solvents are predominantly used to extract and purify soybean seed oils, 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. On the other hand, solvent-based processes are most effective with dried feedstocks or those with minimal water content, which logically poses some challenges on 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.

1.2.2 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 transesterifying 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. 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.

1.2.3 Heated Oil Extraction

Seeing as this extraction method has never been demonstrated and a high degree of uncertainty exists with respect to its viability, we shall not go into detail introducing this extraction technique at this point.

1.2.4 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.

1.3 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 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.

Table 4: Lipid content (% in dry wt. tonnes) and productivity (in mg/l/day) of various microalgae strains (Rocca et al., 2015)

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*

1.3.1 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.

1.4 Sustainability and Environmental Impacts of Microalgae Cultivation and Production

Making aviation less carbon intensive and therefore more sustainable, is the major driving force behind researching and developing alternative jet fuels from renewable biogenic resources. The reduction of GHG emissions is hereby only one aspect that has to be taken into account when evaluating the overall sustainability of alternative aviation fuels and the resources necessary for their production. The following discussion will for this reason assess and evaluate the potential of microalgae as a sustainable feedstock.

Biofuel production from microalgae is often regarded to be more environmentally sustainable than fuels derived from terrestrial energy crops. This is mainly due to the fact that algae can be cultivated on land that is not suitable for cultivation of energy or food crops, which improves land use efficiency. On the other hand, a series of life cycle assessment studies suggest that producing algal biomass is a very energy intensive process, mainly due to the high energy requirements the different processing steps from mixing to refining of the final product outlined above consume. The production of algae can have a variety of environmental impacts that go beyond the consumption of energy in the production process, varying on the production technology (open pond / PBR) and location.

1.4.1 Water Resources and aquatic Impacts

Since microalgae is an aquatic biomass, indicators such as water quality requirements and water consumption need to be considered when evaluating its environmental sustainability (Usher et al., 2014). For the production of biofuels derived from microalgae, a low-cost water supply is essential. Assuming a lipid content of 50%, a minimum of 1.5 liter of water is required to produce 1 liter of biofuel (Bauen et al., 2009). In reality, however, the amount of required water will be much larger to account for evaporation losses in open pond systems and for cooling in PBRs, respectively. The large-scale cultivation potential of fresh water microalgae for biofuels is nevertheless limited in many regions due to the competing markets for water such as domestic and agricultural use (Usher et al, 2014).

As water quality requirements vary depending on algae strains and considering that microalgae show great adaptability to their environment, wastewater streams could be a viable option to reduce the pressure on natural freshwater resources and substitute the nitrogen input required for algal growth. This would be advantageous as significant energy inputs are required to meet the nitrogen demand of microalgae, since synthetic nitrogen fixation processes utilize fossil fuels. As cited in Rösch (2012), tapping into existing nutritious agricultural or municipal waste streams could lower fertilizer demand for nitrogen and phosphorus by 84% and 55%, respectively, and thus improve the energy balance and resource efficiency of microalgae cultivation. On the downside, an excess of nitrogen in aquatic systems can lead to uncontrollable microalgae blooms, leading to toxic conditions (Usher et al., 2014). In addition, aforementioned waste streams could introduce chemical compounds, heavy metals and the like into the system that negatively impact on algal growth and lipid accumulation.

As stated earlier, phosphorus (P) is apart from nitrogen (N) an important fertilizer in algae cultivation. Generally, the requirement for fertilization cannot be avoided as the algal biomass itself consists of ~7% Nitrogen and ~1% Phosphorus (Bauen et al., 2009). P is a non-renewable resource which exists only in inorganic form and must either be mined or recovered from waste (Usher et al., 2014). In this regard, microalgae cultivation could present itself as a viable option to recover P from waste streams, thereby increasing both the environmental as well as economic sustainability.

To safeguard a sustainable supply of N and P, locating large algae cultivation systems in proximity to waste water treatment plants could a viable option to produce biofuels.

As established earlier, the diffusion of carbon dioxide (CO_2) into microalgal cultures is not efficient enough to generate high biomass productivity due to the low CO_2 content of air and the high surface tension of water (Rösch, 2012). For this reason, an additional supply of CO_2 is required for the cultivation of microalgae. Utilizing CO_2 emissions form industrial and fossil fuel power plants would be a viable way to improve the performance of algal fuel production, but only if the algae production site is in proximity to the aforementioned industrial plants and the (liquefied) CO_2 can be transported through pipelines. Long transport distances increase emissions and energy consumption dramatically.

1.4.2 Water Footprint (WF)

The water footprint of a product is an important parameter to evaluate its sustainability. Usher et al. (2014) define WF as the total amount of fresh water embedded in the production of goods and services that includes both surface and groundwater (blue WF) and rainwater (green WF). Seeing as this sustainability indicator and its calculation is highly sensitive to influencing factors such as climate, evaporation rates, photosynthetic efficiency and the like, finding reliable and clear-cut data is challenging. In addition, defining exact boundaries that define what accounts as water influx for the production of a product is also difficult. For this reason, the CORE-JetFuel Consortium decided to exclude this metric in its sustainability assessment of different types of feedstock. Nevertheless, in the special case of the aquatic biomass microalgae, an exception is made and the water footprint of microalgae-derived fuels as a metric for evaluating their sustainability is included.

Although biodiesel is a different product than alternative HEFA jet fuel, Table 5 gives an impression on the water requirements of microalgae-derived fuel compared to other prominent (and for the most part economically viable) biofuels. The range indicates values from waste- and seawater to freshwater, clearly showing that utilizing wastewater streams could indeed vitally contribute to the environmental and economic sustainability of fuels produced from microalgae. The distinction between open pond systems and PBRs additionally confirms the statements made earlier, that PBR are in fact the favorable microalgae cultivation technique – at least in terms of water usage.

Table 5: Water footprints of different transport fuels (Usher et al., 2014)

	Average annual water footprint (m3/GJ)
Natural gas	0.11
Petroleum diesel	0.04–0.08
Soybean biodiesel	287
Sugarcane ethanol	85–139
Microalgae biodiesel (open raceway)	14–87
Microalgae biodiesel (closed bioreactor)	1–2

1.4.3 Land Use

Compared to terrestrial crops, one of the main advantages of algae systems is that they can be cultivated on marginal or non-arable land, thus avoiding land use competition with food production. However, this holds true only to a certain degree as non-arable land not used for agricultural production is limited, particularly in areas where the climatic conditions (radiation, temperature) and topography are suitable as well as where there is access to water, waste nutrients and a sufficient supply of carbon (Rösch, 2012). All of these characteristics have to be met if algae cultivation and the according production of biofuels should be sustainable.

1.5 Net Energy Ratio and Greenhouse Gas Balance

1.5.1 Net Energy Ratio (NER)

As mentioned in the introduction, a broad range of diverging information can be found in the literature concerning the environmental performance of microalgae. This is especially true when reviewing life cycle assessments (LCA) that address GHG emissions emerging from the production of microalgae-derived biofuel and required energy inputs. For this reason, a report by Slade and Bauen (2013) is used that in context of the Aquafuels project (Bauen et al., 20009) reviewed a series of LCA studies quantifying inputs and emissions from the production process of microalgal biofuels.

First, the net energy ratio (NER) of biomass production is considered, which is defined as the sum of the energy used for cultivation, harvesting and drying, divided by the energy content of the dry biomass (Slade/Bauen, 2013). A positive energy ratio is achieved when the NER value is in the range between 0 and 1. If the NER is greater than 1, the process consumes more energy than it produces. The figure below considers both open pond systems and PBRs, as was done in the introduction above.

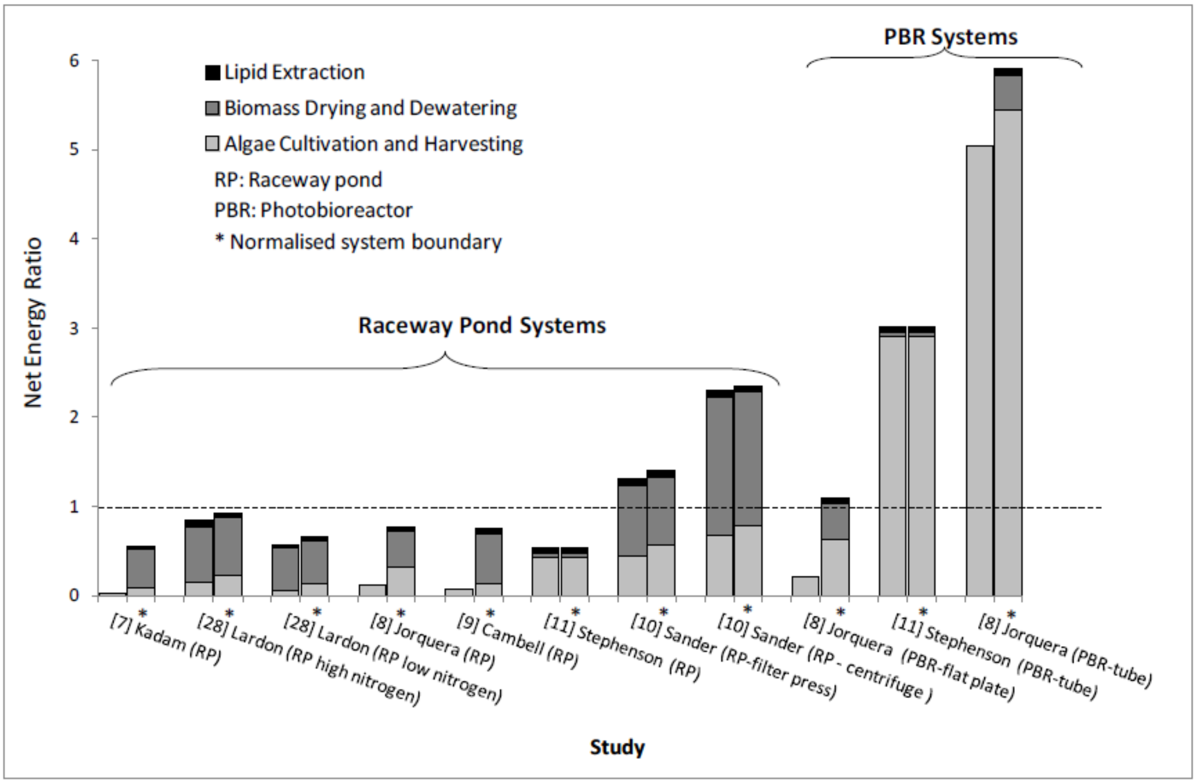

Figure 6: Net energy ratio for microalgae biomass production (Slade/Bauen, 2013)

As can be seen in the figure above, the majority of open raceway pond systems show a better NER than the PBRs considered in the different LCA studies. The biggest share of energy consumed during cultivation in raceway ponds is attributable to the electricity required to circulate the microalgae culture as well as the energy embodied in pond construction. Nitrogen fertilization also consumes a considerable amount of energy. Again, it has to be stated that remarkable variations appear in the different LCAs concerning the three main energy consuming processes described above and their energy fraction in the overall process.

PBRs generally consume more energy than they produce. Here, biomass drying and de-watering are proportionately less important than the energy consumed in cultivation and harvesting (Slade/Bauen, 2013), which is partly due to the fact that higher biomass concentrations can be achieved in PBRs. The majority of energy consumed during cultivation, however, is attributable to pumping the medium around within the PBR as well as for system construction.

1.5.2 Greenhouse Gas Balance

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 3 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.

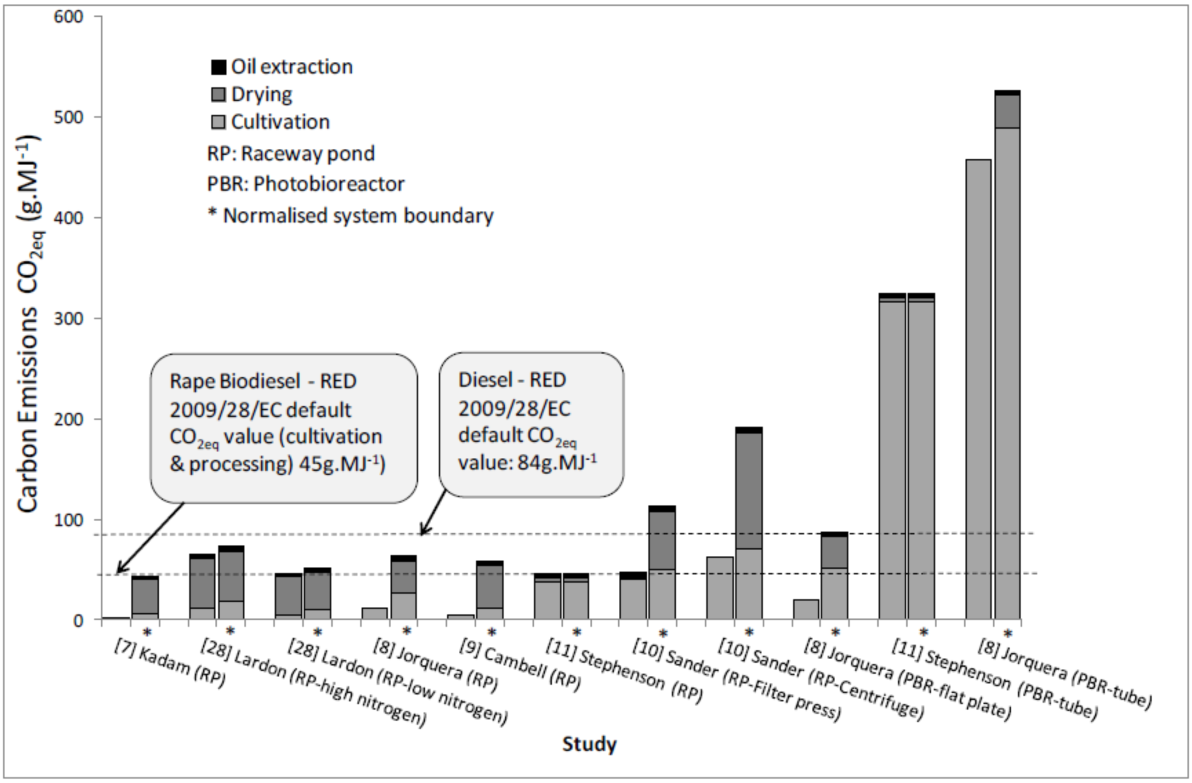

Figure 7: Carbon dioxide emissions from algal biomass production (Slade/Bauen, 2013)

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.

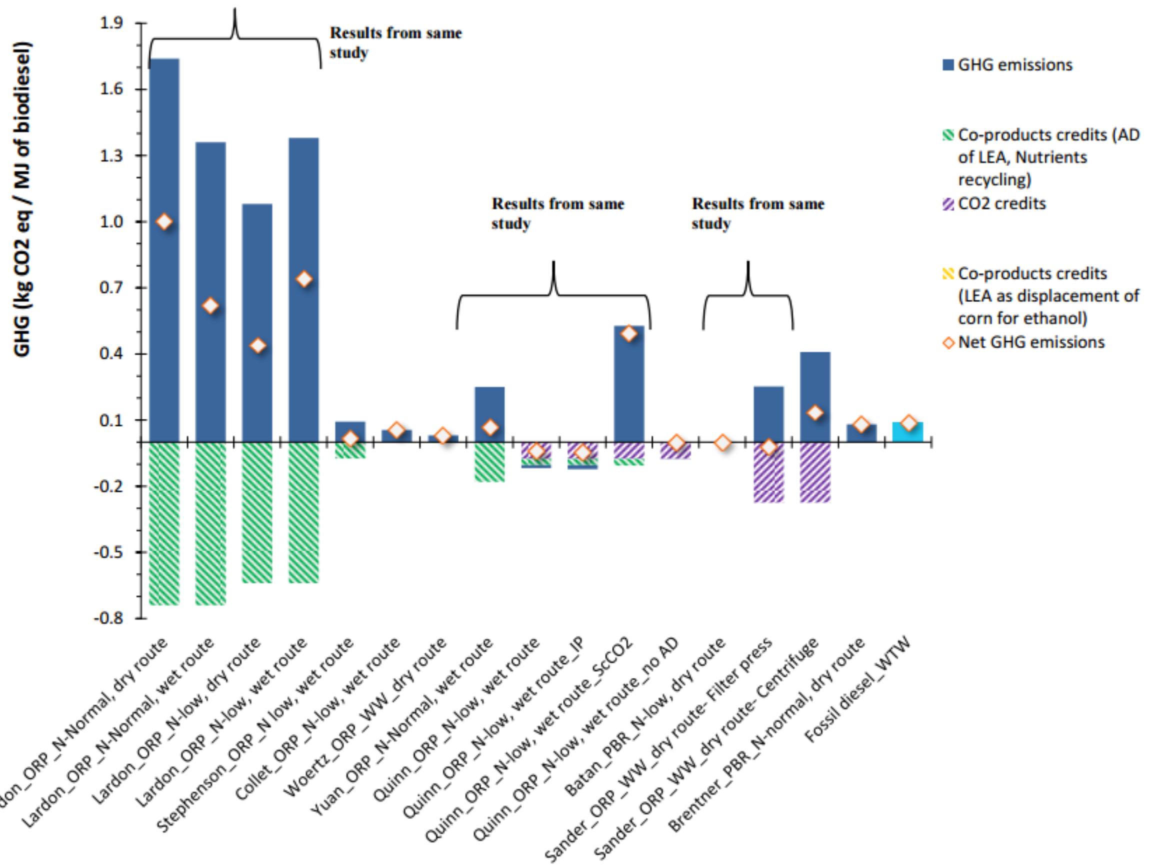

Figure 8: GHG emissions of microalgal biodiesel pathways (Rocca et al., 2015)

1.6 Feedstock Readiness Level (FSRL) of Microalgae

Apart from evaluating feedstocks in terms of its GHG reduction potential, agricultural input requirements and the like, the concept of the Feedstock Readiness Level is applied to a feedstock and its production technology under study. As cited in CORE-JetFuel D2.1, the tool *Fuel Readiness Level* was introduced by CAAFI in 2010 in order to specifically evaluate the technical maturity of alternative fuel production with a focus on the conversion step. In 2011, CAAFI introduced the tool *Feedstock Readiness Level*[5] as the complementary tool for the evaluation of feedstock production technologies with respect to their technological maturity (D2.1 Roth et al., 2014). As mentioned above, the FSRL tool is a companion to the CAAFI (Fuel) Readiness Level tool that provides a means of tracking development and availability of the raw materials (or feedstocks) required to produce alternative jet fuels[6]. In detailing the steps necessary to establish feedstock production in the commercial sector, a complete supply chain system context is implied.

The FSRL Tool covers four components: (1) Production, (2) Market, (3) Policy - Program Support and Regulatory Compliance, and (4) Linkage to Conversion Processes. The FSRL Tool components parallel the FRL. This approach provides an integrated way to demonstrate the mutual requirements of feedstocks and conversion technologies.

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[5] http://www.caafi.org/information/fuelreadinesstools.html

While CAAFI defined the FSRL through a complicated scheme of “components” and “toll gates”, CORE-JetFuel simplifies the FSRL assessment scheme by assigning scores (0 – 5) to the nine different feedstock readiness levels established by CAAFI, thereby integrating readiness levels into the Multi-Assessment-Scheme of the project’s assessment framework (Table 6).

Table 6: Feedstock Readiness Levels and Scores

FSR Score	FSRL	Short description
0	1	Basic principles observed (identification of potential feedstock for specific conversion technology)
1	2	Production concept formulated (identification of production system and environment etc.)
2	3	Proof of concept (initial studies on feedstock potential at lab/experimental scale, e.g. screening genetic resources for yield, requirements etc.)
3	4	Validation of concept (preliminary technical evaluation)
4	5	Validation of production system at field-scale (on-farm, field-scale production trials, assessment of resource requirements, identification of production uncertainties, etc.) (“from lab to pilot scale”)
5	6	Demonstration of feedstock production, full-scale production initiation (establishment of nurseries of planting material, scale-up production (“from pilot to demonstration scale”), etc.)
5	7	First cultivation in operational environment (small commercial scale)
5	8	System complete and qualified, commercialization on-going
5	9	Full-scale commercial plantation in operational environment (sustainable feedstock production capacity established)

For microalgae we assign a FSRL between 6 and 7, meaning that the production of microalgae has reached demonstration scale, and is on the way to be demonstrated in an operational environment. Although microalgae production in open pond systems is taking place in an operational environment on a commercial scale (FSRL 7), still a lot of research (and funding) is required to produce the feedstock microalgae itself and the jet fuel derived from it cost-competitively. This is especially true for PBRs.

In order to overcome the low FSRL of microalgae production and ultimately its environmental as well as economic performance, the production of bioenergy and / or biofuels in combination with biomaterials such as chemicals, fertilizers and animal feed in integrated bio-refineries is a key requirement for making microalgal production economically worthwhile. With a focus on a single product / application, it is unlikely that the use of algae will become sustainable from an economical and environmental point of view (Rocca et al., 2015).

2 Camelina Sativa

After discussing the aquatic biomass microalgae, its environmental performance as well as its potential for the production of alternative jet fuel, we shall now turn our attention to the first terrestrial oil crop of this report, namely camelina. This energy crop has received a lot of attention as a viable and allegedly more sustainable alternative to other oily crops such as rapeseed or soybean. Especially the aviation industry that requires large quantities of feedstock to meet its self-imposed GHG emission reduction targets has shown increased interest in this crop, as it supposedly does not compete with food production, can be cultivated on marginal land and is suitable for the conversion into bio-kerosene via the well-established HEFA pathway.

2.1 Characteristics and Cultivation

Camelina (*Camelina Sativa*), also known as false flax is a broadleaf oilseed flowering plant of the Brassicacae (mustard) family that grows optimally in temperate climates. Camelina can be cultivated in a variety of climatic and soil conditions as a spring or summer annual crop or as a biannual winter crop (Moser, 2010). One of the most beneficial agronomic attributes of camelina is its short growing season of approximately 85-100 days (i.e. from sowing to maturity), giving it the ability to ripen during the rather short catch cropping seasons (Moser, 2010).

Figure 9: Camelina Sativa (Wikipedia, © Fornax, CC – SA 3.0

In addition, the crop shows compatibility with existing farm practices and is capable of withstanding cold weather, drought, arid to semiarid conditions as well as low-fertility or saline soils (Moser, 2010). Other positive attributes of camelina, especially compared to other traditional commodity oil seed crops such as rapeseed or soybean are its low precipitation requirements, namely between 300 – 600mm per square meter year. According to Yuri Herreras Yambanis, founder and CEO of the Camelina Company Spain (CCE), camelina has no irrigation requirements at all, which is a particular advantage for semi-arid regions such as Spain. In addition, camelina needs less pesticides and fertilizers to grow than the previously mentioned traditional oil crops. High yields, however, are only achieved under favorable conditions.

As opposed to the discussion on microalgae, we shall not go too much into detail regarding the technical description of camelina cultivation and subsequent processing of the seeds. Instead, the different steps are briefly described first, subsequently to which focus will be placed on discussing the sustainability of the different cultivation steps in terms of GHG emissions and energy inputs.

2.1.1 Seeding

Crucial for the successful cultivation of camelina is a relatively early seedtime, preferably in March in Spain. Later planting times, for example in mid-April, most commonly result in lower yields. In addition, a firm and moist seedbed is ideal for seeding camelina and a good seed-soil contact is also essential (Grady, 2010). The optimal seeding rate of camelina is 5-7 kg/ha into good soil moisture conditions, with a shallow seedbed depth of approximately 0.5-2.0 cm. The optimal distance between rows is between 13.5 and 30 cm.

2.1.2 Fertilization

Fertilizers are the most important agricultural input in oil crops. As mentioned previously, camelina has relatively low fertilizer requirements, even on poor quality soils. Assuming a productivity rate of approximately 2 t/ha, the following fertilization requirements can be expected:

- Nitrogen (N): 100 kg/ha[7]
- Phosphorus (P): 15-20 kg/ha[8] [30 – 40 kg/ha][9]
- Potassium (K): 60-70 kg/ha[10] [0 kg/ha for Spanish soils][11]
- Magnesium (Mg): 5-7 kg/ha[12]

Environmental impacts of these fertilizers, in particular atmospheric emissions from N will be discussed later on.

The table below summarizes some of the most important properties of camelina:

Table 7: Selected Camelina Properties

Growing Rate (days)	85 – 100
Plant height at maturity (cm)	60 – 90
N requirements (kg/ha)	100 – 110
Seed Yield (kg/ha)[13]	336 – 2240 (2500 – 3000)[14]
Oil Content (in weight percent)[15]	35 - 45
Oil Yield (L/ha)[16]	106 -907

2.2 Harvest

Winter varieties of the crop in Central and Northern Europe can be harvested before the end of July (Zubr, 1996). On a large-scale, camelina is harvested using conventional machinery such as an ordinary combine harvester adjusted for harvesting rape. The crop can be cut directly or swathed and combined (Grady, 2010). Of these two options, direct cutting is the preferred method and may begin once pods turn golden brown and seed moisture is eight percent or less, which is of special importance for storing (Grady, 2010). The low seed weight of camelina (1-1.5 g) poses a challenge to harvesting and transport logistics. However, these challenges have not been identified by CCE.

[7] Zubr, 1996
[8] Thüringer Landesanstalt für Landwirtschaft, 2009
[9] Values stated by Yuri Herreras Yambanis, Camelina Company Spain
[10] Moser, 2010
[11] Values stated by Yuri Herreras Yambanis, Camelina Company Spain
[12] Thüringer Landesanstalt für Landwirtschaft, 2009
[13] Moser, 2010
[14] Thüringer Landesanstalt für Landwirtschaft, 2009
[15] Moser, 2010
[16] Moser, 2010

2.3 Lipid extraction

Extracting the lipid content of the camelina seeds is mainly a mechanical process. After cleaning the seeds and preparing them for the extraction process, they are crushed and pressed. If harvested correctly, drying the seeds is not necessary. Solvents (e.g. hexane) are not required but increase the amount of oil extracted from the seeds. It is therefore mainly an economic decision if comparably higher oil yields justify the costs for solvents. The final step of lipid extraction is the degumming process. So-called gums (or phosphatides) are deposits that emerge from pressing and solvent extraction, the two previous steps of the overall lipid extraction process. The degumming process removes the phosphatides from the oil, preventing sludges from forming during storage and making it ready for the conversion into biodiesel or alternative jet fuel.

2.4 Sustainability and Environmental Impact of Camelina Cultivation and Production

As cited in Singh (2013), for a biofuel to be sustainable it is of utmost importance that it is derived from feedstocks produced with no or little competition with food production, and with no or minor emissions due to land use changes. The literature distinguishes between two different types of land use changes, namely *direct* land use change (dLUC) on the one hand and *indirect* land use change (iLUC) on the other. Both types of land use changes as well as the competition with food production are predominantly characteristics of so-called “first generation” biofuels that are produced primarily from food crops such as cereals, sugar crops and oil seeds (Sims et al., 2009). In order to counteract the adverse effects of the increased global demand for biofuels, the European Parliament and Council have recently (April 2015) agreed to cap the use of “harmful” biofuels from agricultural crops at 7% to reach the European Union’s overall transport targets of 10% renewable energy by 2020, which also includes a law aimed at diminishing harmful effects on the environment from indirect land use change. We shall therefore define dLUC and iLUC first and subsequently evaluate the performance of camelina as a feedstock of inducing the adverse environmental effects mentioned above.

dLUC occurs whenever a specific and identifiable parcel of land that was not previously used to grow a given biofuel feedstock crop is reassigned for the cultivation of that crop, with feedstock grown on this land supplied to a specific biofuel processing facility (Malins, 2012). iLUC on the other hand, occurs when land that was formerly used for the cultivation of food, feed or fiber is now used for biomass production shifting the original land use to an alternative area that might have a high carbon sink, for example forests of wetlands (Gawel, 2011).

Although the iLUC concept itself, its applicability as well as factors determining its magnitude are highly debated in the scientific and political sphere, GHG missions resulting from indirect land use changes have become an important indicator to assess the sustainability of a certain feedstock and the respective biofuel derived from it. Nevertheless, exact values of iLUC-induced GHG emissions are very difficult to obtain and their validity is also debatable. For this reason, the CORE-JetFuel Consortium decided to include iLUC in its assessment only as the risk a certain feedstock shows of inducing indirect land use changes.

Camelina has several characteristics that can potentially contribute to avoiding land use changes and therefore competition with food production. As a crop that is early maturing, adapted to low rainfall conditions, and well-suited for no-till management, camelina has great potential to replace summer fallow acreages (Singh, 2013). Camelina grows particularly well in rotation with wheat due to the previously mentioned low moisture and nutrient requirements of camelina. Rotating camelina with wheat also allows for significantly reducing the use of plant protection chemicals, which positively impacts on the environmental performance of this cultivation system. Camelina additionally provides several benefits to the subsequent wheat crop such as reduced soil erosion, increased soil organic matter, and reduction of wheat pests and diseases (Singh, 2013). In addition to these agronomic advantages of cultivating camelina in crop rotations, no to minor soil carbon is released as a consequence of growing the crop on fallow land, which positively impacts on the overall GHG balance of camelina cultivation. Mixed cultivation systems, e.g. camelina and peas, have also been tested. Furthermore, the ability of the crop to be cultivated in rotation with other crops as well as on marginal land imposes no competition to food production – at least in the quantities camelina is currently produced. Therefore, camelina shows a low risk of inducing iLUC and the accompanying detrimental environmental impacts, making it a very promising feedstock for the sustainable production alternative aviation fuels. Although camelina oil can be used for nutritional purposes, its main application is as a biofuel feedstock. Other than for biofuel production, the oil of camelina can be used as a drying oil that hardens to a tough, solid film after a period of exposure to air. Drying oils, of which linseed oil is another example, are a key component of all oil paints and some varnishes. Due to the limited production of camelina, the risk of iLUC is negligible. Even when production increases over time, the crop will mostly be cultivated on marginal land that cannot be used for the production of other food crops.

After addressing the (positive) sustainability performance of camelina in terms of its risk of inducing land use changes, the following part will give an overview on GHG emissions emerging form cultivation and oil extraction.

In general, the agricultural or cultivation stage has a significant impact on the overall GHG balance of fuels derived from renewable feedstocks. For camelina farming, the main areas to consider in this context include crop nutrients, chemicals and seeding; machinery fuel use, seed drying and cleaning; field N_2O emissions, and the LUC emissions addressed above (Miller, 2013).

Miller and Kumar (2013) estimated GHG emissions and the net energy ratio of producing hydrogenation-derived renewable diesel (HDRD) from canola (rapeseed) and camelina in Western Canada. Although HDRD is not the same end-product as camelina-derived HEFA alternative jet fuel, for the cultivation and oil extraction phase we shall nevertheless consider the results of this study as these two phases of the overall production process apply to both types on end products.

Table 8: GHG Emissions of Camelina Cultivation (Miller/Kumar, 2013)

Operation	Input quantity			Energy coefficients			Emission coefficients			Energy use (MJ/MJ)	Emissions (gCO_{2e}/MJ)
	Units	Used value	References	Units	Used value	References	Units	Used value	References		
b) Camelina farming, base scenario											
Nutrients, chemicals & seeding											
Nitrogen	kg/ha	92.5	[20,24]	MJ/kg	49.45	[43]	gCO_{2e}/g	3.58	[43]	0.176	12.8
Phosphorous	kg/ha	39.9	[24,54]	MJ/kg	14.13	[43]	gCO_{2e}/g	1.07	[43]	0.022	1.6
Potassium	kg/ha	38.9	[24,54]	MJ/kg	8.84	[43]	gCO_{2e}/g	0.69	[43]	0.013	1.0
Sulfur	kg/ha	0.0	[24]	MJ/kg	11.26	[44]	gCO_{2e}/g	2.70	[47]	0.000	0.0
Crop residue	tonnes/ha	1.5	[39]	–	–	–	kg N/tonne	6.00	[48]	–	–
Herbicide	kg/ha	0.7	[24]	MJ/kg	267	[45]	gCO_{2e}/g	17.24	[45]	0.008	0.5
Insecticide	kg/ha	0.0	[24]	MJ/kg	285	[45]	gCO_{2e}/g	18.08	[45]	0.000	0.0
Seeds	kg/ha	8.0	[24]	MJ/kg	2.35	[24]	gCO_{2e}/g	0.39	[24]	0.001	0.1
Machinery & fuel use (diesel)											
Manufacturing & maintenance	–	–	–	MJ/ha	1456	[12]	gCO_{2e}/ha	35,740	[12]	0.056	1.4
Sowing	L/ha	10	[42]	MJ/L	45.25	[46]	gCO_{2e}/L	3336	[45,49]	0.017	1.3
Farm chemical spraying	L/ha	4	[42]	MJ/L	45.25	[46]	gCO_{2e}/L	3336	[45,49]	0.007	0.5
Spreading fertilizer	L/ha	14	[42]	MJ/L	45.25	[46]	gCO_{2e}/L	3336	[45,49]	0.024	1.8
Harvesting	L/ha	25	[42]	MJ/L	45.25	[46]	gCO_{2e}/L	3336	[45,49]	0.044	3.2
Seed transportation	L/ha	8	[42]	MJ/L	45.25	[46]	gCO_{2e}/L	3336	[45,49]	0.014	1.0
Seed drying and cleaning											
Electricity	kWh/tonne seed	11.0	[9,12]	MJ/kWh	9.89	[46]	gCO_{2e}/kWh	880	[50]	0.008	0.7
Diesel	L/tonne seed	1.2	[12]	MJ/L	45.25	[46]	gCO_{2e}/L	3336	[45,49]	0.004	0.3
Field emissions											
N_2O emissions	–	–	–	–	–	–	% as N_2O-N	0.76	[13]	–	13.9
Land use change											
N_2O credit	–	–	–	–	–	–	–	–	–	–	–
Change in soil nitrogen	–	–	–	–	–	–	–	–	–	–	–
Change in soil carbon	–	–	–	–	–	–	–	–	–	–	–
Farming subtotal										**0.39**	**40.2**

As can be seen in the table above, the overall GHG balance of cultivating camelina is influenced by a variety input factors. Hereby, soil emissions resulting from nitrogen fertilizing (N_2O) are of special importance, as these have the highest Global Warming Potential (GWP) in the cultivation process. In addition, fossil fuels consumed by farming machinery and by trucks transporting the feedstock to processing facilities also negatively impact the GHG balance of camelina cultivation. Emissions from land use changes are minor due to the low-tillage requirements of camelina and can therefore be neglected. In general, all of the emissions associated with the production of camelina shown in Table 8 are influenced to a large degree by the efficiency of the cultivation process in terms of seed yield, especially when considering the sustainability of the end product.

Table 9 summarizes GHG emissions that emerge from extracting the lipid content from camelina seeds. The largest share of emissions stems from steam and electricity required in the extraction process as well as from the toxic solvent hexane, which has apart from the atmospheric impacts considered here, other detrimental effects on the environment.

Table 9: GHG Emission of Camelina Oil Extraction (Miller/Kumar 2013)

Operation	Input quantity			Energy coefficients			Emission coefficients			Energy use (MJ/MJ)	Emissions (gCO_{2e}/MJ)
	Units	Used value	References	Units	Used value	References	Units	Used value	References		
b) Camelina oil extraction, base scenario											
Seed preparation											
Drying heat (from diesel)	MJ process heat/tonne seed	54.5	[12]	MJ/MJ process heat	3.23	[12]	gCO_{2e}/MJ process heat	292	[12]	0.013	1.2
Drying electricity	kWh/tonne seed	13.6	[12]	MJ/kWh	9.89	[46]	gCO_{2e}/kWh	880	[50]	0.010	0.9
Oil extraction											
Electricity[a]	kWh/tonne seed	40.8[a]	[12]	MJ/kWh	9.89	[46]	gCO_{2e}/kWh	880	[50]	0.030	2.7
Steam	kg/tonne seed	369	[12]	MJ process heat/kg	2.00	[12]	gCO_{2e}/MJ process heat	126	[12]	0.064	3.4
Cooling water[b]	kg/tonne seed	14,560	[12]	MJ/kg	0.004	[10,67]	gCO_{2e}/kg	0.93	calc.	0.004	1.0
Lost solvent (hexane)[c]	L/tonne seed	1.94	[12]	MJ/kg	44.41	[43]	gCO_{2e}/kg	17,710	[12]	0.004	1.7
Degumming[d]											
Electricity	kWh/tonne seed	2.2	[12]	MJ/kWh	9.89	[46]	gCO_{2e}/kWh	880	[50]	0.002	0.1
Steam	kg/tonne seed	74.3	[12]	MJ process heat/kg	2.00	[12]	gCO_{2e}/MJ process heat	126	[12]	0.013	1.4
Process water	kg/tonne seed	8.3	[12]	MJ/kg	0.01	[12]	gCO_{2e}/kg	2.47	[12]	0.000	0.0
Oil extraction subtotal										**0.14**	**12.3**

2.5 Greenhouse Gas Balance of Camelina-derived Jet Fuel

In the literature, the GHG reduction potential of camelina-derived alternative jet fuels varies between 60% and up to 85% compared to fossil kerosene. As most of the studies considered in this report are based on life cycle assessments with varying system boundaries, input factors such as seed productivity and like, the observed range is within the expected interval.

As opposed to the majority of feedstocks that show suitable properties for the conversion into alternative jet fuels, certified camelina-derived HEFA-SPK (Synthetic Paraffinic Kerosene) blends have been successfully tested and deployed in commercial aircraft. In late 2015, in context of the ITAKA project a batch based on 100% EU camelina, which is being used at the Oslo Airport both for supply via the non-dedicated commingled airport fuel system and for dedicated supply to KLM Cityhopper Embraer E190 planes for flights to Amsterdam[17]. In January 2016, the fuel was also provided to AirBP and Avinor to make it available to all airlines departing from Oslo Airport, which can be regarded as a major milestone of bio-kerosene deployment.

[17] http://www.itaka-project.eu/nav/pages/progress_results_6.aspxhttp://www.itaka-project.eu/nav/pages/progress_results_6.aspx

According to the ITAKA assessment, camelina-derived jet fuel reaches a GHG emission reduction of -60% compared to conventional jet, making this value chain a viable option for decreasing the emission of climate-active gases of the aviation sector.

Camelina is a low-cost feedstock that can be produced sustainably and converted into alternative jet fuel via the well-established HEFA-pathway. The end-product HEFA-SPK shows a considerable GHG reduction potential, which makes it a promising candidate for contributing to making commercial aviation more sustainable.

2.6 FSRL of Camelina

To camelina we assign a feedstock readiness level between 8 and 9, the highest possible level. The commercialization of camelina cultivation is ongoing with economically viable fuel production pathways identified. Under the right conditions, the feedstock can be produced sustainably but has by far not reached its full potential for full-scale commercial operation.

3 Used Cooking Oil (UCO)

Accounting for waste material in the group of biogenic oils and fats is the feedstock 'used cooking oil' (UCO). This type of feedstock is particularly interesting as fuel producers have great experience with converting it into biofuels. Although UCO is most commonly utilized for the conversion into biodiesel, it has also proven its viability in aviation. The ITAKA project, for example, conducted a series of test flights with UCO-based kerosene produced by SkyNRG.[18]. Apart from the advantage of UCO that it can be converted into bio-jet via the well-established HEFA pathway, it is defined as a waste in the RED and is therefore attributed zero GHG emissions at its point of collection (Edwards et al., 2012). Furthermore, according to EU legislation, UCO is also eligible for double-counting, meaning that it can be counted twice for contributing to the 10% renewable energy in transport target defined in the RED. Implementation and incentives in Member States vary.

As the name suggests, used cooking oils, commonly called UCO or WCO (waste cooking oil) are defined as purified oils and fats of plant and animal origin that have been used by restaurants, catering facilities and kitchens to cook for human consumption. They are wastes as they are no longer fit for that purpose and are subsequently used as either feedstock for the production of biodiesel, as fuel for automotive vehicles and heating, or as a direct fuel.[19] As mentioned above, both animal fats and vegetable oils can serve as a source for UCO. Although UCO from vegetable can contain small quantities of animal fats, the following chapter will focus on UCO obtained from vegetable oils. In addition, this chapter will not address the cultivation of the oil crops from which vegetable oils are produced (in Europe mainly rapeseed and sunflower), but will treat UCO as a stand-alone feedstock.

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[18] http://www.itaka-project.eu/nav/pages/progress_results_6.aspx

[19] https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/397476/List_of_wastes_and_residues_year_7_7.3.pdf

3.1 Collection of UCO

As opposed to conventional energy crops that are cultivated on fields and then transported to the processing site, UCO has to be collected at its point of origin, i.e. restaurants and the like. Logically, this collection method is connected to considerable transport distances and already gives a hint on the availability of UCO as a biofuel feedstock (cf. Chapter 9). UCO is most commonly collected by one person from restaurants etc. in a defined area. The waste oil is stored in 60 to 150 litre barrels in restaurant basements. Apart from the difficult collection process, UCO is more than other feedstocks subject to market fluctuations due the variability in restaurant attendance as well as the volatility of the fuel price. The greatest difficulty in the UCO collection business is variable costs, which strongly depend on logistics costs like fuel and tolls (greenea, 2014). Apart from the market fluctuations that collectors have to compensate for mentioned above, sustainability certification puts additional (financial) pressure on the collectors. A field trial in France conducted by a team from greenea[20] who followed a UCO collector observed that after covering 15 – 20 restaurants a total of 1800 kg of UCO was collected. According to greenea, this represents only 0.05% of the monthly need of a UCOME[21] producer. This suggests that imports from non-EU countries such as China might be needed to meet the production goals of the biodiesel, and potentially the aviation sector – particularly as the UCO market in Europe is highly competitive. There is already a fierce struggle noticeable to get access to UCO generating sources, and organised crime has also discovered UCO collection (Spöttle et al., 2013).

In general, there are three collection practices currently applied (Tsoutsos / Stavroula, 2013[22]):

1. Processor decentralized collection: The biodiesel company sets up a door to door collecting system in order to collect directly from the “producers” of UCO (as outlined above)
2. Producer centralized collection: The “producers” of UCO deposit them at centralized depots. The biofuel company collects them directly from the depot
3. Combined supplied collection: The biodiesel company supplies the raw vegetable oils to the “producers” of UCO and collects them for recycling as well

As cited in Tsoutsos / Stavroula (2013), the collection practices mentioned above have several advantages and disadvantages.

Table 10: Advantages and disadvantages of different UCO collection strategies (Tsoutsos/Stavroula 2013)

Strategy	Advantages	Disadvantages
Processor Decentralized collection	Biodiesel processor has direct contact with the oil consumers, so they may educate them on the required quality of the oil (in order to be recycled) and how to reject inappropriate oil	Expensive and time consuming collection process (dependent upon the number of households/consumers involved and the volume/quality of used oil per point

[20] http://www.greenea.com/en/articles/category/12-used-cooking-oil.html?download=63:european-used-cooking-oil-market.
[21] Used Cooking Oil Methyl Ester
[22] https://ec.europa.eu/energy/intelligent/projects/sites/iee-projects/files/projects/documents/d4.3_guide_on_uco_processing_and_biodiesel_distribution_v4tuc.pdf

	Potential to deliver biodiesel to consumers during the collection process, cutting distribution costs and promoting biodiesel use	Waste license required
	Better working relationship and communication between processor and oil consumer	The frequency of collection is usually determined by the oil use
	Eliminates waste collection fees for the oil user	
Processor centralized collection	Low collection cost provided the depot(s) are located close to the processing facility	No direct control over the quality of the oil feedstock
	The collection to a centralized depot may already be established by a separate waste management company, reducing setup costs	Higher raw material cost from depot.
	If the depot can deliver the used oil to the biodiesel processer, no waste carrier license is required by the processor	Biodiesel processor has less control over the efficiency of the supply chain
		The biodiesel processor incurs higher financial risk if purchasing from only one UCO depot
Combined supplied collection	Reduced cost for supply chain activities	Competing with established oil suppliers
	Close supply chain communication	

The collection process is insofar important as it has a direct impact on the quality of UCO, which is crucial for the quality of the end product, i.e. biodiesel or HEFA-SPK. A general issue concerning the quality of UCO is its collection from different sources. Therefore, the main parameters to determine are the level of cleanliness, the level of free fatty acids (FFA) and the water content (Spöttle et al., 2013). The cleanliness as well as the amount of FAAs depend on the products that are fried, the frequency of UCO replacement with fresh cooking oil and the vegetable oil itself that is used for cooking. As the waste oils are collected from a variety of different gastronomic entities with the according range in foods, the final UCO mix needs to be hydrated and filtered in order to produce biodiesel that complies with the EU standard EN14214 (Spöttle et al., 2013).

3.2 GHG balance of UCO-based jet fuel and biodiesel

The GHG balance of alternative fuels derived from UCO is to a large degree dependent on the transportation distances between the collection sites, i.e. restaurants and the like. The energy required for converting UCO into biodiesel / -kerosene plays also a vital, if not the most important role for the GHG balance of UCO. This is mainly due to the fact that both for transportation and conversion fossil energy carriers are utilized. On the one hand, conventional diesel is consumed by trucks and on the other hand, the supply of heat and steam based on natural gas, the supply of fossil-based methanol and an electricity mix for Europe are primarily responsible for the climate-relevant emissions here (Oehmichen/Majer, 2013).

The production of biofuels based on UCO can roughly be classified into 4 main steps. The first step is as mentioned above the collection of the feedstock. It is then pre-treated (filtered), subsequently to which the conversion takes place. Lastly, the end-product is distributed to wholesalers such as gas stations or directly to the end-user. Defining system boundaries similar to these, Seber et al. (2014) calculated the GHG lifecycle emissions of yellow-grease derived HEFA fuels. In line with the limitation made in the introduction of this chapter to treat UCO as a stand-alone feedstock, Seber et al. (2014) consider UCO as a recycled good, meaning that GHG emissions from the production of cooking oil were excluded. Figure 10 shows the lifecycle GHG emissions of diesel and jet fuel based on UCO (yellow grease), and serving as a reference, the respective fossil counterparts.

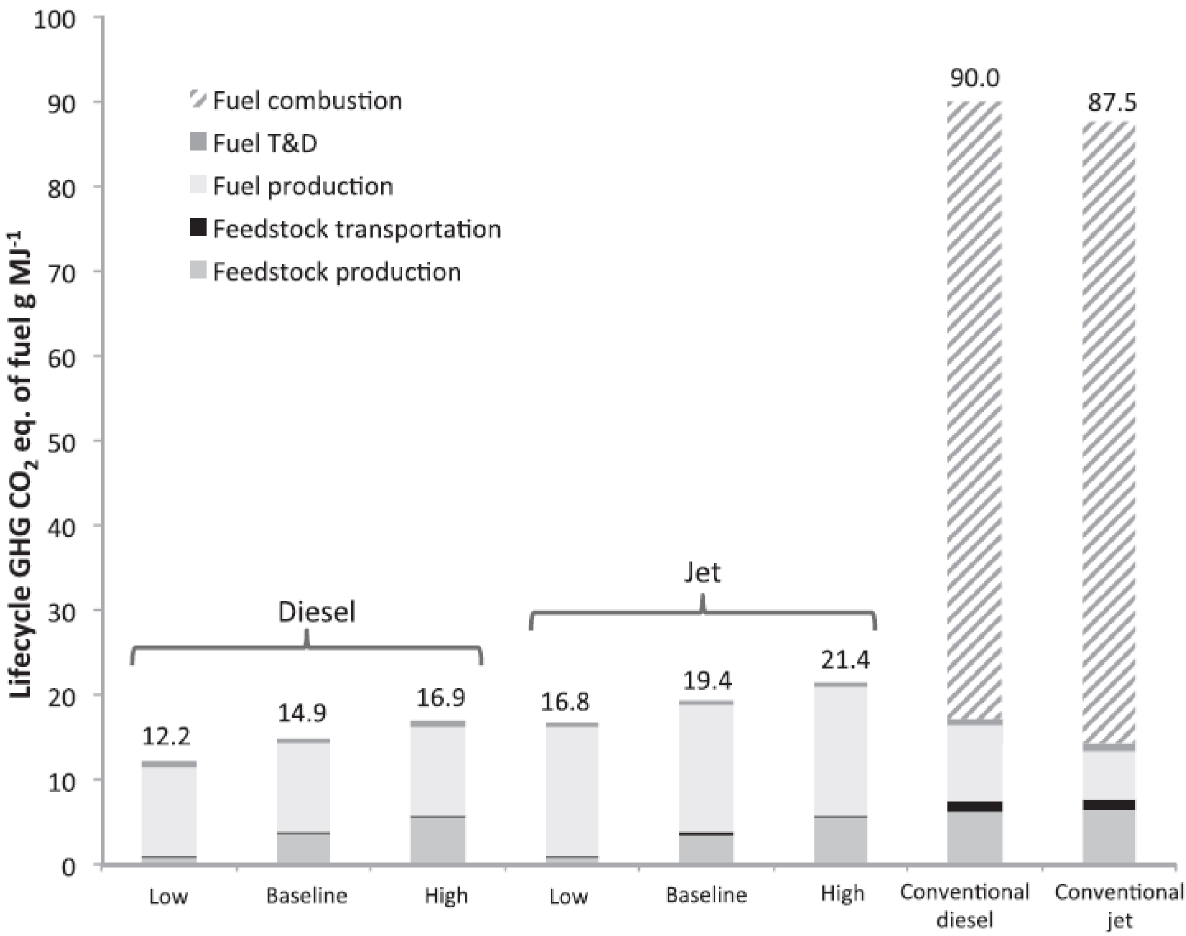

Figure 10: Lifecycle GHG emissions from yellow grease-derived HEFA fuels (Seber et al., 2014)

As can be seen in the figure above, the GHG emissions of the baseline case of UCO-based HEFA jet fuel amount to 19.4 CO_2 eq. per MJ of fuel corresponding to a 78% reduction relative to the conventional jet reference. Furthermore, it can be confirmed that emissions from fuel production are the major contributor, followed by rendering and transportation both for HEFA jet and diesel fuel production cases (Seber et al., 2014). It has to be noted that the emissions of HEFA jet and diesel shown above are not directly comparable due to different product slate choices (maximum distillate versus jet fuel product slate), and different corresponding input requirements (Seber et al., 2014). The lifecycle GHG emission results are, however, in line with other publications such as a report from

Oehmichen and Majer (2013)[23], who calculate a GHG emission reduction potential of UCO-based biodiesel of 83% (14 CO_2 eq./MJ_{FAME}).

Judging by the values stated above, alternative jet fuels based on UCO have a considerable GHG reduction potential, and can therefore contribute to the according targets of the aviation sector. It has to be noted though that the favorable GHG balance is partly attributable to the fact that the RED considers UCO as waste and therefore does not allocate any emissions to this type of feedstock up to its collection. If the GHG emissions emerging from cultivating the raw materials of cooking oil (rapeseed / sunflower) were taken into account, the picture drawn above might change. Considering the limited availability of UCO in Europe (cf. Chapter 9), imports from large UCO producing countries will be necessary if UCO-derived jet fuels are to contribute in a meaningful way to making aviation less carbon intensive. In light of the GHG emissions emerging from shipping, for example, the overall GHG balance of UCO-based jet fuels might be compromised.

Based on a JRC study[24] and examining the appropriateness the RED standard values for biodiesel from waste vegetable (and animal) oils, Oehmichen and Majer (2013) took the considerations stated above into account in their calculations. Here, in one scenario a 100% UCO import and a shipping distance of 18.500 km is assumed, which is added to approximately 1000km transport via trucks and trains (Scenario I). Scenario II in the figure below assumes a smaller proportion of biomass transported by ship and train[25]. As shown in Figure 11, the GHG balance of UCO-based biodiesel does surprisingly not change significantly when immense transportation distances are included.

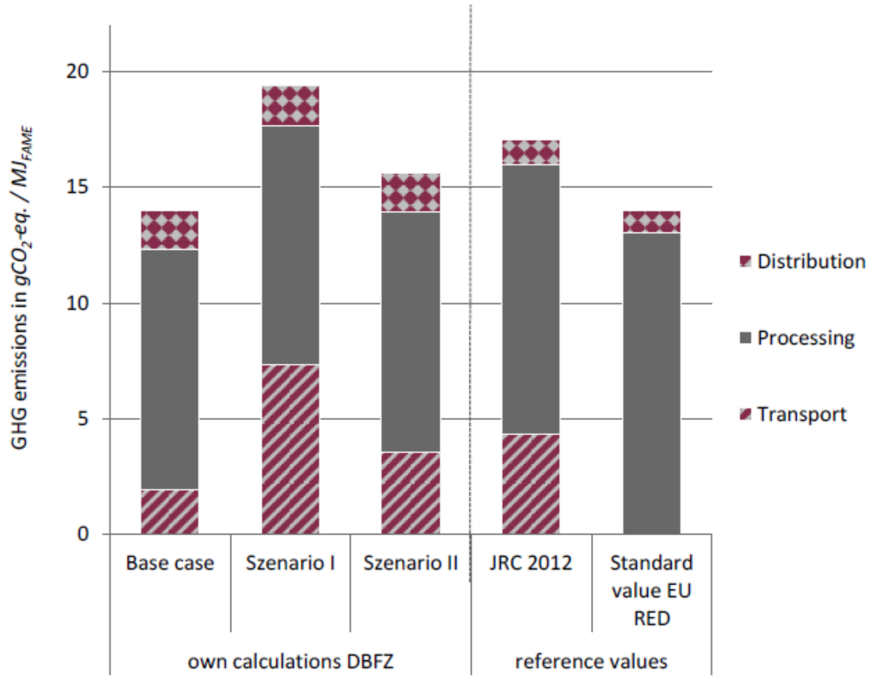

Figure 11: GHG balances of UCO-derived biodiesel taking into account different transport distances (Oehmichen/Majer, 2013)

[23] http://www.ufop.de/files/5313/9151/0489/Web_201401_Study_GHG_calculation_UCO_fat.pdf

[24] http://publications.jrc.ec.europa.eu/repository/bitstream/JRC76057/reqno_jrc76057_default_values_report__online_version1.pdf

[25] Scenario I: 100% Scenario II: 30%

Although transport does account for a major share in the GHG emissions (ocean transport making up 95% of it), conversion is still the largest contributor. When comparing Figure 10 and 11 with each other, it is apparent that the GHG emissions of UCO-based biodiesel only differ marginally, even when transport distances of almost 20.000km are taken into account. This may lead to the conclusion that the aviation / fuel producing industry could easily import UCO and convert it into jet fuels that not only show a favorable GHG emission reduction potential, but also are suitable for the well-established HEFA pathway. To put the values above in perspective, it has to be noted that transport in Scenario I is according to Oehmichen and Majer (2013) responsible for 38% of the GHG emissions, meaning that minimizing transport distances is generally desirable. If UCO imports from non-European should nevertheless be required, sustainability certification is a must.

3.3 FSRL of UCO

As outlined in the previous chapters, UCO collection is well organized and a commercial reality at industrial scale in Europe. Additionally, this type of feedstock is suitable for the well-established HEFA pathway and has successfully been tested in various flights. We therefore assign a FSRL of 9 to used cooking oil, the highest possible level.

4 Rapeseed (Brassica napus)

After introducing different types of oily feedstocks at varying maturity levels, this chapter will introduce and assess one of the most widely cultivated feedstocks utilized for biofuel production in Europe, namely rapeseed. Particularly due to the large-scale cultivation of rapeseed for bioenergy applications, sustainability concerns regarding the competition with food production, fertilizer requirements and the according GHG emissions have been voiced. The following chapters will therefore address if these concerns are substantiated. Although rapeseed oil is due to sustainability concerns not the preferred option of the aviation industry for bio-jet production, it shall nevertheless be introduced in this report as it serves well as a reference for the other feedstocks introduced in this report in terms of their sustainability performance, production potential, economic viability and the like.

Figure 12: Rapeseed field (FNR, 2007)

4.1 Cultivation of Rapeseed

Rapeseed, or winter oilseed rape (WOSR), is one of the most important oil crops in Europe. Apart from traditional applications as food and feed, it is also an important bioenergy crop due to its high oil content of 40 – 44%[26]. For nutritional purposes rapeseed most commonly finds its application for bottled oils and margarines. Winter oilseed rape (WOSR) is sown in August / early September and harvested in the following July.

Rapeseed is planted in rotation with other crops such as winter barley, peas, or early potatoes. Other cereal species such as summer barley or winter wheat can only be planted as a preceding crop to rapeseed – if they can be harvested in time. In practice, however, the most important rotational crop preceding rapeseed is winter barley. Rapeseed as a preceding rotational crop to cereals is particularly advantageous due to the deep roots of the rape plant that store nutrients for the following crops. 10 – 15% increases in cereal yields following rapeseed are possible in this rotation setup.

4.1.1 Fertilization

For rapeseed to reach the desired yields, limestone supply from soil is essential. Limestone does not only serve as a nutrient for the crop, it also increases the activity of microorganisms as well as the availability of other nutrients. Depending on soil type, the pH value should ideally range between 6 and 7.

One of the reasons why rapeseed as an energy crop is criticized is its high fertilizer requirements. WOSR takes up 200 – 250[27] kg of N per ha in the course of its vegetation, which is a considerable amount of fertilizer – the highest of the feedstocks assessed in this report. However, only a portion of this amount is taken up by the seeds (appr. 120 – 140 kg/ha), the rest is stored in the roots that reach down into the soil up to 1.80m in depth. Particularly in the case of rapeseed it is vital to apply N in appropriate amounts over the course of the year, in order to minimize nitrate leaching as well as deformities in plant growth.

Rapeseed additionally requires comparably large amounts of Potassium (K) and Magnesium (Mg). K (150 – 225 kg/ha) is essential for making the crop frost-hardy, for growing blossoms and husks as well as for the crop's water budget. Depending on the pH value of the soil, 15 – 30 kg of Mg is required per hectare. Lastly, Phosphorus (P) is required in quantities of 35-50 kg/ha to safeguard optimal root and seed formation. The GHG emissions resulting from fertilization will be addressed in Chapter 4.3.

It has to be mentioned that the amount of N fertilizer stated by [27] are in the upper spectrum of the range found in the literature. Other sources[28/29] state N amounts ranging between approximately 120 and 140 kg/ha per year. The difference in N application could be due to the sandy soils in the German Federal District Brandenburg, which require higher amounts of fertilizers than other soil types. In Bavaria for example, approximately 170 kg/ha of N are applied to the fields[30]. On the other hand, the values stated by [28] and [29] are based on LCA studies, while [27] states results gained from

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[26] Moser, 2010

[27] Landesanstalt für Landwirtschaft Brandenburg, 2009: http://lelf.brandenburg.de/sixcms/media.php/4055/raps.pdf

[28] http://www.ufop.de/files/9113/3940/7647/Uebersetzung_engl_Ansaetze_Optimierung_THG_Bilanz_von_RME.pdf

[29] http://www.sciencedirect.com/science/article/pii/S0360544213004349

[30] https://www.lfl.bayern.de/mam/cms07/iab/dateien/stickstoffduengung_winterungen_2016.pdf

practice. The EU RED and e.g. the German GHG reduction quota provide strong incentives to optimise rapeseed production with lower N application.

4.2 Rapeseed Production

The European Union is the World's largest rapeseed producer, Germany and France being the largest producers within Europe. Other important rapeseed producing countries include the UK, Poland and the Czech Republic. The total harvest area in Europe amounts to approximately 6.7 Mio. ha[31] in 2015, with a total production of 22 Mt. Figure 13 shows the development of rapeseed production in Europe, highlighting the largest rapeseed producers mentioned above. Forecasts show that the production of rapeseed will slightly increase to 22.4 Mt in 2017

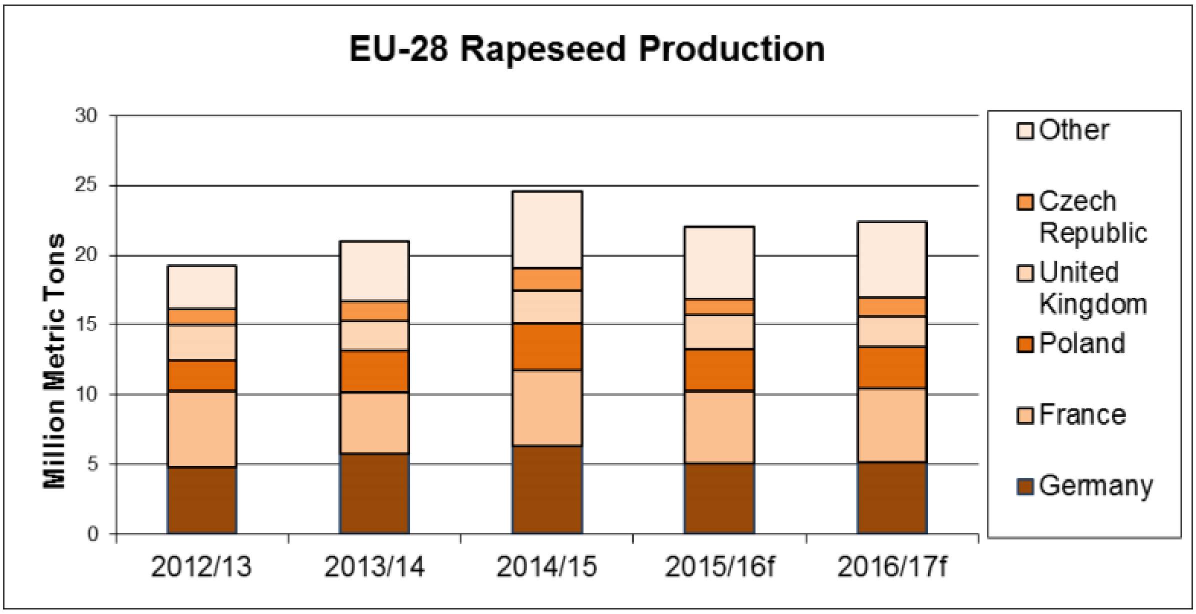

Figure 13: EU-28 Rapeseed Production (USDA FSA, 2016)

As shown in Table 11, Junker et al. (2015) state approximately the same total production of rapeseed in the European Union in 2012. Germany as the largest rapeseed producer is included in an extra column, imports and exports refer to trade with third (non-EU) countries. The trade of rapeseed between Member States is excluded.

[31] http://gain.fas.usda.gov/Recent%20GAIN%20Publications/Oilseeds%20and%20Products%20Annual_Vienna_EU-28_4-1-2016.pdf

Table 11: Market Overview for biodiesel, rapeseed oil, rapeseed, and rape cake (Junker et al., 2015)

	Germany	European Union*
Biodiesel (million t)		
Production	2.73	10.21
Imports	0.82	2.80
Exports	1.08	0.08
Rapeseed oil (million t)		
Production	2.96	8.90
Imports	0.22	0.61
Exports	0.80	0.23
Rapeseed (million t)		
Production	4.82	19.25
Imports	4.11	2.75
Exports	0.16	0.08
Rape cake (million t)		
Production	3.96	12.37
Imports	0.33	0.24
Exports	1.48	0.28

The seed yield per hectare of rapeseed ranges according to Moser (2010) between 2.68 and 3.39 t/ha. The high yields of rapeseed as well as its high oil content make it an economically viable energy crop. Rapeseed oil is for this reason the main feedstock for biodiesel production in Europe, accounting for 65% of the feedstock used for biodiesel production in 2012 (Junker et al., 2015). The next chapter will show how environmentally sustainable this type of feedstock can be produced.

4.3 Sustainability of rapeseed production

Apart from the risk of inducing indirect land uses changes, the major concern regarding the cultivation of rapeseed are GHG emissions resulting from fertilization as well as machinery use. In order to address these concerns, Table 12 depicts the inputs required for rapeseed (canola) production as well as the according GHG emissions resulting from the different production steps.

It has to be noted that the emission values stated in Table 12 are calculated by Miller and Kumar (2013) for Western Canada. For this reason, potential differences in emission factors, allocation method, as well as energy and emission coefficients stem from different farming locations and the respective prevailing conditions in terms of climate regime, soil type and the like. The study by Miller and Kumar is, however, the most comprehensive one found in the literature that details each production step and the GHG emissions resulting from it. In order to compare the results by Miller and Kumar, a study by Oehmichen and Majer (2010) will serve as reference for the European context.

4.3.1 GHG balance of rapeseed production

As highlighted in the table below, N and its oxidized form N_2O originating from the field account for the highest share in the overall GHG emissions of rapeseed cultivation, together they make up more than half of the total GHG emissions of the cultivation stage.

Table 12: GHG emissions of rapeseed cultivation (Miller/Kumar, 2013)

Operation	Input quantity			Energy coefficients			Emission coefficients			Energy use (MJ/MJ)	Emissions (gCO_{2e}/MJ)
	Units	Used value	References	Units	Used value	References	Units	Used value	References		
a) Canola farming, base scenario											
Nutrients, chemicals & seeding											
Nitrogen	kg/ha	123.0	[38]	MJ/kg	49.45	[43]	gCO_{2e}/g	3.58	[43]	0.220	15.9
Phosphorous	kg/ha	14.5	[38]	MJ/kg	14.13	[43]	gCO_{2e}/g	1.07	[43]	0.007	0.6
Potassium	kg/ha	100.5	[38]	MJ/kg	8.84	[43]	gCO_{2e}/g	0.69	[43]	0.032	2.5
Sulfur	kg/ha	25.0	[38]	MJ/kg	11.26	[44]	gCO_{2e}/g	2.70	[47]	0.010	2.4
Crop residue	tonnes/ha	1.5	[39]	–	–	–	kg N/tonne	6.00	[48]	–	–
Herbicide	kg/ha	3.43	[40]	MJ/kg	267	[45]	gCO_{2e}/g	17.24	[45]	0.033	2.1
Insecticide	kg/ha	0.28	[41]	MJ/kg	285	[45]	gCO_{2e}/g	18.08	[45]	0.003	0.2
Seeds	kg/ha	6.55	[13]	MJ/kg	5.83	[9]	gCO_{2e}/g	1.19	[9]	0.001	0.3
Machinery & fuel use (diesel)											
Manufacturing & maintenance	–	–	–	MJ/ha	1456	[12]	gCO_{2e}/ha	35,740	[12]	0.053	1.3
Sowing	L/ha	10	[42]	MJ/L	45.25	[46]	gCO_{2e}/L	3336	[45,49]	0.016	1.2
Farm chemical spraying	L/ha	4	[42]	MJ/L	45.25	[46]	gCO_{2e}/L	3336	[45,49]	0.007	0.5
Spreading fertilizer	L/ha	14	[42]	MJ/L	45.25	[46]	gCO_{2e}/L	3336	[45,49]	0.023	1.7
Harvesting	L/ha	25	[42]	MJ/L	45.25	[46]	gCO_{2e}/L	3336	[45,49]	0.041	3.0
Seed transportation	L/ha	8	[42]	MJ/L	45.25	[46]	gCO_{2e}/L	3336	[45,49]	0.013	1.0
Seed drying and cleaning											
Electricity	kWh/tonne seed	11.0	[9,12]	MJ/kWh	9.89	[46]	gCO_{2e}/kWh	880	[50]	0.005	0.5
Diesel	L/tonne seed	1.2	[12]	MJ/L	45.25	[46]	gCO_{2e}/L	3336	[45,49]	0.003	0.2
Field emissions											
N_2O emissions	–	–	–	–	–	–	% as N_2O-N	0.76	[13]	–	17.0
Land use change											
N_2O credit	–	–	–	–	–	–	g N_2O/ha	−503	[51−53]	–	–
Change in soil nitrogen	–	–	–	–	–	–	g N_2O/ha	1138	[51,60]	–	–
Change in soil carbon	–	–	–	–	–	–	kg CO_2/ha	3187	[51,60]	–	–
Farming subtotal										**0.47**	**50.4**

Even in light of the moderate N fertilizer application that Millar and Kumar use for their calculation, the negative effect of fertilization is obvious. GHG emissions from machinery are in the expected range and thus have only a marginal impact on the GHG balance of rapeseed cultivation.

The study by Oehmichen and Majer (2010) mentioned above comes to a slightly higher result, namely 51.5 CO_2 eq./MJ with an N application of 137.4 kg/ha per year. This value has been retrieved from a JRC study and is according to the authors rather low (at least in the German context). If N amounts are applied as in the example of Brandenburg (200 – 250 kg/ha) stated above, the GHG emissions increase accordingly, thereby further decreasing the GHG reduction potential of alternative fuels based on rapeseed.

After the harvest and the seeds have been cleaned and dried, the oil is extracted from them. As outlined in Chapter 2.3, lipids from oil crops are either removed mechanically or by using chemical solvents such as hexane. In light of the large quantities of rapeseed that need to be processed, solvent extraction is the dominant lipid extraction method at industrial scale. Although the seeds are mechanically pre-treated, solvent extraction is particularly for the subsequent production of biodiesel the option of choice. This is mainly due to the fact that by using solvents the seed's entire oil content of approximately 45% can be extracted, which increases the economic performance of the end product. Figure 14 shows the different production steps required from cleaning the rape seeds to the refined rapeseed oil, which serves as the feedstock for the subsequent conversion.

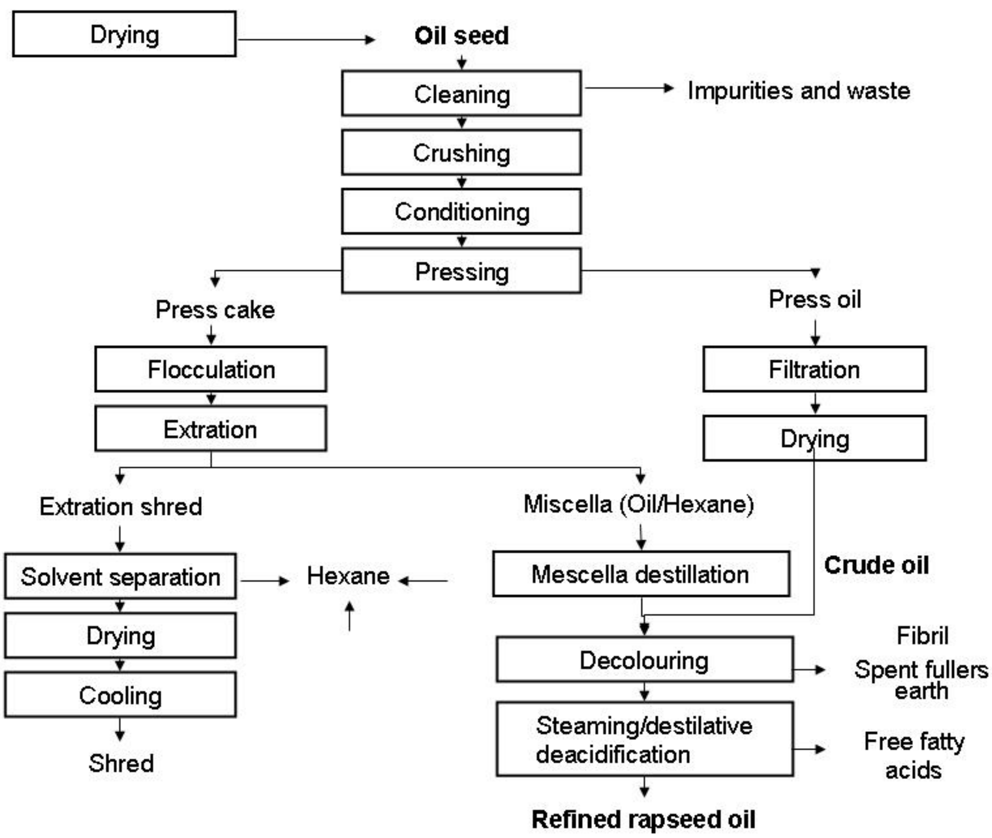

Figure 14: Rapeseed processing production steps[32]

[32] http://gabi-6-lci-documentation.gabi-software.com/xml-data/processes/c59ec712-064c-42b4-bbae-8bf07f46b491.xml

The different steps of oil extraction graphically depicted in Figure 14 require energy, from which in turn GHG emissions emerge. These are listed in Table 13. Steam and electricity needed for extracting the oil from the seeds are hereby the main contributors to the total GHG emissions resulting from the oil extraction process. The third largest share is attributable to spillage of the solvent hexane.

Table 13: GHG emissions of rapeseed oil extraction (Miller/Kumar, 2013)

Operation	Input quantity			Energy coefficients			Emission coefficients			Energy use (MJ/MJ)	Emissions (gCO_{2e}/MJ)
	Units	Used value	References	Units	Used value	References	Units	Used value	References		
a) Canola oil extraction, base scenario											
Seed preparation											
Drying heat (from diesel)	MJ process heat/tonne seed	54.5	[12]	MJ/MJ process heat	3.23	[12]	gCO_{2e}/MJ process heat	292	[12]	0.009	0.8
Drying electricity	kWh/tonne seed	13.6	[12]	MJ/kWh	9.89	[46]	gCO_{2e}/kWh	880	[50]	0.007	0.6
Oil extraction											
Electricity[a]	kWh/tonne seed	40.8[a]	[12]	MJ/kWh	9.89	[46]	gCO_{2e}/kWh	880	[50]	0.020	1.8
Steam	kg/tonne seed	369	[12]	MJ process heat/kg	2.00	[12]	gCO_{2e}/MJ process heat	126	[12]	0.044	4.7
Cooling water[b]	kg/tonne seed	14,560	[12]	MJ/kg	0.004	[10,67]	gCO_{2e}/kg	0.93	calc.	0.003	0.7
Lost solvent (hexane)[c]	L/tonne seed	1.94	[12]	MJ/kg	44.41	[43]	gCO_{2e}/kg	17,710	[12]	0.003	1.1
Degumming[d]											
Electricity	kWh/tonne seed	2.2	[12]	MJ/kWh	9.89	[46]	gCO_{2e}/kWh	880	[50]	0.001	0.1
Steam	kg/tonne seed	74.3	[12]	MJ process heat/kg	2.00	[12]	gCO_{2e}/MJ process heat	126	[12]	0.009	0.9
Process water	kg/tonne seed	8.3	[12]	MJ/kg	0.01	[12]	gCO_{2e}/kg	2.47	[12]	0.000	0.0
Oil extraction subtotal										0.09	10.7

Rapeseed cultivation including machinery use and extracting the oil from the seeds amount to 61.1g CO_2eq./MJ. Depending on the allocation factors[33] applied to the different production steps of the end product biodiesel, total GHG emissions from biodiesel production are usually in the range of 50g CO_2eq./MJ, representing an average GHG reduction potential of approximately 38% compared to the fossil reference value of approximately 84 gCO_2 eq. / MJ. While the GHG reduction potential of 38% of rapeseed biodiesel currently complies with the RED emission-saving requirements of 35%, already in 2017, the mandatory GHG reduction potential of 50% will not be achieved by biodiesel based on rapeseed, which will most likely have an immense economic impact on major rapeseed and biodiesel producing countries in Europe.

As most of the GHG emission values stated in the literature are based on default values as well as assumptions (system boundaries and the like) made in LCA studies, some degree of variation in the overall results can be expected. The GHG balance of biodiesel, for example, might change if climate-friendly or organic fertilizer showing low associated emissions is used, thereby decreasing the overall GHG balance of rapeseed-based diesel. Junker et al. (2015) compute five different scenarios in which they take into account the use of organic fertilizer, low energy-demanding conversion processes as well as deviations from RED default values in other literature, which can vary significantly for oil-extraction and refining. According to their findings, only a combination of climate-friendly produced / organic fertilizers and low energy-demanding conversion processes can theoretically reach GHG emission reduction higher than 50%.

Although the GHG emission reduction potential of a production pathway is not the only sustainability criterion to consider when assessing biofuels, it is nevertheless the most important one – at least when making transport more sustainable is the task. In case of rapeseed, the very high fertilizer requirements of the plant as well as the emissions resulting from fertilization are a clear disadvantage. As rapeseed is a food crop, the risk of inducing ILUC as a consequence of increased cultivation of the crop as a biofuel feedstock has also to be addressed.

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[33] An example of allocation factors and their impact on the overall GHG balance of rapeseed biodiesel can be found in Oehmichen / Majer (2010)

An advantage of rapeseed production is that residues (straw) emerging from its production are tilled back into the soil, leading to minimized depletion of soil nutrients and fertilizer savings. Further information concerning the agronomic advantages of tilling straw back into the soil can be found in chapter 7 on Soil Organic Matter and Soil Organic Carbon. In addition and as mentioned above, due to the tap roots of the rape plant it provides following crops with nutrients and increases their yield. In addition, rape leaves behind good soil conditions, which reduces the effort for soil cultivation of the following crop.

In context of the sustainability concerns of rapeseed production, particularly linked to N fertilization and the corresponding emissions, it has to be mentioned that there are a number of German projects[34] that seek to decrease N application in order to reduce the GHG intensity of rapeseed cultivation. If these projects are successful and the results can be applied to large-scale production systems, rapeseed might be a viable option for renewable jet fuel production in the future.

4.4 FSRL of rapeseed

As rapeseed is cultivated at industrial scale and a major contributor to the economies of a variety of European countries, we assign the FSRL 9 to this feedstock.

[34] https://www.thuenen.de/en/ak/projects/mitigation-of-greenhouse-gas-emissions-from-rapeseed-cultivation/

5 Switchgrass

After introducing three different types of feedstock belonging to the group of triacylglycerides (biogenic oils and fats), we shall now move on to lignocelluclosic biomass, which is the most abundantly available non-food raw material on Earth and mainly consist of cellulose, hemicellulose and lignin (Jonsson et al., 2013). The first lignocellulosic feedstock addressed in this report is switchgrass, a highly versatile grass, used for soil and water conservation, livestock as well as biomass production for conversion into energy (Casler, 2012).

As lignocellulosic biomass is suitable for conversion into alternative jet fuels via a variety of conversion pathways, switchgrass will be assessed in D4.2 and D4.4 for the Alcohol-to-Jet (AtJ) pathway.

5.1 Characteristics and Cultivation

Switchgrass (*Panicum virgatum*) is a warm season perennial C_4 grass native to North America, naturally occurring from Southern Canada to Northern Mexico, mostly as an herbaceous prairie grass. It develops rhizomes (subterranean stem) and is also deep rooting, often more than 2m (Christian et al. 2001). Depending on the variety and climatic conditions it grows 50 – 250cm. As mentioned above, switchgrass uses the C4 pathway and is an efficient user of nitrogen and water, making it a potentially very productive grass.

Figure 15: Switchgrass (Panicum virgatum) (Wikipedia, © Chhe)

Two main types of this perennial grass exist, namely lowland and upland switchgrass. Lowland types of switchgrass are found on wetter sites such as flood plains. They have tall, thick coarse stems and bunch growth habit. The upland type on the other hand is adapted to drier habitats with thinner stems than the lowland type but a higher stem number. Some have a turf-like growth habit.

An advantageous characteristic of switchgrass is that it can be grown on marginal land and is well adapted to low fertility and acid soils, the large and deep roots are very efficient in scavenging nutrients. It is most productive, however, when grown on moderately well to well-drained sites of medium fertility (UKY, 2013).

As switchgrass growth is very slow in the first two years it is essential to eliminate perennial weeds such as crabgrass before sowing. In Europe, switchgrass should be sown in late April or May when soil temperatures are above 10°C and when there is some moisture in the seedbed but when it is not too wet. It can be sown in a conventional manner with a drill or direct-drilled (no-till) or broadcast with a sowing depth of approximately 10cm (Christian et al. 2001). Although little information is available on the optimal seeding rate in Europe, estimates say that a seed rate of 10 - 20 kg/ha is adequate. Establishment is generally slow and difficult, often taking 2 – 3 years until optimal productivity is reached. However, once established, this perennial grass will continue to yield for 10 or more years (UKY, 2013).

Mature switchgrass stands can be harvested either once or twice a year with conventional haying equipment (UKY, 2013). When switchgrass is grown for biomass (fibre, energy) delayed harvest in winter / early spring (after frost) is recommended (Christian et al., 2001). Cutting the perennial grass once a year is beneficial in economic terms and removes fewer nutrients from the soil. Yields range between 8 and 10 tonnes of dry mass hectare in the second year, further increasing in the third year and thereafter to 18-25 tonnes of dry mass per hectare (Elbersen, 2010).

Due to slow seedling growth N should not be applied in the first year, as nitrogen fertilization is not necessary for the development of the crop and encourages weed competition. In order to determine the P and K requirements soils should be tested for pH before planting. Lime is typically not required unless pH drops below 5.0 (Blade, 2010). If deficiencies in P and K exist, they should be applied before planting.

In later years nutrients should be applied at a level that anticipates rising productivity and also takes into account losses of minerals in harvested biomass (Christian et al., 2001). Once switchgrass is successfully established after 3 years, approximately 60 – 170 kg/ha/year (Blade, 2010) should be applied to maximize biomass yield, depending on soil type and initial fertility. Information on P and K requirements of switchgrass is limited with available data being contradictory and mostly generated by greenhouse experiments (Kering et al., 2012), which is why the impacts of P and K fertilization will not be further considered in the course of this report.

5.2 Sustainability and Environmental Impacts of Switchgrass Cultivation and Production

Lignocellulosic feedstocks have been identified as a promising source for the production of alternative aviation fuels as they have the potential to fulfil several sustainability criteria (e.g. lower agricultural input requirements) whilst additionally reducing the risk of increased agricultural land-use competition.

The perennial crop switchgrass has a series of environmental benefits including the improvement of soil health by carbon sequestration, reduction of soil erosion by improving soil quality and stability, the aforementioned low agricultural input requirements as well as less intensive agricultural management practices.

Carbon sequestration is the exchange of carbon between the atmosphere and other reservoirs for storage such as terrestrial ecosystems. This is insofar vital for the sustainability performance of switchgrass as it stores a large portion of the mass of atmospheric CO_2 below ground after the biomass has been harvested, which in turn positively impacts on the GHG balance of the end product, namely bio-kerosene. The soil carbon sequestration rate of switchgrass is found to be 20 – 30 higher than of annual crops (McLaughlin, 1998), resulting in considerable reductions of life cycle emissions of this perennial grass and symbolizing a comparative advantage to other energy crops. In addition, the perennial nature of switchgrass and its productive cycle of 10 years require tillage only in the establishment phase and thus the risk of soil erosion and the release of soil carbon into the atmosphere are reduced.

According to Kim and Dale (2004), the global warming impact associated with producing 1kg of switchgrass is between 124 and 147 g CO_2 equivalent per kg. 50% of the global warming impact in producing switchgrass can be attributed to the field emissions emerging from nitrous oxide (N_2O). In addition, emissions emerging from fossil fuels consumed by farming and transportation machinery account for almost the other half of total emissions associated with the production of switchgrass.

Despite the often-mentioned low nutrient requirements of this perennial grass, the percentages stated above clearly show that the less N fertilization is required in feedstock cultivation, the more sustainable the overall process becomes.

As switchgrass is a non-food feedstock that can be grown on marginal land, the risk of inducing land use changes and the GHG resulting from it is assumed to be relatively low compared to other feedstocks used for biofuel production. However, Staples et al. (2014) calculated the lifecycle GHG footprint of middle distillate (MD) fuel produced by so-called advanced fermentation (AF) and the dLUC GHG emissions emerging from altering previously unused land for the cultivation of switchgrass in course of the production process. The emissions are expressed in CO_2 equivalent per MJ of fuel, with values ranging between 2.9 and 12.2 ($gCO_2eq./MJ_{fuel}$). When dLUC emissions are included in the calculation, the emission values stated above increase to 40.3 $gCO_2eq./MJ_{MD}$. The calculation of these values is based on the assumption that direct LUC emissions are amortized evenly over a 30 year period. Although these calculations depend to a large degree on the specific scenario in which a feedstock is cultivated, they nevertheless show the magnitude of emissions emerging from land use change emissions and their impact on the overall environmental sustainability of a certain feedstock or fuel.

The following table (Staples et al., 2014) shows calculated lifecycle emissions ($gCO_2eq./MJ_{MD}$) emerging from the production of the aforementioned AF MD. For the purpose of this report, we shall concentrate on the emissions emerging from the first two production steps, namely cultivation and transport.

Considering the low yields (18-25 t/ha) of switchgrass especially compared to sugar cane yields sugar cane (68-83 t/ha), emissions emerging from cultivation and transportation appear to be higher. However, this is put in perspective when comparing switchgrass to corn grain that shows a potential yield of 7-11 t/ha and considerably higher emissions in the cultivation phase.

Table 14: Calculated LCA Emissions from Switchgrass, Sugar Cane and Corn Grain (Staples et al. 2014)

		Biomass credit	Feedstock cultivation	Feedstock T&D	Feedstock to platform chemical conversion	Platform chemical to drop-in fuel upgrading	Fuel T&D	Fuel combustion	Total
Sugar cane AF	Low	-70.4	3.1	0.6	0.0	2.5	0.5	70.5	6.8
	Base	-70.4	4.9	1.0	0.0	6.2	0.5	70.5	12.7
	High	-70.4	5.9	1.1	0.0	12.1	0.5	70.5	19.7
Corn grain AF	Low	-70.4	26.2	1.9	13.3	5.6	0.5	70.5	47.6
	Base	-70.4	28.9	2.1	15.6	15.4	0.5	70.5	62.6
	High	-70.4	45.0	3.3	26.9	41.7	0.5	70.5	117.5
Switchgrass AF	Low	-70.4	11.1	1.3	1.8	2.6	0.5	70.5	17.3
	Base	-70.4	17.6	2.1	10.9	6.2	0.5	70.5	37.4
	High	-70.4	39.7	4.7	40.2	4.6	0.5	70.5	89.8

In conclusion, switchgrass has the potential of becoming a viable and relatively low-cost feedstock for the production of alternative jet fuels. Emissions emerging from its cultivation are moderate, advantages being low N requirements, the potential to be grown on marginal land as well as a high rate of carbon sequestration and no tillage requirements.

5.3 Feedstock Readiness Level (FSRL)

While being well-established in its native region North America, switchgrass is neither cultivated at a large scale nor converted into biofuels exceeding pilot stage in Europe. For this reason, we assign a FSRL of 5 to switchgrass, meaning that the production system is validated at field-scale with identified resource requirements and production uncertainties.

6 Short Rotation Coppice (SRC)

The second lignocellulosic feedstock considered in this report is woody biomass grown in short rotation coppice systems. As cited in Wickham et al. (2010), short rotation coppice (SRC) refers to perennial, fast-growing, high-yielding woody crop biomass that is harvested every two to five years and managed under a coppice system. Management practices for SRC (soil preparation, weed control, planting, fertilization, harvest etc.) are more similar to those of agricultural annual crops than to forestry practices (Dimitriou, 2011).

The best known and most widespread dedicated SRC crops commercially grown for bioenergy purposes are poplar (*Populous*) and willow (*Salix*), both belonging to the Salicaceae plant family. Particularly in boreal regions of Europe, for example Sweden, the majority of research work as well as commercial cultivation is carried out. Other regions focusing on developing high-yielding SRC are the United Kingdom (UK), Italy, France, Poland and Germany.

Poplar is in comparison to willow little commercially grown in Central and Northern Europe, with the exception of Germany where poplar is cultivated on larger areas than willow, particularly in Eastern and North-Eastern federal districts of the country. However, poplar is generally cultivated more widely in Southern Europe, as it is considered to be more adapted to the prevailing climatic and soil conditions in these regions.

Figure 16: Short Rotation Coppice Poplar (FNR, © S. Hajkova)

As opposed to the previous chapters, the discussion on SRC will not introduce one specific species of this feedstock group. Instead, the SRC poplar and willow as an example of lignocellullosic feedstock, their environmental advantages and disadvantages will be discussed in more general terms as short rotation coppice. Accordingly, and seeing as there are only minor differences between the two main SRC species in terms of yield potentials and agronomic requirements, in particular the chapter on sustainability can be understood as a more general approach in assessing the potential of SRC as a feedstock for alternative jet fuels.

6.1 Characteristics and Cultivation

Although management practices of SRC are closer to those of agricultural annual crops as mentioned above, a number the physical traits and management practices of SRC do indeed differ. Depending on national regulations and market issues this particularly concerns the fact that SRC plantations are in place for a number of years (10-25 years) and thus take the land out of arable rotations (Dimitriou et al., 2009). In addition, SRC grow much taller than conventional crops before it is harvested, namely five to eight meters.

SRC can be established on variety of different soil types with a preferred pH range of 5.5 – 7.5. Good soil moisture is crucial for successful cultivation but waterlogged soils should be avoided as these will negatively impact on the cutting cycle and overall yields. Ideally, SRC should be grown on aerated, medium textured soil that holds a good supply of moisture. A difference between the two main SRC cultivated at a commercial scale is that poplar has lower water requirements than willow. High water requirements compared to conventional crops is seen as a negative trait of SRC, particularly of willow. Annual precipitation should therefore not fall under 500-600 mm.

The cultivation site should be ploughed in late autumn or early winter to 30cm and left to over-winter in that state to allow frost to break the soil down further (Tubby, 2002). Depending on the water saturation of the soil, SRC should be planted in early spring (February or March). In case soils should be waterlogged, postponing plantation to late spring is possible.

Once established, SRC has very low requirements for nitrogen fertilizing as well as other agrochemical inputs, which can be seen for the reasons outlined in the previous sections as a positive characteristic of this type of feedstock. In addition, inorganic fertilizers can potentially be substituted with sewage sludge, as field trials in Sweden have shown. Furthermore, as no annual soil cultivation (tillage) is required, SRC have a much lower carbon footprint compared with food or biofuel production from annual arable food crops (Heller et al., 2004).

The biomass yield of plantations is typically measured in dry tons per hectare per year. The overall yield is of course dependent on the factors outlined above, e.g. plantation site, climatic conditions (precipitation), cutting cycle, planting density and the like. Poplar shows annual yields in the range between 4 and 16 tons per hectare. An often stated profitability benchmark for SRC production is 10 t/ha/y (Tubby, 2002).

6.2 Sustainability and Environmental Impacts of SRC Cultivation and Production

As discussed in chapter 3.2 on switchgrass sustainability, the rate at which a plant sequesters carbon in soil is an important factor to evaluate the overall GHG balance and therefore its sustainability. With respect to the carbon sequestration potential of a specific feedstock, site-specific biological, climatic, soil and management factors have of course to be taken into account.

With respect to SRC, it has been observed that the total carbon sequestration under these cultivation systems is significantly higher than under arable soils (Baum et al., 2009), which constitutes a comparative advantage of this perennial woody biomass. In SRC plantations the largest share of carbon is accumulated in the top layer of the soil (0-40cm), which stems from the non-tillage requirements of SRC as well as the high amounts of leaf litter (1 – 5 t/ha) deposited on the soil cover in the course of the year (Dimitriou et al. 2011), which additionally benefits soil ecology.

Figure 17: Short Rotation Coppice System (FNR, © D. Hagenruth)

The main GHG emissions resulting from the cultivation of SRC can be allocated to the fossil fuels burned by harvesting and transportation machinery as well as to emissions resulting from nutrient applications.

As we have established before, SRC have relatively low nutrient requirements in form of inorganic fertilizers due to the efficient recycling of N from leaf litter. Some authors (Dimitriou et al., 2009) suggest that the vast majority of Swedish and UK SRC fields are not supplied with inorganic fertilizer at all, which is the case only for the year of establishment, as no N fertilization reduces the competitiveness of weeds that would take advantage of fertilizer application. However, as SRC plantations are intensively managed and harvested to reach high biomass yields, nutrients are removed at a high rate. In average, an annual application of 150kg of nitrogen, 30kg of phosphorus and 80kg of potassium per hectare are recommended for short rotation coppice systems after the establishment year (Wickham, 2010). This is roughly in the same range as the nutrient requirements of the oil crop camelina, which is as we have concluded before a viable feedstock for the sustainable production alternative jet fuels.

According to life cycle assessments conducted in the BurnFAIR project, bio-SPK from the SRC poplar shows GHG emissions of 49,1gCO_2eq./MJ, based on a yield of 25 tonnes dry mass per hectare, meaning that this production pathway would meet the 35% GHG reduction potential of alternative fuels compared to their fossil counterpart that is required in the European Union's Renewable Energy Directive (RED).

6.3 FSRL of Short Rotation Coppices

Although regional differences in terms of total cultivation area exist within Europe, SRC is generally a well-established cultivation system. The two main species poplar and willow are commercially cultivated for bioenergy purposes.

In Europe, France and Italy are by the largest producers of SRC with 236.000[35] ha poplar plantations in France and 119.000 ha in Italy, respectively. Willow plantations in Northern and Central Europe range between approximately 15.000 ha in Sweden and 5.000 – 6.000 ha in Germany (Roth et al. 2014). Commercial machinery for planting and harvesting is also commercially available.

Accordingly, we assign a FSRL of 7 to short rotation coppice as the sustainable feedstock production capacity is established in Europe.

WASTE AND RESIDUES

After introducing biomass that is directly converted into synthetic fuel in the previous chapters, the following section will address waste and residues that emerge, inter alia, from harvesting dedicated crops or managed forests. This chapter is thus divided into two sections, each addressing different sources of the overarching category 'waste and residues'. A third category of waste is organic waste such as household waste. Due to the very limited viability of household waste for the production of bio-kerosene, this category shall be neglected.

The utilization of waste and residues as a biofuel feedstock is to a large degree founded in concerns with regard to the sustainability of biofuel feedstocks and their potential competition with food production, which was addressed in the previous sections. Waste and residues serve as feedstock for so-called advanced biofuels, meaning that they do not compete directly with food production and have a (supposedly) low risk of inducing indirect land use changes. In order to increase the use of biofuels based on waste, residues as well as lignocellulosic biomass (cf. chapters 4&5), a 'double counting provision' was included in the RED, meaning that if a Member State has a 4% national biofuel mandate in place, it can meet this target by supplying 2% biofuels based on waste and residues, as no agricultural land is required to generate waste and residue materials. Consequentially, the double counting provision led to large increase in the consumption of biofuels from used cooking oil (UCO) and animal fats (Spöttle et al, 2013), which was analyzed in Chapter 3 of this report.

Although such a double counting provision is not entailed in the FQD (Fuel Quality Directive), waste- and residue-based biofuels have the advantage of relatively high GHG emission savings, particularly in comparison to so-called first generation biofuels based on biogenic oils and fats. This means that comparably small amounts of biofuels are needed to meet the GHG emission reduction targets in the FQD. In addition, the FQD[36] considers agricultural residues to have zero lifecycle GHG emissions up to the process of the collection those materials, in order to further stimulate the utilization of waste and residues as feedstocks for the production of advanced biofuels. Furthermore, the RED sets in Annex V (D) GHG emission default values (in gCO_{2eq}/MJ) to zero for biofuels and bioliquids based on waste and residues.

Particularly these features make waste and residues an interesting feedstock group for the aviation sector, considering the ambitious self-imposed GHG emission reduction targets as well as the very narrow profit margin most airlines are allegedly operating in.

35 http://www.fao.org/docrep/008/a0026e/a0026e02.htm

36 Annex IV(C)(18)

7 Agricultural Waste and Residues

Agricultural residues cover both primary residues, i.e. harvesting residues such as straw, and secondary residues, i.e. food processing residues and animal excrements (Rettenmaier et al., 2010). As animal excrements are predominantly utilized for the production of biogas, this subsection will focus on residues from crops that show the highest production in the EU, namely barely, maize, oats, olives, rapeseed, rice, rye, soybeans, sunflower, triticale, wheat, and sugar beet (Searle/Malins, 2016). The residues of these crops can potentially serve as a feedstock for the production of alternative aviation fuels. Table 15 depicts energy crops and residues from agricultural and marginal land, including biomass subcategories, its origin as well as the respective type of biomass. In general, crop residue is defined as the non-edible plant parts that are left in the field after harvest (Lal, 2005).

Table 15: Energy crops and residues from agricultural and marginal land (Rettenmaier et al., 2010)

Biomass subcategory	Origin	Type of biomass
Woody and herbaceous energy crops		
Grown on arable land	Arable and permanent cropland incl. SRC	Harvest from arable and permanent cropland incl. annual energy crops and SRC, excl. residues
Grown on grassland	Permanent grassland (meadows and pastures)	Permanent or annual energy crops, excl. residues
Grown on marginal land	Other land (degraded lands, mine dumps...)	Permanent or annual energy crops, excl. residues
Woody and herbaceous agricultural residues		
Primary residues	Agr. cultivation and harvesting activities	Harvesting residues (straw, etc.)
Secondary residues	Processing of agricultural products, e.g. for food	Processing residues (e.g. pits from olive pitting, shells/husks from seed/nut shelling) as well as animal excrements

Exemplary for the various crop residues mentioned above, wheat cereal straw, being the most widely available type of straw in Europe will be addressed in the following section. As shown in Figure 18 cereal crops are comprised of five main parts, namely: grain or seed, leaf material, chaff, stem and roots (Spöttle, 2013).

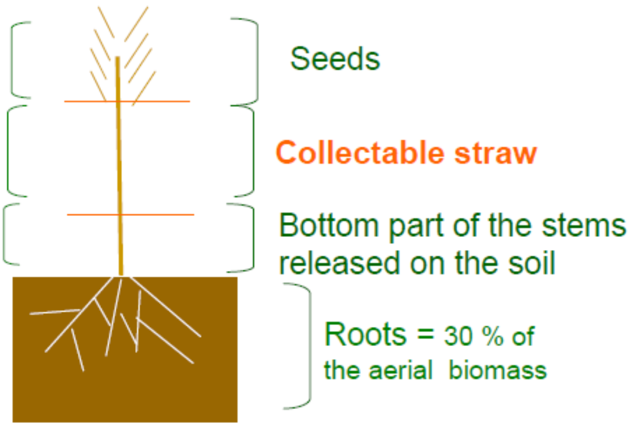

Figure 18: Schematic Overview of a cereal crop highlighting the collectable straw (Panoutsou/Labalette, 2006)

After the main crop has been harvested (i.e. grain / seeds), straw is left over in the field that makes up the crop residue as defined above by Lal (2005). In practice, mainly the stem of the plant is left on the field, also entailing minor amounts of leaf material and chaff. The crop roots, comprising approximately 30% of aerial biomass, are not classified as straw and are therefore not utilized for the production of biofuels / bio-kerosene (Spöttle et al., 2013).

As shown in Figure 19, crop residues have a variety of different uses that can potentially lead to competition between different sectors or applications, for example between the biofuel and heating and cooling sector. Apart from the off-site uses depicted in the figure below, crop residues also have a variety of on-site uses that fulfill important ecosystem functions.

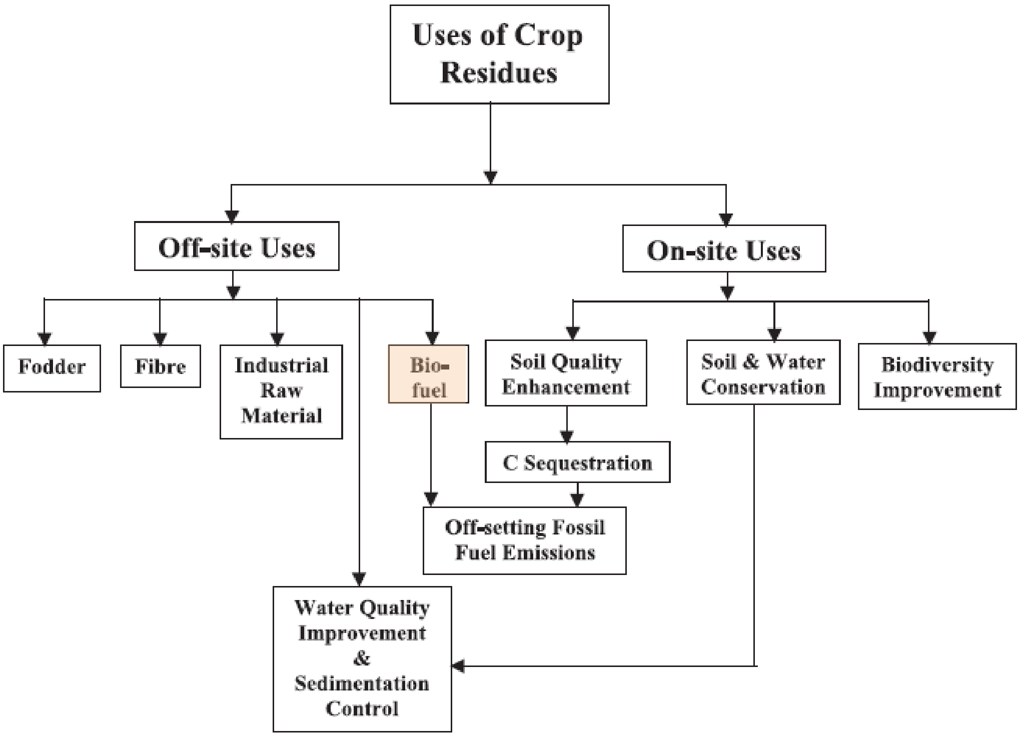

Figure 19: Alternative and competing uses of crop residues (Lal, 2005)

An exact breakdown of the main conventional uses of cereal straw, including alternatives that can potentially substitute straw is given in Table 16.

Table 16: Examples of the main conventional uses of straw (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

In general, the amount of residue produced depends on a variety of factors such as the types of crops, crop rotation, crop mix as well as agricultural practices. In addition, it (the amount of residues) is directly linked to crop production, and depends on yield and cultivated area (Scarlat et al., 2010). The availability of agricultural residues for bioenergy application in general, and for alternative aviation fuels in particular will be addressed in Chapter 9 on 'Sustainable Feedstock Potential in European Union.'

7.1 Harvest

As opposed to the previous chapters that introduced the cultivation techniques of the different feedstocks as well as the according GHG balance, this chapter will not go too much into detail in this regard.

Cereal crop cultivation is of course subject to fertilization. In case of winter wheat for example, fertilization amounts to approximately between 100[(37)] and 200kg/ha of nitrogen being applied to the fields[38] per year. As we have seen in the previous chapters, particularly nitrogen fertilization can have a considerable impact on the GHG balance of a cultivation system, which in turn impacts on the GHG

[37] http://www.umweltbundesamt.de/sites/default/files/medien/378/publikationen/texte_09_2016_aktualisierung_der_eingangsdaten_und_emissionsbilanzen_wesentlicher_biogener_energienutzungspfade_1.pdf

[38] https://www.landwirtschaftskammer.de/landwirtschaft/ackerbau/getreide/getreide-n-duengung.pdf

emission reduction potential of the end product bio-kerosene. However, as stated above, all biofuels based on waste and residues have, according to the RED, no GHG emissions and hence, an assessment of the GHG emissions emerging from cereal crop cultivation is not part of this chapter. A discussion in this regard will, however, take place later on in this report.

The harvest of cereal crops and rapeseed typically takes place between June and August, the exact timing depending on the region, crop type and weather conditions in that year (Spöttle et al., 2013). The first step of the harvest is conducted by combined harvesters which cut cereal crops approximately 10-15 cm above the ground. Subsequently, the grain is 'threshed' in order to separate the chaff from the stem and is then collected, while stem and leaf material falls on the ground. Depending on the configuration of the combine harvester, some chaff may also fall to the ground.

Prior to baling, the straw is left in the field to dry – a process known as 'swathing' in order to reach the desired moisture content. The typical moisture content achieved is around 16% moisture in Northern Europe, but can be as low as 9% to 12% in Southern Europe (Spöttle et al., 2013). The climate and weather conditions have direct impact on the moisture content and overall quality of the straw, as well as the timing of the baling operations. When the moisture content of the straw is too high at the point of harvest, fungi will develop and negatively impact on the straw's quality. In some cases and particularly in the UK, chemical desiccants are applied to speed up the drying process.

When the straw has the desired moisture content it is either baled for transportation and further processing or ploughed back into to soil. On the hand, 'incorporating' or 'chopping' the straw back into the soil fulfills several (on-site) agronomic functions such as the improvement of soil quality or supplying the soil with nutrients, which potentially decreases the need for artificial fertilizers and is in turn connected to reduced GHG emissions. From the farmer's perspective, it is mainly an economic decision whether to sell straw bales or incorporating it in the soil – depending on the relative economic value of the straw and the additional costs of applying fertilizers to compensate for nutrient losses.

The catchment areas of straw converting facilities is comparably large due to the relatively low energy density of straw of approximately 14,5 MJ/kg at 14% water content (Zeller et al., 2013). The low mass density of straw additionally poses certain challenges on transportation, as the capacity of trucks transporting the feedstock is in most cases only partially used. Furthermore, the short harvest time of straw in early summer and late autumn poses additional challenges to conversion facilities as these are dependent on a continuous feedstock supply. This in turn leads to the necessity of storing the feedstock, which translates for large facilities (that convert the according amount of straw) with decentralized storage sites to additional transport and handling costs.

These aspects may lead to high costs of making straw available as a feedstock, the overall costs being proportional to the demand of the facilities or refineries. The economic viability of facilities converting straw to bioenergy is in most cases directly dependent on the costs of making the feedstock available and thus, even minor fluctuations in these costs can determine negative or positive capital values of facility investment (Zeller et al., 2013).

7.2 Sustainability of Agricultural Waste and Residues

The additional transportation and storage requirements of straw outlined above also have an impact on the overall GHG balance of the end product due to the fossil diesel most trucks are operating on. Zeller et al. (2013) calculated GHG balances of three different kinds of fuel derived from cereal straw residue, namely Bio-SNG, Ethanol and FT-Diesel. One of the assumptions made in the calculations is that the energy supply for the conversion process is based on renewable resources, thereby making the conversion less GHG intensive in this regard.

The GHG balance of the three fuels ranges between 13 and 24 $gCO_2eq.$ / MJ of fuel, which is a considerable reduction compared to the standard emission value of fossil fuel of 83.8 $gCO_2eq.$ / MJ of fuel. As the conversion process of the chosen pathways are more complex than in other pilot plants, the higher demand for feedstock is noticeable in the GHG balance. This also applies to the GHG emissions resulting from making the feedstock available, approximately between 24.5 and 60% of the overall result (Zeller et al., 2013).

Although fuels based on waste and residues are considered to have zero GHG emissions in the RED, the calculations above give nevertheless a rough impression concerning the GHG emission reduction potential of alternative aviation fuels based on agricultural waste and residues. Taking into account the high feedstock demand the aviation industry will have in the future to meet its GHG reduction targets, land as well as (residual) feedstock availability and the costs of transporting the feedstock to the bio-refinery are crucial aspects to consider.

As indicated in Figure 19, straw fulfills a series of on-site functions such soil quality improvement that are directly linked to the sustainability of this type of feedstock. Particularly in case of soil quality and nutrient supply, the removal rate of straw and the according amount that is left on the field are essential.

7.2.1 Soil Organic Matter (SOM)

One of the most important soil quality parameters influenced by the removal rate of straw (for bioenergy production) is Soil Organic Matter (SOM), which the EC defines in its Soil Framework Directive[39] as the organic fraction of the soil, excluding undecayed plant and animal residues, their partial decomposition products, and the soil biomass. SOM consists of carbon, hydrogen, oxygen, nitrogen, phosphorus and sulphur.

SOM is particularly important for the soil quality as it influences physical, chemical and biological soil properties. These include the physical structure and stability of the soil, ease of cultivation, ease of root growth, water infiltration rate, erosion, nutrient uptake and biodiversity. Hence, straw is one of the few management tools available for effectively maintaining SOM (Spöttle et al., 2013). In turn, if straw is not incorporated into the soil through cultivation or tilling intensification, thereby leading to a decrease in SOM, the positive impacts described above are reversed. These may include the loss of aggregate stability, increased crust formation, increased runoff and soil erosion, increased compaction, slower water filtration and a slower exchange of water / gases (Spöttle et al., 2013).

In general, the SOM or carbon cycle is based on continually supplying carbon in the form of organic matter as a food source for microorganisms, the loss of some carbon dioxide, and the build-up of stable carbon in the soil (a process called assimilation) that contributes to soil aggregation and formation. Carbon assimilation is a dynamic process necessary for nutrient availability and cycling. Hereby, different sources of organic matter have different assimilation and decomposition

[39] COM (2006) 232

characteristics, and result in different SOM fractions (Gobin et al., 2011). Table 17 gives an overview of the different SOM fractions, their particle size and turnover time.

Table 17: Size and breakdown rate of various SOM fractions (Spöttle et al., 2013)

SOM Fraction	Particle Size (mm)	Turnover Time (years)	Description
Plant residues	≥ 2.0	< 5	Recognizable plant shoots and roots
Particulate organic matter	0.06 – 2.0	< 100	Partially decomposed plant material, hyphae, seeds, etc.
Soil microbial biomass	Variable	< 3	Living pool of SOM, particularly bacteria and fungi
Humus	≤ 0.0053	< 100 – 5000	Ultimate stage of decomposition, dominated by stable compounds

If the rate of assimilation is less than the rate of decomposition, SOM will decline and, conversely if the assimilation rate is greater than the rate of decomposition, SOM will increase (Gobin et al., 2011). Both processes occur concurrently, but are of a different order of magnitude.

7.2.2 Soil Organic Carbon (SOC)

Accounting for the carbon in SOM is Soil Organic Carbon (SOC) – also a crucial soil constituent due to its capacity to affect plant growth both as a source of energy for microorganisms and a trigger for nutrient availability through mineralization. A direct effect of poor SOC is reduced microbial biomass activity and nutrient mineralization due to a shortage of energy sources (Spöttle et al., 2013).

On a global scale, SOC is one of the main pools of carbon. The SOC pool is about double the size of the atmospheric carbon pool and about three times the size of the biotic carbon pool (Gobin et al. 2011). This is insofar important, as tilling soil prior to the cultivation phase and after harvest releases CO_2 into the atmosphere. Particularly highly diverse grasslands, forests and peatlands emit a considerable amount of carbon when being altered into cropland. The RED therefore states that feedstock for the production of biofuels cannot be grown in areas converted from land with previous high carbon stocks such as wetlands or forests.

What the RED fails taking into account when considering agricultural residues to be carbon neutral up to their collection is the potential impact of straw removal on soil carbon stocks and the according emissions resulting from the removal. In Zeller et al. (2013), Wiegmann and Hennenberg calculate lifecycle GHG emissions of wheat production, including straw removal. They find that the emissions of removing straw from the field amount to 10g CO_2eq. / MJ – compared to the incorporation of the straw in the soil. In addition, they find that emissions from fertilizing wheat with N and from machinery (diesel) are in the range of 23g CO_2eq. / MJ.

Other potentially negative effects of removing straw from the field for the purpose of utilizing it for bioenergy production are controversially discussed within Europe, as cereal straw is most often returned to the soil in arable cropping systems in order to replenish it with nutrients as well as to fulfill other agronomic purposes shown in Figure 19. Utilizing residues for the production of biofuels implies a systematic removal of aboveground biomass, which is often criticized, particularly in soils that already have low soil carbon content (Gobin et al. 2011). While the addition or removal of straw has according to Powlson et al. (2011) a relatively small effect on the total SOC in most situations, they also indicate that comparably minor changes in SOC can have disproportionally larger impacts on physical soil properties such as aggregate stability and water infiltration rate (Spöttle et al., 2013).

Crucial both for SOM and SOC is the question how much straw can be sustainably removed from the field without negatively impacting the soil, its functions and properties as well as without compromising other uses of straw such as animal (livestock) feed and bedding, horticulture or industrial uses (pulp and paper, insulating materials).

Determining the sustainable removal rate of straw is not an easy task. The exact amount that should be left on or incorporated in the field to maintain soil quality depends on the site and is subject to local variations, including[40]:

- Farming practices: crop rotation, tillage, fertilization
- Site conditions: soil type, soil fertility, SOM, SOC, soil moisture, topography, risk of erosion
- Climate conditions: wind, precipitation patterns

The magnitude of applying manure (containing a certain amount of straw) to the fields as an alternative to maintaining the SOM has also be taken into account when estimating sustainable removal rates.

Accounting for the site-specific factors mentioned above, sustainable straw removal rates in Europe range between 25% and 50%, the recommended default value being 33% (Powlson et al., 2011).This means that at least 50% of the total amount of straw emerging from wheat cultivation could potentially be utilized for bioenergy production. How much straw (and agricultural residues in general) are sustainably available in the EU is addressed in Chapter 9.

7.3 FSRL of Agricultural Waste and Residues

As agricultural residues are side products of commodity crops such as wheat, all required machinery for harvesting and collecting this type of feedstock is available. In addition, as other bioenergy applications such as electricity, biogas or heating utilize straw as a feedstock at industrial scale, its production shows the according maturity. Seeing as in some cases sufficient supply of straw for conversion into biofuels is compromised, we assign a FSRL of 8.

8 Forestry Waste and Residues

Like their agricultural counterpart, forestry waste and residues are divided into primary and secondary sources. Primary woody forestry residues include leftovers from cultivation and harvesting / logging activities such as twigs, branches, thinning materials and the like. Secondary residues result from all further industrial processing activities, for example sawdust, bark and black liquor (Table 18).

[40] Spöttle et al., 2013

Table 18: Woody biomass and residues from forestry and trees outside forests (Rettenmaier et al., 2010)

Biomass subcategory	Origin	Type of biomass
Woody biomass		
From forestry	Forests and other wooded land incl. tree plantations and short rotation forests (SRF)	Harvests from forests and other wooded land incl. tree plantations and SRF, excl. residues
From trees outside forests (landscape)	Trees outside forests incl. orchards and vineyards, public green spaces and private residential gardens	Harvests from trees outside forests incl. orchards and vineyards, excl. residues
Woody residues		
Primary residues	Cultivation and harvesting / logging activities in all of the above incl. landscape management	Cultivation and harvesting / logging residues (twigs, branches, thinning material), pruning from fruit trees and grapevines etc.
Secondary residues	Wood processing, e.g. industrial production	Wood processing by-products and residues (sawdust, bark, black liquor, etc.)

Due to the variety of different forestry residue sources, the focus of the following chapter will be placed on residues of managed forests, which are in Europe predominantly harvested for the pulp and paper industry. Other sources of woody residues include so-called arboricultural residues from park prunings, woody farm residues from olive grove or fruit tree cuttings as well as sawmill residues.

In managed forests, tree trunks and larger branches are used for timber, while cut-offs, smaller diameter branches and lower quality timber are chipped and used by the pulp and paper industries (Spöttle et al., 2013). Those industries utilize the main 'roundwood' and 'stemwood', while other parts of the tree such as bark, tops, smaller branches, leaves and needles, and stumps are typically not used by those industries.

The terms 'roundwood' and 'stemwood' are often used interchangeably although in technical terms, stemwood is defined as the vertical wood only (i.e. the trunk/stem), while 'roundwood' refers to both the vertical wood and can also include branches if they are large enough, meaning more than 7 cm in diameter (Spöttle et al., 2013). Another (broad) category of forest biomass is thinnings, which are often used for bioenergy and represent smaller or lower quality trees that are removed to allow for the remaining trees to grow more strongly. Harvest or logging residues, meaning stem tops, branches and foliage are formed during thinnings and final fellings. These residues consist of stem harvest losses (e.g. stem tops) as well as branches and foliage that are separated from harvested stemwood (Fritsche et al., 2014).

Figure 20 shows the harvestable sections of a tree, distinguishing between utilized production volume and residual volume. As outlined above, the lower part of the tree, i.e. the trunk or stem, is utilized for timber (logs), while the upper part is mainly used for the production of pulp and paper. The very upper part (leaves, fine branches) hereby accounts for the tree fraction that has no major industrial use and can therefore be used as residue feedstock for the conversion into biofuels and other bioenergy applications. Particularly due to the strong increase of residue-based wood pellet heating systems in private houses a strong competition for forestry residues is noticeable.

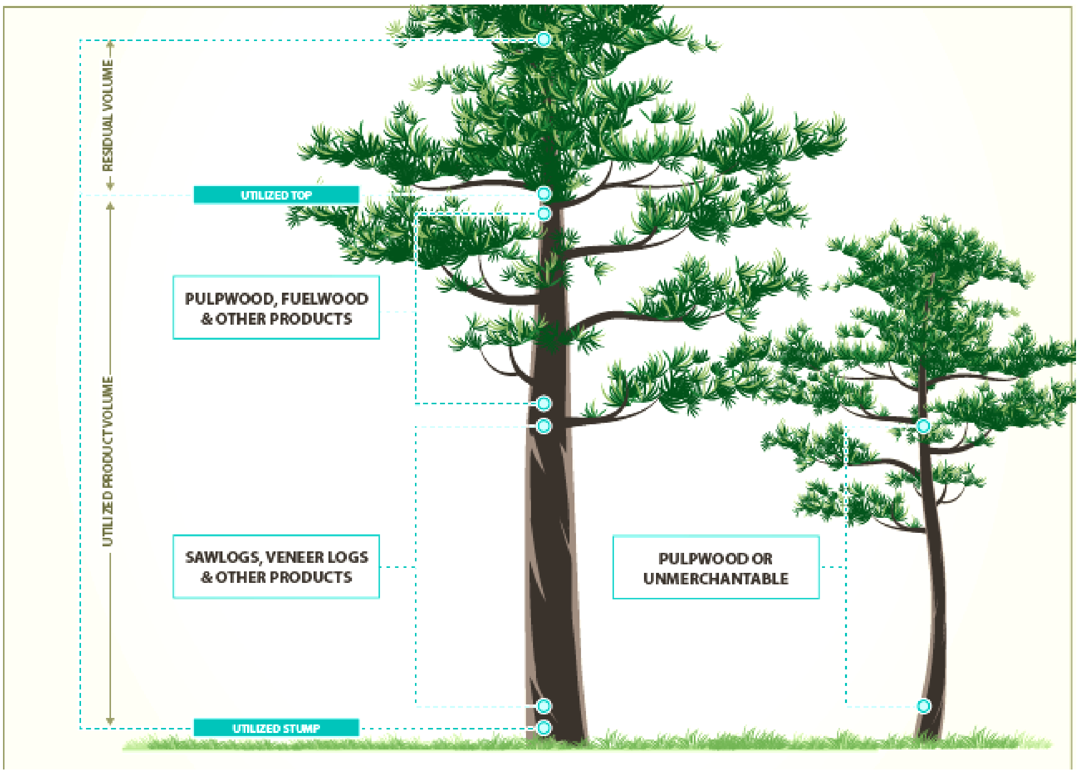

Figure 20: Harvestable sections of a tree (forest2market.com)

8.1 Harvest

Forest management is generally dependent on location, climate and tree species and therefore varies widely within the European Union. In general, there are three main logging methods, namely whole-tree, tree-length and cut-to-length logging. Each one of these methods has several advantages and disadvantages in terms of suitability for the surrounding terrain (e.g. steep slopes) and type of tree, investment and operating costs as well as labor intensity. Figure 21 graphically depicts these logging methods, from which residues emerge that are suitable for bioenergy production. It has to be noted that the partially mechanized short-wood system, a combination of whole-tree and cut-to-length-harvesting chain is predominantly applied in the US (Leinonen, 2004).

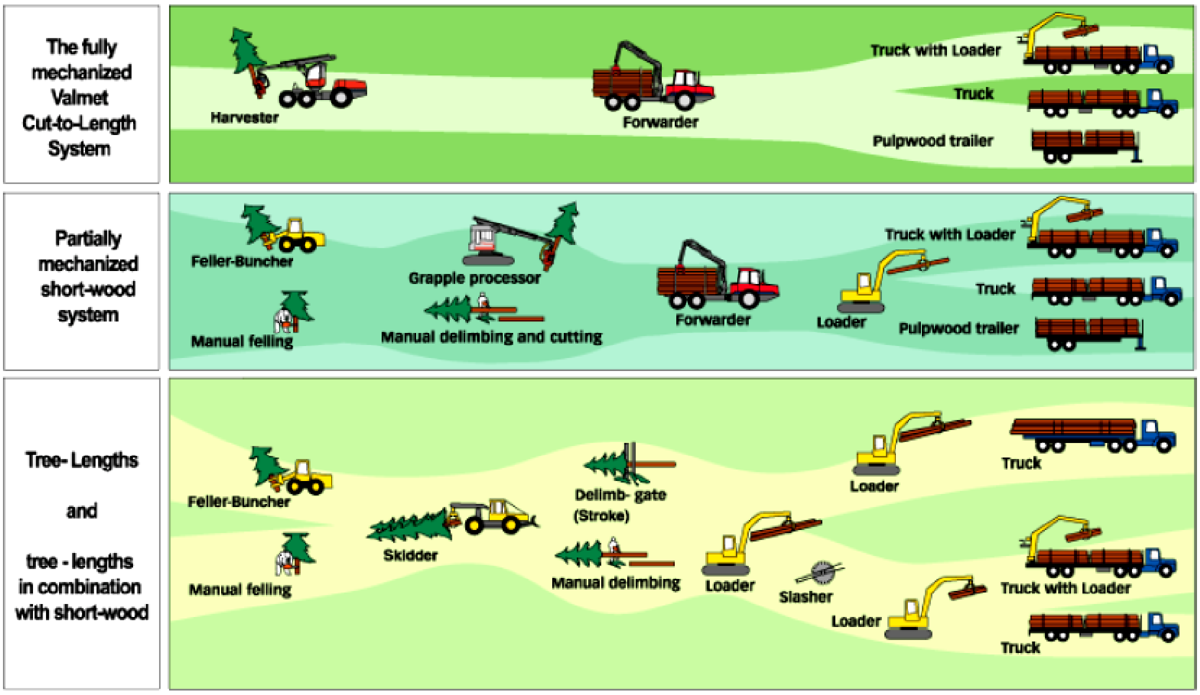

Figure 21: Wood harvesting chains (Partek, 2003)

In the whole-tree logging method the trees are felled at the stump and skidded beside the road for delimbing and / or processing and stocking. In the tree-length logging method trees are felled and delimbed at the stumps and transported to the landing or roadside. In both methods cross-cutting the stems takes place at the landing or at the mill. In the cut-to-length logging method the trees are felled, delimbed and cross-cut at the stump and the products are hauled roadside where they are stocked (Leinonen, 2004).

For the purpose of increasing biodiversity and sustaining the natural nutrient cycle, a certain share of the tree tops and branches should be left in the forest. ´This is actually the case in most Member States of the European Union as the additional costs of collecting tree tops and branches is not justified by demand. Increasingly though, tops and branches are utilized for bioenergy purposes (Spöttle et al., 2013).

8.2 Sustainability of Forestry Waste and Residues

8.2.1 Forest Carbon Stocks and naturally occurring GHG dynamics of forests

One of the main concerns with respect to the utilization of forest biomass as a feedstock is induced land use changes and the GHG emissions resulting from those. This is mainly due to the fact that forests serve as major (soil) carbon sinks, i.e. they are sequestering significant amounts of carbon. According to Matthews et al. (2014), the continued accumulation of carbon stocks in forests in the EU-27 results in sequestration equivalent to approximately between 5% and 10% of current GHG emissions in other sectors in the EU27. Although it is not further defined which sectors are meant, the percentages stated above give nevertheless an indication on the magnitude of the carbon forest soils are able to incorporate.

When assessing lifecycle balances of different forest and wood use options, it is essential to understand the impact that carbon stock changes in these ecosystems have on the overall lifecycle GHG balance. Figure 22 shows the complete biogenic carbon balance of forests, consisting of carbon pools of living biomass (above and below ground), dead organic matter (dead wood and litter) as well as SOC.

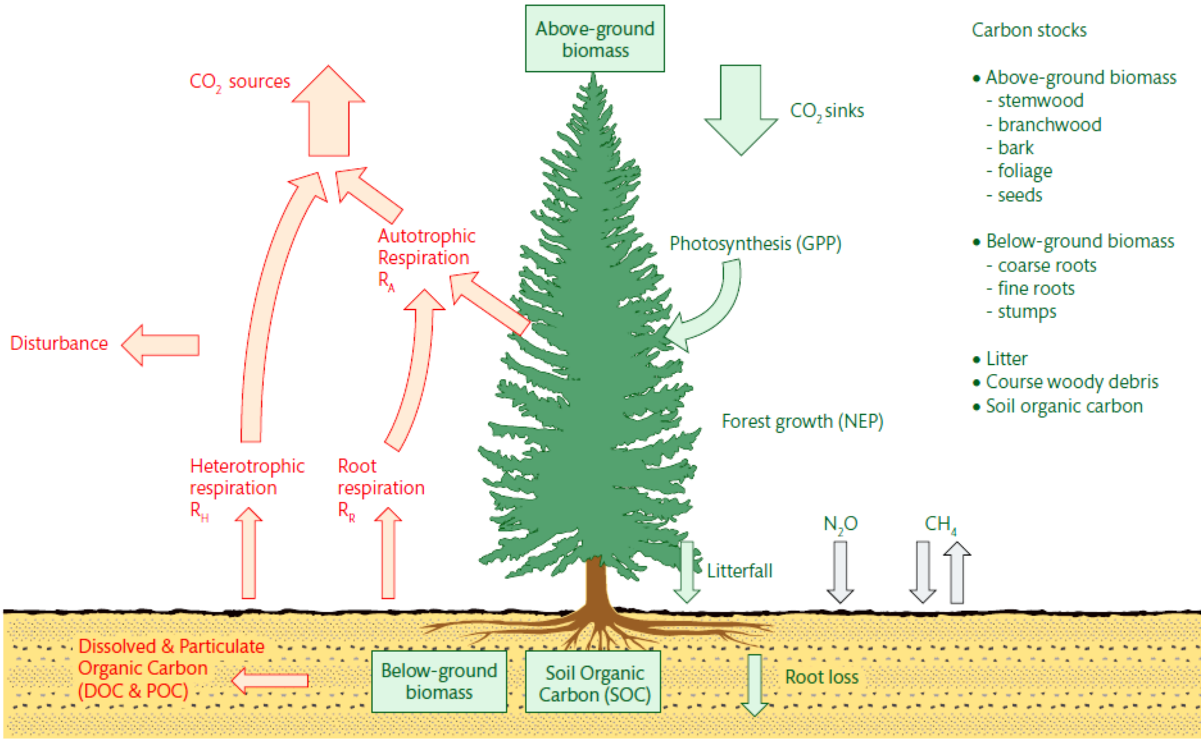

Figure 22: Carbon pools and naturally occurring GHG dynamics of forests (Morison et al., 2012)

Before discussing the GHG balance in terms of emissions resulting from making forest residues available, this section will take a brief look into forest carbon stocks and flows in the EU-27, which amount to approximately 10 Gigatonnes of Carbon (GtC), accounting for 3.5% of the global carbon stocks - according to the FAO (2010). On a global scale, the FAO estimates the forest carbon stock to be 300 GtC. It has to be noted here that the FAO did not include forest soils, deadwood and litter – all three accounting for considerable amounts of carbon. The estimates reported by the FAO are rather an intentionally simple and straightforward interpretation of growing stock estimates from National Forest Inventories (Matthews et al., 2014a).

Pan et al. (2011) on the other hand, do include deadwood and litter (i.e. residues) as well as forest soils in their estimates and state results of 861 GtC in 2010. This estimate is made up of contributions from live trees (363 GtC), deadwood (73 GtC), litter (43 GtC), and soil (383 GtC). Seven Member States hereby account for almost 70% of EU-27 tree carbon stocks. These are in a descending order of the respective carbon stock share: Germany, Sweden, France, Poland, Finland, Romania and Italy (Matthews et al., 2014). Although some countries may have similar forest areas in terms of size, differences in the magnitude of the respective carbon stocks may still be noticeable due to differences in forest characteristics such as species composition, age distribution and density of stands. These figures impressively illustrate the amounts of carbon being stored in forest soils on the one hand and in residue material on the other – and how altering the use of forests can potentially impact on the climate.

8.2.2 GHG Balance of Forestry Waste and Residues

After considering in general terms the different types of carbon stocks in forests, their magnitudes as well as the interplay between them, in line with the previous chapters on sustainability, the following chapter will depict the GHG balance of making forestry residues available and further processing it. Hence, focus is placed on the emission of climate-active gases of the different production steps. Other potential environmental impacts such as the risk of biodiversity loss will also be addressed.

When assessing the GHG balance of forestry residues it has to be noted that parameters such as location, soil type, rotation cycles and intensity in managed forests, type and maturity of the tree, carbon sequestration rate, emissions from harvest machinery and many more all influence the GHG balance of managed forests and therefore of forestry residues.

Morison et al. (2012) analyze in their research report net GHG emissions emerging from forestry residue production - from site preparation over seed plantation to harvest. They also address the impact of forestry residue harvesting, which shall be the subject of the following section.

The increasing demand for forestry residues has led to the development of harvesting techniques that mechanize the removal of woody residue components such as brash and stumps. There is, however, the risk that the increased intensity of forestry residue harvesting and stump removal leads to reduced second rotation forest growth as well as an increase in GHG emissions (Morison et al., 2012).

Since making forestry products (timber, residues etc.) available is highly mechanized, the emissions resulting from, inter alia, site preparation and harvesting operations have to be taken into account. The machinery is powered by fossil fuels (usually diesel), which results in the emission of CO_2 and other climate-active gases, that add on to any related disturbance of the soil, for example in ground preparation.

Following Defra (2010), Morison et al. (2012) use a conversion factor for diesel of 3.179 $kgCO_2eq.$ / l, which includes both direct emissions (emissions from burning the fuel / at the point of use) and indirect emissions (emissions prior to the use of the fuel, i.e. as a result of extracting and transforming the primary energy source, but not accounting for vehicle construction; so-called well-to-tank emission factors).

The (little) information that is available on GHG emissions from machinery preparing the site ranges from approximately 0.3 $tCO_2eq.$ / ha (peaty clay soils in Scotland) to 0.6 $tCO_2eq.$ / ha in Sweden. Table 19 gives an overview of the fuel emissions emerging from standard establishment procedures in the UK.

Table 19: Operational diesel fuel figures for standard establishment procedures (Morison et al., 2012)

Operation	Machinery	Fuel GHG emissions $tCO_2e\ ha^{-1}$	
		Direct	Total
Site preparation	Excavator	0.588	0.699
Site preparation	Scarifier	0.214	0.254
Agricultural conversion	Agricultural plough	0.065	0.078

These figures suggest that the GHG emissions from machinery preparing the site are quite small, even when accounting for a certain degree of uncertainty. The emissions resulting from the soil itself, however, ranging between 10 and 45 tCO_2eq. / ha are by far higher and therefore have a greater impact on the GHG balance of making forestry residues available. Particularly the removal of stumps has to be viewed very critically in this context due to the accompanying high level soil disturbance. It should, however, also be noted that site preparation is a single event for a 50-year or longer rotation length, whereas soil emissions are continual, even if temporarily increased by ground disturbance (Morison et al., 2012).

Once the site has been prepared and the trees reached the desired height / maturity, they can be harvested. In between site preparation and harvest, thinning takes place. As mentioned above, this fulfills the purpose removing lower quality tress so that the remaining trees can grow more strongly. Both for thinning operations and harvest including hauling, GHG emissions emerge. These are shown in Table 20.

Table 20: GHG emissions of UK operational fuel use for forest harvesting procedures. Estimates for thinning and harvesting are based on m^3 overbark (Morison et al., 2012)

Operation	Machinery	Average fuel emissions			Units
		Direct	Indirect	Total	
Thinning	Harvester	4.154	0.788	4.941	kg CO_2e m^{-3}
Harvesting	Harvester	3.206	0.608	3.814	kg CO_2e m^{-3}
	Forwarder	2.405	0.456	2.861	kg CO_2e m^{-3}

Lastly, the felled logs as well as smaller branches (residues) have to be transported from the plantation / harvesting site to be further processed at sawmills for example. As cited in Morison et al. (2012), Table 21 below depicts GHG emission values of hauling machinery transporting timber from the forest to a processing site, also taking into account the increased emissions that occur when the truck is operated on forest roads.

Table 21: GHG emission values for timber haulage from forest to processing (Morison et al., 2012)

	kg CO_2e per t-km
Direct emissions	
On forest roads	0.052
On public roads	0.039
Indirect emissions	
Vehicle manufacture	0.015
Vehicle maintenance	0.013

These values are based on the following assumptions: 40t gross vehicle weight, load 25.5, round trip, fully laden outward journey, empty on return.

Depending on the distance between forest and processing site, the values stated above are multiplied with the hauling distance while considering a certain percentage of forest roads, resulting in GHG emissions per t-km. Based on a survey conducted in the UK, Whittaker et al. (2010) assume an average round trip distance of 164km, 20% of which accounting for forest roads. In this scenario, a typical trip would emit **6.82** kg CO_2eq. / t direct emissions per transported ton, and **4.59 kg CO_2eq. / tkm^{-1}** of indirect GHG emission, amounting to **11.41 kg CO_2eq / tkm^{-1}** in total GHG emissions.

Concerning the GHG emission values stated above, it can be questioned if the UK is a prime example of a thriving forestry sector, meaning if the emission values previously outlined are also representative for other Member States that show a more distinct forestry sector. A recent study (2016) by the Bavarian TFZ[41] (Technology and Support Centre) states a lower GHG emission value of **5.75 kg CO_2eq. / tkm** for the vehicle category >20t. In addition, the study includes a calculation addressing GHG emissions of tractors (176 kW) being used for hauling the timber out of the forest, i.e. off-road operations. Here, the authors use kg CO_2eq. / **MJ** instead of kg CO_2eq. / **tkm,** thereby referring to the emissions of 1MJ of fuel and accounting for the short transportation distances within the forests. Here, the GHG emissions from off-road tractor operations amount to **8.25 kg CO_2eq. / MJ**.

The TFZ GHG emission value of 5.75 kg CO_2eq. / tkm includes the provision and the burning of the fuel, but does not consider vehicle manufacture or maintenance. On the other hand, the TFZ study allocates considerable GHG emissions to off-road operations.

The differences in the GHG balances estimated by the two studies introduced could stem from different assumptions in vehicle weight, round trip distance as well as different definitions of direct and indirect GHG emissions.

Although transportation accounts in most cases for the smallest share of GHG emissions in the feedstock production chain, it is nevertheless a part of the chain that has to be considered when assessing GHG balances of feedstock production. In case of forestry and the residues that can potentially be utilized for fuel production, respectively, it is crucial to avoid soil disturbances wherever possible due to the vast amounts of carbon stored in forest soils. Concerning the transportation of forestry products to processing sites, the GHG emission values stated above suggest that

[41] Technologie- und Förderzentrum im Kompetenzzentrum Nachwachsende Rohstoffe http://www.tfz.bayern.de/mam/cms08/biokraftstoffe/dateien/tfz_bericht_45_expressbio.pdf

transportation distances should be kept as short as possible with processing facilities organized in a decentralized fashion.

8.2.3 Biodiversity Impacts of Forestry Residue Production

Apart from supplying the soil with nutrients, logging residues additionally contribute to forest biodiversity by providing substrates and habitats for a wide range of forest species (Björkman/Börjesson, 2016). Compared with other substrates present in forests, it is not fully clear though how significantly logging residues are impacting on biodiversity. In case a large variety of species should be heavily dependent on logging residues, the increased recovery of these could obviously have detrimental effects on the local biodiversity. Even if only a few species are directly dependent on logging residues, recovery could impact populations because a lack of logging residues may reduce their chance of survival during the clearing phase, for example mosses and vertebrates (Björkman/Börjesson, 2016). There are, however, indications from Norway for example that recovering a fairly large amount of residues from the forest is possible without endangering biodiversity. On the other hand, negative impacts on biodiversity could occur as a consequence of recovering residues from uncommon broad-leaved trees and aspen, as piles of these are attractive habitats for wood-living species. When these piles are removed, the species inhabiting them will also be removed and therefore forest biodiversity declines. In general though, it has to be noted that the overall impact of recovering residues from forests is moderate.

8.3 FSRL of Forestry Waste and Residues

The timber, pulp and paper industry are well established in Europe. Accordingly, machinery to fell trees and transport them to processing sites (saw / paper mills) are available. The forestry industry is generally at an industrialized level, particularly in Northern European countries. We therefore assign a FSRL of 8 to this type of feedstock.

9 Sustainable Feedstock Availability in the European Union

The sustainable availability of biogenic feedstocks is one of the most important issues that needs to be assessed and appropriately addressed if the ambitious GHG emission reduction targets of the aviation sector are to be met, at least partially based on biogenic feedstock-derived fuels. The following chapter will therefore assess the different types of feedstock that have been introduced above in terms of their sustainable availability in Europe.

9.1 Availability of Agricultural and Forestry Waste and Residues

As discussed in Chapter 7 of this report, residue material from agriculture and forestry are becoming important feedstocks for fuel production. The main advantage of cellulosic or ‘advanced’ biofuels compared to so-called first generation biofuels based on oils and fats is that they provide a series of environmental benefits, a much higher GHG emission reduction and a small risk of inducing indirect land use changes being the most important ones. These sustainability advantages have also been taken into account by the European Commission, which included the ‘ILUC Directive’ into the RED and FQD, entailing a 7% cap on the contribution of biofuels (including energy crops) to the RED’s 10% target of renewable energy in road transport and a 0.5% subtarget for advanced biofuels, including those made from cellulosic waste and residues (Searle/Malins, 2016).

Chapter 7.1 on agricultural waste and residues already established that the amount of straw available for bioenergy production is dependent on a variety of different factors and conditions such as the type of crop, crop rotation, crop mix and agricultural practices as well as crop production, the according yield and cultivated area. The availability of agricultural residues depends in turn on the amount that can be removed from land to maintain soil fertility and on their competitive use for agricultural or industrial purposes (Scarlat et al., 2010).

Before discussing the availability of agricultural residues, we shall take a brief look at the magnitude of crop production in Europe in order to get a first impression on the theoretical residue potential of each Member State (Figure 23).

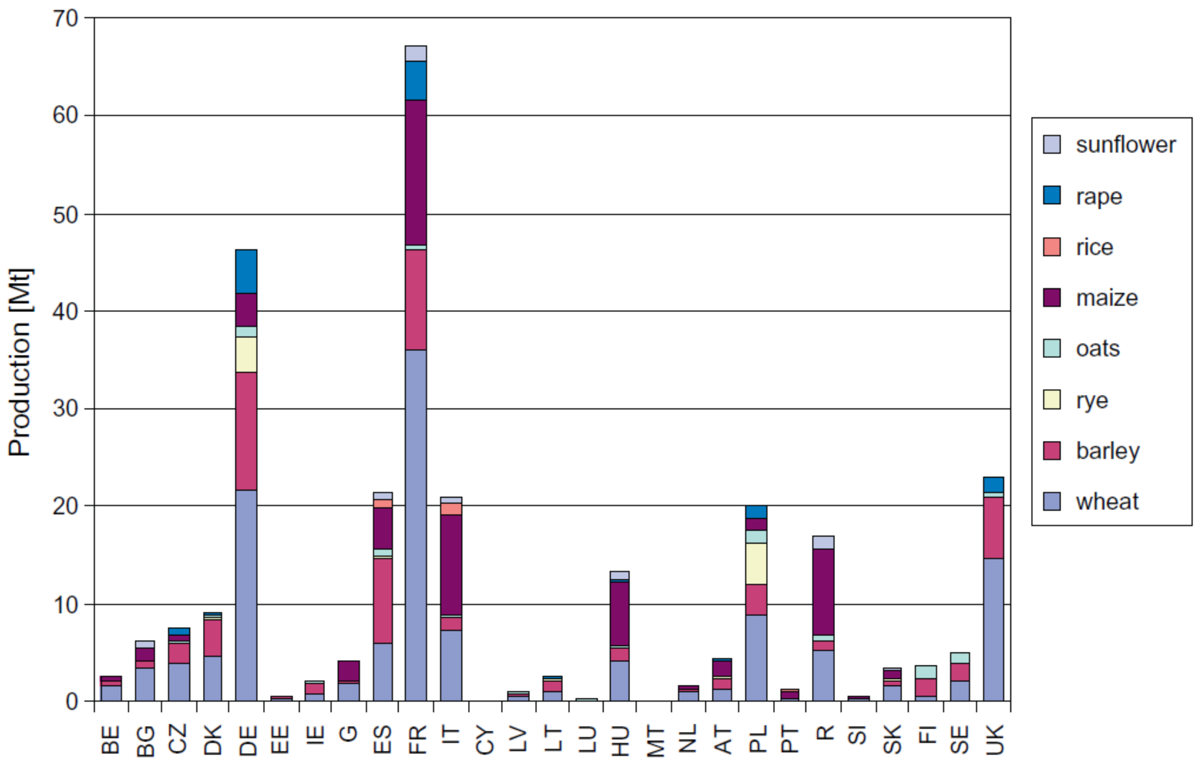

Figure 23: Crop Production in different Member States (Scarlat et al., 2010)

As can be seen in Figure 23, France and Germany show the highest crop production in the EU, followed by the UK, Spain, Italy and Poland. Broadly speaking, wheat is in most Member States the crop that is produced in the highest volumes, ranging between approximately 15 and 35 Mt of wheat annually. These figures already indicate that the countries with the highest population density produce the largest amounts of wheat and therefore presumably have the highest residue potential.

As shown in Figure 24, the total cereal production amounted to 334.2 Mt in 2014 (Eurostat, 2014[42]), almost half of which can be allocated to common wheat.

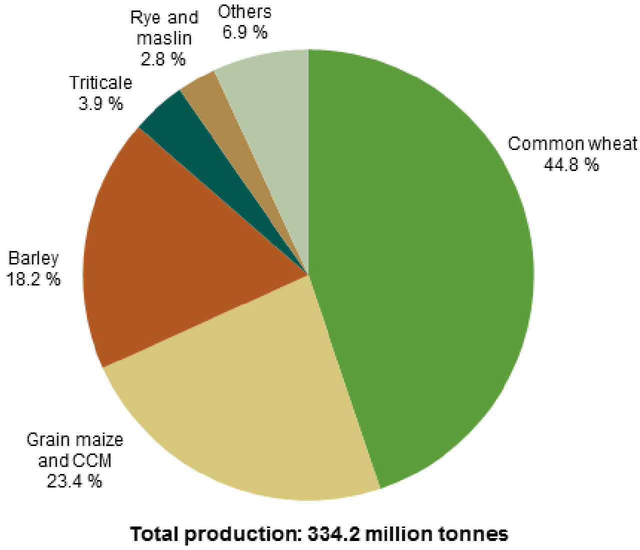

Figure 24: Production of cereals in the EU-28, 2014 (Eurostat)

[42] http://ec.europa.eu/eurostat/statistics-explained/index.php/Agricultural_production_-_crops

Figure 25 shows the development of cereal production volumes in the EU from 2007 to 2014 with a noticeable increase in production for all main types of cereals between 2012 and 2014.

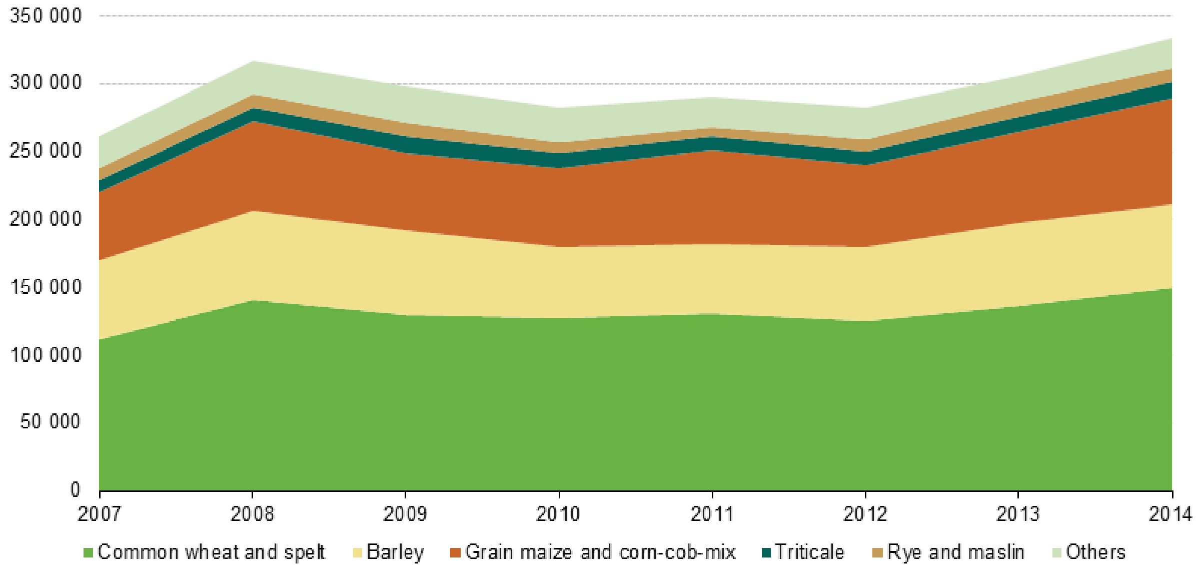

Figure 25: Production of cereal crops in the EU-28, 2007 - 2014 (1.000 tonnes) (Eurostat, 2014)

With these figures in mind, the subsequent section addresses the sustainable waste and residue availability in the EU, which is addressed by a variety of authors in the literature.
Most commonly, the residue potential is calculated by multiplying production of the main commodity crop by a residue ratio, which represents the amount of crop residue per unit commodity crop (e.g. straw:wheat) (Searle/Malins, 2016), also taking into account environmental, agronomic as well as harvesting constraints, i.e. straw removal rate. It should be noted, however, that the residue-to-crop ratio is influenced by parameters such as climatic and soil conditions and farming practices such as tillage, density of planting, fertilization etc. (Scarlat et al., 2010). As sustainability constraints of residue production have been discussed in Chapter 7, the subsequent sections will not go into detail in this regard. Instead, the potentials estimated by different sources will be compared, from which a conclusion will be drawn.

Based on the crop yield per Member State presented in Figure 23, Scarlat et al. (2010) calculated the share of crop residues produced in the EU-27, which is illustrated in Figure 26. The total annual amount of crop residue produced in the EU-27 was estimated at 258 Mt_{dm} / year on average, based on the residue yield and crop area (Scarlat et al., 2010).

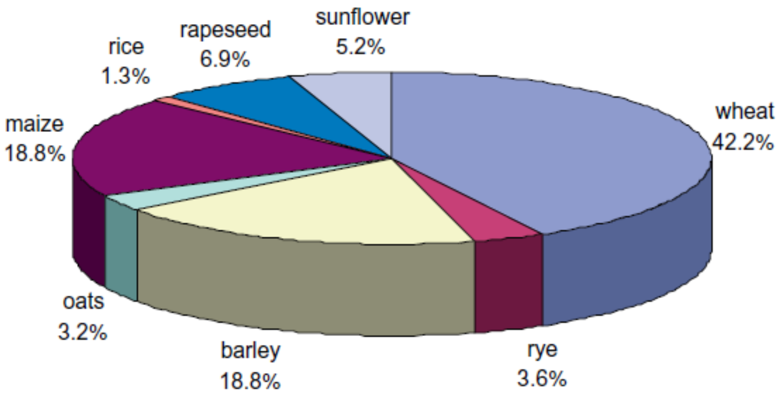

Figure 26: Share of crop residues produced in EU27 (Scarlat et al., 2010)

For the EU-28 Searle / Malins (2016) calculated the current agricultural residue production to be 315.9 Mt dry matter / year, which is in the same range as the production value estimated by Scarlat et al. (2010) and shown in Table 22. It has to be noted that Searle and Malins chose very conservative sustainability indicators both for agricultural and forestry residues, meaning that other authors such as Mantau et al (2010) estimate considerably higher availabilities, particularly for forestry residues.

Table 22: Current agricultural residue production, sustainable field retention, competing uses, and final sustainable availability for biofuel production (Searle/Malins, 2016)

Country	Agricultural residue production (total above ground biomass)	Recommend-ed retention for soil quality	Heat, power and biogas	Other uses	Sustainable availability
Austria	5.4	3.3	0.3	0.4	1.5
Belgium	3.4	1.5	0.2	0.6	1.1
Bulgaria	10.5	8.1	0.0	0.2	2.2
Croatia	3.5	2.2	0.0	0.1	1.2
Cyprus	0.1	0.1	0.0	0.0	0.0
Czech Republic	8.7	6.2	0.2	0.2	2.2
Denmark	8.4	4.9	2.2	2.4	0.0
Estonia	1.1	0.8	0.3	0.0	0.0
Finland	3.6	2.3	0.0	0.2	1.2
France	69.8	44.5	0.4	3.6	21.4
Germany	47.6	23.7	0.0	2.6	21.3
Greece	4.8	3.1	0.3	0.5	0.9
Hungary	15.0	9.6	0.4	0.3	4.7
Ireland	1.7	0.8	0.0	1.1	0.0
Italy	19.4	11.9	0.2	1.7	5.6
Latvia	2.0	1.5	0.0	0.1	0.4
Lithuania	4.4	3.3	0.0	0.2	0.9
Luxembourg	0.2	0.1	0.0	0.1	0.0
Malta	0.0	0.0	0.0	0.0	0.0
Netherlands	2.6	1.0	0.3	1.7	0.0
Poland	28.1	18.5	2.7	2.0	4.9
Portugal	1.2	0.7	0.4	0.3	0.0
Romania	21.7	15.4	0.0	1.2	5.1
Slovakia	4.1	2.9	0.0	0.1	1.0
Slovenia	0.5	0.3	0.0	0.1	0.1
Spain	23.1	16.7	1.0	2.4	3.0
Sweden	4.9	2.7	1.3	0.3	0.7
United Kingdom	20.3	10.3	1.3	6.0	2.8
EU total	315.9	196.1	9.8	26.4	84.6

Figure 27 shows the availability of the main waste and residue groups in the EU Member States. As suspected, countries with a distinguished agricultural sector have the highest straw availability. The same applies for the forestry sector. Figure 28 shows the current and projected total availability of waste and residues in Europe.

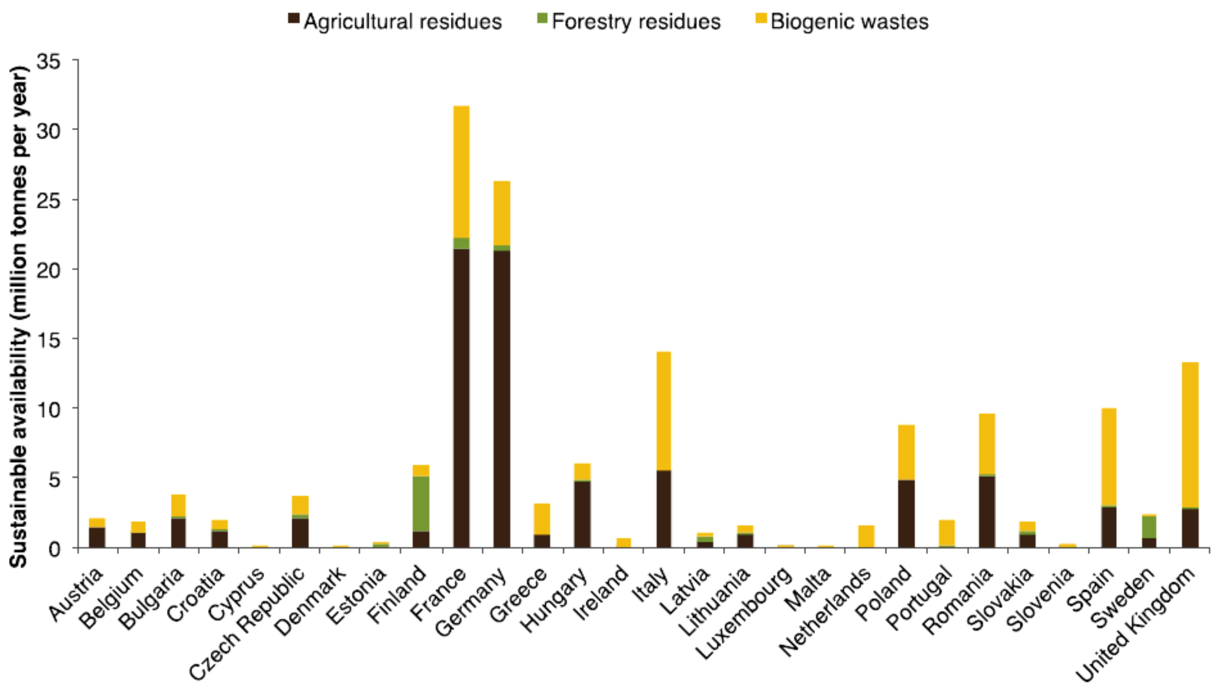

Figure 27: Sustainable availability of waste and residues by category (million tons per year) (Searle/Malins, 2016)

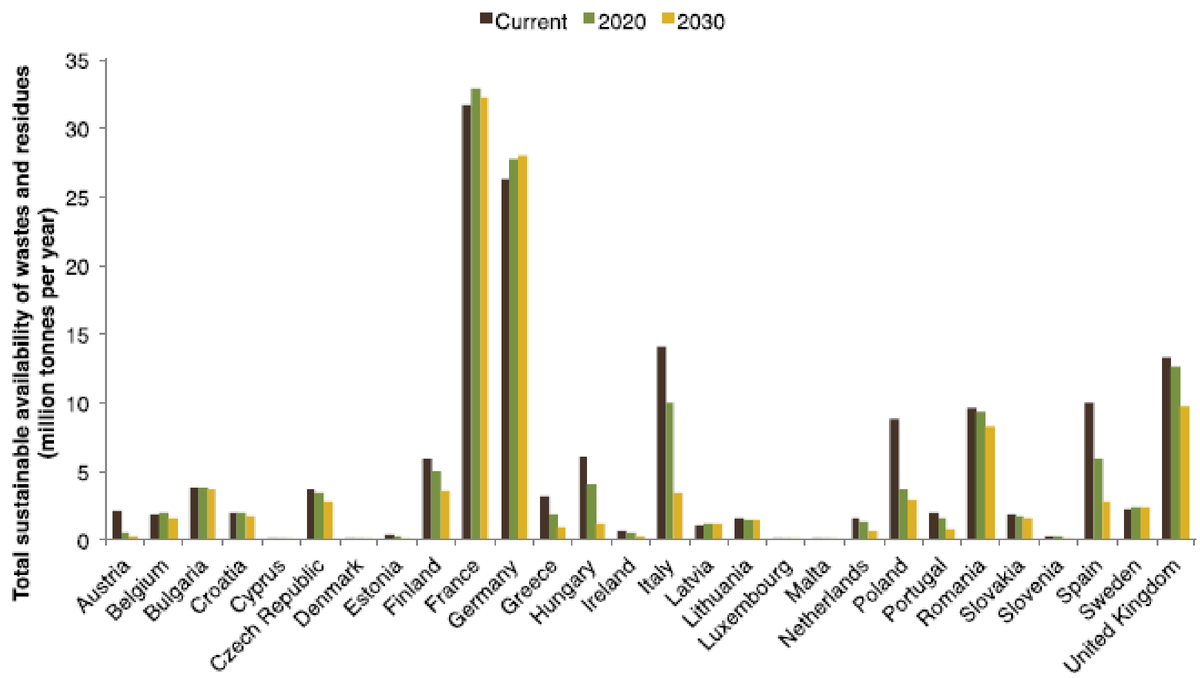

Figure 28: Current total sustainable availability of waste and residues and projected availability in 2020 and 2030 (Mt/y) (Searle/Malins, 2016)

9.2 Availability of Microalgae

As outlined in Chapter 1 of this report, microalgae are believed to have a tremendous production potential due to their high growth rate and high yield per aerial unit. Even more than for terrestrial feedstocks, estimations on the production potential of microalgae vary significantly. 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 29 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 identified and not included in calculating the geographic potential, which amounts according to Skarka to 49 Mt/y for the EU-27.

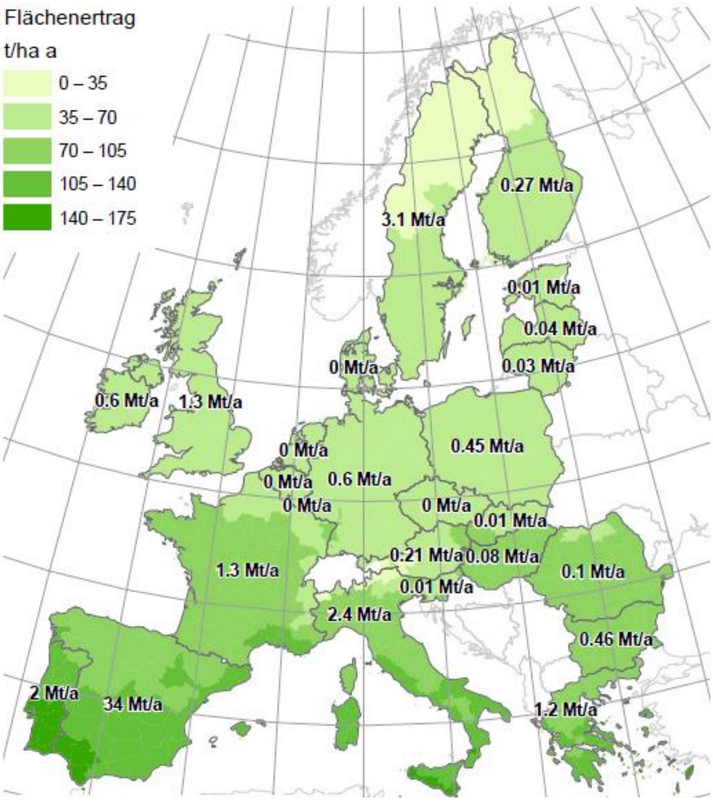

Figure 29: Geographical microalgae production potential in Europe (Skarka, 2015)

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 look at the current actual microalgae production worldwide of 9.200 t/y (cf. Figure 5) 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.

9.3 Availability of Camelina

As camelina is a relatively new crop for the production of bio-jet and most plantations are at field trial level, reliable data concerning the availability of the crop are difficult to attain. In context of the ITAKA project for example, most of the R&D activities in the cultivation stage are concerned with improving the productivity of different varieties of camelina. According to Yuri Herreras Yambanis, founder of the Camelina Company Spain, results from large plantations in Spain (4000 ha) will be available in September 2016. Based on preliminary results of the ITAKA project as well as values stated in the literature, the seed yield ranges between 500 and 2000 kg/ha. In order to estimate the total amount of camelina that could be produced sustainably in Europe, detailed information concerning (marginal) land available for cultivating camelina is required. Apart from the fact several definitions exist for the term 'marginal land', the future production potential will also depend on questions such as:

- How much of the total available marginal land can actually be used for camelina production?
- Is it possible to create a business case with camelina?
- If arable land is used for cultivation, are sustainability advantages partially compromised?
- Instead of the current wide range in seed yield, is a steady high yield achievable?

These are of course only very few of the questions that need to be answered. However, if the development and commercialization of camelina continues at the current pace, this feedstock will most likely play a vital role in making aviation less GHG intensive.

9.4 Availability of UCO

As outlined in Chapter 3, the availability of UCO is compared to other types feedstock very limited, as its collection is quite challenging. The share of used vegetable oils from restaurants and the like that has the required quality is additionally comparably low. Furthermore, as the collection of UCO is conducted by a variety of different players, obtaining reliable statistics stating market actors engaged in UCO collection is very difficult to obtain.

Based on pertinent literature in the field and expert interviews, Spöttle et al. (2013) estimated that approximately 1 Mt of UCO is available from the gastronomy sector in the European Union (Table 23).

Table 23: Maximum estimated UCO potential from gastronomy (Spöttle et al., 2013)

Region	Trad. restaurants, catering & mobile food services	Fast-Food Restaurants	UCO potential trad. restaurants, catering & mobile food services	UCO potential fast-food restaurants	Total UCO potential gastronomy
UCO ratio t/unit/a			0.96	4.11	
Germany	129,448	2,224	124,270	9,141	133,411
Spain	80,314	976	UCO collected from gastronomy:		145,846
UCO ratio t/a			0.96	4.11	
EU-25 (excl. Germany & Spain)	689,579	7,461	661,996	30,665	692,661
TOTAL	899,341	10,661			**971,917**

Due to the fact that the gastronomy sector is well covered by UCO collectors, the values stated in Table 23 can be regarded as the maximum amount of UCO that is available in Europe. Theoretically, UCO from households could contribute to the overall potential, increasing it to approximately 3 Mt in the EU-27. However, seeing as the logistics (and probably the economics, too) of making the UCO household potential available are quite challenging, it will not be a viable option for the foreseeable future.

9.5 Availability of Rapeseed

As stated in Chapter 4.2, the total production of rapeseed in Europe amounts to 22Mt in 2015, and is projected to slightly increase to 22.4 Mt in 2017, despite the uncertainty if rapeseed-based biodiesel will be able to contribute to the GHG emission reduction target of 50% stated in the RED. The projected production increase is mainly attributable to production surpluses in new rapeseed-producing countries such Romania.

9.6 Availability of SRC

As mentioned in Chapter 6.3, SRC is most commonly cultivated in France and Italy, poplar plantation sizes ranging between 236.000ha in France and 119.000ha in Italy, respectively. SRC plantations in Northern and Central Europe are comparably small covering approximately 15.000ha in Sweden (willow), and 5000-6000ha in Germany (poplar). In Romania, approximately 24.000ha[43] of the land area is commercially cultivated with willow. The application of SRC in these countries ranges from agroforestry systems for bioenergy purposes over wood production to environmental purposes such as river bank stabilization.

Apart from competing uses, the overall availability of SRC for the production of biofuels (bio-jet) also depends on framework conditions such as climatic regime, water availability, soil type and the like. In Germany for example, based on site conditions for SRC approximately one-fifth of the cropland (17.7%) and half of the permanent grassland area (53.6%) is categorized as 'suitable' to 'very suitable' by Aust et al. (2013), indicating the potentially realizable increase in SRC production. Altering permanent grassland, however, would be connected to a considerable release of soil carbon detrimentally impacting the sustainability of such a cultivation system, which is addressed by EC 1782/2003.

Aust et al. (2013) estimate the production potential of SRC in Germany between 3.55 Mt_{dm} per year under unsuitable conditions and 17.33 Mio t_{dm} / y under very favorable conditions. Table 24 shows the SRC classes, their relative area of the total available crop- or grassland as well as the according total area SRCs could be cultivated on – not taking into account ecological restrictions, i.e. the conversion of grassland and corresponding GHG emissions, and restrictions of technical, ethical or climatic nature.

Table 24: Percentage and area of SRC-site classes on crop- and grassland in Germany (Aust et al., 2013)

	Cropland			Grassland		
SRC- class	Rel. area (%)	Area (ha*10^6)	Est. biomass (Mio t_{dm} yr^{-1})	Rel. area (%)	Area (ha*10^6)	Est. biomass (Mio t_{dm} yr^{-1})
Unsuitable	11.4	1.36	3.55	9.7	0.45	1.19
Unfavourable	34.9	4.16	19.41	12.9	0.60	2.79
Medium	36.1	4.31	32.50	23.8	1.12	8.41
Favourable	8.9	1.06	12.08	35.6	1.66	18.92
Very favourable	8.8	1.06	17.33	18.0	0.84	13.73

[43] http://www.fao.org/docrep/008/a0026e/a0026e02.htm

If these restrictions are taken into account, the land area that is potentiallly available for SRC production dramatically decreases as shown in Table 25. The potential areas for SRC production are reduced to to 5.7% of Germany's cropland.

Table 25: Suitability of crop- and grassland in Germany for SRC production, restrictions considered (Aust et al., 2013)

	Cropland			Grassland		
SRC- class	Rel. area (%)	Area ($ha^{\dagger}10^3$)	Est. biomass (Mio t_{dm} yr^{-1})	Rel. area (%)	Area ($ha*10^3$)	Est. biomass (Mio t_{dm} yr^{-1})
Very suitable	5.7	676	9.5	33.0	1,534	21.3
Limited suitable	68.8	8,193	58.8	45.9	2,133	17.7
Not suitable	25.5	3,041	16.1	21.1	978	7.0

Although Germany is by far not the most important producer of SRC in terms of cultivation areas, the values stated above give nevertheless an indication on the potential availability of SRC as a bio-jet feedstock in Europe. As outlined in Chapter 6.1, biomass yields of SRC range between 4 and 16 t/ha, 10 t/ha being an often stated profitability benchmark. If multiplied by the total aerial size of poplar plantations in France and Italy, the theoretical annual production potentials amount to 2.4 and 1.2 Mt per year, respectively.

In order to put the values calculated by Aust et al. (2013) in perspective, the simple (and approximate) calculation of multiplying SRC plantation size with an average biomass yield of 10 t/ha is applied to Germany, the current production potential equals 60.000t per year. However, the values stated above also imply that there is a considerable production potential of SRC. If this potential can be unlocked for the production of alternative aviation fuels depends, as with all other biogenic feedstock, on the costs of production, energy requirements etc.

A disadvantage of SRC (and woody biomass in general) is its low energy content and the corresponding difficult conversion. An intermediate solution could be shifting to small-scale applications, i.e. small-scale conversion plants with a small feedstock collection radius that take away large part of the logistical challenges as well as challenges in building a network of supply chains.

10 Sustainability Certification Schemes

In the European Union, all biofuels that are brought into the market, receiving governmental support and / or are counting towards renewable energy targets, have to comply with the sustainability requirements of the EU's Renewable Energy Directive (RED). To demonstrate the sustainability of a biofuel including the processing chain, all biofuels have to be checked by the Member States or must comply with legally accepted 'voluntary' certification schemes that are recognized by the European Commission.

With Directive 2015/1513 the European Commission amended RED and FQD so that alternative aviation fuels may now contribute to the GHG emission reduction targets stated in the two directives. It is, however, up to the Member States to specifically include aviation in their respective national GHG emission reduction targets. So far, only the Netherlands have taken this step and included aviation in their national GHG reduction targets. The feedstock being utilized for the production of bio-kerosene on the other hand has to comply with the various voluntary schemes currently in place.

The end-product bio-jet can be produced via various conversion technologies based on a broad range of feedstock sources (cf. Figure 1). As discussed previously, five conversion technologies are ASTM certified to this date, meaning that the produced fuel complies with the chemical properties of its fossil counterpart, can be blended in varying concentrations in conventional limited kerosene and has proven its safety in ASTM tests under operating conditions. The sustainability of biofuels as well as of the feedstocks utilized for their production on the other hand is (as mentioned above) certified by various schemes out of the ASTM frame.

This chapter will first introduce two of the sustainability certification schemes recognized by the RED, namely the RSB EU RED and the ISCC EU. While the RSB EU RED has received considerable interest by the aviation sector with several airlines being RSB members, the ISCC is the leading certification system in Europe with the most issued certificates.

Subsequent to the brief introduction, a comparison between the two systems including an evaluation of their respective strengths and weaknesses will conclude the chapter.

10.1 Roundtable on Sustainable Biomaterials – RSB

The Roundtable on Sustainable Biomaterials (RSB) is an independent and global multi-stakeholder coalition working to promote the sustainability of biomaterials. Its certification system is based on sustainability standards encompassing environmental, social and economic principles and criteria[44]. The RSB is made up of over 120 organizations from 30 countries and is organized in seven chambers, covering all stakeholder groups crucial for sustainable biomaterials and their certification, respectively. The RSB developed a certification system based on standards involving third party certification bodies, which are overseen by an independent accreditation body, namely Accreditation Services International (ASI).

The RSB established a set of standards that describe requirements related to the institution's certification. While one of the central missions of the RSB is to provide and promote a global set of standards that applies to any type of feedstock worldwide, the RSB also adapted these standards for compliance with the RED, which defines the land-use and GHG criteria for biofuels entering the EU market. The RSB EU RED standards received the European Commission's recognition on July 19, 2011. As this sustainability certification scheme has received considerable interest from the aviation industry, it is introduced first in this report.

10.1.1 Consolidated RSB EU RED – Principles and Criteria for Sustainable Biofuel Production

The RSB EU RED establishes twelve principles and the according criteria for the sustainable production of biomass and biomaterials accounting for environmental, social and economic dimensions of feedstock production and processing. In addition, it provides guidelines on best practices in the production and processing of biofuel feedstock and raw material as well as for the production, use and transport of liquid biomass and biomaterials. The standard described in the RSB EU RED specifies requirements for the certification of sustainable biofuel operations along the entire supply chain and identifies four types of operators subject to different sustainability requirements, namely 'Feedstock Producers', 'Feedstock Processors', 'Biofuel Producers' and 'Biofuel Blenders' (RSB, 2011). In addition, the RSB EU RED states both minimum and progress requirements the aforementioned operators have to comply with. Figure 30 below graphically depicts said principles and according criteria.

[44] www.rsb.org

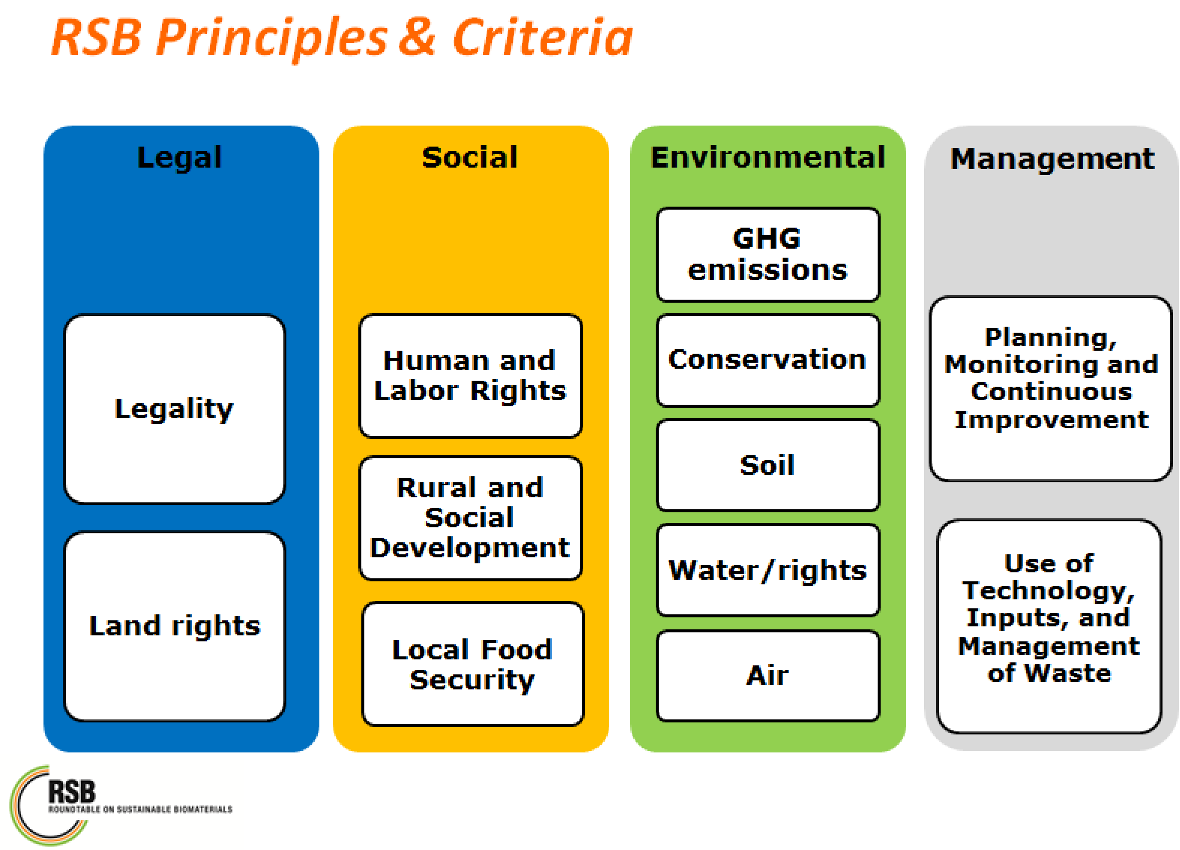

Figure 30: RSB Principles & Criteria (Rolf Hogan, Sustainable Aviation Fuels Forum, Madrid 2014)

Although (positive) socio-economic impacts of feedstock production are essential for increasing the use of bio- and alternative aviation fuels, and must therefore not be neglected when assessing renewable alternatives to conventional fuels, this chapter will focus on the aspects of the two certification schemes that are primarily concerned with the environmental sustainability of feedstock production and further processing.

One of the most important sustainability requirements of biofuels in general is their GHG emission reduction potential compared to fossil fuels. Accordingly, this is a crucial metric in the CORE-JetFuel assessment framework for evaluating the bio-jet production pathways shown in Figure 1.

In the RSB EU RED GHG emissions are addressed by **Principle 3**, which states that biomass and biomaterials shall contribute to climate change mitigation by significantly reducing lifecycle GHG emissions as compared to fossil fuels (RSB, 2011). Principle 3 additionally entails three sub-principles:

- **Principle 3a** states that when a biofuel is produced in a certain “geographical area”, for instance an EU Member State, it has to comply with the respective legislative policies or regulations in force that require certain GHG reductions of said biofuel over its lifecycle. This sub-principle applies to all operators that are subject to the scheme’s sustainability requirements.

- **Principle 3b** states that the lifecycle GHG emissions of a biofuel shall be calculated by using the according RSB methodology, which incorporates methodological elements and input data from authoritative sources, periodically updated and has system boundaries from well to wheel (RSB, 2011). In addition, this sub-principle includes GHG emissions from land-use change and incentivizes the use of co-products, residues and waste in such a way that the lifecycle GHG emissions of the biofuel are reduced (RSB, 2011). This sub-principle also applies to all operators that are subject to RSB's sustainability requirements.

- **Principle 3c** particularly addresses biofuel blends. These shall have on average 50% lower lifecycle GHG emissions relative to the fossil baseline. In addition, each biofuel in the blend shall have lower GHG emissions than the fossil fuel baseline (RSB, 2011).

Another principle included in the RSB EU RED that is vital for the environmental sustainability of alternative aviation fuels and therefore included in the CORE-JetFuel assessment framework, is the impact of feedstock / biofuel production on biodiversity in qualitative term (yes / no option). The RSB EU RED includes biodiversity under the umbrella of "Conservation", Principle 7, which is summarized in tabular form below.

Table 26: RSB EU RED - Principle 7 (RSB, 2011)

Principle No.	Description	Compliance required from:
7	Biofuel operations shall avoid negative impacts on biodiversity, ecosystems, and conservation values	Feedstock Producer, Feedstock Processor, Biofuel Producer
7.a	Conservation values of local, regional or global importance within the potential or existing area of operation shall be maintained or enhanced	Feedstock Producer, Feedstock Processor, Biofuel Producer
7.b	Ecosystem functions and services that are directly affected by biofuel operations shall be maintained or enhanced	Feedstock Producer, Feedstock Processor, Biofuel Producer
7.c	Biofuel operations shall protect, restore or create buffer zones	Feedstock Producer, Feedstock Processor, Biofuel Producer
7.d	Ecological corridors shall be protected, restored or created to minimize fragmentation of habitats	Feedstock Producer, Feedstock Processor, Biofuel Producer
7.e	Biofuel operations shall prevent invasive species from invading areas outside the operation site	Feedstock Producer, Feedstock Processor

10.2 International Sustainability & Carbon Certification - ISCC

Comparable to the RSB, the ISCC is a multi-stakeholder certification system for sustainability and GHG emissions that brings together experts from different biomass supply chains, namely feedstock growers, processors, traders and end-users – with research experts and representatives from environmental and social organizations. It was initially developed by the consultancy company Meo Carbon Solutions and supported by the German Federal Ministry of Food and Agriculture (BMEL) through the Agency for Renewable Resources (FNR).
ISCC certification can be applied to meet legal requirements in the bioenergy markets as well as to demonstrate the sustainability and traceability of feedstock in the food, feed and chemical industries.[45] Simultaneously to the RSB, the European Commission recognized ISCC as one of the first certification schemes to demonstrate compliance with the EU RED requirements in July 2011.

[45] http://www.iscc-system.org/en/iscc-system/about-iscc/

10.2.1 ISCC EU

As opposed to the RSB EU RED, the ISCC EU is only comprised of six principles but with considerably more sub-criteria to be fulfilled. The criteria are categorized according to their relevance in “major musts” and “minor musts”. Hereby, all “major musts” and at least 60% of the “minor musts” must be fulfilled for a successful audit (ISCC, 2015). The standard does not only aim at the prevention of ecological shortcomings but also at the safekeeping of adequate working conditions and the protection of employees’ health on farms (ISCC, 2015), thereby explicitly including social aspects in the certification process.

The following table shows all of the six principles as well as a selection of their respective sub-criteria. The sub-criteria in Table 27 are included or neglected according to their importance for the environmental sustainability assessment criteria used in CORE-JetFuel, and more precisely in this report.

Table 27: ISCC Principles and sub-criteria (ISCC, 2015)

Principle No.	Description	Major	Minor
1	**Biomass shall not be produced on land with high biodiversity value or high carbon stock. HCV areas shall be protected.**		
1.1	Biomass is not to be produced on land with high biodiversity value	X	
1.2	Biomass is not to be produced on highly diverse grassland	X	
1.3	Biomass is not to be produced on land with high carbon stock	X	
1.4	Biomass is not to be produced on land that was peatland in January 2008 or thereafter	X	
1.5	If land was converted after January 1 2008, the conversion and use should not run contrary to principle 1	X	
2	**Biomass shall be produced in an environmentally responsible way. This includes the protection of soil, water and air and the application of Good Agricultural Practices**		
2.1	Environmental impact assessment and conservation		
2.1.1	Environmental impact assessment for certain actions	X	
2.2	Natural water courses		
2.2.1	Natural vegetation areas around springs and natural watercourses are maintained or re-established		X
2.3	Soil Conversation and avoidance of soil degradation		X
2.5	Ground Water and Irrigation	X	
2.6	Use of Fertilizer		
2.6.1	While applying fertilizers with a considerable nitrogen content care is taken not to contaminate the surface and ground water	X	
2.6.2	Fertilizers with a considerable nitrogen content are only applied onto absorptive soils	X	
3	**Safe working conditions through training and education, use of protective clothing and proper and timely in the event of accidents**		
4	**Biomass production shall not violate human rights, labor rights or land rights. It shall promote responsible labor conditions and workers’ health, safety and welfare and shall be based on responsible community relations**		

5	**Biomass production shall take place in compliance with all applicable regional and national laws and shall follow relevant international treaties**		
6	**Good management practices shall implemented**		

Table 28 below directly compares the two certification schemes outlined above according to their main aspects as well as the information therein. In addition, a selection of the main strengths and weaknesses is included in the table. Furthermore, Table 27 depicts key aspects of both schemes and compares these to each other. The coloration indicates the degree of their mutual recognition as well as the level of comprehensiveness of the respective sustainability criteria. Green hereby accounts for full recognition / comprehensiveness, yellow for partial recognition and red for no recognition at all and the complete lack of a certain sustainability criteria, respectively.

Table 28: Comparison of RSB EU RED / ISCC EU (Alberici et al., 2014 / Schlamann et al., 2013)

	RSB EU RED	ISCC EU
Aspect	***Information***	
Basic information on the scheme		
Feedstock Coverage	Multiple agricultural feedstocks	Multiple agricultural feedstocks
Supply Chain Coverage	Full supply chain (feedstock production to biofuel production)	Full supply chain (feedstock production to biofuel production)
Number of companies using the scheme or certified area	25[46] certificates have been issued by RSB EU RED and global version in total, 17 are currently valid (July, 2016)	4,797 have been issued, of which 2,363 are still valid (2014). This includes both ISCC EU and ISCC DE
Recognition of other voluntary schemes	• RSB EU RED accepts any EC recognized scheme for agricultural feedstock, but then only an EU RED compliant claim can be made • RSB accepts Sustainable Agricultural Network and FSC	• ISCC accepts all EC recognized voluntary schemes • BUT: information tracked through the supply according to ISCC
Sustainability Criteria		
Environmental	• RED land criteria: Preservation of high biodiversity land, high carbon stock land (Note: feedstock production on natural or non-natural grassland is not subject to EC decision on highly diverse grasslands) • Soil, water and air protection • Waste Management	• RED land criteria: preservation of high biodiversity land, high carbon stock land, peatlands (Note: any conversion of grassland is currently prohibited within the ISCC system subject to EC decision on highly diverse grasslands) • Soil, water and air protection (not audited in EU if Member State has implemented cross-compliance), 60% “Minor Must” criteria must be met

[46] http://rsb.org/certification/participating-operators/

		• Good agricultural and environmental condition (GAEC) standards – in relation to cross-compliance in Europe (not subject to audit by ISCC auditors)
GHG criteria and calculation methodologies		
GHG savings	• 35% for all biofuels (increasing in line with the RED)	35% for all biofuels (increasing in line with the RED)
What options are available for calculating GHG emissions?	• RED default values • Actual values (RED methodology)	• RED default values • Actual values (RED methodology)
Units	• gCO_2eq/MJ fuel	• gCO_2eq/MJ fuel (final producer only) • gCO_2eq/kg product pre-allocation (supply chain) • gCO_2eq/kg product post-allocation (supply chain – only if RED default allocation factors used in conversion)
Burden of complying with the scheme		
Relative cost of achieving compliance with scheme compared to other schemes	**High** – RSB is the most comprehensive voluntary system and asks economic operators to not only demonstrate compliance with sustainability criteria, but also demands promotion of rural development and ensuring food security	**Medium** – ISCC also demands compliance with environmental criteria beyond RED and social criteria. Furthermore, economic operators have to provide comprehensive set of data for each consignment
Strengths and Weaknesses		
Environmental and Social Criteria	**Strengths** • Advanced targets are defined for the minimum threshold for reducing GHG. The standard has its own target for reducing GHG emissions that go beyond the legal minimum (35% RED). RSB is one of the two	**Strengths** • The standard includes comprehensive requirements on riparian buffer zones. The standard specifies that the size of riparian vegetation areas has to be defined and a time-bound plan for restoring riparian areas

	standards which contain these advanced targets • A social and environmental management system is required. The standard requires that management system incorporate a social and environmental impact assessment. • Detailed procedures are required with regard to biodiversity and conversation, water, and soil. Biodiversity assessments and protection of ecological corridors and endangered species are mandatory. • The requirement pertaining to soil management is comprehensively covered. This applies, e.g., to the topics of soil structure and fertility. The standard does not completely fulfil the CAT criterion, as it does not contain a detailed requirement on topography. • Social groups surrounding communities are covered by comprehensive requirements, e.g. concerning social context and welfare, land availability and rights, grievance procedures for local communities, cultural heritage, and food safety. **Weaknesses** • Weak spots w.r.t. to the criteria handling non-GMO materials. While the standard requires following relevant national or international guidelines on the use of GMOs, there is not a separate supply chain (chain of custody) for non-GMO materials. • Lack of details as regards the criteria about identifying and restoring riparian vegetation • The most hazardous chemicals are not explicitly	where vegetation has been removed must be implemented • Requirements on water management are comprehensively covered • The standard has precise requirements for soil management, which specifies that a soil management plan must be in place • Detailed requirements regarding social and labor conditions • Key requirements w.r.t. surrounding communities are covered. • ISCC is one of the few standards which addresses food security. It explicitly prohibits impairing food security, but does not specify measures that have to be implemented to mitigate the expected impact. **Weaknesses** • A social and environmental management system is not explicitly required. While the standard requires an assessment of social and environmental aspects related to the production process, reporting requirements are not specifically addressed • There are only limited criteria concerning biodiversity and conservation. There are neither criteria on preventing the violation of habitats, e.g. through land set-asides and corridors for wild flora and fauna, nor

	banned. WHO Class 2 chemicals are not expressly banned. Requirements for agrochemicals are not comprehensively addressed • Lack of details w.r.t. to the criterion safe and healthy work conditions • Weak spots regarding the criterion about grievance mechanisms for workers	the restriction of invasive species. Furthermore, the criterion on endangered species is not sufficiently detailed. • Certain criteria, such as biodiversity assessments and the prohibition of very hazardous agrochemicals are offered as voluntary add-ons in the ISCC Plus, however, the ISCC should also incorporate these into the standard as mandatory requirements. • For GMO materials, the standard is currently technology neutral, i.e. currently no separate chain of custody for non-GMOs. • The standard does not contain any criteria on crop rotation / intercropping or requirements regarding topography • The standard does not ban the use of the most hazardous agrochemicals • A criterion on disciplinary practices is not included

Table 29: Comparison of RSB EU RED / ISCC EU - Key Aspects (Alberici et al., 2014)

Aspect	RSB EU RED	ISCC EU
Scope		
Feedstock Coverage	All	All
Recognition of other EU schemes		

Mandatory Sustainability Criteria		
Coverage of RED land criteria		
Soil, water and air protection		
Social		
Economic		
Chain of Custody (CoC) and Traceability		
Mass balance	Continuous	Deficit – 3 months balancing period
Further CoC options	Identity of product preserved, Segregation of product	Physical segregation
Unique ID number for consignment		
Coverage of tracked information through the supply chain	High	High
Auditing		
Unit of certification	First gathering point and supply base	First gathering point and supply base
Certificate validity	3 months – 2 years, depending on risk class	1 year
Relative cost of compliance compared to other schemes		
	high	Medium

10.3 Harmonization of Sustainability Certification Schemes

10.3.1 Sustainability Standards – RED and RFS2

When talking about sustainability certification of biofuels it is important to differentiate between sustainability 'standards' such as the RED or RFS2 (US) that entail a set of mandatory sustainability criteria, and 'voluntary' or 'certification schemes' which provide auditable criteria and indicators for third parties to become certified against (Alberici et al., 2014), for example the RSB EU RED or the ISCC EU outlined above. Standards refer to a set of criteria under which regulated parties should operate, while certification schemes are a way of assuring that the set of criteria are complied with.

Particularly for the aviation industry, a highly competitive sector that is operating on a global scale, the variety of voluntary schemes as well as the different national legislations in place concerning biofuels poses considerable challenges. Hence, the creation of a level playing field for the aviation industry, i.e. harmonizing sustainability certification schemes (and standards) is inter alia of great importance and will therefore be the subject of this chapter.

As the differences and similarities between the RED and RFS2 are described in the CORE-JetFuel Deliverable 5.4 (Final Report on Policies, Incentives and Regulation), this chapter will not feature such a comparison. Instead, the case will be made for a mutual recognition of the two legally binding sustainability standards and the criteria therein, respectively.

As opposed to the harmonization of voluntary certification schemes, the mutual recognition would apply to the mandatory sustainability requirements of biofuels in national legislation. Such a mutual recognition of the two standards could potentially enable alternative aviation fuels to be freely traded between the EU and the US, thereby considerably increasing opportunities for deployment. An enhanced level of streamlining of the RED and the RFS2 could also provide a strong basis to develop an internationally accepted approach to the sustainability of biofuels, as they are the two major legislative sustainability standards for biofuels in place today (Alberici et al., 2014).

Both the RED and RFS entail requirements for GHG savings and restrictions on land conversion. Although some differences in the requirements exist, these do not count as the major factor hindering the mutual recognition. Nevertheless, there are a number of practical steps the EC and EPA (Environmental Protection Agency (US)) could take in order to achieve a higher level of harmonization of the following aspects[47]:

- **Land conversion restrictions:** Agreement on a common reference date in the RED (currently 01.01.2008) and the RFS (currently 19.12.2007) – easy to implement, no impact on compliance. The current situation is that farmers who want to export feedstock to the US have to demonstrate that the land the feedstock is grown on had been in use for the same purpose prior to 19 December 2007.
- **Analysis of bio-jet pathway GHG emissions:** The GHG calculation methodologies in the RED and RFS2 share a common basis, although some differences exist. Irrespective of which GHG calculation methodology is applied, alternative aviation fuels should realize significant

[47] Alberici et al., 2014

GHG emission reductions and meet current (and future) GHG emission reduction targets set in the two standards, irrespective of which GHG calculation methodology is used. In addition, all improvements on a fossil fuel comparator should be recognized and not limited by thresholds.

- **Agreement on a common (fossil) jet fuel comparator:** The fossil fuel comparator is a fundamental parameter in the calculation of GHG savings. Currently, both the RED and RFS2 entail a comparator for road transport fuel, but not for jet fuel. A necessary step would be to seek a common agreement on an appropriate comparator so that GHG savings are calculated on a consistent basis.

Opposed to the minor differences that could be harmonized relatively easily, meaning with small administrative effort, major differences between the RED and the RFS2 can be found in the approach taken on the chain of custody and auditing. The RFS2 for example allows a "mass balance" chain of custody but requires that imported fuel is fully separated in order to "preserve" the identity of domestically produced fuel.

With respect to the auditing procedure, the main difference between the two standards is that the RED only permits independent auditing while in the RFS2 internal auditors are entitled to conduct the auditing. Compared to the aspects outlined previously, the mutual recognition of these aspects would require greater effort as well as a focus in discussions between the EC and the EPA.

A mutual recognition of the two standards as outlined above would have several advantages, such as the potential facilitation of global bio-jet deployment. In addition, other countries may follow this example and implement similar sustainability criteria. Furthermore, the aspired recognition would use systems that are already in operation and have proven practicability, which in turn facilitates implementation.

What may hinder the realization of the mutual recognition is the considerable time it may take for the EC and EPA to reach a consensus on the specifics in this matter, for example concerning the auditing procedure or specific sustainability criteria such as (indirect) land use changes. In addition, as negotiations would be held at the political level, the aviation industry would supposedly[48] not have a formal role in the process.

10.3.2 Voluntary Certification Schemes – RSB EU RED and ISCC EU

The harmonization or mutual recognition of certification schemes approved by the RED is often considered as a desirable development, as it allows feedstocks to be certified by one scheme, and then to pass through the chain of custody of a second scheme (Alberici et al. 2014). The ideal situation would be if a biofuel feedstock is certified under RSB, for example, goes through the chain of custody of another scheme but still retains RSB certification. This would be beneficial for entities located in the downstream supply chain that might not be certified to the scheme that was used for the feedstock certification, thereby avoiding "double-certification" and making the overall certification process more efficient and cost effective.

In general, the harmonization of the voluntary sustainability certification schemes currently in place could be a way of increasing the overall up-take of voluntary schemes in the biofuel market (Alberici et

[48] At ICAO level, there is currently a proposal to start working on sustainability criteria for alternative aviation fuels. In order to speed up this process, European resources could potentially dedicated to these negotiations

al. 2014). An obstacle to overcome with respect to the broad mutual recognition of some of the schemes is the varying level of ambition concerning the sustainability criteria they entail, meaning that those schemes that have very stringent and wide ranging sustainability criteria may be reluctant to recognize schemes whose scope is less demanding (Alberici et al. 2014).

Initiatives seeking to harmonize the various certification schemes have already started in the European biofuel market. The ISCC EU for example accepts raw material from all voluntary schemes that are recognized by the RED, the exception being waste and residues as, according to the ISCC, their sustainability and traceability cannot be guaranteed. The feedstock is then tracked through the ISCC chain of custody system and the claim made in the market is ISCC (Alberici et al. 2014). In addition, all information travelling with the consignment has to be in accordance with the ISCC criteria, which in turn means that a feedstock certified by another scheme is obliged to have unique reference number when being processed into ISCC certified fuel.

The RSB, the certification scheme that so far is preferred by the aviation industry, also recognizes all of the other voluntary schemes approved by the EC for agricultural feedstock production. In this case, however, only a so-called “EU RED compliant” claim can be made in the market. With this approach, the RSB EU RED claim is protected and reserved for raw material that is certified by RSB (Alberici et al. 2014).

The advantage of harmonizing voluntary certification schemes recognized by the EC is that it provides a larger degree of flexibility in the supply of biomass from producers that are already certified by one or the other schemes. In addition and as outlined above, a mutual recognition of the different schemes avoids the need for certification under multiple schemes and therefore makes the process itself more cost efficient for feedstock and fuel producers, and ultimately for the end-user, for example airlines.

A potential disadvantage that has to be addressed is the risk that the original certification claim could be lost through mutual recognition or that some schemes may be reluctant to recognize other schemes for the fear of losing market share. Furthermore, double counting of biomass (and claims) is a potential risk if schemes are mutually recognized. As this can also have an impact on the acclaimed GHG balance of certified fuel, it needs to be avoided. As outlined above, although recognition between the schemes would be desirable, since these schemes by private organizations, there is only very little that can be done at policy level with respect to stimulating such a mutual recognition. It is therefore important to increase the level of mutual recognition of legal sustainability requirements, as policy makers can (and are tasked to) directly influence this process.

11 Mapping of R&D Activities in the Field of Feedstock and Sustainability

A list of identified EU-funded R&D projects concerned with the feedstocks that have been introduced in the course of this report is given in Table 30. Generally it has to be noted that this table does not represent all the information on feedstock and sustainability that was collected in context of WP4. Instead, it should be understood a selection of projects that research, cultivate or process one of the specific feedstocks introduced above. In addition, it has to be noted that R&D activities are very rarely concerned with solely the feedstock but rather consider an entire value chain or parts of it, for example from cultivation to conversion or improving the logistics of a certain type of feedstock. For this reason, D4.4 features a chapter on the integrated evaluation of number of value chains, whose bases are the feedstocks outlined in this report. The collection of R&D activities has been conducted in the first reporting period of the project, i.e. from September 2013 – April 2015.

Table 30: List of identified EU-funded R&D projects concerned with the feedstocks discussed

Position	Acronym	Call	Duration	EU funding (total cost) [10^6 €]		Feedstock	Fuel
1	4FCROPS	FP7-KBBE-2007-1	2008 – 2010	0.99	1.26	Non-food crops	Food, feed, fiber, fuels
2	Aquafuels	FP7-ENERGY.2009.3.2.1	2010-2011	0.74	0.86	Microalgae	biodiesel
3	Aufwind		2013- 2015	CO		Microalgae	HEFA-SPK
4	BABETHANOL	FP7-ENERGY-2008.2.3.1	2009 - 2013	3.1	4.4	lignocellulosic material	ethanol
5	EnAlgae	INTERREG IVB North West Europe, 6th call	2011 - 2015		14.6	Micro- and Macroalgae	
6	ITAKA	FP7-ENERGY.2012.3.2.2	2011 - 2015	9.8	17.5	Camelina	HEFA-SPK
7	BIOBOOST	FP7-ENERGY-2011-1	2012 – 2015	5	7	Waste and residues	Biofuel
8	BIOFAT	FP7-ENERGY-2010.3.4.1	2011 - 2015	7.7	10	Microalgae	Biodiesel / bioethanol
9	EUROPRUNING	FP7-KBBE-2012-6-singlestage	2013 – 2016	3.4	4.6	Agricultural residues	Logistics
10	INFRES	FP7-KBBE-2012-6-singlestage	2012 – 2015	3.0	4.6	Woody biomass / residues	Logistics
11	LOGISTEC	FP7-KBBE-2012-6-singlestage	2012- 2016	3.5	5.1	Lignocellulose	Logistics
12	MIRACLES	FP7-KBBE-2013-7-single-stage	2013 – 2017	8.9	11.9	Microalgae	

13	OPTFUEL	FP7-ENERGY-2007-2-TREN	2009 - 2012	12.8	7.2	Woody biomass (from SRC)	Liquid FT fuel (diesel)
14	PROETHANOL2G	FP7-ENERGY-2009-BRAZIL	2010 – 2014	0.9	2,5	Wheat straw, sugar cane bagasse	
15	S2Biom	FP7-ENERGY-2013-1	2013 – 2016	4	5.2	Non-food biomass	Availability
16	SUPRA BIO	FP7-BIOREFINERY_CP	2010 - 2014	12.3	17.5	Poplar / Straw / Waste Wood	DME, Ethanol, Butanol
17	Recoil	IEE/11/091/SI2.616369	2012 -2015	1.4	1.7	UCO	Biodiesel

The projects listed in Table 30 are plotted in correlation with the respective project budget (circles) and graphically depicted in Figures 31 - 34, including the total funding of the different quadrants of Stokes' Quadrant Model. An exhaustive elaboration of the model can be found in CORE-JetFuel Deliverable D2.1 and should therefore not be featured here.

With respect to the R&D projects displayed in Figure 31, it can be seen that the research on the different types of feedstock is either placed in Pasteur's Quadrant (use-inspired basic research) or in Edison's Quadrant (pure applied research). This is insofar not surprising as research on the utilization of fuels derived from biogenic feedstocks will always be strongly motivated by product development, particularly in aviation.

However, especially in case of microalgae and to some degree in case of SRC, research efforts are also put in generating a deeper and more holistic understanding of plant genetics, solar radiation efficiencies as well as other vital characteristics and influencing factors without necessarily aiming at technology applications. On the other hand and again especially in case of microalgae, research of the considered projects is particularly concerned with making the cultivation and production processes more efficient in terms economic viability and energy efficiency (including the according reduction of GHG emissions) with the aim of reaching market maturity and deployment. In case of lignocellulosic biomass, a lot of research and demonstration effort is placed on improving the logistics of making this type of feedstock available and transporting it to the processing site.

11.1 Overall European R&D portfolio identified in the field of feedstock and sustainability

Figure 31 also features a graphic representation of the funding distribution over the different Quadrants of Stokes' Model. Edison's Quadrat, representing pure applied research, hereby accounts with 64% (74.1 Mio. €) of the total funding volume for the largest share of the overall R&D portfolio in the area of feedstock and sustainability that was considered in this report. Considering the highly product-orientated research field that is aviation as well as the research activities engaged in making fuels based on biogenic feedstock available for this sector, the distribution shown in Figure 31 was expected. It is, however, interesting that only four projects that are allocated in Pasteur's Quadrant (use-inspired basic research) make up approximately one-third of the total funding volume, i.e. 40.2 Mio. Euro, or 34%. The projects allocated in Pasteur's Quadrant are so-called flagship projects such as ITAKA with a considerable amount of funding. While the

ITAKA project has successfully shown that supplying airports with bio-jet fuels and operating aircraft with these fuels is feasible, a lot of research and development activities have been concerned with challenges in establishing a new crop for the production of bio-kerosene, i.e. camelina. Reaching a steady productivity was of special importance in this regard. The ITAKA project is exemplary of the R&D portfolio in Pasteur's Quadrant to the extent that large parts of the value chain are established, for example the HEFA conversion pathway, while others require more research in order to reach commercial level, i.e. camelina production a FSRL of 9. Figure 32 also shows the entire R&D landscape that was assessed in the field of feedstock and sustainability, but additionally depicts the main type of research conducted in the different Quadrants corresponding to the different types of feedstocks introduced in this report.

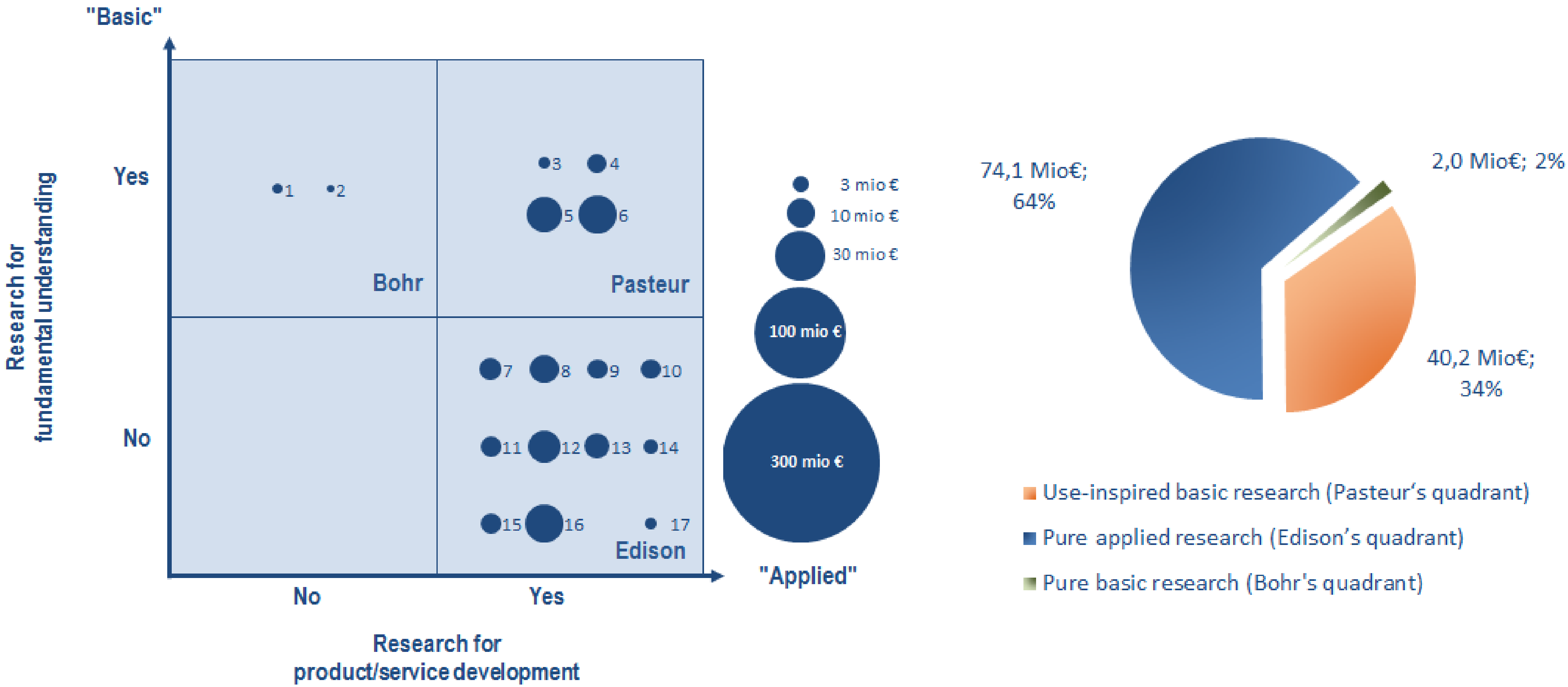

Figure 31: European R&D portfolio identified by C-JF in the field of feedstock and sustainability / Quadrant-specific funding volumes

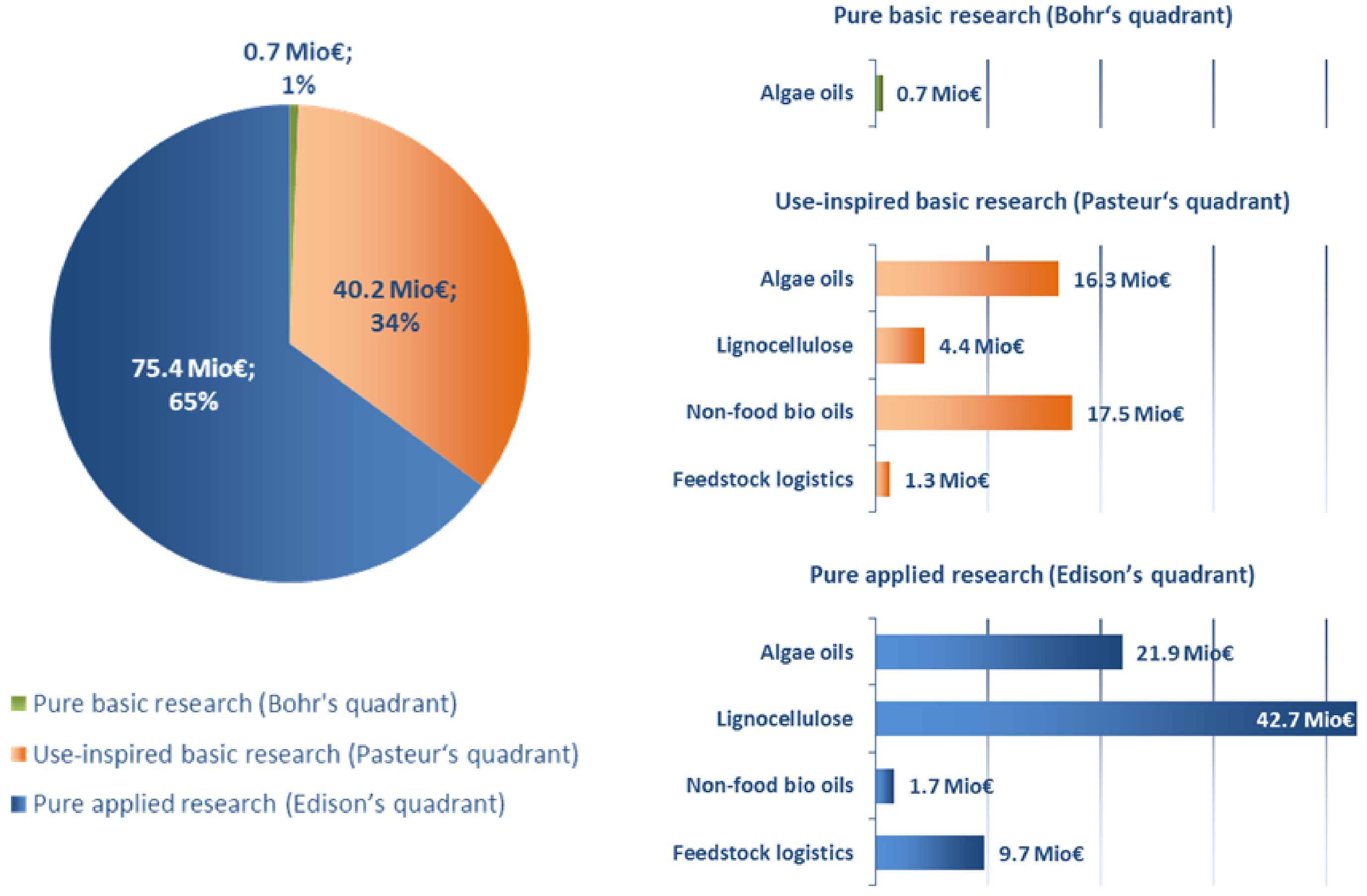

Figure 32: European R&D portfolio identified by C-JF in the field of feedstock and sustainability / Quadrant- and oil type-specific funding volumes

11.2 European R&D portfolio in oily types of feedstock

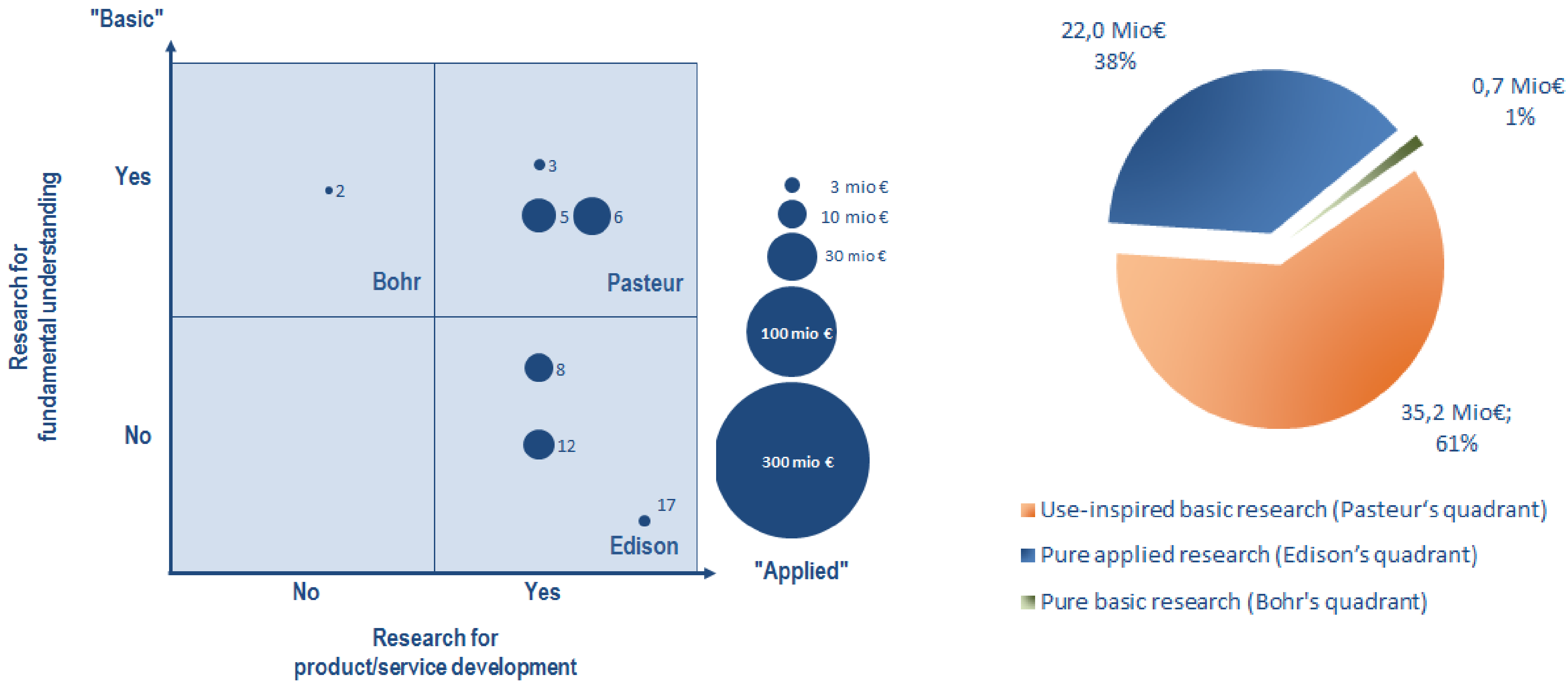

Figure 33: European R&D portfolio addressing oily feedstocks identified by C-JF / Quadrant-specific funding volumes

Figure 33 displays the mapping of R&D projects that are concerned with feedstocks belonging to the group of oils and fats. A majority of the projects depicted above can also be found in Figure 34, which highlights the identified projects concerned with microalgae, their cultivation and application as a potential bio-jet feedstock. Considering that oil crops such as rapeseed are well established particularly for the production of biodiesel, additional research in this respect is not required at European level. Special consideration shall be given to project 17, called “Recoil” which aims to increase sustainable biodiesel production and its local market intake by enhancing household UCO collection and transformation[49], by assessing UCO to biodiesel chain best practices, surveys and the like. As mentioned in Chapter 9.4 of this report, although UCO is a well-established feedstock (FSRL 9) for the production of biodiesel and HEFA bio-jet, its availability from gastronomy is very limited and almost fully exhausted. Finding ways to collect UCO from households in order to increase the availability of this feedstock is therefore important. Although concerns exist regarding the quality of UCO from households as well as with respect to the logistical feasibility, assessing this potential and perhaps making it available to the different transport sectors is recommended.

11.3 European R&D portfolio in the field of algal biomass

With approximately 60% of the total funding, use-inspired research makes up the most important branch of R&D activities concerned with oily feedstocks. It has to be noted though, that most of the projects depicted in Figure 33 are concerned with microalgae, explaining the larger share of funding in Pasteur's Quadrant. For this reason, Figure 34 below solely considers microalgae projects.

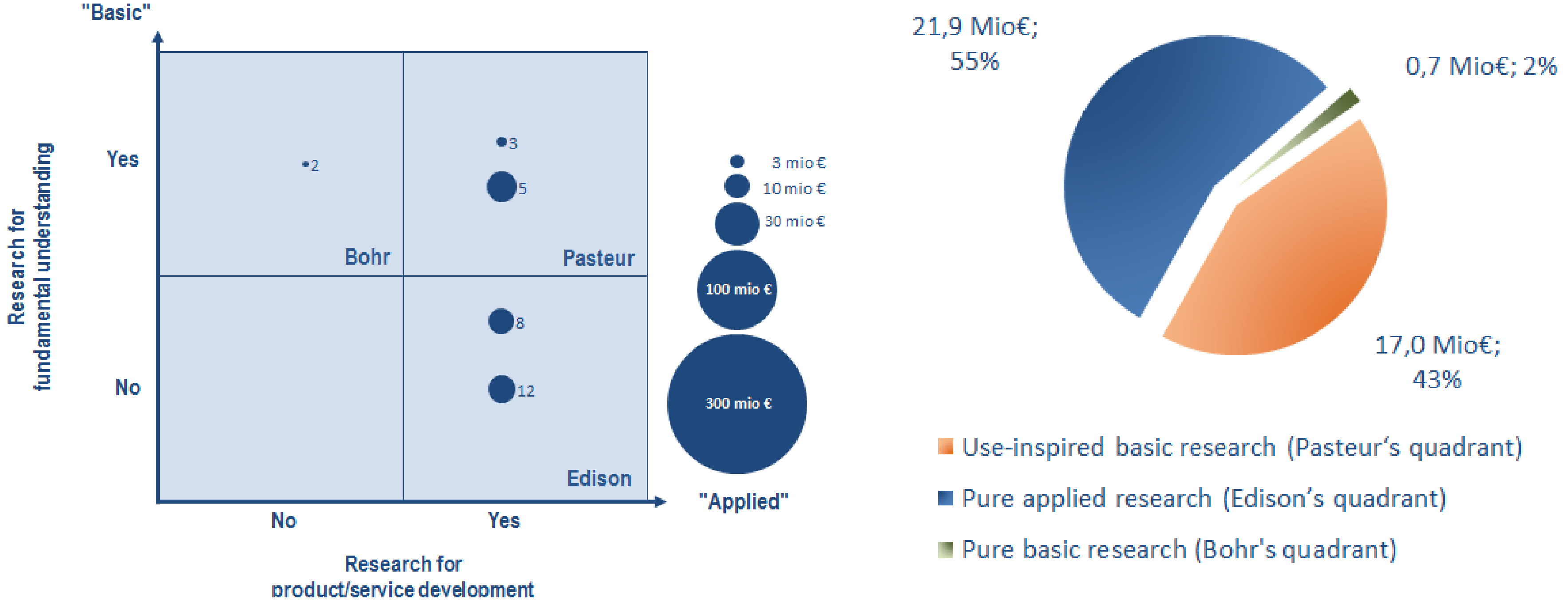

Figure 34: European algae R&D portfolio identified by C-JF / Quadrant-specific funding volumes

[49] http://www.recoilproject.eu/index.php?option=com_content&view=article&id=32&Itemid=168&lang=en

Judging by the funding distribution over the three Quadrants, it seems that the focus of the algae R&D portfolio is placed on applied research with the two projects allocated in Edison's Quadrant each showing a funding volume of approximately 10 Million Euro. Particularly project no. 8 called "BIOFAT" is interesting as it seeks to integrate the entire value chain of algae-based biofuel production from optimized growth, starch and oil accumulation, to downstream processing (biorefinery) including biofuel production by increasing energy efficiency, economic viability and environmental sustainability[50] of two pilot facilities.

The results of this project will also be of importance to the aviation industry, as microalgae show a very large (theoretical) production potential. Making their cultivation and conversion into biofuels more sustainable and economically viable is therefore crucial for potentially unlocking the vast past production potential.

The promising R&D activities outlined above shall, however, not hide the fact that a considerable amount of basic research is necessary for improving the sustainability and economic viability of microalgae production, particularly in PBRs. Especially the considerable range in GHG balances and NER reported by numerous LCA studies has to be addressed and found a solution for, respectively.

In general, there is an almost equal balance between use-inspired basic research and pure applied research activities in microalgae production. The one project located in Bohr's Quadrant called "Aquafuels" is pure basic research in the sense that it compared different LCA studies available in the literature that address microalgae, its cultivation as well as the corresponding GHG emissions and NERs.

If microalgae are to contribute in a meaningful way to making the aviation sector less GHG intensive, R&D activities that show a good balance between scaling-up production to demonstration level while seeking to improve the shortcomings outlined below will be necessary in the medium- to long-term time horizon.

11.4 European R&D portfolio in the field of woody biomass and residue materials

As opposed to the R&D landscape depicted in the previous chapters, research in the field of woody types of biomass (lignocellulose) and residue materials has a clear focus on application. This becomes evident when looking at Figure 35. All projects with the exception of one are allocated in Edison's Quadrant, making up over 90% of the funding of the identified projects in this area. Particularly in case of lignocellulose, a lot of the projects are concerned with improving the logistics of feedstock collection, which is often brought forward as a hindering factor concerning this type of biomass, inter alia from CORE-JetFuel Stakeholders.

In order to make fuels based on lignocellulose economically more attractive, CORE-JetFuel stakeholders recommended shifting to decentralized small-scale applications, i.e. small scale conversion plants with a small feedstock collection radius that take away a large part of the logistical challenges as well as challenges in building a network of supply chains. Such a decentralized approach is followed by project no. 7, called "BIOBOOST". Although the feedstock in this project is focusing on waste materials and residues, the approach is the same.

[50] http://www.biofatproject.eu/Project/

Another matter often being brought forward to increase the production of alternative aviation fuels is utilizing synergies by developing bio-refineries. This approach is followed by the project with the highest funding volume in Figure 35, namely the project SUPRA-BIO (No. 16). The project researches, develops and demonstrates a toolkit of novel generic processes together with advanced intensification and integration methodologies that can be applied to range of bio-refinery scenarios based on sustainable biomass feedstocks[51].

Although bio-jet is not explicitly included in the list of biofuels that can potentially be produced in the integrated bio-refineries, the feedstocks as well as conversion pathways considered in the project would allow for the production of bio-kerosene as a side-product of more valuable products such as value added chemicals. This is exactly the approach CORE-JetFuel stakeholders are recommending and should therefore be further explored and developed.

Another project worth mentioning is S2Biom (No. 15) that seeks to support the sustainable delivery of non-food biomass feedstock at local, regional and pan-European level.[52] In addition, the identification of the potential of current and future biomass supply, of the corresponding appropriate conversion technologies as well as improving logistical challenges in feedstock collection is part of the work carried out in this project.

All of these briefly mentioned objectives are crucial for, and can be transferred to the sustainable and economically viable production of alternative jet fuels. In general, very few of the identified projects are explicitly concerned with developing a certain type of feedstock for bio-jet production or solely with the beginning of the value chain, i.e. feedstock production. Instead, entire value chains or larger parts of it are subject of the European R&D activities identified in this report. Due to the low value of bio-kerosene compared to other (bioenergy) applications, farmers have currently a low incentive to sell their feedstocks to bio-jet producers.

Although it is not of high importance to the farmers to whom they sell, making bio-jet fuels more competitive not only compared to fossil fuels but also other bio-products (chemicals, materials, road transport etc.) is vital if a larger share of biomass is to be directed towards aviation.

Based on the analysis above, the European R&D portfolio in the area of feedstock and sustainably seems to be well-balanced, pure applied research activities being the dominant type of research. In longer-term perspective, even more research located in Edison's Quadrant will be necessary to push the production of feedstocks that currently show a low FSRL. These types of feedstock will become even more important post 2020, when the support of oil crops by the RED is faded out and the 7% cap on these types of feedstocks is in force, respectively.

Taking into account competing uses for biomass as well as the considerable amounts of feedstocks the aviation sector will require for meeting its GHG emission reduction targets, more research has to be conducted in the assessment of the sustainable biomass availability in Europe. Before a prioritization of biomass for different application sectors is discussed, an assessment of biomass demand sectors will be required in order to determine if such a prioritization of biomass is really necessary – and if so, which application sector can make the best use of the sustainably available biomass.

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[51] http://www.suprabio.eu/suprabio-at-a-glance/
[52] http://www.s2biom.eu/en/

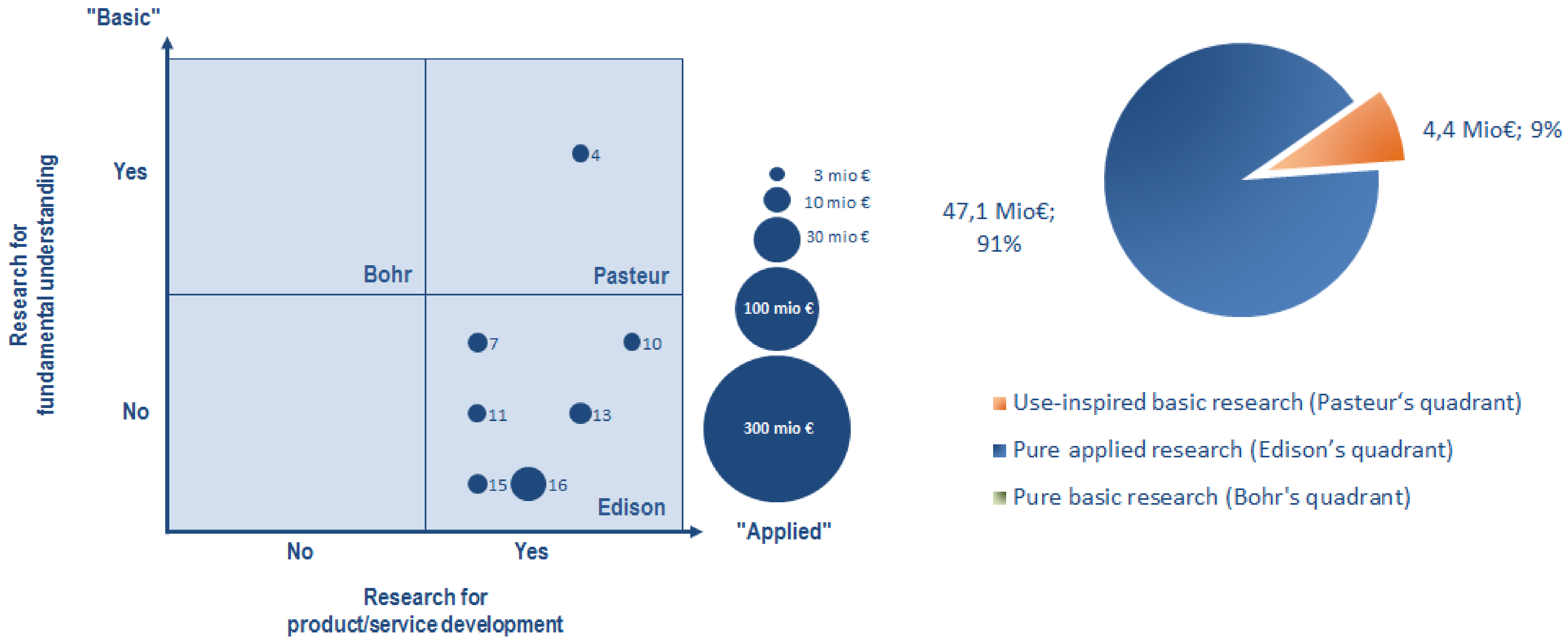

Figure 35: European R&D portfolio in woody biomass and residual materials identified by C-JF / Quadrant-specific funding volumes

Table 31 summarizes the different types of feedstocks that have been described and assessed in this report. The table features a selection of indicators that are in the author's point of view of special importance when assessing the viability of different feedstock sources for the production of alternative aviation fuels. The coloring corresponds to the color scheme chosen Figure 1, the schematic overview of bio-jet production pathways identified by the CORE-JetFuel project.

Table 31: Overview of the assessed feedstocks

Feedstock Group	Source	FSRL	Lipid / Energy Content	GHG balance	Yield / Productivity	Production	Production Potential / Availability	Conversion Ratio
Oils and Fats	Microalgae	6 – 7	15 – 60% (dry weight)[53]	45 – 550 g CO_2 eq./MJ[54]	Open Pond: 5 – 25g/m^2/day PBR: 60 – 650 g/m^2/day[53]	9.200t (2015)	Europe: 41Mt/y (technical potential[55]	N/A
	Camelina	8 – 9	35 – 45% dry weight)[56]	Cultivation: 40.2 g CO_2 eq./MJ Oil extraction: 12.3 g CO_2 eq./MJ[58]	336 – 2240kg/ha[56]	500 – 2000t/ha[56]	N/A	N/A
	UCO	9	N/A	RED: 0 g CO_2 eq./MJ up to collection	N/A	N/A	Europe: ~ 1 t/y[57]	N/A
	Rapeseed	9	40 – 44% dry weight)[56]	Cultivation: 50.4 g CO_2 eq./MJ Oil extraction:	2.68 – 3.39 t/ha[56]	22Mt (2015)[59]	Europe: 22.4 Mt (2017)[59]	10.4 MJ/kg jet fuel[60]

[53] Petrick et al., 2013
[54] Bauen et al., 2009
[55] Skarka, 2015
[56] Moser, 2010
[57] Alberici et al., 2014

				10.7 g CO_2[58] eq./MJ[58]				
Lignocellulosic Biomass	SRC	7	Heating value at 15-25% moisture content: 16.7 – 19.7 MJ/kg[61]	Bio-SPK: 49.1 g CO_2 eq./MJ[62]	4 – 16 t/ha[63]	France: 2.4 Mt/y Italy: 1.2 Mt/y[64]	Germany: 9.5 Mt/y (on 'very suitable' land)[64]	4,5 MJ/kg jet fuel[60]
	Switchgrass	5	Heating value at 15-25% moisture content: 16.8 – 19.1 MJ/kg	Cultivation: 17.6 – 39.7 g CO_2 eq./MJ[62]	18 – 25 t/ha[65]	N/A	N/A	4,5 MJ/kg jet fuel[60]
Waste and Residues	Agricultural	8	Heating value at 15-25% moisture	RED: 0 g CO_2 eq./MJ up to collection	3.75 t/ha (wheat straw)[61]	315.9 Mt/y[66]	Europe: 84.6 Mt/y(sustainable availability)[66]	N/A

59 USDA FSA, 2016
60 Riegel et al., 2015
58 Miller/Kumar, 2013
61 Zeller et al., 2013
62 burnFair project
63 Tubby, 2002
64 Aust et al., 2013
65 Elbersen et al., 2010
66 Searle/Malins, 2016

			content: 13MJ/kg[61]	Straw removal: 10 g CO_2 eq./MJ Machinery and N fertilization: 23 g CO_2 eq./MJ				
	Forestry	8	Heating value at 15-25% moisture content: 17.5 – 20.8 MJ/kg[61]	RED: 0 g CO_2 eq./MJ up to collection Transportation: 8.25 kg CO_2 eq./MJ[61]		67.59 Mt/y[66]	Europe: 9.23 Mt/y (sustainable availability)[66]	N/A

12 Conclusions

This final report introduced and evaluated eight different types of renewable biogenic feedstocks at varying maturity levels in terms of their commercialization, yield and production potential. In addition, said feedstocks (and their cultivation) were evaluated by applying a series of sustainability indicators that helped in determining their overall sustainability, which is of vital importance in contributing to the reduction of aviation's environmental impacts, particularly its GHG emissions.

The chosen feedstocks represent examples of three of the main feedstock groups suitable for the conversion into alternative aviation fuels. Microalgae, camelina, UCO and rapeseed constitute examples of biogenic oils and fats. Switchgrass and short rotation coppice are examples of lignocellulosic biomass. In addition, agricultural as well as forestry waste and residues represent a feedstock source that is due to various sustainability advantages promising for the production of alternative sustainable jet fuels.

While microalgae have received a lot of attention as a promising biofuel feedstock due to their supposedly high production, minimal competition with food production and the like, it has been shown that particularly their cultivation is very energy intensive and therefore connected to increased GHG emissions. In addition, considerable energetic inputs are required to prepare the biomass for lipid extraction, which is in turn energy and GHG intensive as well. In addition, water requirement particularly of open cultivation systems are high and therefore problematic from an environmental point of view. Increased efforts and (financial) resources are required to commercialize the feedstock microalgae, i.e. elevating it above demonstration scale. Accordingly, numerous R&D activities in Europe are dedicated to microalgae and its suitability for fuel production.

The terrestrial crop camelina has proven to be a viable candidate for the production of alternative fuels with an overall GHG reduction potential of the derived HEFA-SPK of 60%. Camelina is a low-maintenance crop, can be grown in a variety of climatic and soil conditions and requires relatively low nutrient inputs. Camelina does not compete with food production and the meal as a by-product of seed pressing can be utilized as feed for livestock. All of these factors make it a sustainable crop that can considerably contribute to making aviation less carbon intensive. In the European context, research is focused on further commercializing the crop and creating incentives for the deployment of camelina-derived kerosene.

Rapeseed is the most important biodiesel feedstock in Europe, annual production exceeding 22 Million tonnes. Major concerns consist, however, with respect to the sustainability of cultivating this crop, mainly due to the considerable amount of fertilizers required for cultivation. In addition, biodiesel based on rapeseed can even under starkly minimized N applications not reach a GHG reduction potential of 50%, making it no longer a viable option to contribute to the GHG emission reduction targets anchored in the RED.

UCO and fuels based on waste oils, respectively, have a high GHG emission reduction potential as well as a number of other sustainability advantages. Although well organized, the collection of this type of feedstock is challenging. In addition, the potential availability of approximately 1 Million tonnes per year from gastronomy is not sufficient if UCO is to contribute in a meaningful way in making aviation less carbon intensive.

Lignocellulosic biomass is of special interest for the aviation industry as it does not compete with food production at all and can be converted into different types of fuels via a variety of conversion pathways. In addition, lignocellulosic biomass requires little agricultural inputs (N fertilization) and is of fast growing nature. Both switchgrass and SRC have low fertilization requirements, use N efficiently and show high rates carbon sequestration and can be cultivated on a variety of different soils and in different climates.

In Europe, SRC harvest is commercially mature, while switchgrass cultivation is not commercially established. R&D activities with respect to switchgrass concentrate on establishing this feedstock on larger scale in Europe. In order to make SRC a viable feedstock for the aviation industry, R&D activities should focus on decentralized production systems with a small-scale collection radius, thereby decreasing logistical challenges and increasing economic viability.

No competition with food production, low risk of inducing ILUC, high potential availability and a series of other (sustainability) advantages are positive properties of waste and residue materials such as straw. On the other hand, competing uses with other well-established bioenergy and biomaterial applications, energy-intensive conversion as well as the on-site agronomic importance of straw are hindering factors for its utilization as a bio-jet feedstock.

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