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Technology options for feeding 10 billion people

Recycling agricultural, forestry & food wastes and residues for sustainable bioenergy and biomaterials

Study

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STOA

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Abstract

The purpose of this study is to examine and review biorefinery technology options that exist to convert biomass in the form of agricultural crop and forestry residues and waste from the whole food chain into biomaterials and bioenergy. It assesses the technological options, including the sustainability of the processes involved. The study forms part of a bigger project commissioned by the European Parliament's STOA ('Science and Technology Options Assessment') office under the heading of 'Technology options for feeding 10 billion people'.

Advanced biofuels and innovative bio-based pathways based on wastes and residues show considerable potential and should be further developed especially as Europe is already seen by some as having a lead in relevant technologies. However, there are also considerable uncertainties for investors and indeed all market participants and thus a major task is to ensure good transparency and better information concerning the availabilities of the waste and residue streams, the opportunities for processing, and the benefits to consumers. In addition, because, by definition, bio-based economic developments necessarily interact with ecosystems, there has to be visible assurance that the bio-products are indeed environmentally preferable with respect to GHG emissions, water, soil and biodiversity compared with their fossil-based counterparts. The conclusion is thus encouragement should be given to this sector, but with enhanced transparency of all aspects of its development, and with equally strong sustainability safeguards.

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AD	Anaerobic digestion
ADEME	Agence de l'Environnement et de la Maîtrise de l'Énergie (French Environment and Energy Management Agency)
AFEX	Ammonia fibre explosion. *A biomass pre-treatment process*.
BCFN	Barilla Center for Food and Nutrition, international organisation
BBP	Butyl benzyl phthalate
BEE project	Bioenergy Europe project
BioSG	Bio-synthetic gas
BioSNG	Bio-synthetic natural gas
BLTC	Biomass Logistic and Trade Centre
BMVBS	Bundesministerium für Verkehr, Bau und Stadtentwicklung (German Federal Ministry of Transport, Building and Urban Development)
BNEF	Bloomberg New Energy Finance
BTL	Biomass-to-liquid
CAP	Common Agricultural Policy
CAPRI	Common Agricultural Policy Regionalised Impact model
CBD	Convention on Biological Diversity
CENER	CENER - National Renewable Energy Centre of Spain
CHP	Combined heat and power
CIMV	Compagnie industrielle de la matière végétale (France). *Company specialised in refining lignocellulosic biomass. Coined the term CIMV, referring to the biomass fractionation process.*
CNG	Compressed natural gas
CO	Carbon monoxide
CO_2	Carbon dioxide
CSES	Centre for Strategy & Evaluation Services
DBFZ	Deutsches Biomasseforschungszentrum (German Biomass Research Centre)
DDGS	Dried distillers grains with solubles
DME	Dimethyl ether (or *methoxymethane*). *A widely used propellant for aerosol products (eg hairspray). Can be dehydrated from methanol or synthesised from gas, coal or biomass. Can be liquefied and used as a transport fuel.*
ECF	European Climate Foundation
ECN	Energy Research Centre of the Netherlands
EEA	European Environment Agency
EFI-GTM	The Global forest sector model at the European Forest Institute; model of economic indicators for the forest sector products
EFISCEN	The European Forest Information Scenario Model; forest research projection model indicators
EFSOS	European Forest Sector Outlook Study (2011)
ERRMA	European Renewable Raw Materials Association
EXIOPOL	Integrated project funded under the EU's 6th framework programme, priority 6.3 Global Change and Ecosystems
FAEE	Fatty acid ethyl esthers. *Biodiesel from esterification of fatty acids with ethanol*
FAME	Fatty acid methyl esthers. *Biodiesel from esterification of fatty acids with methanol*

FAO	Food and Agricultural Organisation of the United Nations
FDCA	Furan dicarboxylic acid
FERN	International NGO focused on EU's involvement in forests
FP7	EU's 7th Framework Programme for Research and Technological Development
FSC	Food supply chain
FT	Fischer Tropsch (synthesis)
GHG	Greenhouse gas
HDPE	High-density polyethylene. *A polyethylene thermoplastic obtained from petroleum or biomass, with a good chemical resistance and high rigidity. Widely used in the production of plastic bottles, corrosion-resistant piping, containers, plastic lumber.*
HMF	Hydroxymethyl furfural. *An organic compound, derived from dehydration of certain sugars. Occurs in our diet, in heat-processed foods including milk, fruit juices, spirits, honey.*
HDRD	Hydrotreated renewable diesel
HRJ	Hydrotreated renewable jet
HVO	Hydrotreated vegetable oils
IA	Impact assessment
ICCT	International Council for Clean Transportation
IEA	International Energy Agency
ILUC	Indirect land use change
INEOS Bio	Referring to the US advanced biofuel facility and its process of thermochemical biomass gasification, producing ethanol as a product
ISCC	International Sustainability & Carbon Certification
IVC	In-vessel composting
JEC	JRC, EUCAR, Concawe (research consortium)
JRC	Joint Research Centre of the European Commission
LCA	Life-cycle assessment
LCW	Landscape care wood
LER	Land as an environmental resource (study by Hart *et al*, 2013)
LIIB	Low Indirect Impact Biofuel
LDPE	Low-density polyethylene. *Made from the monomer ethylene, has long branching chains, and is the first grade of polyethylene. Mainly used for manufacturing plastic bags.*
LLDPE	Linear low-density polyethylene. *A linear polymer (polyethylene) with short uniform branches; has a higher tensile strength and puncture resistance than LDPE. Primarily used for manufacturing flexible tubing, but also plastic bags and sheets, pipes.*
LNG	Liquified natural gas
LowCVP	Low Carbon Vehicle Partnership
LULUCF	Land use, land use change and forestry
MBT	Mechanical biological treatment. *This process refers to the mechanical separation of waste, followed by the treatment of the biological component through either AD, composting or biodrying processes.*
MFF	EU Multiannual Financial Framework
MEG	Monoethylene glycol. *An organic compound and a precursor to polymers. Most commonly used as a raw material for industrial applications, as an automotive antifreeze, and in the production of polyester (PET) resins, films and fibres, solvents, etc.*
MHT	Mechanical Heat Treatment. *This process is the mechanical separation of waste, followed by the heat treatment, for example, through autoclaving.*

MMA	Methyl methacrylate. *An organic compound, synthetized most commonly through the acetone cyanohydrin (ACH) process. Used in the manufacture of methacrylate resins and plastics (eg Plexiglas), and also of adhesives and sealants, advertising signs and building panels, textile finishes, etc.*
MOGD	Mobil-olefins-to-gasoline-and-distillate. *Mobil's (US Company) commercially available olefins conversion process, where methanol is used as a feedstock for gasoline and diesel.*
MSW	Municipal solid waste
MTBE	Methyl tertiary butyl ether. *An organic compound, obtained from chemical reaction of methanol and isobutylene. Used as a gasoline additive.*
NER 300	Funding programmes by the European Commission, European Investment Bank and Member States; financed through the receipts from the sale of allowances under the New Entrants' Reserve (NER) of the European Emissions Trading Scheme, for innovative low-carbon energy demonstration projects.
NNFCC	UK National Non-Food Crop Centre
NREL	National Renewable Energy Laboratory (USA)
NREU	Non-renewable energy use
NUTS	Nomenclature of Territorial Units for Statistics
PBL	Environmental Assessment Agency (Netherlands)
PDO	1,3 propanediol. *Mainly a building block for polymers, also used as a solvent and antifreeze agent. Biochemical production is via the fermentation of sugars or glycerol.*
PE	Polyethylene. *Thermoplastic polymer, the most common plastic. Mainly used in packaging (eg plastic bag, plastic films, geo-membranes, bottles).*
PEF	Polyethylene Furandicarboxylate. *A completely bio-based alternative to PET. Made by using Furan dicarboxylic acid in conjunction with bio-based monoethylene glycol (MEG).*
PET	Polyethylene Terephthalate. *Member of the polyester family of polymers. Commonly used in the production of synthetic fibers, beverage and food containers (eg plastic bottles).*
PHA	Polyhydroxyalkanoates. *Bio-polymer used in the production of bioplastics; biodegradable and relatively heat resistant.*
PHB	Poly 3-hydroxybutyrate (PHB). *Non-toxic biodegradable polymer used in the packaging industry (eg drink cans), in the production of disposable utensils and razors, and also for a variety of medical applications. Made by biological fermentation from sugars.*
PLA	Polylactic acid. *Bio-polymer used in the production of bioplastics, and also fibre applications including in textiles; biodegradable.*
PP	Polypropylene. *Thermoplastic polymer with a variety of uses ranging from the packaging and apparel industries, to automotive components and laboratory utensils.*
PUR	Polyurethane. *PUR is a compound from polymers/plastics family, with a variety of end-use applications, including car parts, insulation of buildings and refrigerators, adhesives and composite wood panels. Bio-based polyols are used for polyurethane synthesis, resulting in plastic materials with a high potential for technical substitution of petrochemical based plastics.*
PVC	Polyvinyl chloride. *Made from vinyl chloride, common form of plastic. A broad range of uses including the construction industry, medical devices (eg blood bags, feeding tubes), and various consumer products.*
R&D	Research & Development
RDP	Rural Development Programme
RED	Renewable Energy Directive
SMEs	Small and medium enterprises

SOC	Soil organic carbon
SOM	Soil organic matter
SRC	Short Rotation Coppice
SWOT	Strengths, weaknesses, opportunities and threats (analysis)
Syngas	Synthetic gas
UCO	Used cooking oil
UNECE	United Nations Economic Commission for Europe
USDA	United States Department of Agriculture
VOC	Volatile organic compounds
VDLUFA	Verband Deutscher Landwirtschaftlicher Untersuchungs- und Forschungsanstalten (Association of German Agricultural Analytic and Research Institutes)
WEF	World Economic Forum
WFD	Waste Framework Directive
WRAP	Waste Resources Action Programme
WWF	World Wide Fund for Nature

EXECUTIVE SUMMARY

The purpose of this study is to examine and review biorefinery technology options that exist to convert biomass in the form of agricultural crop and forestry residues and waste from the whole food chain into biomaterials and bioenergy. It assesses the technological options, including the sustainability of the processes involved. The study forms part of a bigger project commissioned by the European Parliament's STOA ('Science and Technology Options Assessment') office under the heading of 'Technology options for feeding 10 billion people'.

Driven largely by concerns about climate change and a more general desire to steer the economy away from dependence on non-renewable raw materials, there is an EU-wide drive to emphasise the potential of a bio-based economy (evidenced by the Bioeconomy Communication, European Commission, 2012). Added to these general concerns, the focus on the potential offered by utilising waste and residue streams is partly motivated by the experience with biofuels policy which has encountered strong criticisms about both its GHG credentials and impacts on food prices. These problems might be avoided by using wastes and residues rather than food crops.

This study therefore first assembles the evidence on the volumes of these bio-resources, the challenges for mobilising them, the technologies for their processing, and the variety of products – both energy and importantly materials, which could be produced from them. The study then addresses the issues concerning the sustainability of the processes and products which can be derived from wastes and residues, considering both their GHG impacts as well as wider environmental issues. This latter aspect is important because many of the waste and residue streams are (or could be) recycled to agricultural and forest soils; therefore the environmental implications of breaking such cycles must be understood. Finally, some conclusions and recommendations for policy are offered.

The waste and residue resources

Food wastes are composed of raw or cooked food materials, including food loss before, during or after meal preparation in the household, as well as food discarded in the manufacturing/production, distribution, wholesale/retail and food service sectors (including restaurants, schools and hospitals). They comprise materials such as vegetable peelings, meat trimmings, spoiled or excess ingredients from prepared food, bones, carcasses and organs. The estimates do not include waste from agricultural production itself.

These materials are heterogeneous in their dry matter content and composition, so their sheer mass is not a revealing statistic; the estimated energy content is more meaningful. The European Commission estimate the annual food waste arising is 89 million tonnes; this could generate 0.22 Exajoules (EJ) of energy, representing around 0.5 per cent of total EU final energy consumption of 46.19 EJ in 2011.

Four factors contribute to the difficulty of mobilising this resource. First, the absence of a harmonised definition makes regulation difficult. Second, it is difficult to bring about routine and comprehensive separation of food waste from other wastes especially at the household level. Third is the high cost of dealing with the highly diffuse sources of food waste from the very large numbers of manufacturers, processors, distributors, wholesaler, retailers and food service companies, cafes, restaurants and public canteens in schools and hospitals, and especially, of course, households. Fourth, increasing efforts are being made to prevent and reduce food waste through waste-reduction campaigns and initiatives, through the setting of bio-waste targets and possibly even future reduction targets at the EU level. This could reduce significantly the amount of food waste generated adding to the uncertainty about future availability of this waste stream, which can inhibit investment.

Agricultural crop residues arise on farms in the form of straw, maize stover, residues from sugar beet, oilseeds, grass cuttings, and pruning and cutting materials from permanent crops, and in the crop processing sector in the form of olive pits, seed husks, nut shells. By far the largest source of crop

residues is the straw and stover from grain crops (wheat, barley and maize). The estimates of the total energy value range from 0.8 to 2.64 EJ of energy potential from these residues, ie between 1.7 and 5.7 per cent of EU final energy consumption.

There are essentially two overarching challenges to mobilising these residues. Transport costs are high because the residues are highly dispersed and have high bulk and low value. This limits the range over which they can, economically, be collected for processing and makes it important that processing plants are optimally located. To perform this mobilisation requires appropriate investment in machinery and equipment, this may be beyond individual farmers and necessitate cooperative action or specialised contractors. Harvesting costs can also be high in relation to the value of the material. Second, many have existing uses and established practices, particularly for recycling organic materials back to the soil. There is poor awareness of sustainable extraction rates in relation to local conditions. There are therefore real risks that over extraction could cause detrimental reduction of soil organic matter (SOM) with knock-on effects for wider soil functionality, soil biodiversity and erosion risk.

Forestry residues are commonly divided into primary and secondary residues. *Primary* residues, which are the focus of this study, include residues accruing from cultivation, harvesting or logging activities from trees within and outside of forests. The latter includes orchards, vineyards, landscape management (including from urban and residential green spaces). *Secondary* residues accrue in the wood processing industry, such as sawdust, woodchips, black liquor. These by-products of the processing industry are already mostly utilised in a variety of uses such as fibreboards and panels, and so are not considered further here. As with agricultural residues, definitions of forest residue categories differ across studies.

The range of estimates of energy from forest residues is from 0.51 EJ to 2.7 EJ/year. This suggests that crop residues and forest residues offer similar magnitudes of potential, with a similar wide range of uncertainty, due to different assumptions about definitions, extraction rates and sustainability.

There is a risk of environmental damage if excessive forest residue extraction were to take place. This could reduce SOM, destabilise the carbon-to-nitrogen balance, increase erosion risks, and reduce nutrient availability in particular through removal of branches and tops. Stump removal can have particular negative effects on carbon stocks. In general, increased deadwood removal can have negative consequences for biodiversity. Establishing sustainability guidelines for acceptable extraction rates is therefore critical.

In short, there appears to be a significant potential bio-resource from food waste, crop and forest residues. Summing the minimum and maximum energy potentials cited by the studies summarised above, shows that these three sources offer a range of potential energy output from 1.55 to 5.56 EJ per year. The majority (over 90 per cent) of this energy is offered by the crop and forest residues. This represents an impressive three to 12 per cent of total final energy consumption, or 15 to 55 per cent of current electricity consumption in the EU. These magnitudes are, however, subject to considerable estimation issues so should only be taken as broad approximations. Also, not all this bio-resource will, or should, be used to produce energy, much should be allocated to bio-based materials. However, mobilising and exploiting these bio-resources to anything like these potentials requires significant practical, organisational and financial challenges to be overcome, and, as is explored in more detail in Chapter 4, the sustainability of these pathways is far from assured.

The technologies

The number of products, both energy and materials, which can be derived from biomass is potentially very large. However, in reality, products will be limited by three important factors: The amount and type of feedstock available, market and policy driven demand for the products, and the investment and production decisions taken on the ground.

Much of the technology for dealing with biomass is well understood and long established. Generally, the biomass raw materials will require some physical pre-treatment, for example to separate components, dry, chop, and pelletise. Then, the processing will either follow a thermochemical process (based on hydrogenation, gasification or pyrolysis) or a biochemical pathway (based on transesterification, fermentation or fractionation, the latter also serving as a type of pre-treatment).

The current market of the bio-based chemical and polymer industry is growing rapidly. In 2011, it was estimated that global bio-based chemical and polymer production was around 50 million tonnes with a market size of $3.6 billion, compared to a production volume of chemicals and polymers from petrochemical sources of 330 million tonnes globally (de Jong *et al*, 2012). Some sectors are experiencing rapid growth; for example between 2003 to the end of 2007, the global average annual growth rate in bio-based plastics was 38 per cent whilst in Europe, the annual growth rate was as high as 48 per cent in the same period.

Looking forward, the bio-based chemicals industry is developing rapidly, both in the EU and globally. Many of the chemicals already produced or planned for the near future are derived from plant sugars, either through catalytic and chemical transformation, or through fermentation by bacteria and yeasts. While some are already produced from lignocellulosic materials, particularly the pentose derived chemicals xylose, furfural, and arabinose, the larger scale commodity chemicals are currently produced from the simpler hexose sugars found in the sugar and starch food crops such as sugar cane, wheat, maize and sugar beet. This is because technical (and economic) issues associated with using lignocellulosic materials are yet to be overcome, one of the key issues being the heterogeneity of many wastes and residues.

The sustainability of bio-based products

The resource efficient use of biomass is essential given the anticipated scale-up of biomass to be used for energy purposes and bio-based products along with the growing demand for food and feed. An important part of the drive for resource efficiency is to utilise wastes and residues as potential feedstock sources instead of dedicated energy crops. Apart from striving to get most from available biomass and hence land and water resources by putting wastes and residues to productive use, another relevant consideration is to prioritise waste and residue sources and to combine several biomass applications in a cascade of uses, starting with high value and low bulk uses (such as pharmaceutical and fine chemicals) down to energy uses which have lowest unit values and greatest bulk.

Assessing the sustainability of all these pathways must always take into account that some of the wastes and residues to be used as feedstocks were previously used in ways which provided direct environmental benefits. Prime examples are the use of straw as a soil improver, the retention of forestry residues in forests to benefit biodiversity and carbon stocks, and the composting of food waste instead of recovering its energy value via anaerobic digestion. The driving forces in matching feedstock uses and products in this process should be the level of GHG savings per unit of biomass compared to using fossil based raw materials, and also the relative economic value that can be obtained from a given volume of biomass. Put simply, biomass can end up in bulk applications where high volumes of biomass are needed to generate a unit of value added – these include bioenergy but also some biomaterial uses – or in high-value applications where relatively small volumes of biomass generate high-value products.

The review of a wide range of lifecycle assessments (LCA) for different treatments for biowaste shows the superiority of AD over other pathways. Available LCAs for advanced biofuels attribute significant GHG savings potentials to these pathways. Analysis of the aggregate GHG savings potential from bio-based products shows that there may be important discrepancies between a ranking of products based on their per unit savings potential compared with their aggregate savings potential (taking into account projected production levels).

Turning to the wider environmental impacts, there is often a loose presumption that bio-based materials and products are 'natural' and so are bound to be 'greener' and kind to the environment. Such presumption is not safe. First, thorough GHG accounting has to be done, and this is the major focus of LCAs. But, when dealing with terrestrial bio-resources whose origins and extraction involve deep interventions and management of ecosystems by man, it is imperative also to consider the environmental impacts on soil, water and biodiversity as well as some broader other considerations.

The single most significant threat to sustainability from utilisation of wastes and residues concerns soil. The main issue is that increased removal of both agricultural crop and forestry residues can impact negatively on soil organic matter, soil structure and soil biodiversity. This would represent significant additional environmental pressures given that many European soils are already degraded. Research from different parts of Europe suggests that levels of soil organic carbon (SOC), the main constituent of soil organic matter (SOM), are declining on agricultural land. There is evidence that SOC in European forests has seen slight increases in some places but data are uncertain. Generally speaking, EU-wide monitoring of SOC is complicated, one reason being the lack of harmonised data.

The study identified six lessons for sustainability. First, it is imperative to maintain ***monitoring*** of the situation and the Bioeconomy Observatory proposed by the European Commission could be a useful body for this task. Second, it is important that any future policy stimulus for these technologies is conditional upon firm ***evidence of positive environmental outcomes***. Third, ***safeguards*** should be developed to ensure against environmental damage, particularly to soil quality, by the extraction of crop and forest residues. Fourth, ***more robust LCA data*** should be compiled as it becomes available on the GHG performance for advanced biofuels and bio-based materials as there are few examples commercially operating at present. Fifth, given evidence to suggest that using biomass for bio-based materials rather than burning them for energy recovery leads to higher GHG savings in many cases this suggests reviewing the ***balance of current policy support*** to bioenergy versus other biomass using product pathways. Finally, sixth, urgent consideration should be given to reviewing the ***GHG accounting framework of the Renewable Energy Directive*** which excludes soil carbon stock changes arising from residue extraction, as these are considered 'zero emission' up to their collection.

The future of an EU bio-based industry processing wastes and residues

Speaking of a new use of what was formerly considered a waste product turns a waste disposal problem into a question of raw material availability. What was formerly considered a liability which had to be disposed of with least cost, now becomes an asset which has to be mobilised and then efficiently utilised and transformed. This immediately means that waste becomes the wrong word setting up wrong thinking.

It is often the case that some of the waste material had alternative uses. This certainly applies to many agricultural wastes or residues like straw, or forest and wood processing 'wastes'. In these situations, the new technology or new set of environmental, economic or policy factors which creates the drive to mobilise the material creates competition with the existing uses. Rational resource use dictates that the now probably scarce, and certainly scarcer than formerly, resource should be allocated between traditional and new uses such that the marginal revenue in each use is equated, ie normal economic allocation rules now come into play.

Of course the new uses are likely to start at a low level and generally speaking they involve processing large-volume low-value materials so economies of scale are likely. Hence, it may take some time before the new uses can compete on level terms with traditional uses. This might, in some circumstances, warrant infant industry assistance to get these processing routes established. These will most likely be contested by the traditional users whose raw material prices are likely to rise.

However, as the new uses have effectively shifted out the demand for the raw materials, this could further worsen the terms of trade with non-market ecosystem services. That is, the supporting, regulating and cultural ecosystems services, and the biodiversity which underpins these, for which

land managers are not rewarded by the market, are likely to suffer further neglect at best or reductions at worst.

The conclusions of a SWOT analysis are that, on balance, advanced biofuels and innovative bio-based pathways based on wastes and residues show considerable potential and ***should*** be further developed, especially as Europe is already seen by some as having a lead in relevant technologies. There are sound infant industry arguments, in addition to the market failure arguments, which justify further collective action to stimulate the development of this sector. However, there are also considerable uncertainties for investors and thus a major task is to ensure transparency and better information concerning the availabilities of the waste and residue streams, the opportunities for processing, and the benefits to consumers. In addition, because, by definition, bio-based economic developments necessarily interact with ecosystems, there has to be visible assurance that the bio-products are indeed environmentally preferable with respect to GHG emissions, water, soil and biodiversity compared with their fossil-based counterparts.

The overall conclusion is thus encouragement should be given to this sector, but with enhanced transparency of all aspects of its development, and with equally strong environmental safeguards.

1 INTRODUCTION

The purpose of this study is to examine and review biorefinery technology options that exist to convert biomass in the form of agricultural crop residues and forestry residues as well as food waste to biomaterials[1] and bioenergy. It aims to assess the technological options, including the sustainability of the processes involved. The study forms part of a bigger project commissioned by the European Parliament's STOA ('Science and Technology Options Assessment') office under the heading of 'Technology options for feeding 10 billion people'.

1.1 General study context

The use of biomass resources in a wide range of industrial sectors is not new. Biomass has a very long history of use as an energy source, both for process and space heating as well as fed to animals to provide traction power. Similarly, non-energy or 'material' uses of biomass also have a long tradition. Examples are provided by the construction and furniture sectors as well as for pulp and paper and textiles. In this sense, the growing policy discussion of the 'bioeconomy' (see also Box 1 for definitions) builds on a strong foundation of well-established uses of biomass both inside and outside the food and feed sector. The renewed focus on biomass as a resource goes in hand with emerging technology options that offer new bio-based products in a range of sectors.

In the field of energy, discussions in relation to the bioeconomy focus on advanced conversion technologies that are able to process diverse feedstocks to produce liquid and gaseous transport fuels for many uses (both road and aviation). Wood is the traditional resource for the construction and furniture industries but new wood products have been developed over the years, such as the use of forest residues for plywood and fibreboard. The newest bioeconomy uses of biomass are for the manufacture of bio-based chemicals, plastics and pharmaceutical products. All such uses of biomass make use of 'biotechnologies' in their production processes, with varying sustainability credentials.

Box 1: Definitions of key terms

Biomass: biological material derived from living or recently living organisms. This definition therefore excludes fossil biomass (coal, oil and natural gas).

Bioenergy: energy extracted from biomass as defined above. This includes biomass used for heat and electricity generation (via direct combustion of biomass or through biogas from anaerobic digestion) as well as liquid biofuels for transport produced through conventional or advanced conversion routes.

Biomaterials, *bio-based materials* or *bio-based products*: non-food products and materials derived from biomass as defined above. This is to distinguish biomass-based materials from fossil, mineral, and metal-based materials, which are generally derived from non-renewable resources. Bio-based materials are often defined as excluding traditional and established products such as pulp and paper, and wood products, a definition that fits the scope of this report which covers advanced technologies and products. The biomaterials category refers to a broad range of products including high-value added fine chemicals such as pharmaceuticals, cosmetics, food additives, etc., to high volume materials such as general bio-polymers or chemical feed stocks.

[1] including bioplastics and biochemicals

Biotechnology: any technological application that uses biological systems, living organisms, or derivatives thereof, to make or modify products or processes for specific use.

Biorefinery: refers to the 'processing of biomass into a spectrum of marketable products (food, feed, materials, chemicals) and energy (fuels, power, heat)' (IEA Bioenergy Task 42).

Bioeconomy: 'encompasses the production of renewable biological resources and the conversion of these resources and waste streams into value added products, such as food, feed, bio-based products and bioenergy'. It is an economy-wide concept in the sense that it 'includes the sectors of agriculture, forestry, fisheries, food and pulp and paper production, as well as parts of chemical, biotechnological and energy industries' and one with a 'strong innovation potential' (European Commission, 2012). It is worth noting that this definition and others omit from the scope of the bioeconomy non-marketed ecosystem services, such as regulating, supporting and cultural ecosystem services.

Sources: Keegan *et al* (2013); CBD (1992); European Commission (2012; 2013); http://www.iea-bioenergy.task42-biorefineries.com.

The present study is strongly related to recent initiatives proposed to advance the European bioeconomy, such as those put forward in the Commission's communication on 'A Bioeconomy for Europe' (European Commission, 2012). The Communication makes the case for the bio-economy by referring to five 'inter-connected societal challenges' that the strategy put forward should help overcome (Box 2). It is also carried out within the context of the on-going discussion about the sustainability of bioenergy. In particular, it is questioned whether conventional biofuels produced from food and feed crops are effective in reducing greenhouse gas (GHG) emissions. Concerns relate to the effects of any direct and indirect land use change associated with using new or existing cropland for the purpose of growing biofuel crops. These land use changes may be associated with biodiversity loss and significant additional greenhouse gas emissions. The second major concern is the effects of the increased demands for agricultural crops on the level and volatility of food prices. The European Commission has published a legislative proposal in October 2012[2] to address ILUC by a set of amendments to the Renewable Energy Directive[3] and the Fuel Quality Directive[4].

[2] Proposal COM(2012)595 for a directive of the European Parliament and of the Council amending Directive 98/70/EC relating to the quality of petrol and diesel fuels and amending Directive 2009/28/EC on the promotion of the use of energy from renewable sources.

[3] Directive 2009/28/EC of the European Parliament and of the Council of 23 April 2009 on the promotion of the use of energy from renewable sources and amending and subsequently repealing Directives 2001/77/EC and 2003/30/EC, OJ L140/16, 05/06/09.

[4] Directive 2009/30/EC of the European Parliament and of the Council of 23 April 2009 amending Directive 98/70/EC as regards the specification of petrol, diesel and gas-oil and introducing a mechanism to monitor and reduce greenhouse gas emissions and amending Council Directive 1999/32/EC as regards the specification of fuel used by inland waterway vessels and repealing Directive 93/12/EEC.

Box 2: A bioeconomy for Europe – responding to five societal challenges

Ensuring food security: by *inter alia* 'developing the knowledge-base for a sustainable increase in primary production', encouraging 'changes in production and consumption patterns' including 'healthier and more sustainable diets' and supporting 'more resource-efficient food supply chains' in line with existing initiatives.

Managing natural resources sustainably: through 'productivity increases while ensuring sustainable resource use and alleviating stress on the environment'. Reaching an 'internationally shared understanding of biomass sustainability' would facilitate addressing global impacts.

Reducing dependence on non-renewable resources: to make the EU a 'low carbon society where resource efficient industries, bio-based products and bioenergy all contribute to green growth and competitiveness', whereby existing sectoral funding initiatives and policies contribute to 'help understand current and future biomass availability and demand and competition between biomass uses, including their climate change mitigation potential'.

Mitigating and adapting to climate change: by contributing to EU climate policy and the low-carbon roadmap including via 'increased carbon sequestration in agricultural soils, sea beds and the appropriate enhancement of forest resources'.

Creating jobs and maintaining European competitiveness: especially through growth in the areas of 'sustainable primary production, food processing and industrial biotechnology and biorefineries'.

Source: European Commission (2012)

1.2 Defining the scope of the study

The analysis in this report centres on the following three topics related to the European bioeconomy:

1. The mobilisation of waste and residue streams from the agricultural, forestry and food sectors;
2. Technological options to convert biomass into biomaterials and bioenergy and the state of the biorefinery industry; and
3. An assessment of the sustainability of bio-based products compared to traditional products.

As regards the type of feedstocks that are considered as part of the report, certain choices were made to define the scope which are worth summarising upfront. These choices are motivated by the specifications for the overall study[5] and the primary focus on advanced conversion technologies for the production of bioenergy and biomaterials, most of which are not commercialised at this stage. With regard to **biological waste streams**, the scope is limited to food waste. While the processing of food waste into energy via anaerobic digestion (AD) does not classify as an advanced technology[6], it is nevertheless included in this report given that one focus of the overall study is to limit waste and losses in the food system in order to enhance overall food security[7]. Recognising that a certain fraction of food waste is likely to remain unavoidable even with enhanced recycling efforts in the future, the purpose of this study is to highlight the potential of processing this waste stream via AD as a waste management option that has the potential to generate significant GHG benefits over other waste

[5] As agreed with STOA and as also set out in the project plan discussed at the kick off meeting.

[6] It is noted later on, however, that it is considered a more technically complex AD feedstock.

[7] The issue of food waste is further investigated in Study Area 4 of the 'Feeding 10 Billion' study.

management options (apart from avoidance). Another high volume biological waste stream is ***sewage sludge***. This waste stream has important potential in the spectrum of renewable energy sources, and it may also involve some slightly more advanced technology, however it also is not considered as part of this study. The reasons are that the recovery and recycling of energy, fertiliser (nitrogen and phosphate) and organic matter from human sewage creates a distinctive set of cultural, technical and institutional issues. Whilst the technical issues of heavy metal and pathogen contamination and smell can now be resolved, the cultural and institutional issues set this waste stream apart and are not pursued here. With regard to ***agricultural residues***, the specifications of the study limit the scope to crop residues, implying that animal excrements, manure and slurry, are not considered. While these are clearly important in magnitude (as set out in section 2.2.1), they were not considered necessary for further investigation in this study, given the established practices in some Member States to process them to energy via AD. Finally with regard to ***forestry residues***[8], the focus is on primary residues such as those accruing from cultivation, harvesting or logging activities from trees within and outside of forests. Secondary residues from the wood processing industry such as sawdust, woodchips and black liquor are outside of the scope. These are often already used in a range of applications for example in the panel industry or for heat and electricity generation. Given this scope for the report, it was not always possible to obtain estimates of potential quantities of wastes and residues which precisely lined-up with the boundaries defined here. Any such inconsistencies will be highlighted in the relevant sections of the report.

Chapter 2 identifies the relevant waste and residue streams from the agriculture, forestry and food sectors that have the potential to be used to produce biomaterials and bioenergy. The range of challenges and barriers that may hinder their mobilisation are also considered. This includes issues concerning recycling processes as well as logistical issues related to the transportation of biomass, the economic viability of which may be limited in cases of bulky, and often widely distributed wastes and residues.

Chapter 3 links the waste and residue streams identified in Chapter 2 to the range of potential end products, and identifies the technological options required for biomass conversion as part of the biorefineries industry. It distinguishes between thermochemical and biochemical conversion routes. This chapter also examines the state of development and potential for future development of the biorefinery industry, focussing on the current situation of biorefinery and related conversion plants producing biomaterials and/or bioenergy in Europe, with some insights into the situation worldwide.

Chapter 4 reviews the *environmental* sustainability of a range of technology pathways for both biofuels and bio-materials and brings together evidence comparing bio-based products with their 'traditional' counterparts. It includes a review of life-cycle assessments (LCAs) as well as a review of wider environmental impacts such as on water, soil and biodiversity.

Chapter 5 draws conclusions on the future for a bio-based industry in Europe based on the information gathered in the preceding chapters. It presents the strengths and weaknesses of an EU biorefinery sector based on wastes and residues and outlines the opportunities and threats the sector faces. The last part of the chapter considers what conditions and public policies may be required to ensure the optimal development of the European bioeconomy.

[8] These were not part of the original scope of the study but were included at a request by supervising MEP Vittorio Prodi.

2 MOBILISING WASTE AND RESIDUE STREAMS FROM THE AGRICULTURE, FORESTRY AND FOOD SECTORS

This chapter first identifies the waste and residue streams that are relevant for the production of bioenergy or biomaterials – focussing on food waste and agricultural crop and forestry residues. It then reviews their availability as a resource base for the bioeconomy. This considers the available literature, making use of existing systematic reviews of bioenergy potentials (Rettenmaier *et al*, 2010) and relevant recent estimates provided by specific studies. Estimates are reported in common energy units to enable comparison. This has proved challenging in the case of food waste which is typically reported in units of mass.

Having identified the main waste and residue streams, the step is to consider the challenges and barriers to their mobilisation. These include waste collection and separation, the necessary infrastructure of food waste as well as logistical challenges of mobilising dispersed crop residues. Understanding the barriers to successfully mobilising waste and residue sources is important, as they will influence the development of the associated technologies. Indeed some mobilisation challenges may well act as a barrier to investment in technological development. At the same time, reasonably advanced technologies may be a prerequisite for incentivising changes in, for example, agriculture and forestry management practices to overcome mobilisation barriers.

A number of different approaches and methodologies are used to estimate biomass potentials, which in turn lead to different concepts of 'potential', as set out in Box 3. Understanding these differences is important for understanding the practical relevance of estimates of potentials from different studies.

Box 3: Estimates of potential – estimation approaches and underlying concepts

To understand waste and residue streams and their potential to be used for industrial purposes, it is important to be precise about the terminology used to describe reported estimates of potential supply. Important and frequently encountered terms include theoretical, technical, economic and sustainable potentials. ***Different approaches*** to estimate potentials typically yield different types of potentials. Smeets *et al* (2010) distinguish between three broad approaches:

1) the resource-focused approach producing estimates of potential based on the available biomass resource base, yielding theoretical and/or technical potentials;
2) the demand-driven approach based on cost-supply analysis or energy-system modelling evaluating the competitiveness of bioenergy compared to traditional sources of energy and estimating economic potentials; and
3) integrated assessment modelling, a traditional tool for climate policy analysis that takes into account socio-economic drivers as well as physical and climatic constraints and is able to yield theoretical/technical as well as economic potentials.

In the case of studies estimating forest biomass potentials, Rettenmaier *et al* (2010) put forward 'wood resource balances' as the third category, an approach that integrates demand and supply elements by taking into account production statistics but also assumptions about consumption.

It is useful to think about the ***different potential categories*** as adding subsequent layers of constraints to the amount of biomass available. Using the example of household/consumer food waste, the *theoretical* potential of food waste could be considered as all food waste generated. However, it is clear that not all of food waste is accessible for use in energy production, due to constraints of separation and collection infrastructure and in particular the participation of households in these infrastructures. The *technical* potential can be considered as the total food waste generated, less the amount of food waste that is not properly separated and collected. The *economic*

potential of food waste can be seen as the share of the technical potential that it is economically viable to transform into energy, taking into account prevailing market conditions and policy support measures. The *sustainable* potential of food waste should take into account the order of the waste hierarchy (prioritising prevention over reuse, recovery/recycling, energy recovery and disposal)[9] and the fact that a significant proportion of food waste could be avoided and would therefore no longer be available for use in energy production. Bentsen and Felby suggest that 'as a general rule it can be expected that different potentials rank as: Theoretical > Technical > Economic > Sustainable', referring to the size of the different categories of potential (2010, p14).

Source: Own compilation

2.1 Food waste

While the residue streams addressed in the next sections may be converted for a range of energy and material uses, it can be expected that food waste will primarily be used for energy purposes in the form of biogas obtained through anaerobic digestion. Before entering into a discussion on food waste and its potential for energy use, it should be noted that at present there is ***no harmonised definition*** of food waste in Europe, or even in the literature on the topic, which complicates the process of comparing and assessing estimates for this feedstock as they are based on different definitions and assumptions.

A European Commission study from 2010 defines food waste as being composed of raw or cooked food materials, including food loss before, during or after meal preparation in the household, as well as food discarded in the manufacturing/production, distribution, wholesale/retail and food service sectors (including restaurants, schools and hospitals). It comprises materials such as vegetable peelings, meat trimmings, spoiled or excess ingredients from prepared food, bones, carcasses and organs (European Commission, 2010). The estimates in that study do not include food waste from agricultural production. In its studies on the subject, the FAO distinguishes between food 'losses' (which take place at the production, post-harvest and processing stages) and food 'waste' (which occurs at the retail and final consumption stages and relates to retailer and consumer behaviour) and only considers edible food mass to make up food losses and waste. The term food 'wastage' is used to encompass both of these elements (FAO, 2011 and FAO, 2013). In a slight variation on the FAO definition, a BCFN paper distinguishes between food losses (occurring during growth, harvesting, processing and initial agricultural transformation stages) and food waste (occurring during industrial processing, distribution and final consumption) (BCFN, 2012). In its definition of food waste, the Waste Resources Action Programme (WRAP) in the UK distinguishes between food waste that is avoidable (still edible eg slices of bread, apples, meat), possibly avoidable (eaten by some people but not others eg bread crusts, and food edible if cooked a certain way eg potato skins) and unavoidable (non-edible eg bones, egg shells, pineapple skins).

There are many different causes of food waste. In the **manufacturing/production** sector, much food waste is largely unavoidable[10] (eg bones, carcasses, certain organs), although technical malfunctions

[9] As set out in the Waste Framework Directive (WFD), Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives.

[10] It should be noted, however, that in the manufacturing stage, there are many by-products of plant and animal material processing which have always been regarded as recoverable saleable products for non-food purposes and that should therefore not be considered as available for energy recovery. Crop refiners, such as sugar and cereal mills, produce a range of animal feeds as by products (eg molasses, brewers' grains, various protein

(eg overproduction, misshapen products, product and packaging damage) also play a role. Arisings of potentially recoverable raw materials in the distribution sector may come about because of supply chain inefficiencies and issues with storage and packaging. In the **wholesale/retail** sector, they may also come about through supply chain inefficiencies, difficulties in anticipating seasonally varying demand which resulting in overstocking, marketing strategies (eg two-for-one deals), highly-stringent marketing standards, and temperature sensitivity. In the **food services** sector, sources of food waste can include over-generous portion sizes, logistical issues, cultural factors about the acceptability of taking leftovers home from restaurants, low awareness of food waste (although this is improving), and customer preferences (eg school cafeterias in particular have difficulty meeting children's preferences). Whilst it is important for consumers to maintain freedom of choice over their own food habits, the causes of **household** food waste may include inefficient use of food, differing judgements by consumers on the value of food, the exercising of personal food preferences (eg discarding apple skins, potato skins, bread crusts), misinterpretation or confusion over food date labelling (leading to food which is still safe for consumption being discarded), suboptimal storage (eg management of domestic fridges/freezers) and packaging, and socio-economic factors (eg single person households and weekly shopping habits) (European Commission, 2010).

2.1.1 Estimates of potential

Before presenting estimates available from the literature, it should be noted that estimating the amount of food waste is inherently difficult and any estimates arising should be treated with caution. It is not always clear, for example, whether differing dry matters across sources of food waste are taken into account. Also, sources of food waste vary enormously in their calorific value, protein and vitamin content (in other words in their nutrient value) and in their monetary values per tonne. Table 1 provides an overview of two of the main estimates of food waste generation that are available. Whilst the figures compiled by the European Commission and the FAO are broadly similar for the waste arising per capita from the total of distribution, food service and households, there are very different estimates for manufacturing and production because of differing definitions and data (see table notes).

Table 1: Summary of estimates of annual food waste – total tonnage and kg per capita

Manufacturing/ production	Distribution/re-tail/ wholesale	Food service/ catering	Households	TOTAL
Million tonnes/ year for 2006 (European Commission, 2010)*				
34.7 (39%)	4.4 (5%)	12.2 (14%)	37.7 (42%)	89
kg per capita/year in 2006 (European Commission, 2010)*				
70 (39%)	9 (5%)	25 (14%)	75 (42%)	179
kg per capita/year (FAO, 2011)†				
280-300 (73%)	95-115 (27%)			375-415

Source: Own compilation based on studies cited. **Notes**: Note that manufacturing /production includes agricultural waste in the FAO study, but not in the European Commission study; *estimates for the EU-27; †estimates for 'Europe and North America'

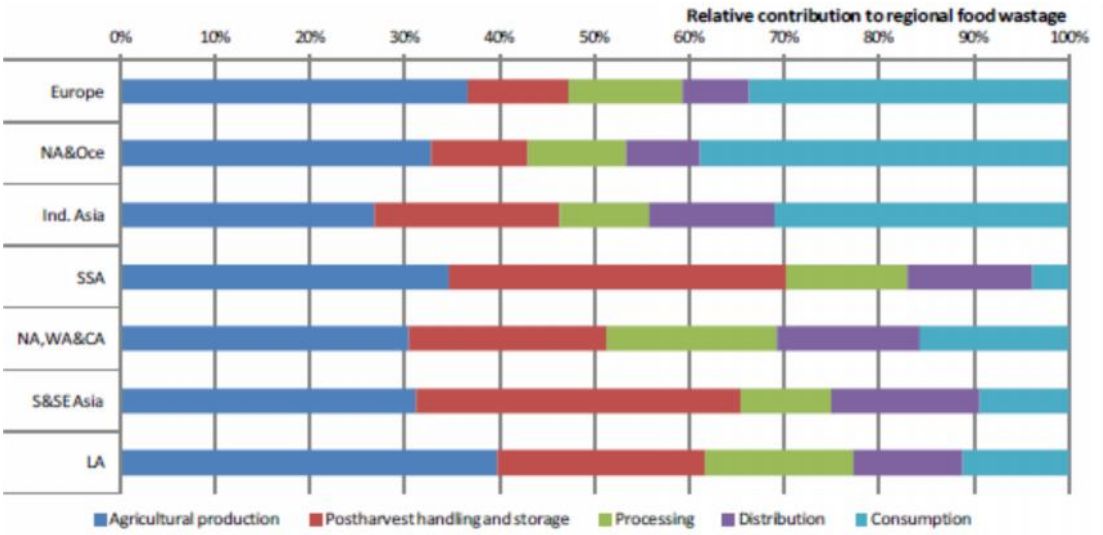
sources) and the livestock sector yields a stream of by-products that can be rendered into animal fats, part of which is used as a valuable feedstock in the oleochemical industry.

A recent study by the FAO estimates the global volume of food wastage to be 1.6 billion tonnes of 'primary product equivalents', while the total wastage for the edible part of food is 1.3 billion tonnes – out of 6 billion tonnes of global agricultural production (for food and non-food uses). Around 15 per cent of global food wastage occurs in Europe (FAO, 2013). An earlier study by the FAO estimated that roughly one third of food produced for human consumption is lost or wasted globally, with per capita food 'loss' (ie at the production, post-harvest and processing stages) in Europe and North-America of 280-300kg per year, and per capita food 'waste' (ie at the retail and consumption stages) in Europe (and North-America) of 95-115kg per year, giving a total of 375-415kg per year (FAO, 2011).

A study by the Institution of Mechanical Engineers presents similar headline estimates, stating that of global food production of four billion metric tonnes per annum, some 30-50 per cent (or 1.2–2 billion tonnes) is never eaten.

Figure 1 below, taken from the 2013 FAO study, indicates the food wastage percentages at each step of the food supply chain (FSC) for total food commodity for seven world regions. It suggests that for Europe, around 37 per cent of wastage occurs during agricultural production, around 10 per cent during post-harvest handling and storage, around 12 per cent during processing, around 7 per cent during distribution, and around 34 per cent during the consumption phase.

Figure 1: Relative food wastage, by region and by phase of the food supply chain



Source: FAO (2013). **Note:** Europe = Europe; NA&Oce = Australia, Canada, New Zealand, USA; Ind. Asia = China, Japan, Rep of Korea; SSA = Eastern Africa, Middle Africa, Southern Africa, Western Africa; NA,WA&CA = Central Asia, Mongolia, Northern Africa, Western Asia; S&SE Asia = South-Eastern Asia, Southern Asia; LA = Caribbean, Central America, South America

A European Parliament Resolution on avoiding food wastage, adopted in 2012, highlights that some estimates suggest that up to 50 per cent of healthy, edible food is lost along the entire food supply chain and becomes waste that is landfilled or disposed of in other ways[11]. The 2010 European

[11] European Parliament Resolution of 19 January 2012 on how to avoid food wastage: strategies for a more efficient food chain in the EU (2011/2175(INI)), http://www.europarl.europa.eu/sides/getDoc.do?pubRef=-

Commission study provided a best estimate that 89 million tonnes of food waste, equivalent to 179kg per capita, were generated in the EU in 2006 (European Commission, 2010). The study estimated that this food waste generation was divided between the different stages of the food waste chain as follows:

- Manufacturing/production: 34.7 million tonnes or 70kg per capita (39 per cent of total, and most of which is unavoidable);
- Households: 37.7 million tonnes or 75kg per capita (42 per cent of total, and around 60 per cent of which could be avoidable according to WRAP);
- Retail/wholesale: 4.4 million tonnes or 9kg per capita (5 per cent of total); and
- Food service/catering: 12.2 million tonnes or 25kg per capita (14 per cent of total).

The difference between the FAO and European Commission estimates may be due to several factors. For example, the FAO estimates include waste from the agricultural sector, whilst the Commission estimates do not. The FAO estimates are for 'Europe and North America', whereas the Commission estimates are more specifically for the EU-27, and production processes and consumption behaviour may vary between EU and non-EU countries.

The 2010 European Commission study also produced estimates for the amount of food waste generated in individual EU Member States, based on national data and studies where possible, and based on extrapolated Eurostat data, available trends and general assumptions where no national level data were found. This is summarised in

Table 2 below. Based on this, the highest generators of food waste in terms of absolute tonnage are the UK (14,257kt), Germany (12,258kt), Italy (10,497kt) and Poland (9,412kt); the lowest are Slovenia (144kt), Luxembourg (82kt) and Malta (31kt). However, when expressed as kg per capita, by which the data in the table is sorted, the highest food waste generators are the Netherlands (541kg/capita), Belgium (345kg), Cyprus (327kg) and Estonia (265kg); the lowest are Malta and Romania (both 76kg), and Slovenia (72kg). Overall, the EU-15 countries tend to have higher generation per capita than the EU-12 countries.

Table 2: Estimated total food waste generation in the EU Member States, total kilo tonnes (and percentage) and kg per capita (arranged by the last column)

Member State	Manufacturing food waste		Household food waste		Retail/ wholesale food waste		Food service/ catering food waste		Total (kt)	Total (kg per capita)
	kt	%	kt	%	kt	%	kt	%		
N'lands	6,412	73%	1,838	21%	145	2%	446	5%	8,841	541
Belgium	2,312	64%	935	26%	93	3%	287	8%	3,627	345
Cyprus	187	75%	48	19%	7	3%	9	4%	251	327

//EP//TEXT+TA+P7-TA-2012-0014+0+DOC+XML+V0//EN&language=EN. Note that this document cites the study prepared by the European Commission (2010) at the start of the Resolution.

Member State	Manufacturing food waste		Household food waste		Retail/ wholesale food waste		Food service/ catering food waste		Total (kt)	Total (kg per capita)
	kt	%	kt	%	kt	%	kt	%		
Estonia	237	67%	82	23%	12	3%	25	7%	356	265
Poland	6,566	70%	2,050	22%	339	4%	457	5%	9,412	247
UK	2,519	18%	8,300	58%	366	3%	3,000	21%	14,257	236
Ireland	466	51%	292	32%	37	4%	115	13%	911	216
Sweden	601	31%	905	47%	110	6%	299	16%	1,915	212
Austria	571	33%	785	45%	267	15%	104	6%	1,726	209
Finland	590	59%	215	22%	47	5%	144	14%	996	189
Italy	5,663	54%	2,707	26%	522	5%	1,605	15%	10,497	179
Hungary	1,157	66%	395	22%	90	5%	121	7%	1,763	175
Luxemb'g	3	4%	63	77%	4	5%	13	16%	82	175
Germany	1,849	15%	7,676	63%	733	6%	2,000	16%	12,258	149
Denmark	102	13%	495	63%	46	6%	148	19%	791	146
France	626	7%	6,323	74%	562	7%	1,080	13%	8,591	136
Spain	2,171	37%	2,137	36%	389	7%	1,195	20%	5,892	135
Portugal	632	45%	385	28%	94	7%	289	21%	1,400	132
Lithuania	222	55%	111	27%	30	7%	41	10%	404	119
Slovakia	348	58%	136	23%	48	8%	65	11%	596	111
Latvia	126	50%	79	31%	20	8%	27	11%	253	110
Bulgaria	359	44%	288	36%	69	9%	92	11%	808	105
Czech Republic	362	44%	254	31%	91	11%	123	15%	830	81
Greece	73	8%	413	46%	99	11%	304	34%	889	80
Malta	0.3	1%	22	71%	4	13%	5	16%	31	76

Member State	Manufacturing food waste		Household food waste		Retail/ wholesale food waste		Food service/ catering food waste		Total (kt)	Total (kg per capita)
	kt	%	kt	%	kt	%	kt	%		
Romania	488	30%	697	43%	192	12%	259	16%	1,635	76
Slovenia	42	29%	72	50%	18	13%	12	8%	144	72
EU-27	34,756	39%	37,702	42%	4,433	5%	12,263	14%	89,154	179

Source: European Commission (2010); totals may not add up to 100% as all figures rounded to the nearest kilo tonne for presentation purposes. **Note**: These are 'best estimates' at the time available, mainly based on 2006 data from Eurostat but updated by some more recent national sources.

Table 3 uses a different method to estimate the possible total food waste generated in the EU-27 in recent years up to 2010. This is calculated from Eurostat data, based on 'total animal and vegetal wastes' (EWC_09, which may include some green wastes in addition to food waste, but which forms the most reliable waste category for which all MS have data) minus 'animal faeces, urine and manure' (EWC_093). The figures used are for all economic sectors, plus households.

Table 3: Possible total food waste in the EU-27, 2004-2010

Year	Possible household food waste, kg per capita	Total possible food waste, kg per capita	Possible total food waste, Mt
2010	52	184	92.2
2008	48	195	96.9
2006	43	235	116.2
2004	33	240	117.5

Source: Eurostat, Generation of waste (env_wasgen), http://epp.eurostat.ec.europa.eu/portal/page/portal/waste/data/database, accessed 20/12/12

This data suggests that total potential food waste has been steadily diminishing in recent years, falling by 23 per cent between 2004 and 2010. However, it is worth noting that over the same period, the amount of potential food waste generated per capita by *households* appears to have been steadily growing, increasing by nearly 58 per cent between 2004 and 2010. Indeed, the European Commission (2010) suggested that if no further action is taken to address food waste, the amount generated in the EU will increase by 40 per cent between 2006 and 2020, to around 126 million tonnes. The modelling used in the study was based on assumptions relating to increases in population (of around 4 per cent) and wealth (of between 1.5 and 5 per cent annually), which would contribute to associated increases in food waste.

Again, the differences between the set of Eurostat statistics in Table 3 and those in the FAO and European Commission studies are likely to be due to varying definitions of food waste (in particular the fact that the Commission study does not take into account the agricultural production phase) and to different methods for data collection. All the studies and data sources used for this report

acknowledge that data is not always complete or comparable, and that various assumptions and extrapolations have to be made when analysing data.

When analysing the potential of using food waste as an energy source, it should be noted that efforts are being made (and are expected to be strengthened in the future) to reduce food waste. Therefore, it is difficult to accurately predict the future potential of food waste as an energy source.

Because the physical composition of different waste streams is so different the sheer mass of waste does not reveal much. It is important also to focus attention on the energy potential of food waste. Food waste is not suited for direct energy generation through conventional combustion processes, because it has high moisture content. Biological technologies such as anaerobic digestion (AD) are therefore required to extract the maximum energy content. The literature suggests that around 70-80 per cent of food waste is moisture or water. Curry and Pillay (2011) posit that the amount of volatile solids (VS, the portion of solids with calorific value) in food waste is around 90-95 per cent of the total solids (dry material) or 28-29 per cent of the wet weight. They also point out that food waste has a higher yield of biogas per dry tonne than most other AD substrates (eg 15 times higher than cow manure).

Curry and Pillay (2011) suggest that through anaerobic digestion, an average dry tonne of food waste has the potential to generate 367 m^3 of biogas (65 per cent methane and 35 per cent CO_2) with an energy content of 6.25 kWh/m^3. Applied to the FAO figure of 1.3 billion tonnes of global food waste generated per annum, this would generate 894.6 TWh annually or 3.22 EJ[12]. This represents almost 5 per cent of total global electricity use (20,181 TWh) in 2008.

Applying the same formula, the 89.15 million tonnes of total food waste generated in the EU (according to the European Commission, 2010) would generate 61.3 TWh or 0.22 EJ. This assumes that the food waste figures are in wet tonnes. The 0.22 EJ represent around 2.2 per cent of total EU electricity use in 2011 (9.96 EJ) or 0.5 per cent of total EU energy consumption in 2011 (46.19)[13].

2.1.2 Potential for mobilisation and barriers

There are several specific challenges and barriers facing the mobilisation of food waste. These include issues to do with waste definitions, the separation of food waste and its collection, including the diffuse sources of food waste. On the positive side, food waste is a suitable AD substrate in its own right without the need for co-digestion with other categories of feedstock such as energy crops. This is important from a sustainability point of view. The exclusive use of food waste in AD does, however, require a range of food waste types to be used as a substrate simultaneously in order to achieve effective anaerobic digestion and hence good biogas yields. At the same time, food waste is also, technically, a suitable feedstock for co-digestion with other substrates such as manure and slurry[14]. This could therefore be an interesting option to reduce reliance on energy crops such as maize as co-substrates for AD of manure and slurry.

However, the use of food waste as a feedstock is ***more technically complex*** than for many other common AD feedstocks, making its processing more costly. Also, the potential requirement for front-end processing of food waste prior to anaerobic digestion and also technical and operational

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[12] Calculated as follows: billions tonnes of food waste * typical percentage of volatile solids in food waste * m^3 of biogas generated per dry tonne of food waste * kWh of energy per m^3 of biogas = TWh generated (1.3 billion tonnes * 0.3 * 367 m^3/ tonne* 6.25 kWh/ m^3 = 894.6 TWh). TWh are multiplied by 0.0036 for conversion into EJ.

[13] Eurostat (2013) EU-27 final energy consumption (of electricity) (data code B_101700)

[14] Andrew Needham (Biogen), *pers comm* (June 2013)

compliance with legislative requirements may act as barriers to mobilisation of this feedstock for its exclusive use or for its co-digestion with manure or slurry on farms[15].

With regard to establishing the amount of food waste available, the European Parliament Resolution on avoiding food wastage points out that there is ***no harmonised definition*** of food waste in Europe, and specifically notes that a separate definition of food residuals for biofuels or biowaste would be useful to identify waste that can be reutilised for energy purposes[16,17]. The European Commission (2010) also concluded that reliable statistical data and time series for all Member States on food waste are crucial, to allow for more robust and reliable estimates and forecasting to inform effective EU and national level policy-making and action on the issue. The lack of reliable data illustrating the extent of food waste may provide a barrier to the creation or further development of the infrastructure and/or technologies needed to exploit this source to its maximum potential.

There are also issues relating to the ***separation*** of food waste from other types of waste. Food waste may be separated at source from other types of waste, mixed with other organic (notably garden) waste, or mixed with unsorted or residual household/municipal waste (the 2010 European Commission study estimated that at least 8.4 per cent of municipal waste is composed of food waste). A proportion of food waste may also be composted at home, disposed of via the sewer (usually via the kitchen sink) or fed to animals. The way in which food waste is separated and disposed of clearly has an impact on the ease with which it can be collected and used for energy generation, impacting on its potential. Source separation and separate collection of food waste would provide the greatest potential for its use, whereas home composting, disposal via the sewer or feeding to animals removes it from the potential stream altogether. Home composting (provided the compost is then utilised) and feeding food waste to animals are effective reuse routes so it is preferable not to consider this material to be waste.

The ***diffuse sources*** of food waste provide a challenge with respect to the separate collection of this waste stream and also make it more difficult to find a suitable location for a food waste AD plant, with the challenge of sourcing an adequate quantity of food waste potentially exacerbated by competition between plants. Food waste is generated by households, manufacturers, processors, distributors, wholesalers, retailers and food service companies. There are a great number of each of these, in particular households, shops, restaurants, schools and hospitals. The more numerous and dispersed sources tend to produce the smallest quantities of waste materials. This makes it difficult to set up efficient separate collection systems for food waste, both in practical and financial terms. Whilst some separate food waste collection infrastructure have been developed in some Member States, these are

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[15] In the UK, for example, the need for secondary containment, odour control and separation of 'clean' and 'dirty' areas is a legislative requirement for food waste processing, but not for AD of slurry, manure and crop based feedstocks. These additional requirements would make it potentially economically unviable to co-digest food waste and animal wastes on farms (Andrew Needham (Biogen), *pers comm*, June 2013).

[16] European Parliament Resolution of 19 January 2012 on how to avoid food wastage: strategies for a more efficient food chain in the EU (2011/2175(INI)), http://www.europarl.europa.eu/sides/getDoc.do?pubRef=-//EP//TEXT+TA+P7-TA-2012-0014+0+DOC+XML+V0//EN&language=EN

[17] The EU FUSIONS project, funded by the European Commission's DG RTD, is currently working towards proposing a definition of food waste in late 2013. This will take into consideration issues such as whether to include only edible or edible and inedible fractions, and how to take into account resources and raw materials which could be eaten but are currently not. The proposed definition is likely to use the term 'food wastage', as this can encompass both food losses and waste, and would not conflict with the legal EU definition of waste. EU FUSIONS is also looking to identify system boundaries for the food chain (ie where the food chain starts and ends): http://www.eu-fusions.org/.

not adequate to provide complete and comprehensive coverage for the separate collection of this waste stream across the EU.

A further potential barrier to the mobilisation of food waste as a source of energy is the fact that increasing efforts are being made to ***prevent and reduce*** food waste. Many efforts are being made to encourage less wastage through waste-reduction campaigns and initiatives (eg the 'Every Crumb Counts' Joint Food Wastage Declaration, a voluntary agreement made in June 2013 by ten trade associations representing different parts of the food chain[18]), through the setting of biowaste targets and possibly even future reduction targets at the EU level. This has the potential to reduce significantly the amount of food waste generated, which adds to the uncertainty about the future potential volume of the waste stream. According to the Commission's Directorate General for Health and Consumers, up to 60 per cent of household food waste discarded in Europe could be avoided, with 20 per cent of this food being thrown away simply due to confusion about food date labelling (European Commission, 2011a). The European Parliament Resolution on avoiding food wastage called on the Commission to deliver specific initiatives targeting food waste, and to create specific food waste prevention targets for Member States, as part of the waste prevention targets to be reached by Member States by 2014[19]. While prevention of food waste clearly is the highest priority, the uncertainty this creates may inhibit investment in the infrastructure and technologies needed to exploit food waste as an energy source.

2.2 Agricultural crop residues

Agricultural residues are assessed in a range of studies, mostly as part of biomass for energy resource assessments (see Box 4 for a selection of studies). They are often divided into primary and secondary residues. *Primary* residues refer to those residues arising directly from agricultural activities and can include dry and wet residues such as livestock slurry and manure, crop residues, grass cuttings and pruning and cutting materials from permanent crops. *Secondary* agricultural residues are those stemming from the processing of agricultural produce, such as olive pits, seed husks, nut shells and slaughter wastes (Elbersen *et al*, 2012)[20].

In line with the scope of the study (see section 1.2), this report limits the consideration of agricultural residues to crop residues. These represent over a third of total agricultural residues in 2004, increasing to over 50 per cent in 2020[21]. Manure is another important agricultural residue, whose importance, however, is projected to decrease (Figure 2). The most appropriate way of converting manure into energy is via anaerobic digestion, an established conversion route not further considered in the context of this study as was set out earlier. Crop residues include:

- Cereal straw;
- Sugar beet residues;
- Maize stover;

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[18] http://fooddrinkeurope.eu/industry-in-focus/food-wastage-declaration/

[19] European Parliament Resolution of 19 January 2012 on how to avoid food wastage: strategies for a more efficient food chain in the EU (2011/2175(INI)), http://www.europarl.europa.eu/sides/getDoc.do?pubRef=-//EP//TEXT+TA+P7-TA-2012-0014+0+DOC+XML+V0//EN&language=EN

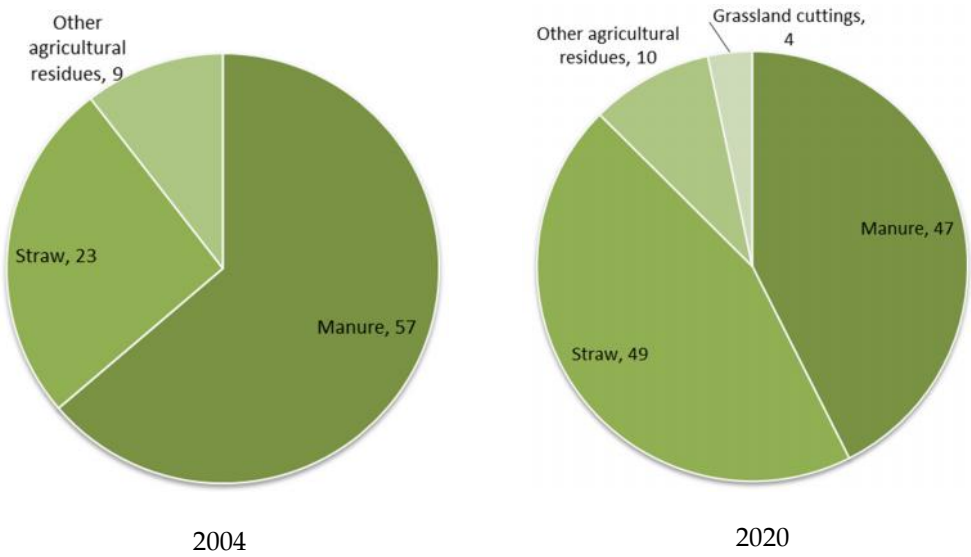
[20] Though this classification could be debatable and some of the sources included under secondary residues according to this definition may be considered waste from the food processing sectors in other studies.

[21] The large increase in straw potential from 2004 to 2020 is explained by the simultaneous increase in cereal production and decrease in livestock farming (and the associated decline in straw demand for bedding). The underlying projections for the agricultural sector have been modelled by the CAPRI model.

- Residues from the cultivation of other crops such as sunflower and rapeseed; Biomass arising from the pruning and cutting of permanent crops (orchards, vineyards etc)[22].

Despite this focus, it is not always possible to distinguish the potential of crop residues distinct from agricultural residues more generally from the available literature.

Figure 2: Estimates of potential of agricultural residues (EU-27, in Mtoe)



Source: Own compilation based on Elbersen *et al* (2012). **Note**: Other agricultural residues refer to cuttings and prunings of permanent crops such as orchards, vineyards and olives. Grassland cuttings refer to potential cuttings from abandoned agricultural grassland to (no figures provided for 2004).

2.2.1 Estimates of potential

This section looks at estimates of potential for crop residues as well as for total agricultural residues, where those are not distinguished further. Box 4 provides an overview of a selection of European studies estimating potentials and a detailed review study. The different studies reviewed here estimate that crop residues are in the range of 0.82 and 2.64 EJ/year[23]. This broad range includes current and projected 2020 estimates. The upper end of this range do appear to offer a significant potential contribution to current final energy (six per cent) or final electricity (26 per cent) consumption in the EU. However, to reach these potentials would require overcoming a set of barriers to mobilisation (section 2.2.2) and would raise important questions with regards the impacts of residue extraction on soil quality and biodiversity in particular (further discussed in section 4.3). An even wider range of up to 0.8 to 3.57 EJ/year is reported for total agricultural residues (which may

[22] Some studies consider prunings and cuttings to be part of forestry residues (or residues from other wooded land).

[23] To put these figures into perspective: final energy consumption in the EU-27 in 2011 was 46.19 EJ and final electricity consumption was 9.96 EJ according to Eurostat (Eurostat code B_101700, label 'final energy consumption').

include manure). A more detailed break down of the evidence on energy potential from agricultural residues is set out in Table 4 and in the remainder of this section.

Table 4: Summary of results for agricultural (crop) residues from selected studies (EJ/year)

	BNEF (2010)*	Elbersen et al (2012)	
	2020	2004	2020
Crop residues	2.02 / 2.64	1.35	2.49
DBFZ and Oeko-Institut (2011) range of straw estimates:			
Min-max	0.82 - 1.83		
Rettenmaier *et al* (2010) ranges of total agricultural residue estimates:			
Min-max for 2010-2019	0.8 - 3.57		
Min-max for 2020-2029	1.02 - 3.2		

Source: Own compilation based on the cited studies. See also Table 20 (Annex 1) for a comprehensive overview reporting results in different units (energy and mass). **Notes**: *all figures are for the 'base case'. The two reported figures refer to crop residues excluding and including sugar beet residues, respectively.

Box 4: European projects and studies estimating or reviewing crop residue potentials

EEA (2006): This earlier, influential study by the European Environment Agency assessed the amount of biomass technically available in Europe from the agriculture, forestry and waste sectors while respecting a set of environmental criteria.

BEE project [Rettenmaier *et al*, 2010]: The aim of the EU funded Bioenergy Europe project[24] is to 'improve the accuracy and comparability of future biomass resource assessments for energy'. As part of the project outcomes, Rettenmaier *et al* (2010) have compiled a 'Status of Biomass Resource Assessments' including a comparative analysis of around 150 studies at different spatial scales estimating biomass potentials. The review covers all studies estimating crop residue potentials that had been published at the time and which are not listed separately here.

German Biomass Research Centre (and partners) [BMVBS, 2010]: A study commissioned by the German government (BMVBS, 2010) has investigated biomass potentials from crops as well as residues for Germany as well as globally. One focus of the study is on the spatial impacts of increased bioenergy usage on the regional scale and how regional planning can help in promoting sustainable bioenergy solutions.

Bloomberg New Energy Finance [BNEF, 2010]: In a study commissioned by the commercial companies Novozymes and DMS, BNEF (2010) have looked into the potential for 'Next-generation ethanol and biochemicals' and provide a technical assessment of residue availability from agriculture, forestry and municipal solid waste (MSW).

Biomass Futures project [Elbersen *et al*, 2012]: EU funded project[25] with one work package focusing on biomass supply and availability. In this context, Elbersen *et al* (2012) compiled an 'Atlas of EU biomass potentials', including some estimates from previous studies as well as newly

[24] http://www.eu-bee.com (funded by the European Commission under FP7)

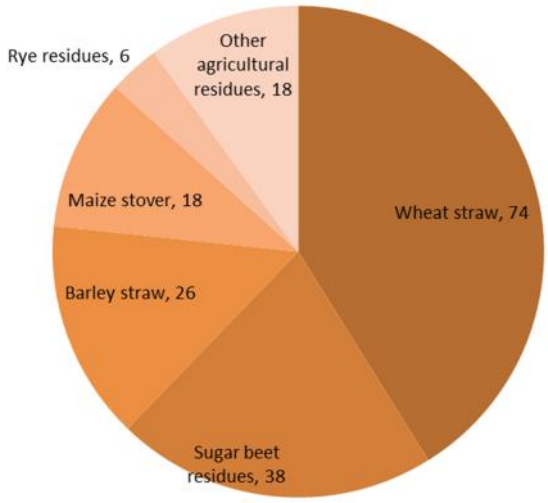
[25] http://www.biomassfutures.eu/ (funded by the European Commission under the Intelligent Energy Europe programme)

modelled potentials for 2004, 2020 and 2030. The impacts of sustainability criteria on biomass availability are investigated as well. Results are available for NUTS2 level in most cases and are visualised in the form of biomass potential maps.

Source: Own compilation

In order to understand better the relative importance of different crop residues, Figure 3 shows the BNEF estimate, given prevailing cropping patterns, that wheat straw is by far the single most important source of crop residues. When other cereals (wheat, barley and rye) are taken into account, cereal straw as a whole is projected to account for roughly 60 per cent of all crop residues by 2020. Most studies estimating agricultural residues potential do not provide a breakdown according to feedstocks as shown in Figure 3, but provide more aggregated results. At the same time, where figures are reported for a certain biomass category, for example, straw potentials, these are not always comparable given that 'straw' is understood to comprise residues from different types of crops in different studies[26].

Figure 3: Estimates of potential of crop residues in 2020 (EU-27, million tonnes)



Source: Own compilation based on BNEF (2010). **Note**: These estimates are not to be compared to those in Figure 2 given the different units. Figures from different studies are made comparable further down this section.

A comprehensive review was compiled as part of the EU BEE project (Rettenmaier *et al*, 2010). Out of the 150 studies reviewed by the overall project for different biomass categories, six selected studies are examined in detail and re-calibrated in order to make their results on agricultural residues comparable at the EU-27 level. The results of this exercise are summarised in Table 5, although it should be noted that the majority of results fall within a narrower range of 1.5 to 2 EJ/year.

[26] Unreported results for different crop residues in the EU-27 from BMVBS (2010) summarised in a study by DBFZ and Oeko-Institut (2011) confirm the dominant role of wheat straw. This study does not consider sugar beet residues, however.

Table 5: Estimates of potential of agricultural residues for the EU-27

	2000-2009	2010-2019	2020-2029	2030-2039	>2050
Minimum (EJ/yr)	0.11	0.8	1.02	0.9	0.6
Maximum (EJ/yr)	2.06	3.57	3.2	2.84	

Source: Rettenmaier *et al* (2010), Table 59. **Note**: These ranges cover results for different scenarios from six selected studies that have been re-calibrated by the authors in order to enable comparison (see Annex 1 for details on the calibration process).

These figures are not focussed exclusively on crop residues, and also include studies that consider manure as part of agricultural residues. In order to complement these figures, DBFZ and the Oeko-Institut (2011) reviewed a range of studies that focus on straw potentials. Some of the studies reviewed included those examined under the BEE project, but a more recent study (BMVBS, 2010) was also added. This review yields a range of 50 and 110 million tonnes of *straw* dry matter per year, or between 0.82 to 1.83 EJ/year (unspecified for which year, as the modelling horizon varies across studies). Given the focus on crop as opposed to agricultural residues more generally, reviewed estimates are lower. The study by Bloomberg New Energy Finance (BNEF, 2010) (not incorporated into the reviews above), estimated the potential to be 180 million tonnes or 2.93 EJ/year in 2020[27], ie at the high end or even above ranges reported above[28].

Further recent estimates for European biomass potentials are not covered by the reviews referred to above are available for both straw and other agricultural residues from, for example, permanent crops[29] (Elbersen *et al,* 2012). Both categories together represent a potential of 83 million tonnes in 2004 growing to 153 million tonnes in 2020 (or 1.35 EJ/year in 2004 to 2.49 EJ/year in 2020). The large increase is due mainly to changes in straw availability resulting from an increase in cereal production and a decrease in livestock farming (see also Figure 2).

The straw potentials are estimated using a methodology developed by the JRC (JRC and CENER, 2007; Scarlat *et al*, 2010) which are applied to crop production figures modelled by CAPRI to obtain 2020 and 2030 projections. Rather high straw extraction rates of 40 per cent (for wheat, rye, oats and barley) to 50 per cent (for other crops) are assumed. However, further reductions are made from this to account for existing uses (bedding and mushroom production), so it is not entirely clear what the ultimate extraction rate of straw for energy is (see also Box 5 for a discussion on sustainable extraction rates).

Spatially explicit results are available in the form of maps giving a useful visual representation of the considerable regional variation in the agricultural residue potential across the EU (Elbersen *et al*, 2012).

[27] Considering the results for cereal straw only, these still fall beyond the upper range of estimates reviewed by DBFZ and Oeko-Institut (2011) of 50-110 million tonnes.

[28] The study uses a rather conservative straw extraction rate (25 per cent of residues are harvested; out of those harvested 30 per cent are assumed to have existing uses) but rather optimistic, linearly extrapolated crop yield assumptions towards 2020, Table 19 in Annex 1 provides further details on the assumptions in the BNEF (2010) study.

[29] Straw includes the crop residues from wheat, rye, oats and barley as well as rice, and maize, sunflower and rapeseed. Other agricultural residues comprise 'woody residues of fruit trees, nuts and berry plantations, olives, citrus and vineyards'.

The variation follows existing and estimated future patterns of agricultural activities. The top cereal producers are those with the highest straw potential (see

Figure 21 in Annex 1). With regard to other residues, those from olive cultivations and vineyards dominate, although these are restricted mostly to Southern Europe.

The results reported in this section highlight the rather large ranges found across studies. The three main reasons for deviation in the results identified by Rettenmaier *et al* (2010) are related to the chosen 'biomass type', 'methods and approaches' and 'time frame'. Other sources of variation include assumed extraction rates. These are set out in Box 5.

Box 5: Sources of variation in estimates of potential

Biomass type: The boundaries of what agricultural residues constitute are not defined uniformly and in some instance include wood waste and manure, while in other cases only cereal crop residues are included[30];

Methods and approaches: Different studies make use of different concepts of 'potential', such as theoretical, technical, economic or sustainable and the concepts themselves may be interpreted differently (see also Box 3). Related to this is the fact that studies differ with respect to the restrictions modelled such as sustainability considerations constraining potentials and the role of competing uses[31];

Time frame: Different studies work with different projection periods, estimating for example current, 2020 or 2030 potentials. The evolution of estimates of potential over time depends on a range of factors. Future cropping patterns are important when estimates are derived from a resource-focused approach (given that crop residue availability follows directly from the level of crop cultivation). When economic considerations are taken into account including relative costs of bioenergy sources, this will have a bearing on the results. Increases in future fossil energy prices make alternatives, including bioenergy, more attractive therefore increasing economic potential estimates that take such considerations into account. These issues are discussed by Rettenmaier *et al* (2010) using the examples of some of the studies reviewed; however, they conclude that the impacts of parameters that change over time on the evolution of estimates of potential are far from clear (see further discussion below). Searle and Malins (2012) argue that future estimates of crop potentials needs to take into account changes in the harvest index factor, ie the ratio between grain output to total plant biomass. Projecting residue potentials into the future usually relies on future yield estimates. However part of, for example, wheat yield increases are derived from increasing the harvest index factor, implying that future crop residue increases are proportionately smaller than future grain yield increases.

Of further importance are the ***assumed extraction rates*** for crop residues (discussed further in Section 4). Crop residues already have existing uses for other (commercial) purposes beyond their potential use for energy, some of which can help deliver ecosystem services. These include the role of residues in maintaining and improving soil quality and importantly soil organic matter; the use of straw in livestock rearing (bedding and feed); as well as uses in horticulture and building (Kretschmer *et al*, 2012, provide a comprehensive discussion). A sustainable level of extraction

[30] Table 54 in Rettenmaier et al (2010, p126) provides details on the residue streams included in the different studies reviewed.

[31] See Table 52 in Rettenmaier *et al*, (2010, p124) for an overview of types of potentials and constraints modelled.

should take these existing uses into account. With regard to cereal straw, the most important source of crop residues, WWF (2012) refer to ranges from 20 to 40 per cent that could be sustainably extracted, though detailed assessments are lacking. Consultation of agricultural experts in selected EU countries suggests a level of 25 to 30 per cent, whereas EEA (2006) suggest a slightly higher level of 33 to 37 per cent (Kretschmer *et al*, 2012)[32].

Source: Own compilation

2.2.2 Mobilisation and its barriers

To mobilise crop residues requires both the collection of residues as well as their transport. ***Transporting agricultural residues*** is usually feasible only over short distances because they are bulky with a low energy density, ie an unfavourable energy content to weight ratio. Transporting them to a processing plant is only economically (as well as environmentally) viable for smaller distances requiring lower transportation fuel inputs. This is a challenge because agricultural residues are highly dispersed; this means that the siting of processing plants and the availability of residue sources in their surroundings are important considerations.

Existing uses and established practices are important in determining the harvest and collection of agricultural residues. In the case of crop residues, good practice dictates that a certain share should be left *in situ*, ie on the field, to maintain soil organic matter and wider soil quality (eg Kretschmer *et al*, 2012; WWF, 2012). The required levels of *in situ* use are highly locally specific, depending on soil quality and climatic parameters. This, in turn, represents a barrier to the mobilisation of residues as farmers may be unaware of the sustainable extraction rates. Other existing uses within and outside of the agricultural sector were mentioned above as limiting the available potential for the biorefinery sector and are summarised in detail for cereal straw in Kretschmer et al (2012)[33]. The ***lack of suitable machinery*** for the collection of straw is a further barrier to harvest and collection, but one that is rather of a short-term nature and that could be overcome by investment if the economics for it are favourable or by the use of contractors. Also some broader economic considerations may impede the marketing of straw beyond the agricultural sector. Box 6 provides a summary of these issues in relation to straw, the dominant crop residue in the EU.

Another issue raised is the ***prohibitive costs of crop residues as a resource*** (Searle and Malins, 2012). A US study[34] found the cost of harvesting crop residues to be four times the price bioenergy plants are willing to pay. It is possible, however, that biorefineries that produce higher value products such as platform chemicals could afford to pay higher prices for biomass than bioenergy plants. Energy sector

[32] While these studies refer to the shares of straw available for *energy* production, they are nevertheless considered valid for the context of this study given the almost inexistent use of straw for other biorefining activities currently and/or in the past, so that resources used in biorefining have not already been subtracted from sustainable potentials. Hence, the potential for energy from such studies can be interpreted as a potential for energy and materials. One exception is BNEF (2010) who explicitly account for a small share of future straw use for bio-chemicals when reporting the potential for the energy sector.

[33] Searle and Malins (2012) discuss that several of the (mainly global) biomass potential studies they reviewed do not appropriately consider mobilisation challenges and existing uses as a barrier and correct these studies' estimates accordingly.

[34] Committee on Economic and Environmental Impacts of Increasing Biofuels Production, U.S. National Academies National Research Council, Renewable Fuels Standard: Potential Economic and Environmental Effects of U.S. Biofuel Policy, (2011), page 447.

modelling[35] similarly projects that the EU's agricultural residue potential will remain heavily underutilised up to 2020 and 2030, with only about 11 per cent of the potential being used. Uslu and van Stralen (2012) explain this lack of mobilisation by 'technical obstacles in transportation and combustion processes and related costs' (p12).

Box 6: Summary of agricultural sector barriers to mobilising straw

Kretschmer *et al* (2012) summarise the barriers to building up straw supply chains within the agricultural sector as follows:

- Lack of appropriate infrastructure, particularly specialist machinery for bailing (this is more a short-term barrier that can be overcome by investment or the use of contractors);
- Natural and climatic conditions that determine (straw) yields as well as sustainable extraction rates so as to maximise soil organic content and other soil quality parameters;
- Competing existing uses of straw and farming practices which farmers may be reluctant to give up (for example those that form part of traditional mixed farming systems). One explanation for this might be a higher economic value of using straw on-site within the farming system (compared to the price of alternatives) and financial support for the use of straw as a soil improver (provided under Rural Development Policy in some Member States);
- Underdeveloped markets which favour 'quick disposal' strategies such as ploughing in or even burning of straw (though the latter as been banned in most EU Member States) and lack of information about appropriate straw prices;
- Lack of information and guidance for farmers on the appropriate use of straw in relation to the sustainable management of soils resulting in ignorance about the levels of surplus straw that could be sustainably mobilised.

Source: Kretschmer *et al* (2012)

In terms of what ***solutions that might be put in place to overcome barriers***, Kretschmer *et al* (2012) suggest that existing programmes and guidance tools under EU agricultural policy can be used in order to improve understanding about the level of *in situ* use of crop residues needed and those available for extraction. Given the local specificity of some of the mobilisation related issues, above all the right amount of straw left *in situ*, regional approaches to biomass development are being promoted as a planning concept that would allow taking into account sustainable limits of residue availability and link these to the siting of bioenergy/biorefinery plants. BMVBS (2010) have investigated this approach at the example of a region within Germany and promote a biomass development concept as a regional planning tool. Kretschmer *et al* (2011) analysed the potential of an environmentally responsible bioenergy sector in the UK whose development would require regional oversight to match biomass demand and supply. Furthermore, cooperative arrangements of, for example, farmers forming producer groups or associations that would then market their residue harvest to merchants ('middle men') or even a group of farmers investing in bio-refinery capacity jointly could be envisaged. Rural development policy can play a role in supporting supply chain functioning (Kretschmer *et al*, 2012; Voytenko and Peck, 2012).

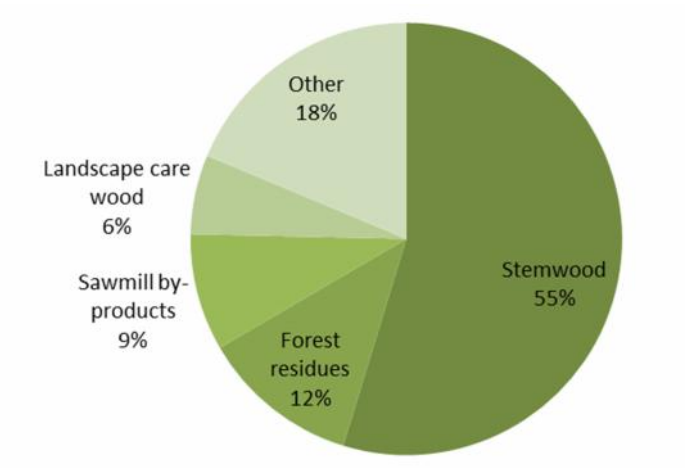
[35] As part of the Biomass Futures project taking as its basis the biomass potential estimates by Elbersen *et al* (2012).

2.3 Forestry residues

This section provides a short review of forestry residues potentials, considered as an important resource for the biorefining sector. Forestry residues are commonly divided into primary and secondary residues. *Primary* residues, which we focus on here, include residues accruing from cultivation, harvesting or logging activities from trees within and outside of forests. The latter includes orchards, vineyards, landscape management (including from urban and residential green spaces). *Secondary* residues accrue in the wood processing industry, such as sawdust, woodchips, black liquor[36]. As with agricultural residues, definitions of forest residue categories differ across studies[37].

With regard to the relative size of different categories within the forest biomass category, the EUwood study[38] (Mantau *et al*, 2010) illustrates that the majority (70 per cent) of the wood supply balance in 2010 came from forests and was primarily stemwood[39] (coniferous and non-coniferous). Forestry residues accounted for 12 per cent of the overall potential wood supply in 2010 (and 17 per cent of the total *forest* biomass potential). Landscape care wood[40] accounts for six per cent of the overall potential wood supply in 2010, see Figure 4.

Figure 4: Composition of the potential EU wood supply in 2010



Source: EUwood project (Mantau *et al*, 2010) based on Wood Resource Balance 2010 (medium mobilisation scenario supply estimates). **Note**: The category 'other' includes black liquor, post-consumer wood, other industrial residues, bark and solid wood fuels. Stemwood includes coniferous and non-coniferous wood.

When considering forest biomass potentials to meet energy demands it is important to understand the relative assumptions and definitions that are considered within different studies. This is particularly

[36] We do not further consider tertiary forestry residues, ie used wood, including waste wood and waste paper, which are rather classified as waste (Rettenmaier *et al*, 2010).

[37] For example, Elbersen *et al* (2012) include prunings and residues from orchards in their estimates of potential for 'other agricultural residues', which were addressed in Section.

[38] This was a major recent assessment of EU wood resources prepared for the European Commission.

[39] Stemwood is defined as stems with >7cm diameter.

[40] This is defined as 'primary woody biomass from trees outside forests' and includes 'woody biomass from maintenance operations (tree cutting and pruning activities in agriculture and horticulture industry), other landscape care or arboricultural activity in parks, cemeteries, etc., maintenance along roadsides and boundary ridges, rail- and waterways, orchards and gardens (Mantau *et al*, 2010).

important in relation to sustainability, which may infer the long-term potential of a forest to meet demands irrespective of environmental impacts, or may relate to an assessment of potentials that are environmentally benign[41]. Within the scope of this study, it has not been possible to assess fully the environmentally sustainable potential of forest residues for use in the energy or biorefinery sector. This is partly due to the lack of consistent definition of 'sustainable' in this context and thus lack of data or comparable data between studies. As a guide, this potential would be equal to or less than those figures quoted below. A brief commentary on forest potential estimates can be found in Hart *et al*, 2013 (Chapter 5).

2.3.1 Estimates of potential

This section reviews a range of recent studies that have estimated the potential for forest residues to be used for energy (Rettenmaier et al, 2010; BNEF, 2010; Elbersen *et al*, 2012; Mantau *et al*, 2010; and Hart *et al*, 2013). Estimates for primary forestry residues range widely from 0.09 EJ in 2020 (BNEF, 2010) to 1.82 EJ in 2020 (Mantau *et al*, 2010) driven by very different sets of assumptions and estimation approaches. Further estimates are reported for different forestry biomass categories as evidenced below. An overview of some of the estimates for primary forestry residues (excluding some of the sub-categories spelled out in the remainder of the section) is given in Table 6.

Table 6: Summary of results for selected forestry residue estimates (EJ/year)

EUwood - Mantau *et al* (2010) (medium mobilisation; excl bark and LCW)		
2010	2020	2030
1.03	1.04	1.05
EFSOS II (excl stumps and other biomass, eg thinnings)		
Realisable potential 2010	HIGH 2030	MEDIUM 2030
0.80	1.25	0.82
Rettenmaier *et al* (2010) Stemwood + primary forestry residues:		
Min-max for 2010-2019	0.51 - 2.70	
Min-max for 2020-2029	0.66 - 2.70	
BNEF (2010) Biorefinery potential, existing and energy uses subtracted		
2020	0.09	

Source: Own compilation based on the cited studies.

A review carried out as part of the ***BEE project*** (Rettenmaier *et al*, 2010) considers 21 studies estimating forest biomass potentials, with further studies reviewed for country specific information, such as for Germany and Finland. Table 7 summarises the ranges of estimates, which vary significantly. Sources of variation include differences in estimation approaches, assumptions with regard to harvesting intensity and sustainability constraints, and categorisation of forest biomass sources (see Annex 2 for further details).

[41] ie the potential can be realised with little or no negative environmental impacts.

Table 7: Estimates of annual potential of forestry biomass for the EU-27 (BEE project)

	2000-2009	2010-2019	2020-2029	2030-2039	>2050
Stemwood and primary forestry residues					
Minimum (EJ/yr)	0.47	0.51	0.66	1.78	
Maximum (EJ/yr)	2.82	2.70	2.70	2.70	
Secondary forestry residues					
Minimum (EJ/yr)	1.05	0.96	1.17	1.46	
Maximum (EJ/yr)	1.84	2.04	2.25		
Total forestry biomass potentials					
Minimum (EJ/yr)	1.24	1.55	1.73	1.78	1.80
Maximum (EJ/yr)	4.27	4.07	3.88	3.73	2.33

Source: Rettenmaier *et al* (2010), Tables 26-28. **Notes**: These ranges cover re-calibrated results for different scenarios from eight (in the case of stemwood and primary residues and total potential), respectively four (in the case of secondary residues) selected studies (see also Annex 2 on the re-calibration procedure). Only one study reported results for >2050 (Ericsson and Nilsson, 2006); these are for total forest biomass and are therefore only included under that heading. Estimates for stemwood and primary forestry residues are combined in this review.

An important study with regard to forestry biomass potentials is the ***EUwood study***[42] (Mantau *et al*, 2010). The study is based on demand and supply balances provided by the Wood Resource Balance[43]. It presents both historical balances (2005 and 2007) and extrapolated balances (2010, 2020 and 2030). Results for 2020 and 2030 are interpreted as estimates of potential that are subject to higher degrees of uncertainty and are therefore calculated for different scenarios to showcase the impact of different potential development paths. Three development paths were explored, a low, medium and high mobilisation scenario, distinguished for example by different sustainability constraints (see Annex 2 for a more detailed introduction to the EUwood study).

The Wood Resource Balances show that, even disregarding novel material uses, meeting traditional wood demands such as from the construction, furniture and paper industries (forecast based on GDP projections) and renewable energy targets is likely to lead to a supply shortage, even when both primary and secondary residues are considered. In 2010, the total woody biomass potential outweighed total demand by about 170 million m^3 (994 million m^3 potential versus 826 million m^3 demand). However, looking at the projected balances for 2020 and 2030, Mantau *et al* (2010) note that demand will outstrip supply sometime between 2015 and 2020 in the medium mobilisation scenario[44] due to the significant demand increase from the energy sector[45]. These results are commensurate with

[42] Study produced for the European Commission to assess different scenarios of future wood supply available for energy use and meeting EU renewable energy targets.

[43] Methodology to bring together information on physical wood supply with the different sources of demand for wood developed by Mantau (2005) (see also Box 3).

[44] The *medium mobilisation* scenario was selected as the one that resembles most closely a 'business-as-usual' path. It is characterised by limited growth in biomass mobilisation; adherence to existing biomass harvest guidelines; (some) protection of forests for biodiversity purposes; and limited fertiliser application (see Annex 2 for a more detailed summary). As a result of the different scenario designs, the supply-demand balance is projected to turn negative closer to 2015 in the *low* and around 2025 in the *high mobilisation* scenario.

[45] These results of the EU Wood Study are illustrated in fact sheets provided by the study (see Annex 2).

those in the revised European Forest Sector Outlook Study (EFSOS) II projections (UNECE/FAO, 2011) as described in Hart *et al* (2013).

Results for relevant forestry residues categories are represented in Table 8. The potentials appear rather large compared to the combined stemwood and primary forestry residue potential in the BEE study (Table 7), perhaps resulting from more optimistic assumptions about harvesting levels and/or less stringent sustainability constraints in the EUwood study.

Table 8: Estimates for EU-27 wood supply potentials for selected biomass categories (medium mobilisation)

	2010	2020	2030	2010	2020	2030
	million m^3			EJ		
Forest residues	118	120	120	1.03	1.04	1.05
Bark	24	23	23	0.21	0.20	0.20
Landscape care wood (use)	59	66	74	0.51	0.58	0.64
Total	200	209	217	1.75	1.82	1.89

Source: Mantau *et al* (2010). **Notes**: The figures in the table are for the ***medium mobilisation scenario.*** In the case of landscape care wood (LCW), 'use' refers to 'potential that is or will be used' determined again according to a high, medium and low scenario, but this time accounting for different demand levels with constant supply; shows that under neither of the scenarios the full LCW potential becomes utilised due to high 'procurement costs' associated with small volumes of biomass from scattered locations and of low density (Mantau *et al*, 2010, Chapter 5).

A very different methodology is applied in the ***Blooomberg study*** (BNEF, 2010), summarised in Annex 1 (Table 19). Estimates of potential for forestry residues for the year 2020 are extrapolated based on historical data from the wood and paper industry over the period 1980-2008. The residue potential accruing from industrial round wood processing is calculated and then the volume of residues currently used in the wood panel industry and the paper industry is subtracted. The remaining potential is technically available for the energy sector, of which 80 per cent is assumed to go directly into power generation through for example combustion. As a result, the residue potential for the biorefinery industry is relatively modest at 6.2 million tonnes (0.09 EJ)[46], or just three per cent of the total residue potential in 2020[47]. To put this in context, agricultural residues account for around 80 per cent and municipal solid waste 17 per cent of the total residue potential calculated. The results of this study illustrate the impact of taking into account existing uses of residues.

The ***Biomass Futures Atlas*** (Elbersen *et al,* 2012) uses results from the EUwood project for most of the forestry categories. However and as mentioned before, prunings and residues from orchards are included under agricultural residues. The potentials for these classes have been calculated based on land use information derived from the CAPRI model, representing more detailed information than was used in the EUwood study, according to Elbersen *et al* (2012). Landscape care wood is, however, included in primary forestry residues. The potential for landscape care wood is taken from the

[46] Based on a conversion factor of 1 t = 0.36 toe as used by Elbersen *et al* (2012) for primary forestry residues and sawmill by-products.

[47] 225 million tonnes in the base case scenario.

EUwood study after from which Elbersen *et al* excluded the potential from agricultural permanent crop land as this has been included under agricultural residues[48].

The ***Land as an Environmental Resource (LER)*** study (Hart *et al*, 2013) takes a similar approach to estimating forest biomass potentials as that in EUwood. The study builds on the EUwood results, as updated for the EFSOS II study and models future biomass availability to 2020 and 2030 using the EFISCEN and EFI-GTM models with minor adjustments to the EFSOS II data as in the EXIOPOL project49. Potential forest biomass for energy is not identified specifically, but rather the study considers the impact of an 'energy wood' policy scenario[50] on current biomass supply from EU forests in the context of a medium and maximum mobilisation scenarios.

Considering the impact of two mobilisation scenarios on forest biomass potentials to 2020 and 2030 the LER study identified significant potential to increase biomass extraction from forests under the high mobilisation scenario (Table 9). The maximum mobilisation scenario is driven partly by a high demand for forest biomass for energy and results in significant trade offs between other ecosystem services provided by forests, in particular biodiversity and carbon cycles. Under the medium mobilisation scenario biomass production was moderated by current good practice guidelines in relation to biomass extraction and less of a focus on extracting wood for energy purposes. The medium mobilisation scenario is very close to the estimated realisable potential from forests in 2010, which takes into account the environmental, technical and social constraints that reduce the amount of woody biomass that could theoretically be harvested from European forests.

Table 9: Maximum biomass potential from EU forests as assessed in EFSOS II

EU-27	**Realisable potential 2010**	**Potential in 2030**		**Realisable potential 2010**	**Potential in 2030**	
Units of output	million m^3			EJ		
		HIGH	MEDIUM		HIGH	MEDIUM
Stems/Roundwood	605	622	603	5.27	5.42	5.25
Residues	92	143	94	0.80	1.25	0.82
Stumps	9	101	9	0.08	0.88	0.08
Other biomass*	11	15	12	0.10	0.13	0.10
Total	719	880	719	6.24	7.67	6.25

Source: UNECE/FAO, 2011 as cited in Hart *et al*, 2013. Own conversion into EJ. **Notes**: *includes woody biomass from early thinnings which in some countries are termed energy wood thinnings: includes small dimension trees that would otherwise be left in the stand as well as some low diameter round wood. HIGH is 'High biomass mobilisation', MEDIUM is 'Medium biomass mobilisation'.

[48] See Table 3.3 in Elbersen *et al* (2012) for the resulting potential estimates.

[49] http://www.feem-project.net/exiopol/, Verkerk *et al*, in prep.

[50] The EFSOS II study assumes that renewable energy targets in 2020 are achieved with a substantial contribution from the forestry sector, and that the woody biomass demand for energy use remains at the same level until 2030. For 2010, 50 per cent of the renewable energy demand is expected to be met from woody biomass with the figure dropping to 40 per cent by 2020 and 2030. See UNECE/FAO (2011).

The 2010 estimates and the 2030 potential estimates under the medium mobilisation scenario provided here in Table 9 are broadly comparable to those provided by the EUwood study when considering the same categories of biomass (stems, residues and sumps). The figures here are marginally more conservative in the order of around 20 million m^3, which likely reflects differences in updated figures from the EFSOS II study and additional constraints applied in the LER study.

2.3.2 Mobilisation, its barriers and some sustainable solutions

The estimates of woody biomass potential in the EU stem from a range of assumptions regarding the technical, economic and environmental constraints that limit what could be mobilised in an otherwise un-restricted world. Many of the assumptions that underpin estimates of potential signal some of the barriers to mobilisation that need to be overcome, or accepted, in relation to mobilising forest biomass and residues for energy. For example, theoretical potentials can be quoted as the total forest biomass that could be harvested annually within biophysical limits without depleting the existing forest stock. In reality, these potentials are rarely reached, with limitations of the extraction of wood from physical and technical limits (eg slope and accessibility) or economic limits in relation to the cost of extraction versus revenue generated or the relative profitability of alternative uses of the materials. Nor are these potentials necessarily desirable from an environmental perspective, in order to preserve ecosystem functions and ensure the long-term future of the forest system. Sometimes the term 'maximum sustainable' potential is used, which takes into account many of the above points; however, there is no commonly accepted definition of maximum sustainable potential which can be used here (Lindner *et al,* 2010b). Instead, this section focuses on identifying the different mobilisation barriers set out in the literature and highlight some of the more environmentally responsible[51] solutions to overcoming those barriers.

Sustainability considerations are important in understanding the potential of forestry residues. Residue harvesting, particularly stumps, needs to take into account sustainability limits in order to avoid negative impacts on carbon balances, soil productivity, soil and water quality, as well as biodiversity (see Hart *et al*, 2013; Raulund-Rasmussen *et al*, 2011; Mantau *et al*, 2010; Raulund-Rasmussen *et al*, 2007). Increasing the extraction of forest residues and biomass beyond a certain point will inevitably lead to trade-offs between productivity and environmental and economic sustainability. Understanding the impacts of different management scenarios is therefore key to choosing the right path forwards in meeting wood energy demands.

There are different potential approaches that can be taken to increase forest biomass extraction whilst respecting also the multi-functionality and sustainability of forests. This could be through the increased extraction of biomass from all areas of forest whilst ensuring sustainability limits are observed, or it could be through the segregation of forest stands into particular functions, such as forest reserves or biomass production. Policy tools such as advice and incentives provided through Member State Rural Development Programmes (RDPs)[52] could help guide foresters and land managers in the way they balance the different demands from forests in the future[53].

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[51] Some studies, such as EU Wood, include solutions to increasing biomass extraction from forests that could be questioned in light of sustainability considerations, such as shortening rotation lengths, fertilisation and removing legal constraints. Such solutions are not considered further in this study.

[52] As set out under the second Pillar of the Common Agricultural Policy (CAP), Council Regulation EC No. 1698/2005.

[53] For a review of the impacts of different approaches to forest management for increasing wood production whilst respecting other non-provisioning ecosystem services, see Hart *et al*, 2013.

The sustainable management of forest stands can also play an important role in helping to increase mobilisation of otherwise underutilised forestry biomass. For example, and particularly in the Mediterranean region, better coordination of policies for preventing forest fires with bioenergy policies could mobilise the collection and use of timber and residues for bioenergy (or biomaterial) processing where this results in GHG savings (see Box 7 for a discussion of the aspect at the example of an available US study). Such coordination could again be provided using existing policy tools such as incentives and advice provided through Member State RDPs and forest extension services.

Beyond sustainability considerations, there are ***economic limitations*** on the volume of forest biomass and residues that can be extracted. Removing more biomass from forests, particularly in the form of residues, will require additional labour and machinery, increased extraction time as well as transport and logistics. ***Extraction costs*** can be particularly prohibitive especially with early thinnings and extraction of residues. ***Biomass prices*** can also have an impact on the end use of certain residues or forest biomass although the impact and drivers of these prices is influenced strongly by existing policies, economic growth patterns and comparative material or energy prices (UNECE/FAO, 2011). The price and cost of forest biomass will likely also have a major influence on the source of biomass, whether this comes from domestic forests and residues, whether there is an economic incentive to import biomass from outside of the EU (Hart *et al*, 2013) or which fraction of woody biomass is made available for energy or biomaterial use (Elbersen *et al*, 2012).

Box 7: The GHG balance of thinnings as a way to prevent forest fires – evidence from the US Pacific Northwest

One aspect to be considered in this section is the role of forest residue motivated as part of improved forest and scrub management to reduce forest fire risk. While potential positive synergies could arise (Mantau *et al*, 2010; Dunjo and Giovanni Pardini, 2003; Conti and Fagarazzi, 2005; Proenca and Pereira, 2010; Navarro and Pereira, 2012), the greenhouse gas implications of such practices are unclear. Unfavourable emission balances are a potential outcome. Taking the example of the Pacific Northwest United States, Schulze *et al* (2012) remark that policies promote the thinning of forests, foremost for bioenergy production but with the additional justification that this would reduce crown fire risk. Referring to Hudiburg *et al* (2011), this practice is found to be counterproductive in terms of GHG emissions, in other words that the thinning practices lead to higher GHG emissions than would arise from forest fires[54]. What can be argued in any case is that the biomass potential accruing from forest fire mitigation practices is most likely limited to Southern European and Mediterranean countries.

Source: Own compilation

Technical limitations for harvesting of forest biomass also play a role in determining available potentials. Most estimates of forest biomass potentials include some limitation in relation to accessibility constraints such as sloping or wet ground or distance to infrastructure by considering only the area of Forest Available for Wood Supply (FAWS) (Forest Europe *et al*, 2011). However, there are some technical limitations in relation to the different technologies used to extract timber and residues, or simply as part of the process or normal forest harvesting. For example some residues and woody biomass is lost before it can be utilised, such as loss or damage during harvesting (Nurmi,

[54] This assessment is depending on the climatic region considered; it should therefore be noted that the Pacific North West has a quite different climate than Mediterranean EU, for example.

2007; Peltola *et al,* 2011), or in some cases logging residues are used to strengthen the bearing capacity of soft soils during the harvesting process (Driessen *et al,* 2001).

Another important barrier to mobilising forest biomass for energy is that of ***fragmented forest ownership*** and whether or not the forests are under some form of management. Private owners with small properties may be less motivated to sell wood as harvesting may not be economically significant, transaction costs too high, or due to other management objectives than wood production (Straka *et al*, 1984; Amacher *et al*, 2003). Where ownership is fragmented, it can require more coordination in order to bring about the change in management necessary to increase biomass extraction at a sufficient scale.

Targeted policy measures could play a small role in helping to overcome some of the technical and economic barriers. This could include measures that are part of Member States' RDPs[55] as well as wider extension services and advice for forest managers. The improved organisation and increased cooperation between forest owners could help also to overcome economic barriers as well as issues of fragmentation[56]. Strengthening forest biomass supply chains can also play an important role, for example via cooperative arrangements such as 'Biomass Trade Centres' (Box 8) and public-private partnerships.

Box 8: Biomass Logistic and Trade Centres to secure local wood fuel supply

The EU funded 'Biomass Trade Centres' project has produced guidelines on setting up regional Biomass Logistic and Trade Centres. These are further elaborated during the on-going Phase 2 of the project, where a particular focus is on implementing biomass quality standards[57]. A Biomass Logistic and Trade Centre (BLTC) is a regional supply centre providing wood fuels, run by farmers and/or forest entrepreneurs. The central aim of the centres is to secure a high-quality, local source of wood fuel all year round to the heating systems of both private households and businesses and to construct a collective rural marketing channel for biomass fuels and energy services. The product range includes fuel wood, forest wood chips, other biomass fuels, and energy services. Services provided include fuel delivery, involvement in wood energy contracting projects, and expert advice on all issues relating to the proper use of wood fuels. The project inter alia aims to 'contribute to balancing the [wood energy] supply and demand sides at the regional level through promotion of good practice examples of energy contracting, promotion material and workshops where suppliers and potential users will meet and discuss'.

There are a number of BLTCs based in different regions around Austria (Styria), Italy (Veneto, Lombardia, Toscana), Slovenia (Nazarje, Visoko, Trebnje, Oplotnica), and Germany (Bavaria), with Croatia, Greece, Ireland, Romania and Spain being further countries of focus. In Styria, best practice stipulates that every operating group has to be a local farmers' association with at least ten forest owners – so that the entire added value remains in the region. There is a minimum storage quantity

[55] See for example Articles 47 to 29 of Council Regulation EC No. 1698/2005 that provide support for improving the environmental performance of forests, restore forest potential and provide non-productive investments. It should be noted that Council Regulation EC No. 1698/2005 is soon to be superseded by the new proposed EAFRD. For a summary of the potential measures this may include see Allen *et al*, 2012.

[56] Increased cooperative support measures are proposed for the future CAP post 2013 – see COM(2011)627/3

[57] The project website is: http://www.biomasstradecentres.eu and http://www.biomasstradecentre2.eu for Phase 2. 'Three step' guidelines for a successful project realisation: http://www.biomasstradecentre2.eu/scripts/download.php?file=/data/pdf_vsebine/literature/BLTC_Guidelines.pdf.

in any biomass centre of 500 solid cubic metres of energy wood (the energy equivalent of one million kilowatt hours of primary energy). As a minimum, the range of products must include firewood, wood chips and split logs from regional forests; the import of raw materials is not allowed.

Source: Own compilation.

Climate change might impact the potential for the utilisation of woody biomass for energy or biomaterials in future. For example, higher temperatures and CO_2 concentrations could increase the potential productivity of forests, alternatively more pests and disease or changed weather patterns might have the opposite effect, such as the damaging effects of greater frequency of extreme weather and storm events on forest stands. Whereas modelling studies have often shown increased productivity under climate change in different parts of Europe (Zimmermann *et al*, 2011; Reyer *et al*, 2012), several recent studies indicated observed evidence of drought-induced growth declines (Hart *et al,* 2013 citing: Piao *et al*, 2011; Choat *et al*, 2012; Kint *et al*, 2012). It is likely therefore that climate change impacts in forests will include both negative and positive impacts, with adverse impacts dominating across most of Europe in the mid and longer term (Lindner *et al*, 2010a).

Increasing the mobilisation of non-forest wood[58] is another means of meeting energy demand from woody biomass without encountering some of the mobilisation barriers from traditional forest systems. The mobilisation of non-forest wood would require an understanding of the current available resource through the establishment of inventories of wood resources outside the forest studies (Mantau *et al*, 2010; Kretschmer *et al*, 2010; BMVBS, 2010). This could be part of an overall regional approach to bioenergy sourcing and use, whereby the siting of bioenergy or biorefinery plants, including pre-treatment facilities, would take into account regional wood supplies (forest and non-forest wood) and the proximity to where forestry residues are collected (see for example PBL/ECN, 2011)[59].

2.4 Summary of estimates of potential from the food, forestry and agricultural sectors

Having reviewed estimates of potential for the different biomass categories of interest – food waste, agricultural crop residues and forestry residues – the following Table 10 summarises the findings of this chapter with regard to available volumes, barriers to mobilise these, as well as possible environmental impacts. These will be further elaborated in Chapter 4, which sets out how the collection of agricultural and forestry residues can impinge on important ecosystem services related to soil and water resources and harm biodiversity, if no caution is taken.

Prior to considering environmental impacts, the next chapter considers the various conversion routes, focusing on the conversion of biomass via biochemical and thermochemical conversion routes. An important characteristic of different biomass sources and one which (partly) determines their suitability for one or the other conversion route is its composition. Some of the wastes and residues reviewed here are inherently heterogeneous, like municipal waste streams, overcome to some degree by separate collection of 'sub-streams' such as food waste. Also forest residues that contain bark can

[58] Non-Forest wood includes: landscape care wood, short rotation coppice, recovered wood and the residues of the forest industries (Mantau *et al*, 2010).

[59] The study stresses the importance of planning the infrastructure for the collection and pre-treatment of forestry residues in order to reduce transport distances.

be difficult to process. Other residue streams are relatively homogeneous, for example wheat straw, a requirement for certain conversion routes as discussed in the next chapter.

Table 10: Summary of estimates of potential, barriers to their mobilisation and possible environmental impacts

<table>
<tr><th>Estimated potential</th><th>Barriers to mobilisation</th><th>Possible Environmental impacts</th></tr>
<tr><td colspan="3">Food waste</td></tr>
<tr><td>Estimated 89 Mt generated in EU-27 (179 kg per capita)*, of which:
• Manufacturing/production: 39%
• Distribution/retail/wholesale: 5%
• Food service/catering: 14%
• Households: 42%.

Energy potential calculated (based on 89 Mt and AD): 0.22 EJ (around 2.2% of 2011 EU electricity use or 0.5 per cent of total 2011 EU energy consumption)</td><td>• Lack of reliable data illustrating the extent of food waste;
• Limited separation of food waste from other types of waste (source separation and separate collection of food waste would provide the greatest potential for its use);
• Diffuse sources of food waste make the separate collection of this waste stream challenging;
• Uncertain outlook on future waste volumes
• AD of food waste is more technically complex (and hence costly) than many other common AD feedstocks.</td><td>Danger that increased valorisation of food waste as an energy source would undermine efforts to prevent and reduce food waste (ie environmentally preferable waste management options in line with the waste hierarchy set out in the WFD).</td></tr>
<tr><td colspan="3">Agricultural crop residues</td></tr>
<tr><td><table>
<tr><th>All in EJ/year</th><th>BNEF</th><th>Elbersen et al</th></tr>
<tr><td></td><td>2020</td><td>2004 2020</td></tr>
<tr><td>Crop residues</td><td>2.02 / 2.64</td><td>1.35 2.49</td></tr>
<tr><td colspan="3">DBFZ and Oeko-Institut (2011) estimated range straw:</td></tr>
<tr><td>Min-max</td><td colspan="2">0.82 - 1.83</td></tr>
<tr><td colspan="3">Rettenmaier et al (2010) estimated ranges agricultural</td></tr>
<tr><td>Min-max for 2010-2019</td><td colspan="2">0.8 - 3.57</td></tr>
<tr><td>Min-max for 2020-2029</td><td colspan="2">1.02 - 3.2</td></tr>
</table></td><td>• Transporting agricultural residues feasible over relatively short distances only (low energy density), demanding a careful siting of processing plants;
• Competition with existing uses of residues and established practices that farmers may be reluctant to give up;
• Unawareness about the sustainable level of extraction rates in the presence of local climatic and biophysical conditions;
• Unfavourable economics at the farm level of harvesting and marketing residues (eg investment in suitable machinery for collection not profitable, existing uses are of higher value).</td><td>Extraction of crop residues beyond sustainable limits (defined at local level taking into account the prevailing biophysical and climatic conditions) can lead to detrimental reduction of SOM with knock on effects for wider soil functionality, soil biodiversity, erosion risk etc.</td></tr>
<tr><td colspan="3">Forestry residues</td></tr>
<tr><td>All in EJ/year:<table>
<tr><th colspan="3">EUwood (medium mobilisation; excl bark and LCW)</th></tr>
<tr><td>2010</td><td>2020</td><td>2030</td></tr>
<tr><td>1.03</td><td>1.04</td><td>1.05</td></tr>
<tr><td colspan="3">EFSOS II (excl stumps and other biomass, eg thinnings)</td></tr>
<tr><td>Realisable pot. 2010</td><td>HIGH 2030</td><td>MEDIUM 2030</td></tr>
<tr><td>0.80</td><td>1.25</td><td>0.82</td></tr>
<tr><td colspan="3">Rettenmaier et al (2010) Stemwood + primary forestry</td></tr>
<tr><td>Min-max 2010-2019</td><td colspan="2">0.51 - 2.70</td></tr>
<tr><td>Min-max 2020-2029</td><td colspan="2">0.66 - 2.70</td></tr>
<tr><td colspan="3">BNEF (2010) Existing and energy uses subtracted</td></tr>
<tr><td>2020</td><td colspan="2">0.09</td></tr>
</table></td><td>• Proper understanding of sustainability impacts to determine appropriate extraction level;
• Prohibitive extraction costs and other economic factors;
• Technical limitations (such as limited accessibility) for harvesting of forest biomass;
• Fragmented ownership of forests and potentially resulting in undermanagement;
• External impacts including (future) climate impacts, such as extreme weather and storm events affecting forest stands.</td><td>Similar to crop residues, excessive residue extraction would reduce SOM, destabilise of carbon to nitrogen ratios, increase erosion risks, reduce nutrient availability (the latter in particular through removal of branches and tops. Stump removal can have particular negative effects on carbon stocks. Increased deadwood removal with potential negative consequences for biodiversity.</td></tr>
</table>

Sources: As cited in the previous relevant sections. **Note**: *Food waste estimates from European Commission (2010), for the year 2006 and more recent estimates for some Member States.

3 TECHNOLOGY OPTIONS TO CONVERT BIOMASS INTO BIOMATERIALS AND BIOENERGY AND STATE OF THE BIOREFINERY INDUSTRY

The number of products, both energy and materials, which can be derived from biomass is potentially very large. However, in reality, the future development of these markets will be determined by the interplay of three important factors:

1. The amount and type of **feedstock available** – As the feedstock provides the raw materials for the production of bio-based materials, chemicals and fuels, the availability of feedstock has a crucial influence on what can be produced.
2. **Demand** for the large range of potential bio-based products. The demand for many of them, particularly the novel products such as speciality chemicals, pharmaceutical products and biodegradable plastics, will be market driven. In common with any new products, it takes time to progress from launch of the product onto the market, through the stages of early adoption and late adoption to achieve full market maturity. The rate at which these processes take place may be accelerated by policies to encourage innovation and investment. For other biomaterials and especially bioenergy, the prime motive for encouraging their use is environmental – that is to bring about a net gain as far as GHG emissions are concerned compared to continuing with established products and sources based on fossil fuels. There also may be other environmental net gains to be had from the bio-based economy concerning water use and quality and biodiversity preservation. The demand for these products, and certainly in the initial stages when the bio-based product prices may be higher than the fossil fuel-based alternatives, is highly dependent on consumer preferences for 'green' products, and also on the collective actions, or policies, deployed to encourage, enforce, or incentivise their use.
3. The **investment and production** decisions taken on the ground. There is a wide gap between the products that can, in theory, be produced from biomass, and what is currently being produced or will be produced in the coming decades. Whether this gap narrows depends upon two factors; the maturity of the technology, and its economic viability. Lignin, for example can be used to produce a plethora of different chemicals including adhesive and resins, but is unlikely to be used unless several technical challenges can be overcome (PNNL, 2007). More elaborate discussions on costs and commercial maturity will form part of Chapter 5.

This chapter aims to elucidate the most promising technology options for developing a biomaterials and bioenergy (with a focus on advanced biofuels) industry from waste and residue materials in the EU. Identifying appropriate and promising technology options for the biorefinery sector is less about identifying cutting-edge innovation and more about identifying a combination of conversion approaches compatible with the characteristics of the available resources[60]. The chapter therefore considers first the different conversion technologies in view of what feedstocks they can use and the current and prospective markets for the products they produce. It then considers the technological maturity, both in the EU and the rest of the world, and the potential for large-scale uptake of these different technology options with positive effects for economic growth, to consider those technologies

[60] Adapting conversion technologies to local resource availability, maximising bioenergy and other biomaterial outputs in so doing, has led to the development of the ´integrated biorefinery' concept. The FP7 project 'Eurobioref' provides an illustration of this concept: http://www.eurobioref.org/index.php?option=com_content&view=article&id=66&Itemid=76.

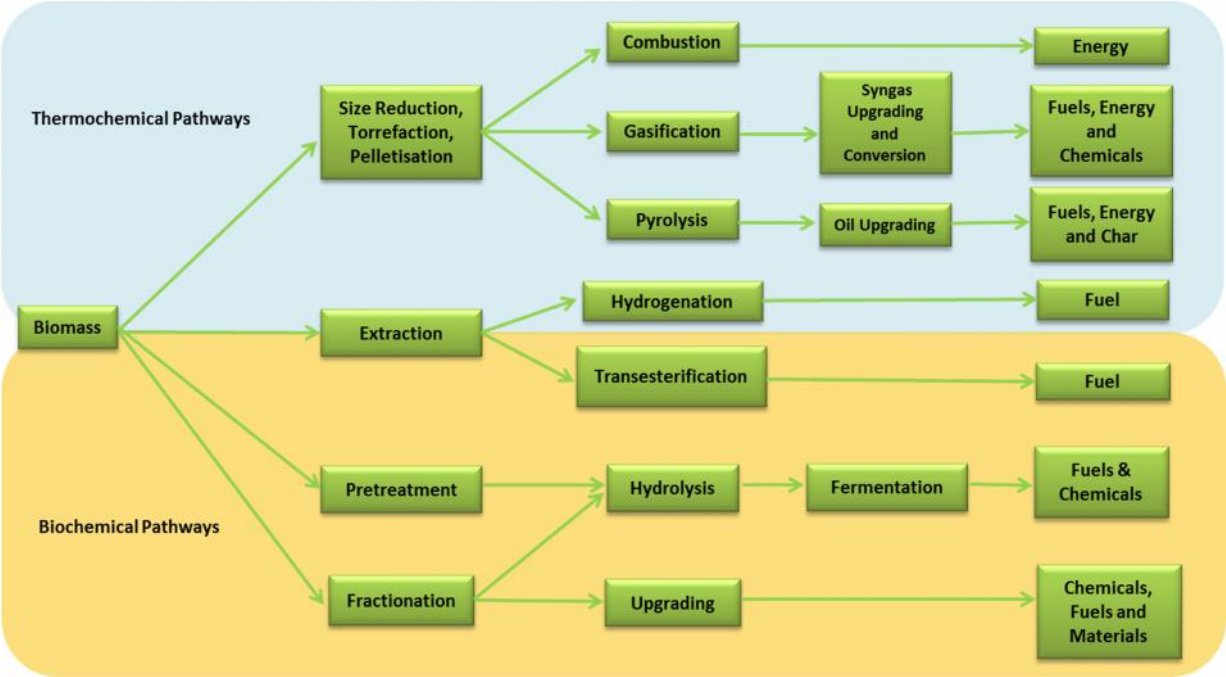
which have the best opportunity for developing a sustainable 'biomass to bio-based products' industry in the EU in the future.

3.1 Technology options for converting biomass to biomaterials and energy

There a large number of technologies which can be used to convert biomass to bioenergy and biomaterials. These can be broadly categorised as either thermochemical or biochemical conversion technologies.

Conversion technologies vary significantly both in terms of feedstock preference (or absolute requirement) and in terms of the end products they produce. A diagram summarising the different ways in which biomass can be converted to products is shown in Figure 5.

Figure 5: Overview of thermochemical and biochemical conversion pathways for biomass



Source: **Own compilation**

These conversion processes, the feedstocks they use, and the products they can produce are explained in the following sections.

3.1.1 Thermochemical conversion

The principal focus of thermochemical approaches has been on developing diesel and kerosene replacements for the road and aviation sector, although the production of gasoline and other chemicals is also possible (Evans, 2007). Thermochemical processes are heat and therefore energy intensive, requiring the establishment of a controlled process where heat input can be sufficiently monitored. The temperature required to convert feedstock through the application of a thermochemical platform involves conduction using a temperature of at least 300°C (Bergeron *et al*, 2012). The implications for lifecycle emissions will be discussed in Chapter 4.

There are three main thermochemical conversion technologies:

- Hydrogenation – a process which converts vegetable and animal oils into a high quality product which can be directly used as a fossil fuel substitute;

- Gasification – a process which converts biomass to a gas comprised of hydrogen and carbon monoxide and from which a wide variety of chemicals, fuels and energy forms can be derived;
- Pyrolysis – a process which converts dry biomass to a bio-oil which is currently mainly used for energy production.

In addition, there are other thermochemical systems at the research and development stage, including thermal liquefaction/hydrous pyrolysis, which takes a wet material and converts it into what is known as biocrude, which is chemically identical to fossil petroleum and can be used to derive similar products (Evans, 2007).

Gasification and pyrolysis can potentially convert a range of biomass types with high input-output efficiency and these are therefore interesting technology options to convert residues and wastes that do not occur in large and geographically concentrated volumes. Interest, especially in gasification, is high owing to the wide range of products that it can produce. Nevertheless, the only fully commercial thermochemical technologies using biomass at the time of writing is vegetable and animal oil hydrogenation and the gasification of glycerine to produce methanol[61]. Gasification and pyrolysis technologies for electricity and power production are commercial throughout the world. The commercial use of biomass for gasification and pyrolysis is not commercial at present, except for the production of methanol via gasification mentioned above. In the majority of cases, some kind of pre-treatment is required before conversion.

The following section briefly describes the main thermochemical conversion technologies, in particular focussing on the pre-treatment methods, conversion process, the feedstocks that can be used and the markets for which the end products can be used.

Hydrogenation

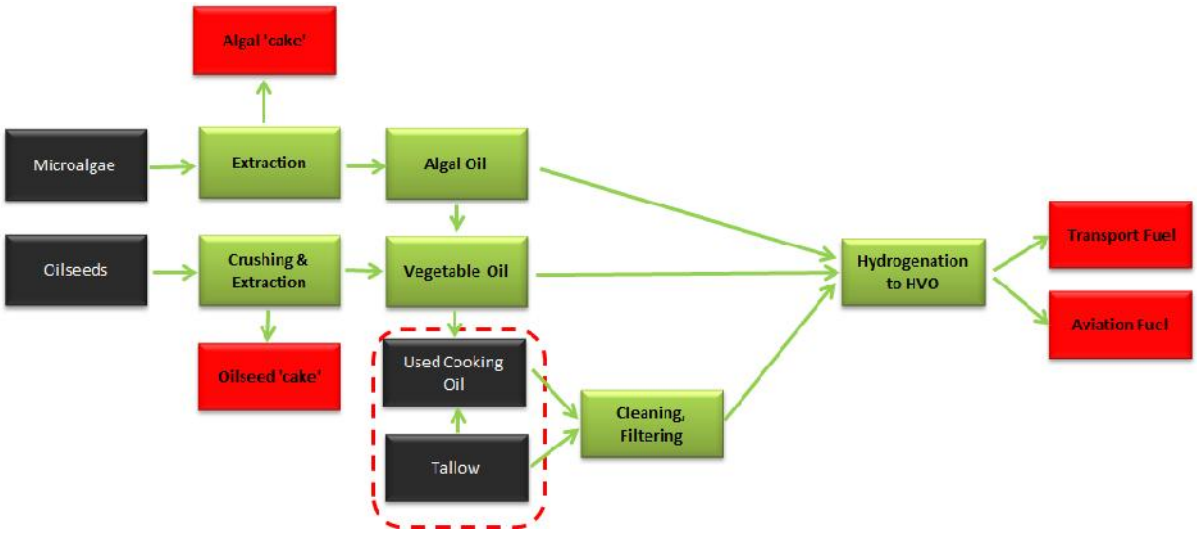
Hydrogenation[62] (also known as hydrotreatment) is a process whereby hydrogen is added, at high temperature and with a chemical catalyst, to cleaned vegetable and animal oils. It is a commercial technology in Europe, and is based on oil refining technologies in the petrochemical sector[63]. The hydrogenation process produces Hydrotreated Vegetable Oils (HVO), also known as Hydrotreated Renewable Jet (HRJ), Hydrotreated Renewable Diesel (HDRD), NExBTL Diesel or Green Diesel. The conversion process from vegetable oil to HVO is more than 95 per cent efficient (meaning 95 per cent of the energy content of the raw material is contained in the processed HVO) (Evans, 2007). A diagram illustrating the hydrogenation process is shown in Figure 6.

[61] Glycerine is primarily derived as a by-product of biodiesel production and has a range of existing applications.

[62] Note that in some cases, hydrogenation is considered a 'chemical' conversion process that is separate from either thermochemical or biochemical platforms.

[63] Alternative Fuels Data Center (2013), http://www.afdc.energy.gov/fuels/emerging_green.html

Figure 6: Hydrogenation of biomass - derived oil



Source: Own compilation. Notes: Black boxes represent feedstocks, green boxes represent intermediary steps and red boxes represent end products. For comprehensiveness, this diagram includes feedstocks that are not part of the scope of the study. The only feedstocks considered to be part of the study are used cooking oil and tallow as residues from the food processing industry, highlighted by the dashed red line.

Hydrogenated vegetable oils are chemically similar to fossil fuels, so they can be blended with fossil fuels in any given proportion[64] (Aatola *et al*, 2008). Indeed they can be used as a direct replacement for fossil fuels in some applications, including road transport and aviation. They are sometimes known as 'drop in' fuels. There are several HVO processing facilities in the world, including two in Europe, in the Netherlands and Finland. HVO/HRJ can be produced from any animal or vegetable oil feedstock, including virgin oils such as rapeseed oil, sunflower, soy, palm, jatropha, camelina and algal oils and waste oils such as used cooking oil and tallow (animal fats) (Aatola *et al*, 2008).

Pre-treatment for thermochemical processes

While thermochemical conversion processes can accept a range of different feedstocks, the fuel specifications of feeding systems may be limited. Therefore, some form of pre-treatment may be required to make the feedstock homogenous (in terms of size, composition or both). Moreover, as biomass is a low energy density feedstock, pre-treatment processes may be used to concentrate the biomass, so that the material can more economically be moved from the source of biomass production to the site of conversion, and be stored. There are three main pre-treatment methods for thermochemical conversion processes and these may be used either singly, or in combination with other methods depending upon the exact specifications of the downstream conversion process. These are:

- *Size reduction* by any of several mechanical processes, such as chopping or hammer milling.
- *Pyrolysis* is the thermal decomposition of biomass in an oxygen-free environment. Depending upon process conditions, it can form a liquid product which contains around 75 per cent of the energy originally contained within the biomass. Pyrolysis may be used as a first step in gasification processes. Pyrolysis is described in more detail in a separate section.

[64] Ibid.

- *Pelletisation* converts biomass into a smaller, uniform size. It helps improve biomass flow, and increases grinding ability.
- *Torrefaction* is a mild pyrolysis process where biomass is heated at 200-300°C in the absence of oxygen. It forms a charcoal-like product, with increased uniformity, increased grinding ability, and repels water. Torrefaction may be used after pelletisation processes.

Gasification

Biomass gasification is the breakdown of the carbon contained within a biomass material at high temperature and in an oxygen-limited environment, to form a gas known as synthesis gas (syngas) (E4Tech, 2009; Evans and Smith, 2012). Syngas is made up of hydrogen and carbon monoxide plus a variety of different contaminant and trace gasses depending on the feedstock used.

Once formed, syngas can be converted to a variety of different end products, including methane and hydrogen, alcohols such as ethanol and methanol, synthetic diesel and gasoline (E4Tech, 2009). These in turn can be used for energy, fuels, or used for the production of bio-based materials and chemicals. An overview of biomass gasification and the variety of related pathways is shown in Figure 7.

To date, gasification has predominantly been commercially used with fossil fuels such as gas and coal. However, gasification can, in principal, be used with a range of different biomass feedstocks including low-cost mixed municipal solid wastes (MSW), wood and residues and pyrolysis oil (discussed below) (E4Tech, 2009). This makes it an attractive process in areas where a variety of feedstocks are available. Gasifiers need to be developed to deal with the inherent specificities of different biomass materials, whilst syngas conversion processes need to be developed to take account of the fact that syngas derived from biomass has a different level of contamination to that derived from fossil fuel materials (Evans and Smith, 2012). These challenges need to be resolved before biomass gasification is commercialised.

In general, biomass gasification requires a relatively dry feedstock for example straw, wood, black liquor and glycerine, although municipal solid waste may also be used (Evans and Smith, 2012). Processes to deal with higher moisture contents are being developed, for example the pyrolysis of algal biomass. The following sub-processes fall into the gasification category:

- *Fischer Tropsch Synthesis (FT):* Fischer Tropsch is the conversion of syngas into liquid hydrocarbons at temperatures of 200-350°C. There are numerous types of products resulting from this process, each varying according to temperature, pressure and type of catalyst used (E4Tech, 2009). It is a well-established technology, having been used for decades, first with coal, then more recently natural gas (Evans and Smith, 2012). When a low temperature is used, this can form a waxy product which can be broken down into synthetic diesels, kerosene and naphtha[65]. The process conditions can be changed to change the proportion of components formed. At higher temperatures, the FT process can form gasoline products. It should be noted that existing FT reactors have been developed to process materials at the fossil fuel scale, and this large scale is a particular challenge for biomass. As a result, FT reactors more appropriate for biomass are being developed, including micro-scale reactors (Evans and Smith, 2012).
- *Conversion of syngas to methane*: Methane can be produced from syngas through a methanisation process to form a bio-synthetic natural gas (BioSNG). It can be integrated into the existing natural gas supply and demand infrastructure to supply heat and power. It can

[65] Naphtha is a hydrocarbon mixture which can be used as a feedstock for the production of petrol fuel, industrial and cleaning solvents and olefins such as polyethylene and polypropylene.

also be used as a transport fuel, though its use would be limited to vehicles that have been modified to run on CNG or LNG, and unless a dedicated infrastructure for fuelling is put in place, its uptake will be limited to captive fleets.

- At the time of writing, BioSNG is at the pilot demonstration scale of development. There are several demonstration plants throughout Europe (Box 14).
- *Converting syngas to hydrogen:* Hydrogen is one of the principal gases within syngas alongside carbon dioxide. The amount of hydrogen in the gas can be increased by using a chemical reaction (known as the water gas shift reaction[66]), followed by separation techniques to isolate the hydrogen.
- Hydrogen is extensively used in chemical manufacturing, the largest market is for the production of ammonia (via the Haber Bosch process), oil refining and methanol production. There do not appear to be any projects utilising a BTL (biomass-to-liquid) approach to produce hydrogen at the pilot or commercial scale and, although there has been research in this area, this does not appear to have progressed further. Hydrogen could be used as a vehicle fuel (either in dedicated hydrogen cars) or in mixtures with diesel and gasoline, although it contains much less energy than petrol and diesel on a per volume basis so requires more frequent refuelling (NNFCC and LowCVP, 2010). The use of hydrogen as a fuel requires dedicated storage and refuelling infrastructure. Hydrogen, as a gas, is bulky and has a low energy density. This can be improved by compressing the gas or compressing it into a liquid form, requiring materials capable of high pressure storage[67]. The development of a publically available refuelling infrastructure is a requirement to promote the market uptake of hydrogen vehicles. In this respect, the Commission's clean transport package[68], which proposes targets for hydrogen refuelling points in those Member States where some refuelling points already exist at the moment the directive would enter into force, is a step towards achieving this aim.
- *Conversion of syngas to methanol*: Syngas can be converted to methanol through a two-step process – first converting syngas to crude methanol through heat, pressure and the use of catalysts, and then by distillation of the crude methanol to form methanol (E4Tech, 2009).
- Most methanol is produced from gas, and some, especially in China, is produced from coal. It seems that the only commercial BTL biomethanol plant is in the Netherlands, which utilises waste glycerine to produce biomethanol[69]. Other facilities appear to be at a pilot and experimental scale, utilising a wide range of different feedstocks including agricultural wastes in Japan, woodchips and waste wood.
- Methanol is a major commodity chemical and is widely used as a chemical intermediate in the chemical industry. Its principal use is as a feedstock for producing formaldehyde in the construction industry. Methanol can also be used as a fuel blended with bioethanol or be used

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[66] Carbon monoxide (CO) in the syngas is sacrificed by reacting it with steam to yield carbon dioxide and additional hydrogen. This process requires both heat and pressure, and is commonly used in the petrochemical refining industry. It is used in all BTL operations to optimise syngas composition for downstream conversion.

[67] http://www.fueleconomy.gov/feg/hydrogen.shtml

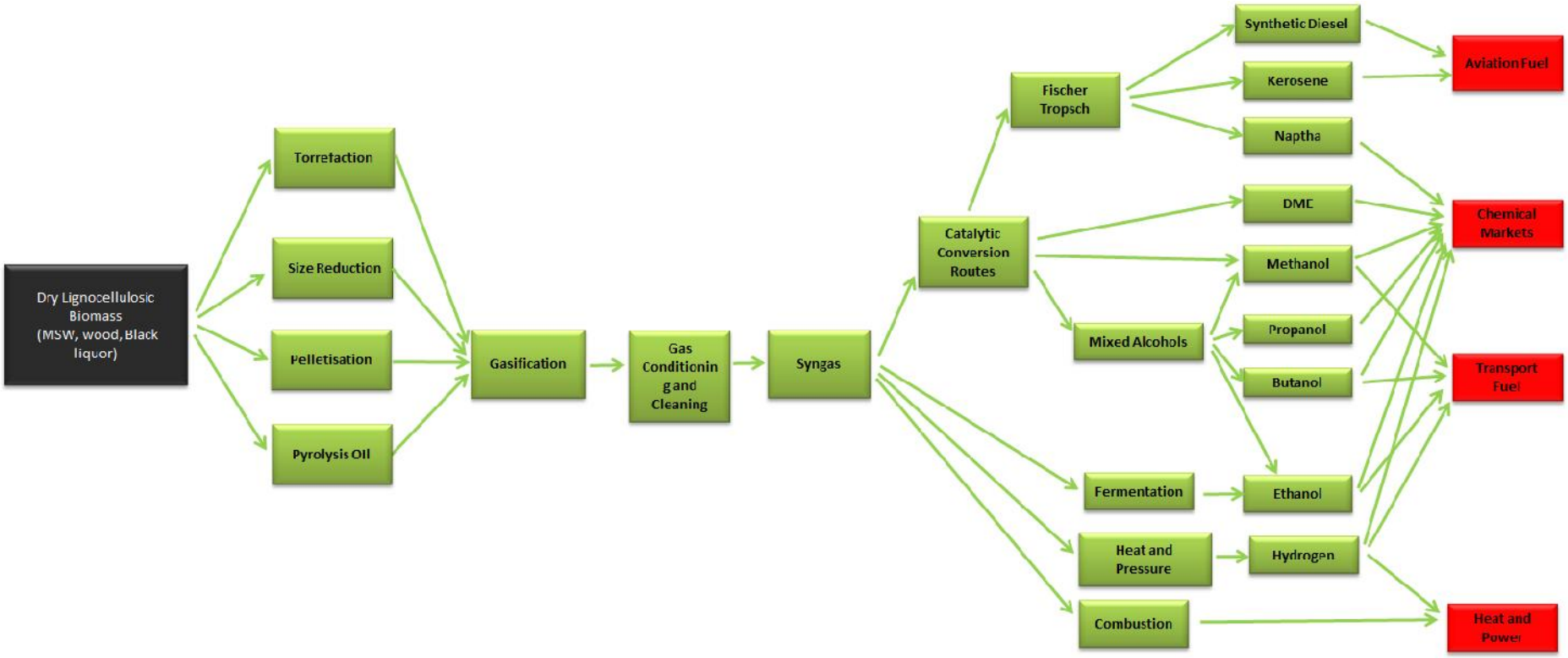
[68] http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2013:0018:FIN:EN:PDF

[69] Also note that an EU grant of 199 million euros (under the NER300 programme) has been awarded to the project 'Woodspirit' in the north of the Netherlands. The aim is to set up an advanced biofuel plant to convert wet wood into methanol via torrefaction and gasification of woody biomass, into syngas: http://www.biomcn.eu/news/news/158-brussels-grants-a-199-million-euros-subsidy-to-dutch-biomass-refinery-initiative.html.

as a feedstock for a number of other fuels such as biodiesel (FAME), dimethyl ether (see below), methyl tertiary butyl ether (MTBE) and to gasoline and diesel (via what is known as the Mobil-Olefins-to-Gasoline-and-Distillate (MOGD) process) (Evans and Smith, 2012).

- *Conversion of syngas to mixed alcohols:* Syngas can be converted to a range of mixed alcohols through the use of catalysts similar to those used in FT and methanol production (E4Tech, 2009). The ratio of alcohols produced varies according to technology. Mixed alcohol synthesis processes produce a mixture of methanol, ethanol, propanol, butanol, and smaller amounts of heavier alcohols. There are a number of companies working in this area, using a variety of different waste feedstocks including wood, sawdust, manure and lignite.

Figure 7: Overview of biomass gasification processes



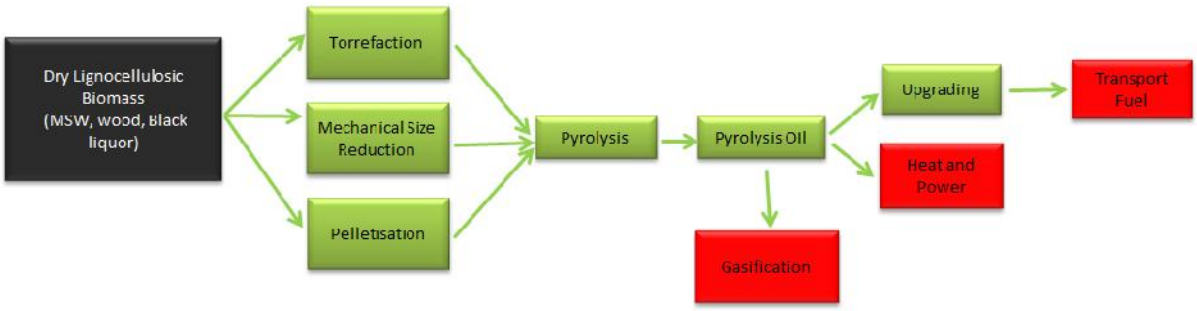
Source: Own compilation. **Note**: The black box represents feedstocks, the green boxes represent intermediates and conversion processes and the red boxes represent final uses.

- *Conversion of syngas to dimethyl ether (DME)*: There are two ways to convert syngas to DME. The first is to produce a methanol intermediate (as described for the methanol process above) and then chemically dehydrate it to form DME. This process gives the flexibility to produce either methanol or DME as the market dictates. The single-stage production process uses chemical catalysts but gives less flexibility. The EU funded Bio-DME project[70] is investigating the use of black liquor gasification to produce DME for biofuels and have developed a pilot plant in Pitea, Sweden. DME can be used as a biofuel or used as a chemical intermediate. If used as a biofuel, it would need to be liquefied, and would need a dedicated storage, refuelling and vehicle infrastructure for its use. As a result, it may be limited to captive fleets[71].
- *Fermentation approaches for converting syngas to ethanol*: In contrast to the largely thermal processes mentioned above, syngas may also be converted to fuels and chemicals using bacteria such as *Clostridinium ljungdahlii* and *Clostridium carboxidivorans* P7. The fermentation of syngas has a number of advantages over the thermal and catalytic mentioned processes above, including that they operate at low pressure and temperature reducing costs; they achieve high yields of the desired product and are potentially less sensitive to contaminants in the syngas (E4Tech, 2009). The reaction time from biomass to distilled ethanol has been proven to be short (7-8 minutes) compared to fermentation of sugars, which often last for 1-2 days (Evans and Smith, 2012). This technology is at the demonstration scale and is largely being developed for fuel applications. It is expected to be commercialised in 2013 in the USA.

Pyrolysis

Pyrolysis is the thermal decomposition of biomass, in an oxygen free environment, to form three products; a gas, a solid charcoal-like material ('biochar') and organic vapours which can be condensed to form what is known as bio-oil, biocrude or pyrolysis oil. The proportion of these materials formed depends upon the processing conditions used. Fast pyrolysis, which uses higher temperatures (450-600°C) and pressure, maximises the formation of the bio-oil product whilst minimising the formation of char and gasses, whilst slow pyrolysis maximises char and gas formation whilst minimising oil formation. Pyrolysis is a commercial technology, with around 70-75 per cent of the feedstock converted to a bio-oil. Bio-oil has a heating value of around half that of fossil oil. An overview of the conversion of biomass by pyrolysis is given in Figure 8.

Figure 8: Overview of the conversion of biomass materials by pyrolysis



[70] http://www.biodme.eu/

[71] Captive fleets can include municipal waste collection vehicles, urban busses, heavy goods vehicles and taxis. Typically, they are return-to-base vehicles that have a dedicated refuelling infrastructure at their depot. This refuelling infrastructure is distinct from the publically available infrastructure.

Source: Own compilation. **Note**: The black box indicates feedstocks, the green boxes represent intermediates and conversion processes and the red boxes indicate end uses.

Pyrolysis oil is currently used for heat and power production. It may also be used as an energy carrier for gasification, as it is more uniform and easier to transport than biomass. A number of significant technical challenges hinder its direct use as a transport fuel including its instability, high water and metal content and its acidity, although upgrading processes could be developed to promote its blending into diesel and petrol fuels (NNFCC and LowCVP, 2010). The charcoal-like material (char) formed from the pyrolysis process may be used in agriculture though it is thought that the market for biomaterials from slow pyrolysis may not be large enough to incentivise the penetration of slow pyrolysis procedures on an economy of scale (Desbarats *et al*, 2011). The gas is often used within the pyrolysis process to provide process heat (Evans, 2007).

Most pyrolysis processes are only suitable for dry feedstocks (typically less than 10 per cent moisture content) which exhibit limited variability such as low cost lignocellulosic materials and wastes (Zafar, 2009), although there are some processes which can handle wetter materials (for example algae).

Hydrothermal upgrading / Thermal liquefaction

Hydrothermal upgrading is the high pressure/high temperature treatment of very wet materials. It can produce a solid product (hydrothermal carbonisation), a liquid product (hydrothermal liquefaction) or a gaseous product (hydrothermal gasification). Hydrothermal liquefaction forms a thick, high energy density liquid material known as biocrude, (which makes up around 45 per cent of the product), gas and water (Evans, 2007). Thermal liquefaction is currently at the R&D scale.

Biocrude is chemically identical to fossil petroleum, and as such, it could potentially be used to produce the same products as are currently produced from petroleum (Evans, 2007). It can be separated into heavy and light components. The light component can be upgraded to transport fuels, whilst the heavy component can be used as a feedstock for co-firing in power stations (Evans, 2007). The gas component can be burned to produce heat for the thermal liquefaction process.

A wide range of feedstocks are suitable for thermal liquefaction, including wood, agricultural residues, the biological fraction of municipal solid waste and very wet biomass materials (up to 80 per cent moisture content), for example microalgae, slurries and wet grass[72]. It is therefore very distinct to gasification and pyrolysis procedures, which require dry feedstocks.

3.1.2 Biochemical conversion

The global demand for sugar-based products is expected to increase by 50 per cent by 2030, particularly given the increasing political and industry momentum behind the development of the bioeconomy and potential diversification of the market for end products such as bioplastics. Current feedstocks for industrial sugar-based applications include potatoes, cereal grains, and sugar based crops such as sugar cane and sugar beet. However, recognising the negative issues associated with using food crops for industrial products, there is a drive to develop processes which can utilise lignocellulosic materials and wastes.

A major focus of biochemical approaches has been on developing alcohols such as ethanol and butanol for the road transport sector, bio-based chemicals and bioplastics which are used in a range of

[72] http://www.fnr-server.de/cms35/fileadmin/allgemein/pdf/veranstaltungen/NeueBiokraftstoffe/5_HTU.pdf

sectors including chemicals, food and feed, detergents, paper and pulp, textiles and bioenergy (eg Kamm and Kamm, 2007). Another important, established biochemical process is transesterification to produce biodiesel. By-products of biotechnological processes also result in the manufacturing of some antibiotics, vitamins, and amino acids[73]. Biochemical processes are less heat and energy intensive than thermochemical approaches, but require a more consistent feedstock.

There are two main biochemical conversion technologies:

- *Fermentation* – a biological process using yeasts or other microorganisms which converts sugars into a large range of bio-based chemicals;
- *Transesterification* – a process which converts vegetable and animal oils into a fossil fuel replacement.

These approaches fundamentally differ in their feedstock, the conversion technology used and the range and type of end products which can be obtained. However, both technologies require some form of pre-treatment of feedstocks to isolate either the oil or sugars. The pre-treatment technology used is dependent on the feedstock and can have a fundamental effect on the quality and quantity of the final product. The following sections briefly describe the main pre-treatment technologies used to convert biomass to sugars and how these products can be used. The last sub-section considers the main technologies for the pre-treatment of biomass to extract oils and their conversion to different products.

Lignocellulosic biomass to sugars: Pre-treatment technologies

There are two types of pre-treatment technologies for the conversion of biomass to sugars through biochemical routes. These are:

- Biomass pre-treatment (referred to here as 'simple biomass pre-treatment');
- Biomass fractionation.

Within each of these categories a number of alternative approaches exist. These are explained in detail in NNFCC (2009), on which the following sub-sections draw.

Simple biomass pre-treatment

The aim of simple pre-treatment methods is to achieve a softening of biomass and loosening of cell walls to facilitate the access of enzymes to break down sugars within the biomass (known as enzymatic hydrolysis or saccharification) (Harmsen, P *et al* 2010; NNFCC, 2009). These can be classified as either:

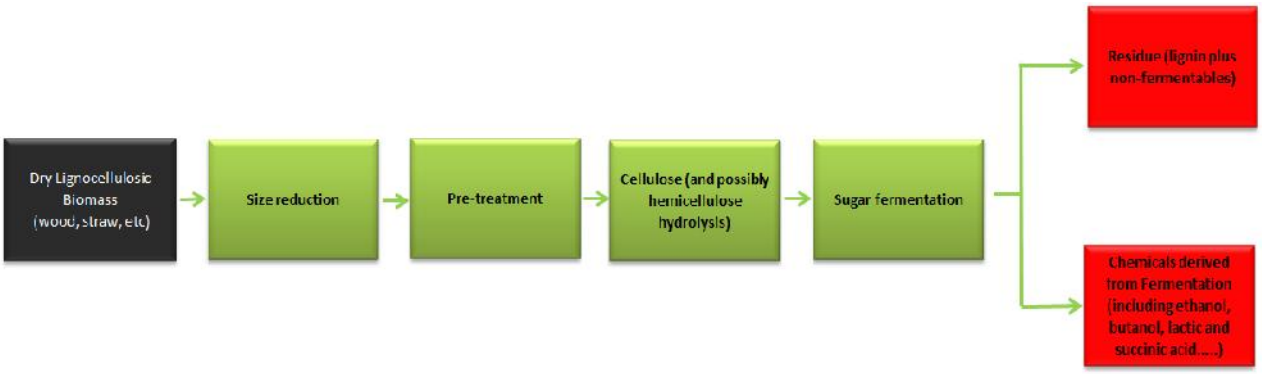
- Acid based pre-treatments (such as dilute acid, concentrated acid or liquid hot water);
- Alkaline pre-treatments (such as Ammonia Fibre Explosion, lime, ammonia recycle percolation, wet oxidation);
- Extractive pre-treatments (so called organosolv technologies).

These options may be used alone, in combination and/or in conjunction with heat depending upon the biomass type and the desired products. In general, however, the outcome is the same, lignocellulosic biomass is converted from a solid form to a loose mixture of cellulose, hemicellulose and lignin (see also **Error! Reference source not found.**), which makes it easier for enzymes to break down the component sugars. The sugars can be fermented to a range of different products (including biofuels and platform chemical products) leaving a residue material comprising of lignin, non-

[73] European Technology Platform for Sustainable Chemistry http://www.suschem.org/priorities/enabling-technologies/industrial-biotechnology.aspx

fermentable components and unfermented hemicellulose and cellulose which can be burned to provide power. Figure 9 illustrates this chain. To date, there are no commercial biomass pre-treatment technologies, and there is no clear preferred technology. AFEX, ammonia recycle percolation and liquid hot water treatments appear to be still at the lab scale, whereas the others appear to be more developed (NNFCC, 2009).

Figure 9: Biomass pre-treatment process



Source: Own compilation. **Note**: The black box indicates feedstocks, the green boxes represent intermediates and conversion processes and the red boxes indicate end uses.

Biomass Fractionation

The aim of biomass fractionation, which is distinct from simple biomass pre-treatment, is to separate the three principal components of biomass; lignin, cellulose and hemicellulose into three distinct product streams as shown in Figure 10 (see also **Error! Reference source not found.**), with high purity and high efficiency (NNFCC, 2009). This significantly increases the range of potential products which can be obtained from biomass although this comes with increased cost. Several processing technologies exist, which, as for pre-treatment technologies, vary in their suitability for different feedstocks and have an influence over the quality of the final product.

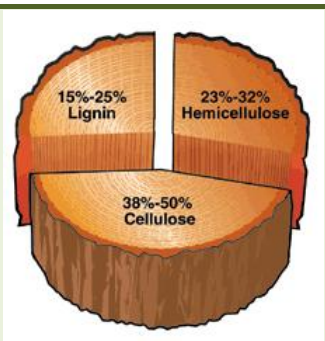
These are broadly grouped into two categories:

- Purevision Process;
- Organosolv processes (Organosolv, Alcell Process, Acetosolv, Formacell, Milox, NREL Clean Fractionation)[74].

Biomass fractionation offers a considerable opportunity to produce several high quality, high value products from biomass. While commercial development has so far been limited, there is great potential in the production of many product streams as part of an integrated biorefinery as is, for example, being explored through the FP7 BIOCORE project[75].

Box 9: The building blocks of plant biomass

Plant biomass is made up of cellulose, hemicellulose and lignin. Their relative shares depend on the plant species. Example ranges for wood are shown in the picture to the right. NNFCC (2009; appendix 2) contains further details, showing the relatively low lignin content of straw or corn cobs compared with woody biomass. Cellulose and hemicellulose are both polymers consisting of long chains of sugar molecules. The lignin fraction of biomass is made up of very complex non-sugar type molecules and one of its main functions is to hold together the cellulose fibres. Therefore, unlike starch, cellulose and hemicellulose, lignin is not a viable source of fermentable sugars. However, it has a higher calorific value than the other biomass components (as much as 50 per cent higher). This embedded energy can be released via combustion, providing a source of energy for other processes, or lignin can be thermally treated via pyrolysis to produce a range of potentially useful chemicals (also section 3.2.1).



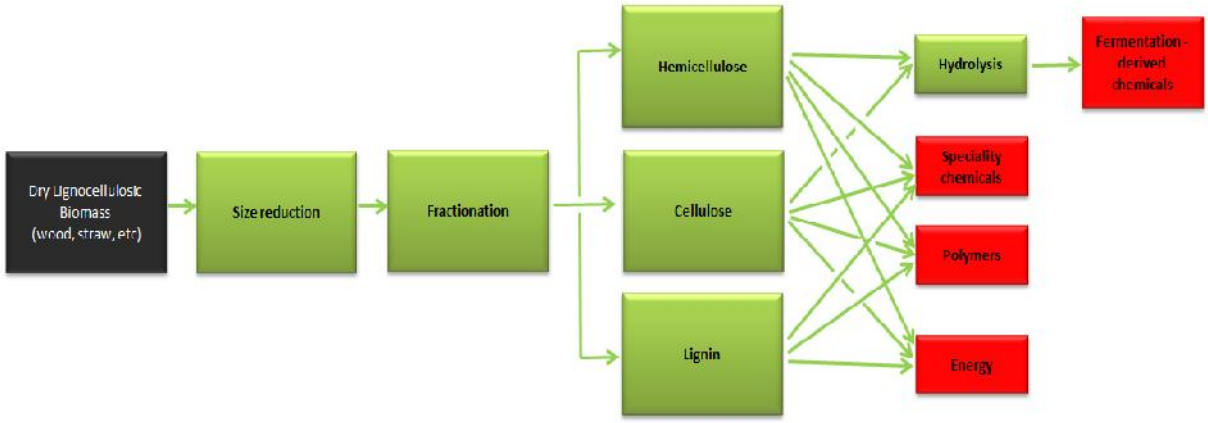
Wood composition, *Credits*: P. Daniel Cassidy, Sarah F. Ashton (Univ. of Georgia). *Source*: http://tinyurl.com/bawrrso

Sources: http://www.inforse.org/europe/dieret/Biomass/biomass.html; Zhu and Zhuang (2012); Pandey and Kim (2011)

[74] All of these are explained in more detail in NNFCC (2009), Appendix 2.

[75] http://www.biocore-europe.org/

Figure 10: Biomass fractionation processes



Source: Own compilation. **Note**: The black box indicates feedstocks, the green boxes represent intermediates and conversion processes and the red boxes indicate end uses.

Conversion technologies: Fermentation of sugars and other routes

The fermentation of biomass-derived sugars offers a considerable opportunity to produce a wide range of different bio-based chemicals (Figure 11). While fermentation approaches typically use yeasts, other microorganisms such as bacteria and even microalgae may be utilised depending upon the composition of the sugar and the desired end product. The majority of fermentation approaches are currently based on glucose metabolism. The utilisation of other sugars depends upon the identification of fermentative pathways for those sugars, and their introduction into industrially useful microorganisms. This is termed industrial biotechnology (IB).

There are several chemicals which are commercially produced from plant sugars including ethanol, butanol, succinic acid and lactic acid. The potential products which can be derived from fermentation are very large. In most cases, the products are high volume, low value products which can be used as a substitute for oil-derived products.

Of course, fermentation approaches are only one potential route for using bio-based sugars. Other conversion routes may be more appropriate than fermentation-based routes, especially when higher value products can be obtained, as a result of higher purity or quality. A wide range of products can be obtained depending upon the technology used (discussed further in section 3.2.1), for example:

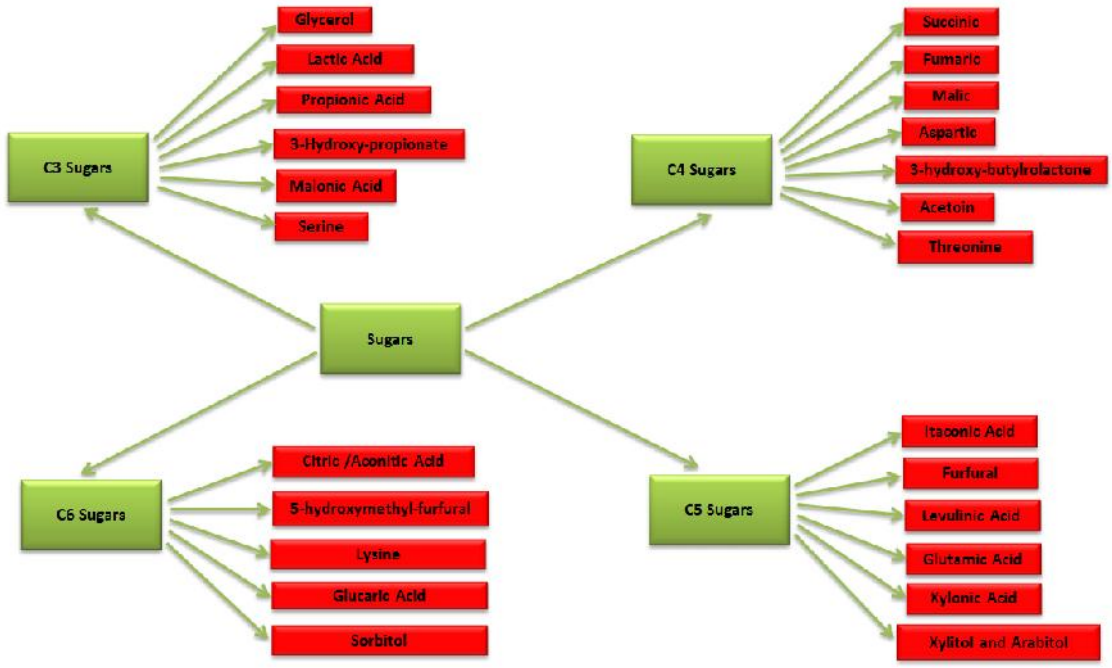
- The cellulose derived from biomass fractionation is of a similar quality to cellulose known as 'dissolving pulp' and which can be used for the production of a wide range of products including bio-based plastics (cellophane), pharmaceuticals and clothing amongst others.
- Similarly, hemicellulose may also be too valuable to be used for fermentation, and may be used for polymer[76] products such as the barrier material developed by Xylophane[77] and as food materials such as Xylitol[78].

[76] Polymers are substances with a molecular structure consisting of a large number of repeating units. Polymers come in natural and synthetic form. Examples of the former include proteins, starches, cellulose and latex; examples of synthetic polymers are polyethylene terephthalate (PET), polyethylene, polyamide and many other

- Moreover, given the high quality of lignin materials derived from biomass fractionation, these may find added-value applications aside from simple combustion such as resins, plastics and carbon fibres.

This reinforces the key differentiating point between simple biomass pre-treatment and biomass fractionation technologies – although biomass fractionation is significantly more expensive than simple biomass pre-treatment, the quality of the products provides the opportunity to exploit high value markets. In contrast, the poorer quality material derived from simple biomass pre-treatment can only be converted to relatively low value, high volume applications such as energy and bulk chemicals.

Figure 11: Chemicals derived from fermentation of sugars



Source: Adapted from Werpy and Petersen (2004)

Conversion of oil-containing materials to oils

- **Pretreatment**: Some form of treatment is required to convert oil-containing products to oils suitable for oleochemical products. The pre-treatment needed will vary on the material:
    - The isolation of oil from oil crops (eg rape, soya), requires crushing and hexane treatment;

materials with a wide range of properties and uses. All materials that we commonly refer to as plastics are synthetic polymers (http://scifun.chem.wisc.edu/chemweek/polymers/polymers.html).

[77] See the box on 'Skalax – A Hemicellulose-based Barrier Material' in section 3.2.1 below.

[78] A sugar alcohol used as an alternative sweetener, in dental care and other medical purposes.

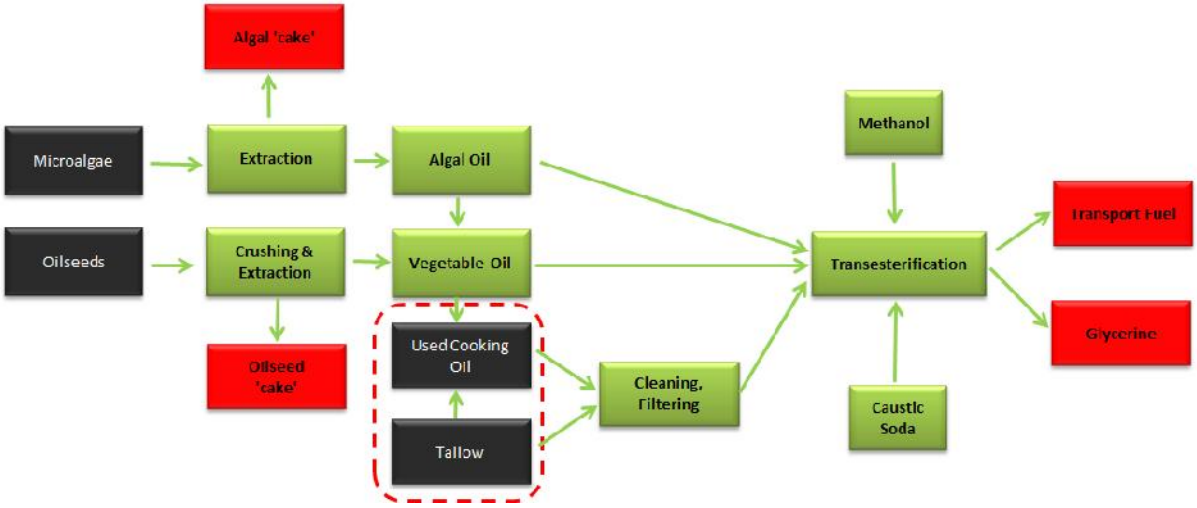
- The purification of oils from waste materials such as tallow and used cooking oil will require cleaning and filtering before conversion (WEF, 2010).

Transesterification is the biochemical conversion process used to produce biodiesel through the conversion of vegetable oils, algal oils or animal tallow (see

Figure 12; note the pathway is similar to the hydrogenation one, depicted in Figure 6). The conversion of oils to biodiesel requires the addition of either an acid or alkali catalyst (typically caustic soda) in the presence of methanol to produce Fatty Acid Methyl Esters, FAME. The methanol can be substituted for ethanol to form Fatty Acid Ethyl Esters (FAEE) as used in some European countries (i.e. France). The transesterification process produces glycerine as a co-product. This can be used as a fuel and energy source, or, if cleaned up, in the production of a range of different bio-based chemicals.

Other oleochemical uses: Plant and animal derived oils can be used, to a greater or lesser extent, in ea wide range of different products including personal care products, soaps and detergents, paints and coatings, de-inking chemicals, printing inks, plastic release agents, as a rubber production aid, food, healthcare and in waxes and candles (Dommett, 2009). These are all well-established technologies and are widely utilised, so will not be discussed further here. More specifically, oleochemicals can produce biodegradable lubricants (which are favoured for use in environmentally sensitive areas), green solvents (particularly in paints to avoid VOC production) and in the production of bioplastics (including polyurethanes[79], Poly(hydroxyalkanoate) (PHA) and Poly 3-hydroxybutyrate (PHB)[80]. The production of bioplastics is a particularly fast-growing sector, as discussed in section 3.2.3.

Figure 12: The conversion of biomass derived oils to biodiesel



Source: Own compilation. **Note**: The black box indicates feedstocks, the green boxes represent intermediates and conversion processes and the red boxes indicate end uses.

[79] http://www.sciencedaily.com/releases/2007/07/070702151141.htm

[80] http://www.wlv.ac.uk/default.aspx?page=31938

3.1.3 Summary – conversion technologies

The aim of this section was to provide an overview of the portfolio of technologies for the conversion of biomass resources to biofuels and bio-based materials. Important distinguishing factors of the different technologies include their cost, their complexity as well as their development status. The choice of conversion technology has important implications for the quality of the final products derived, in turn influencing their marketing potential and their cost. An overview of the plethora of products which can be obtained from biomass and their status of development is provided in the next section.

3.2 The biorefinery industry – current status and future outlook

The previous section outlined the conversion routes which can be used to produce biomass intermediates. This section considers how these intermediates can be converted to bio-based products and the commercial status of these different products. Conversion processes have a significant impact on the products which can be derived from biomass. With this in mind, the current and future markets for bio-based materials will be considered for the following three categories of products:

1. Macromolecules – cellulose, hemicellulose and lignin;
2. Products from thermochemical conversion routes – synthesis gas and pyrolysis oil;
3. Products from biochemical and chemical conversion routes – sugar fermentation and catalytic conversion.

The focus will be confined to those products which are commercial, in development or at lab scale. For those products which are not fully commercial the information provided is restricted to the developers and the location of plants. Throughout this section, there are a number of boxes with practical examples which explain in more detail the different ways in which biomass can be used in the production of a range of chemicals, fuels and material products. The isolation of, and markets for, extractive products derived from biomass, such as tannins, pigments and waxes, are not documented here, despite the large potential for these products as part of a 'cascading' approach to biomass use.

3.2.1 Macromolecules

Lignocellulosic biomass can be chemically disrupted to isolate its component polymer materials, namely cellulose, lignin and hemicellulose. These polymer products can be used to produce a wide range of chemical products or even broken down and used in the production of fuels and other chemicals. The ways in which lignocellulosic macromolecule breakdown products (specifically cellulose and hemicellulose) can be used is covered in section 3.2.3.

The unique functionalities of biomass are already exploited in the commercial production of a wide range of chemical products. These range from high quality, high value products in the case of cellulose, to low quality, low value applications where the form, but not the quality is important in the case of lignin (NNFCC, 2009). A plethora of other applications are being developed, especially from hemicellulose and lignin. In all cases, the applications which a product can be used for will vary according to the quality of the product, in particular the level of contamination and the molecular weight distribution.

Deployment and timescales

The production of lignocellulosic polymers is not new. Cellulose pulp is already used in a number of high value markets, including the production of clothing fibres, films and filters. This cellulose is derived from pulp from the acid sulphite pulping process which has undergone an additional processing step, known as dissolving pulp. Dissolving pulp is a high quality material, with a low level of contaminants; however, even in this case, the purity of the pulp determines its applications.

Similarly, high value applications exist for hemicellulose polymers, but in contrast to cellulose polymers, these appear to be niche products, developed by single producers. Not surprisingly given the proprietary nature of these products, there is little information in the public domain about how hemicellulose quality affects its uses for these applications. Lignin, mostly in the form of lignosulphonates that is lignin that has been modified to become water soluble, is also used for a variety of low value applications including as an animal feed, as dust control, binders and as dispersants, but the quality of this lignin is relatively poor. Both cellulose and lignin products are derived from wood materials through the pulping industry; whilst there is relatively little information about what the hemicellulose products are derived from, they appear to be largely limited to cereal brans.

Table 11: Status of biomass-derived polymer markets as of 2012

Product	***Applications***	***Maturity***
Cellulose Fibres	*Textiles, clothing, packaging*	*COMMERCIAL*
Cellulose Ethers	*Personal care, pharmaceuticals, detergents, cosmetics, paint, food etc*	*COMMERCIAL*
Nitrocellulose	*Explosives, lacquer, food products*	*COMMERCIAL*
Cellulose Esters	*Films, moulding, extrusion, fibres and lacquers*	*COMMERCIAL*
Hemicellulose	*Barrier films in packaging*	*DEVELOPMENT*
Hemicellulose	*Adhesives*	*COMMERCIAL*
Hemicellulose	*Medicinal (wound barriers)*	*COMMERCIAL*
Hemicellulose	*Agronomy (seed coatings and soil stabilisation)*	*COMMERCIAL*
Hemicellulose Alkylpolypentosides	*Cosmeceuticals (ie cosmetic ingredients)*	*COMMERCIAL*
Lignin	*Phenols and adhesives (eg for applications in the wood based panels industry)*	*DEVELOPMENT*
Lignin	*Dispersant (ie to increase fluidity and stabilisation) in concrete, textile dye etc*	*COMMERCIAL*
Lignin	*Dust control (eg on unpaved roads)*	*COMMERCIAL*
Lignin	*Binding agent (eg in animal feed), resins, oil well drilling, mud additive*	*COMMERCIAL*
Lignin	*Vanillin (artificial vanilla flavour)*	*COMMERCIAL*

Source: Own compilation based on NNFCC (2009; 2011)

There is considerable scope for developing new applications for biomass polymers. Biomass fractionation, in particular, has the potential for producing high quality cellulose, hemicellulose and lignin materials which can be used in an astonishing range of applications. In some cases, the materials may be similar to existing products, for example, the cellulose derived from biomass fractionation is similar to that derived from a pulping route. However, in other cases, the material may be of significantly higher quality, for example, lignin derived from biomass fractionation is more consistent and pure, and as a result, can be used for the production of phenols and adhesives. This

development of high value products from lignin derived from biomass fractionation is an aim of the FP7 funded BIOCORE project (Box 12).

Practical examples

The three examples outlined below show a variety of different polymer applications for biomass materials. The first case study considers a commercial processes for the production of cellulose fibres which are used in a wide variety of different applications, the second case study considers a process for the production of hemicellulose polymers which is at the demonstration stage of development, and the third case study outlines a R&D project which is investigating the production of resins amongst a raft of other products from lignin.

Box 10: Cellulose Fibres – An alternative for cotton and more

High quality cellulose pulp can be used to produce manufactured or regenerated cellulose materials, including the production of viscose (rayon) and lyocell (also marketed as Tencel) as an alternative to cotton and of cellophane, a common packaging film. Regenerated cellulose refers to the dissolving of cellulose and subsequently 'regenerating' into the form of films or fibres. These processes are commercial where based on dissolving pulp originating from the acid sulphite pulping process. The market is characterised by a range of players globally; at the same time, the bulk of cellulose fibre production (around 75 per cent) is concentrated with a top 10 of manufacturers. These include Birla (12 per cent), Acordis (10 per cent), Lenzing and Celenese (both 8 per cent), Eastman (6 per cent), RGM (4 per cent) and Rhodia (3 per cent).

The ability of biomass fractionation techniques to yield cellulose of sufficient quality to be used in lyocell and viscose processes has been investigated. Research suggests that current fractionation techniques, followed by an additional bleaching step, can yield cellulose of sufficiently high quality to suit the lyocell production process, which is tolerant to variations in quality. Rayon production via the viscose process is more sensitive to contaminants, and not all fractionation processes yield sufficiently high quality cellulose.

Source: Own compilation based on NNFCC (2009)

Box 11: Skalax – A hemicellulose-based barrier material

Skalax is biodegradable barrier material derived from xylan, a hemicellulose material found in a wide range of agricultural by-products such as the husks and hulls of cereals, and an additive approved for food contact applications. It forms an effective barrier to oxygen, grease, aroma, mineral oils and harmful leachable products and can be applied using conventional coating technologies. Skalax can substitute for aluminium and metallised foils and oil-based plastic barriers in a wide range of applications including, but not limited to, the packaging of dry soups and sauces, oxygen-sensitive dairy products, greasy snacks and pet foods, as well as aromatic products such as spices and coffee. The future market for migration barriers is estimated to be in excess of €100 million[81].

A spin-out from Chalmers University, Sweden, Xylophane, who have developed the Skalax product, have a pilot production facility in Gothenburg, Sweden. RenewPACK, a four-year, €3.3 million project

[81] http://www.xylophane.com/_wcm/documents/new_environmentally_friendly_migration_barrier_2011-11-07.pdf

running from 2012-2016 and funded through the EU LIFE+ programme, aims to demonstrate the scale-up of the production, use and end of life options for the Scalax material[82].

Source: Own compilation based on sources cited

Box 12: Sticky stuff from lignin – The development of phenol replacements from lignin

Athough lignin is a widely produced by-product of the pulping industry, its use for high value chemicals is hampered by quality issues including salts and particulates contamination (NNFCC, 2011). As a result, it is currently used in applications where the form, but not the quality of the lignin is important. The development of higher quality materials from lignin will depend upon the isolation of higher quality lignin biomass, such as that derived from biomass fractionation, where yields of 95 per cent with 5 per cent cross contamination have been reported (NNFCC, 2009; 2011).

The BIOCORE[83] project, a four-year €20 million FP7 project running from 2010-2014, is investigating the production of chemicals from the cellulose and lignin streams resulting from the CIMV biomass fractionation process. A variety of different applications for biorefinery lignin are being investigated, including the feasibility of using pyrolysis oil derived lignin to be used in the production of polyurethane adhesives for the wood based panels industry. The project has demonstrated that unmodified lignins derived from pyrolysis can substitute for up to 40 per cent of the phenol in adhesives, but where lignins are modified before pyrolysis, substitution of up to 70 per cent is possible.

Source: Own compilation based on sources cited

3.2.2 Products derived from thermochemical conversion routes – synthesis gas and pyrolysis oil

All carbon containing materials can be broken down through thermochemical conversion routes. The end product mix depends upon the conversion technology used, but can include chemicals which can be used as building blocks for the production of other chemicals and fuels. A wide range of products can be achieved through thermochemical conversion routes (syngas and pyrolysis routes) as shown in the diagram from Werpy and Petersen (2004) shown in Annex 3.

As discussed in section 3.1.1, gasification can use a wide of range of carbon containing raw materials, ranging from virgin materials such as farmed wood, crop residues, bioenergy crops, to waste materials such as glycerine and municipal solid waste and produce a synthesis gas, which can be converted to a wide range of fuel and chemical products. Once the synthesis gas has been produced, the feedstock from which it has been derived becomes irrelevant (Evans, 2007). Similarly, pyrolysis can use a wide range of feedstocks to produce: a char-like material known as biochar, gasses which can be condensed to form pyrolysis liquid which can be upgraded to form biofuels or used for chemicals production, and off gases which can be used to power the pyrolysis process (Evans, 2007; Desbarats *et al*, 2011).

Deployment and timescales

[82] See http://www.xylophane.com/ for more information, including on the RenewPACK project.

[83] http://www.biocore-europe.org/

Thermochemical conversion technologies are not new. The use of gasification processes for fuels production has been commercial for decades, having been developed to produce liquid biofuels from coal in Germany and South Africa in the inter-war years (Evans and Smith, 2012). Interest was renewed in the times of the oil crises of the 1970s; later environmental concerns were a motivation to pursue syngas pathways to derive cleaner (for example virtually sulphur free) fuels and chemicals (Spath and Dayton, 2003). More recently, both gasification and pyrolysis have been widely used for the production of energy (electricity and power), particularly using waste materials (E4Tech, 2009). Therefore, while use of many thermochemical routes is not novel, their use for biofuels and bio-based chemicals production is novel.

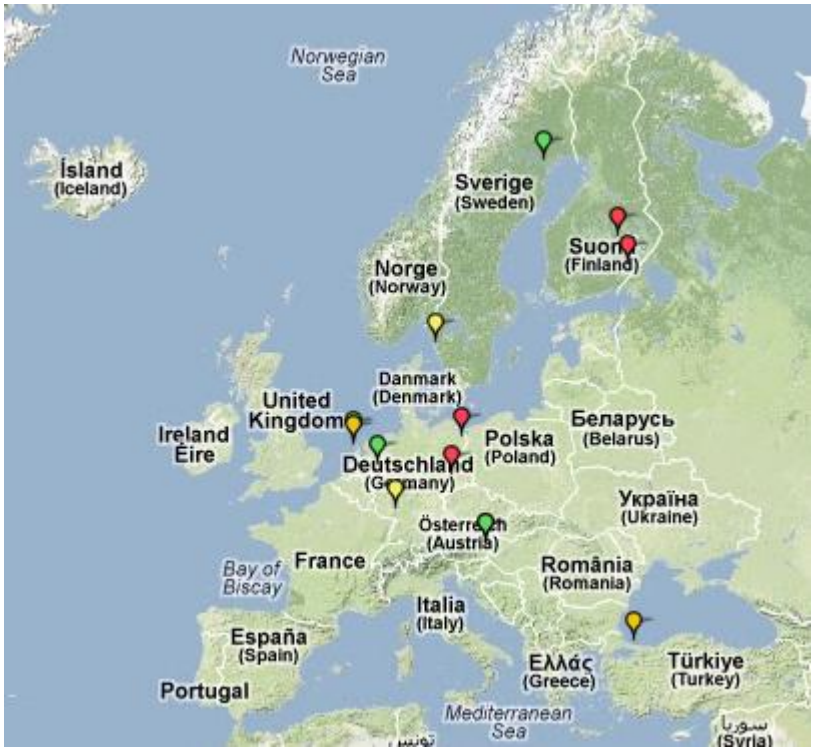
Biofuels

A variety of biofuels can be derived from thermochemical treatment of biomass. In this section, we consider the range of biofuel products which can be derived from thermochemical routes, current and planned production capacities and producers, and whether they are located in the EU or elsewhere in the world.

There are a number of routes by which biofuels can be produced from biomass using thermochemical approaches. These include biofuels which are produced by the biomass to liquids (BTL) route, pyrolysis and other routes. These fuels may be used as a partial or full substitute for petrol/gasoline (ethanol), diesels (synthetic diesel) or used in new transport infrastructures (hydrogen). The biofuels industry is growing rapidly, and thermochemical routes are expected to be one of the key tools used to convert plant biomass to biofuels.

The map below (Figure 13), taken from the IEA Task 39 database, shows that several countries within Europe, particularly in Western Europe, are active in the commercialization of advanced biofuels from thermochemical conversion, either at the pilot, demonstration or commercial scales. As of October 2012, there were 3 plants in operation (shown in green – not at commercial scale though), four plants under construction (shown in orange and yellow) and four plants had ceased operations (shown in red). Table 12 below shows the current status of thermochemical fuels production both worldwide and in the EU.

Figure 13: Thermochemical biofuel plants in Europe as of 2012



Source: IEA Task 39 – 2nd Edition of http://demoplants.bioenergy2020.eu/projects/mapindex (Bacovsky *et al*, 2013). **Notes**: Green represents operational plants (through none of them at commercial scale), planned plants are shown in orange, yellow are plants under construction and red represents projects which have stopped.

At the time of writing there are no thermochemical conversion plants at the commercial scale anywhere in the world. Nevertheless, several commercial plants are close to operationalization, both in Europe and rest of the world. These are all based on the use of wastes (and to greater or lesser extent) residues from agriculture. In the EU, the GreenSky project in London plans to use wastes and residues to produce aviation biofuels, as elaborated in the 'Practical examples' below. Several other plants around the world are planned to follow this plant. In North America, several plants are planned which will use gasification to produce a syngas, which is then fermented to other products, including ethanol (INEOS Bio[84]) and mixed alcohols (Enerkem[85]).

The use of thermochemical routes to produce synthetic diesel, BioSNG and upgraded pyrolysis oil are currently at the demonstration scale of development, whilst the production of DME is less well developed at the pilot scale. The EU appears to be a leader in the development of BioSNG, with several plants in Austria, Sweden and Netherlands investigating the development of this fuel.

84 http://www.ineos.com/businesses/INEOS-Bio/News/~/Commissioning-under-way-at-Florida-cellulosic-ethanol-plant/

85 http://www.enerkem.com/en/technology-platform/process.html

Table 12: Status of thermochemical fuels production in Europe and the world by end-product as of 2012

Syngas product	EU plants	Worldwide plants
Ethanol		Ineos Bio (2013)
		Tembec (n.d.)
Synthetic Diesel		Virent (2009)
		Greasoline (2011)
Synthetic Jet Fuel (Kerosene)	GreenSky London (2014)	Several around the world planned.
Mixed Alcohols		Enerkem Mississippi (n.d.) Enerkem Varennes (n.d.) *Enerkem Alberta (2013)*
		Enerkem Westbury (2009)
		Enerkem (2003)
BioSNG	Biomasse-Kraftwerk Guessing (2008) ECN (Consortium Groen Gas 2) (2013) Goteberg Energi AB (2013)	
	ECN (2008)	
Pyrolysis Oil		Licella (2008)
Fischer Tropsch (FT) liquids (not stipulated)	Vienna Institute of Technology / Bioenergy 2020+ (2005)	*Research Triangle Institute* Gas Technologies Institute (2012) Southern Research Institute (2008)
Dimethyl ether (DME)	Karlsruhe Institute of Technology (2013)	
General (end product not stipulated)		NREL Golden (1985)

Source: Own compilation based on IEA Task 39, http://demoplants.bioenergy2020.eu/projects/mapindex. **Note**: Plants in **bold** are operational, plants in *italics* are in construction, plants in normal type are in planning. Purple boxes denote pilot scale plants, orange boxes represent demonstration plants and green boxes represent commercial plants. Dates refer to expected or actual operation date and are based on details in the IEA task 39 database[86].

Bio-based chemicals

In the context of thermochemical conversion routes, bio-based chemicals can be derived from syngas as well as from pyrolysis oil (de Jong *et al*, 2012). Some products derived from these conversion routes are highlighted here, whilst section 3.2.3 provides a fuller introduction to the bio-based chemicals market where sugar-based platforms from biochemical conversion routes prevail[87].

Syngas platform: Syngas, which consists mainly of hydrogen and carbon monoxide, can be produced from a range of feedstocks, including biomass, the most common one used being natural gas (Werpy

[86] http://demoplants.bioenergy2020.eu/

[87] This concurs with the findings of Werpy and Petersen (2004) whose selection of top twelve chemical building blocks includes no thermochemical derived ones.

and Petersen, 2004). Once the synthesis gas has been produced following a thermochemical conversion process, the feedstock from which it has been derived becomes irrelevant (Evans, 2007). However, the bio-based process still needs to overcome challenges associated with higher levels of contaminants contained in the syngas. So while the conversion of syngas to a range of products is commercial already (yielding amongst others hydrogen, ammonia, methanol, alcohols and aldehydes), bio-based routes are facing additional challenges. Hydrogen and methanol have been identified in a US study as those chemical building blocks with the best near-term prospect among the bio-based conversion routes due to the relatively high yields obtainable from biomass (Werpy and Petersen, 2004; Spath and Dayton, 2003)[88].

Hydrogen, which is the largest use of syngas overall, is primarily used in the production of ammonia, whose main application in turn is as fertiliser. All these processes are well established (Spath and Dayton, 2003). Methanol can be converted into a range of secondary chemicals (see Werpy and Petersen, 2004, or Annex 3), some of which are further highlighted in section 3.2.3, including as its principal use is as a feedstock for producing formaldehyde in the construction industry, as well as methyl esters, formaldehyde, acetic acid and dimethylether to name a few.

Pyrolysis oil platform: Pyrolysis through the thermal decomposition of biomass can yield a range of bio-based products derived from the cellulose, hemicellulose and lignin components of the biomass important ones of which are discussed elsewhere in the report. Major high value compounds derived from pyrolysis oil foreseen include phenols, organic acids, furfural, hydroxymethylfurfural (HMF) and levoglucosan (de Jong *et al*, 2012, de Wild *et al*, 2011).

Some demonstration projects are being pursued in the field of pyrolysis though their primary aim seems to be the production of advanced biofuels through pyrolysis. These include an announced investment (March 2012) of EUR 20 million by Fortum to build an industrial scale plant based on fast pyrolysis technology in Finland producing electricity and heat initially and in the future also 50,000 tonnes of bio-oil per year. Forest residues and other wood based biomass are anticipated as bio-oil raw materials. The operation is planned to start in autumn 2013[89]. The FP7 funded EMPYRO project ('Polygeneration through pyrolysis') aims to set up a commercial-scale demonstration plant for the simultaneous production of oil, process steam, electricity and organic acids through fast pyrolysis in the Netherlands. The plant is foreseen to be operational by the end of 2013 and to be run on woody biomass. Among the aims of the project is the recovery of acetic acid as part of the pyrolysis oil production process[90].

Practical examples

Box 13: Jet Fuel from Rubbish – The GreenSky Project

As a result of inclusion in the EU ETS as of 2012, the aviation industry needs to reduce its GHG emissions. Thus, airlines are investigating a range of options to reducing their emissions, including the use of biofuels. Unlike in other sectors, such as road transport, there are no alternative low-carbon fuels to kerosene besides biofuels.

The GreenSky London project is a collaboration between British Airways and Solena. The facility will

[88] In addition, an IEA study mentions as promising chemicals from syngas (some of which are already discussed in the biofuels section above) methanol, ethanol, dimethylether (DME) and Fischer-Tropsch diesel.

[89] http://www.fortum.com/en/mediaroom/pages/fortum-invests-eur-20-million-to-build-the-worlds-first-industrial-scale-integrated-bio-oil-plant.aspx

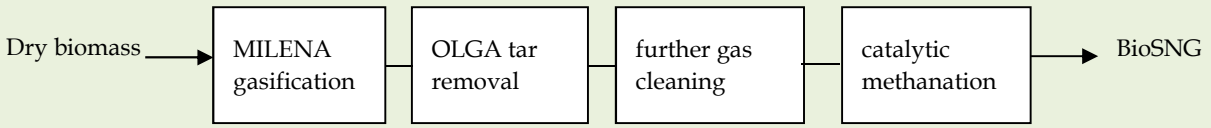
[90] http://www.empyroproject.eu/

use around 500,000 tonnes of municipal waste (which would otherwise go to landfill), agricultural residues and waste wood for processing using Solena's high temperature gasification process to produce a synthesis gas. This will be converted to 50,000 tonnes of aviation kerosene, 50,000 tonnes of synthetic diesel and naptha and 40 MW power, using the Fischer Tropsch technology developed by Velosys. The facility will produce an inert slag material which can be used in construction operations. The facility is due to begin production in 2015. The key advantage of the technology planned to be used at this plant is its feedstock flexibility, which is able to use any carbon containing material.

Source: Own compilation based on http://www.solenafuels.com/node/73

Box 14: BioSNG – a bio-based alternative to natural gas

The EU has taken a leading role in supporting the development trajectory of BioSNG, a renewable alternative to natural gas. Pilot plants have been set up in the UK, Netherlands, Switzerland, Austria, and Sweden. The clear advantages of BioSNG refer to the possibility of exploiting the existing infrastructure to supply heat and power, and also the well-established trade and supply network. ECN, a large Dutch energy research institute, started R&D activities on BioSNG in 2000. Ever since, it has refined the process of converting dry lignocellulosic biomass by MILENA indirect gasification and OLGA tar removal. In order to fulfil its ambition of achieving higher efficiency from converting biomass to BioSNG, and developing large-scale production, ECN partnered with HVC, a waste company. As a result, two demonstration plants were set up. The first installation became operational in 2012, and features ~10 MW combined heat and power (CHP) capacity. The second demo plant, of ~50 MW SNG capacity, will incorporate in its processing facilities further gas cleaning and catalytic methanation. This last phase of gas upgrading consists mainly in the removal of water and CO_2. The general process is illustrated in the scheme below.



Source: http://www.biofuelstp.eu/spm2/pdfs/Poster_ECN.pdf).

For the realisation of the green natural gas targets in the Netherlands, it is estimated that ~240 PJ of BioSNG would need to be produced annually. Because of lack of sufficient domestic supply, roughly 20 million tonnes of imported biomass would be required for this, anticipated to be primarily clean woody biomass from industrial forestry. This questions the sustainability of locating large scale BioSNG production in the Netherlands, a country without a strong domestic forestry sector. It is mentioned, however, that essentially all types of biomass materials are suitable as a feedstock for the process.

Source: Own compilation based on http://www.biosng.com/sng-vision/biomass-availability/

3.2.3 Biochemical conversion routes – Sugar fermentation and catalytic conversion

Both hemicellulose and cellulose can be broken down through either chemical or enzymatic methods to produce simple sugars which can then be converted, either through fermentation or through catalytic approaches to products or used as building blocks for the production of other chemicals and fuels. A very wide range of potential products can be developed from plant-based sugars and is shown in the diagram from Werpy and Petersen (2004) in Annex 3.

Deployment and timescales

It is pertinent to note that many of the products which are currently being produced at the commercial scale are largely from sugars from food based products such as wheat, maize, sugar beet, sugar cane and tapioca. These contain simple hexose sugars such as glucose which are easily fermentable and cheaply available. However, with increasing concerns over the indirect land use change effects, the impacts on food prices, and other environmental risks associated with growing food crops for non-food purposes, there is increasing interest and activity focusing on the use of waste and residue materials for both biofuels and biochemical production. Several products are currently produced, or could potentially be produced from glycerine which is a co-product of the biodiesel industry. Indeed, the affordable price of some wastes and residues such as glycerine is driving the market growth for new glycerine based intermediate chemicals such as propylene glycol, epichlorohydrin and methanol, but the continued growth of these markets will depend upon a continuing supply of affordable glycerine[91].

Biofuels

A variety of biofuels can be derived from the chemical and biochemical treatment of biomass. In this section, we consider the range of biofuel products which can be derived from the fermentation (including anaerobic digestion) and catalytic conversion of sugars, current and planned production capacities and producers, and whether they are located in the EU or elsewhere in the world.

There are a number of routes by which biofuels can be produced from biomass using biochemical or chemical approaches. These include biofuels which are produced by the fermentation of sugars (bioethanol, biobutanol and farnesane[92]) and those produced by anaerobic digestion of biomass (biomethane from upgraded biogas). These fuels may be used as a partial or full substitute for petrol (ethanol and butanol), diesels (farnesane) or compressed or liquefied natural gas (biomethane). Helped by EU renewable energy policy, the biofuels industry is growing rapidly, and fermentation and catalytic approaches are expected to be of the key tools used to convert plant biomass to biofuels. Advanced biofuels, derived from lignocellulosic biomass, are expected to increasingly contribute towards EU biofuels targets in the second half of this decade (Eurobserver[93]).

The map below (Figure 14), taken from the IEA Task 39[94] database, shows that several countries within Europe, particularly in Western Europe, are active in the commercialization of advanced biofuels, either at the pilot, demonstration or commercial scales. As of October 2012, there were 13 plants in operation (shown in green), four plants under construction (shown in orange) and two plants had ceased operations (shown in red).

[91] http://www.prnewswire.com/news-releases/bio-based-chemicals-market-to-grow-to-122-billion-by-2021-says-2nd-edition-market-research-report-on-the-world-market-for-bio-based-chemicals-168735676.html

[92] A hydrocarbon and diesel replacement that is chemically hydrogenated from farnesene, a fragrant oil chemical.

[93] http://www.eurobserv-er.org/pdf/baro210.pdf

[94] http://www.task39.org/

Figure 14: Biochemical Biofuel Plants in Europe as of 2012

Source: IEA Task 39 – 2nd Edition of http://demoplants.bioenergy2020.eu/projects/mapindex (Bacovsky *et al*, 2013). **Note**: Planned plants are shown in orange, green represents operational plants and red represents projects which have stopped.

Currently, the only fuels to be produced at a commercial scale through biochemical or chemical conversion routes anywhere in the world from lignocellulosic materials, are ethanol and biomethane. It is particularly noticeable that the vast majority of current and planned plants at the pilot, demonstration and commercial scale, both in the EU and world-wide are for the production of lignocellulosic bioethanol. The production and use of biomethane, derived from the anaerobic digestion of wastes and residues, as a transport fuel is geographically more restricted, with Sweden a notable pioneer and leader in terms of deployment.

There are several biochemical biofuel plants currently in operation worldwide, located in North America, Europe and South America (Table 13). It is worth noting that of these, only two (both based in Europe) currently use lignocellulosic materials to produce bioethanol. However, there are several plants in planning or due to be operationalized soon which will use lignocellulosic materials to produce bioethanol. Indeed in 2013, two plants based on municipal solid waste and agricultural wastes and one using a hybrid thermochemical and biochemical technology where a syngas is fermented to produce ethanol (described in section 3.1.1) are due to be operationalized. Several other lignocellulosic ethanol plants are currently in the planning stages and due to be operationalized after 2013.

There are several commercial biofuel plants which utilise food-based sugars for the production of farnesane using microorganisms including one in the EU. There is also a demonstration plant for the production of biobutanol in the EU. While these plants are based on sugars (most probably hexose sugars from food plants) at present, they may use lignocellulosic sugars in the future. Indeed

Butamax, the biobutanol producer, has indicated the potential to use lignocellulosic sugars in the future[95].

Table 13: Status of biochemical fuels production in Europe and the world by end-product as of 2012

Biochemical product	EU plants	Worldwide plants
Ethanol	Beta Renewables (2012) Borregaard (1938) INEOS Bio (n.d.)	Zeachem Boardman (2014) Frontier Renewable Resources (n.d.) LanzaTech Freedom Pines (2013)* GraalBio (n.d.) Abengoa Kansas(2013) Ineos Bio (2013)* Poet DSM Project Liberty (2013) Fibreright (2013)
	Abengoa Bioenergy Arance (2013) Sekab (2014) Biogasol Born Biofuel 2(2013) Abengoa (2008) Clariant (2012) Inbicon (2009) Borregaard (2012) Chempolis (2008)	Lanzatech Concord (2013)* *Lanzatech Beijing (2013)** Petrobras Blue Sugars (2011) BP Biofuels (2009) DuPont (2010) Fibreright (2012) Mascoma Iogen (2004) *LanzaTech BaoSteel New Energy Co (2012)*
	Beta Renewables (2009) PROCETHOL 2G (2011) Inbicon (DONG Energy) (2003)(2005) Aalborg University Copenhagen Born Biofuels 1 (2009) Weyland AS (2010) SEKAB/EPAP (2004)	Lignol Innovations (2009) Aemetis (2008) NREL Golden (1994 and expanded 2011) Abengoa New Energies (2007) Poet Scotland (2008) Petrobras (2007)
Butanol	Butamax Advanced Biofuels (2010)	
Diesel hydrocarbons (Farnesane)	Amyris Antibioticos (2011)	Amyris Sao Martinho (2013) Amyris Tate and Lyle (2011) Amyris Biomin (2010)
		Amyris Campinas (2004)
		Amyris California (2008)
Range of Fuels		Zeachem Bordman (2011)
Biomethane (from AD)	Many – Predominantly in Sweden	

Source: Own compilation based on IEA Task 39, http://demoplants.bioenergy2020.eu/projects/mapindex. **Note**: Plants in **bold** are operational, plants in *italics* are in construction, plants in normal type are in planning. Purple boxes denote pilot scale plants, orange boxes represent demonstration plants and green boxes represent

[95] http://www.butamax.com/_assets/pdf/global_agriculture_fact_sheet.pdf

commercial plants. Dates refer to expected or actual operation date and are based on details in the IEA task 39 database[96]. Plants with an asterix (*) utilise a hybrid thermochemical/biochemical technology.

Bio-based chemicals

A wide range of chemicals can be derived from biomass. In this section, we consider the range of non-fuel chemical products which can be derived from biomass, current and planned production capacities and producers, and whether they are located in the EU or elsewhere in the world. Several case studies give more detailed information about the markets, processes and applications for several promising chemicals derived from biomass.

The current market: The bio-based chemical and polymer industry is growing rapidly. In 2011, it was estimated that global bio-based chemical and polymer production was around 50 million tonnes with a market size of $3.6 billion[97], compared to a production volume of chemicals and polymers from petrochemical sources of 330 million tonnes globally (de Jong *et al*, 2012). Some sectors, in particular, are experiencing rapid growth; for example between 2003 to the end of 2007, the global average annual growth rate in bio-based plastics was 38 per cent whilst in Europe, the annual growth rate was as high as 48 per cent in the same period.

There are already a large number of chemicals produced from biomass as shown in Table 14. These products vary by scale from niche specialty products such as furfurals, to large scale commodity products such as ethanol. What is particularly striking is that, for the same bio-based chemical product such as Epichlorohydrin, Lactic Acid, Lactide and 1,3 Propandiol (PDO), there is a disparity in scale, often by orders of magnitude, between EU plant capacities (between 1-10 kt per year) and those elsewhere in the world (50 kt upwards), with larger scale commodity chemical production based on sugars largely based outside the EU. There is less of a disparity in scale of development in other chemicals, however, including succinic acid and PHB. Only bio-based acetic acid has been commercialized within the EU albeit at a small scale, whereas a large range of bio-based chemicals, including propylene glycol, polyols, ethylene and its derivatives, 1,2 propanediol, butanol and isobutanol are only being developed outside of EU.

The future market: The potential for further growth in this area is huge, for example, it has been suggested that over 90 per cent of the global annual plastic production could technically be substituted by bioplastics (Shen, 2009). One report expects the bio-based chemicals market to grow to $12.2 billion by 2021, accounting for 11.5 million tonnes of bio-based chemical production at the end of the decade (SBI, 2012). In particular, markets for bio-based polyethylene (the most common plastic) and epichlorohydrin are showing annual growth rates in excess of 10 per cent (SBI, 2012). Bio-based polymers production capacity will triple from 3.5 million tonnes in 2011 to nearly 12 million tonnes in 2020, according to nova-Institut (2013), with the fastest growth expected for bio-based drop-in PET and PE/PP polymers as well as PLA and PHA. Geographically, the industry is developing mostly in Asia and South America, as a consequence Europe's share in bio-based polymer production capacity is expected to drop from 20 per cent in 2011 to 14 per cent in 2020.

As shown in Table 15, there are many biochemical products in the development pipeline with pilot, demonstration and commercial scale plants due online in the coming years. These include PHB, 1,4 butanediol, propylene, MMA, isoprene, acrylic acid, propionic acid, and adipic acid. The scale and location of these plants is more evenly spread, with the EU developing MMA, 3 HP and propionic

[96] http://demoplants.bioenergy2020.eu/

[97] http://www.nnfcc.co.uk/tools/global-bio-based-chemicals-market-activity-overview-spreadsheet. The $3.6 billion translate into around €2.6 billion using an average 2011 exchange rate of ~0.72 from http://www.oanda.com/currency/historical-rates/.

acid, the rest of the world developing propylene, acrylic acid and adipic acid, and both regions developing PHB, 1,4 butanediol and isoprene at various scales.

Table 14: Commercial bio-based chemicals production capacity – Europe and worldwide

Biochemical Product	EU Plants	Worldwide Plants	Other Developers
Ethanol (derived from the fermentation of sugars). *See 'Practical examples' for applications.*	Many Plants	Many Plants	
Ethylene (derived from dehydration of ethanol). Applications include the manufacture of polyethylene plastics (LLDPE, LDPE and HDPE) or oxidised to ethylene oxide, used in the production of ethylene glycol.		Braskem (200 ktpa) 2010 Dow Chemicals/Mitsui (350 ktpa, 2014) Genencor/Danisco (780 ktpa, 2012) Solvay/Indupa (120 ktpa, 2007, 2012)	
Acetic Acid (sugar fermentation to ethanol and oxidation of ethanol). Primary applications in the food industry (eg pickled foods), pharmaceuticals, cosmetics, textiles.	Waker AG (0.5 ktpa – 2010)		
Lactic Acid (derived from the fermentation of sugars). *See 'Practical examples' for applications.*	Galactic (1.6 ktpa – 2009)	Hi Sun (5.5 ktpa- 2008) Natureworks (155 ktpa- 2015) Natureworks (155 ktpa – 2005) Purac (100 ktpa – 2007) Tong-Jie-Lang (0.1 ktpa – 2007)	
Lactide (chemically derived from lactic acid). *For use in the production of bio-plastics.*	Purac (5 ktpa- 2008)	Purac (75 ktpa – 2012)	
Epichlorohydrin. *Glycerine based intermediate chemicals. Primarily used for producing glycerol, plastics, resins, elastomers.*	Solvay (10 ktpa – 2010)	Dow Chemicals (1 ktpa – 2011) Solvay/Vinylthai (100 ktpa – 2014) Solvay/ Vinylthai (100 ktpa – 2012) Yang Nong Jiang Su (150 ktpa – 2011) Dow Shanghai (150 ktpa – n.d.)	Samsung Korea (30 ktpa) Fuijian Haobang (5 ktpa) Spolchemie
1,3 propanediol (PDO) (fermentation of sugars or glycerol). Mainly a building block for polymers, also used as a solvent and antifreeze agent.	Metabolic Explorer (8 ktpa, 2010)	Tate and Lyle/Dupont (60 ktpa – 2010) Metabolic Explorer (50 ktpa – 2013) Bio-Xcell/ Metabolic Explorer (n.d.)	Huamei Biomaterials
Propylene Glycol (1,2-Propanediol). Organic compound made from propylene oxide, used		ADM (100 ktpa – 2010) Cargill/ Ashland (65 ktpa, 2008)	

as chemical feedstock for the manufacture of unsaturated polyester resins.		Dow Chemicals (1 ktpa n.d.) Senergy (30 ktpa – 2008)	
Butanol (fermentation of sugars, but catalytic routes in development). Most commonly used as a solvent, as an intermediate in chemical synthesis, and as a fuel (to replace petrol).		Shi Jinyan (50 ktpa – 2014) Laihe Rockley (150 ktpa) Cathay Industrial Biotech (100 ktpa)	Abengoa, Green Biologics Eastman, Cobalt Technologies, Celtic Renewables, Working Bugs
Isobutanol (fermentation of sugars). A form of bio-butanol, primarily used as a solvent; potential to be used as an advanced biofuel.		Gevo (50 ktpa – 2012)	Butamax
Succinic Acid (fermentation of sugars). Main applications as a flavouring agent within the food and beverage industry.	Bioamber (DNP-ARD) (3 ktpa – 2009) CSM/BASF (15 kpa 2011) Roquette/DSM (10 ktpa – 2012) 2 plants	Bioamber (17 kta – 2013) Bioamber (34 ktpa – 2014) Lanxess (20 ktpa – 2012) Myriant (15 ktpa – 2013) Myriant / Davy Process Tech (15 ktpa – 2013)	
Furfural (chemical treatment of hemicelluloses). Bio-based alternative for the production of fuel, fertilizers, plastics, paints, wood treatment oils, paints.	TFC Belgium	Many	
Itaconic Acid (Methylenesuccinic acid) (fermentation of sugars). Its domains of application include paper and architectural coating industry; biodegradable.	Many Producers	Many Producers	
Xylitol and Arabitol (chemical treatment of hemicelluloses). Xylitol is a sugar-free sweetener with applications in pharmaceutical, healthcare, and food industries.	Many Producers	Many Producers	
Isoprene (fermentation of sugars). A liquid hydrocarbon, used to a large extent as a monomer in the production of polyisoprene rubber (IR) and butyl rubber, and to a lesser extent for special chemicals (eg vitamins), perfumes.	Genencor/Goodyear (0.01 ktpa, 2014)	Votorantim / Amyris (680 ktpa – 2012)	
Sorbitol (catalytic hydrogenation of glucose). A sugar alcohol mainly used as a sweetener, for medical			

applications, in health care, food and cosmetics industry.			
Polyols. Alcohol comprised of multiple hydroxyl groups. Applications include food science and polymer chemistry.		Bayer (35 ktpa – 2011)	Novomer (CO_2)
Polyhydroxyalkanoates (PHA) (sugar fermentation). Bio-polymer used in the production of bio-plastics; biodegradable and relatively heat resistant.	Metabolix/Antibioticos (10 ktpa)	Meredian (15 ktpa – 300 ktpa) Tianjin GreenBio Materials (10ktpa)	Newlight/Biomer (GHG to PHA)

Source: Based on nova-Institut (2012); GreenChems Blog (http://greenchemblog.wordpress.com/); de Jong *et al* (2012). **Note**: Chemicals in shaded rows are explored in a series of 'practical examples' below.

Table 15: Bio-based chemicals in development – Europe and worldwide

Biochemical Product	EU Plants	Worldwide Plants	Other Developers
Acrylic Acid (fermentation of sugars to 3 HPA and chemical dehydration). Wide applications in the manufacture of paints, printing ink, floor polishes, etc.		OPX Biotechnologies/DOW (0.02 ktpa – 2015) Cargill/Novozymes (0.01 ktpa n.d.)	Genomatica, Metabolix, Myriant, Arkema, BASF
Propionic acid and 3 hydroxypropionic acid (3HP). Potential building block for organic synthesis or high performance polymers.	Pertorp (1 ktpa – 2012)		BASF/Cargill/Novozymes
Propylene (from ethylene or ethanol via chemical treatment). Thermoplastic polymer with a variety of uses ranging from the packaging and apparel industries, to automotive components and laboratory utensils.		Braskem (30-50 ktpa) 2013	Global Bioenergies,Dow Chemicals, Coskata/Total/IFP (syngas)
1,4 Butandiol. *Organic compound obtained from butane. Applications as a solvent, and in the production of plastics, elastic fibres.*	Bioamber (23 ktpa – 2014) Grupo M&G Genomatica (20 ktpa- 2013) Novamont (20 ktpa – 2013)	Genomatica (0.02 ktpa) 2010	
Bio-Isobutene (2-Methylpropene). Bio-based alternative to petrochemical production route. Bio-isobutene can be converted into fuels, plastics and elastomers.			Gevo/Lanxess, Global Bioenergies
Methyl methacrylate (MMA) (from methanol, ethylene and carbon monoxide). Used in the manufacture of methacrylate resins and plastics (eg Plexiglas), and also of adhesives and sealants, etc.	Evonik Industris 0.01 ktpa		MRC and Lucite (2016), Evonik and Arkema (2018), Ascentix BioTechnologies
Levulinic Acid (from chemical treatment of starch and HMF, or pentoses). Organic compound, categorized as a keto acid; potential precursor to biofuels.		Seget	Maine Bioproducts
Adipic Acid. Chemical intermediate with wide applications in the plastics and textile industries; precursor for nylon production.		Verdezyne 0.04 ktpa – 2013)	Rennovia, DSM, Amyris, Genomatica, BioAmber, Aemetis

2,5-Furan Dicarboxylic Acid (FDCA) (chemical dehydration of hexose sugars). *See 'Practical examples' for applications.*			Avantium
Glucaric Acid (catalytic oxidation). Derived from glucose. Largely used in food and pharmaceutical industry.			Rivertop
Polyhydroxybutyrate (PHB). Biodegradable polymer used in the packaging industry (eg drink cans), in the production of disposable utensils and razors, and also for a variety of medical applications.	Bio-on (10 ktpa – 2013) Biomer (1 ktpa)	Tianjin GreenBio Material Co (10 ktpa, 2009) Yikeman, Shandong (3 ktpa n.d.) Zhejiang Tian An (2 ktpa n.d.) PHB Industrial Brasil SA (0.1 ktpa n.d.)	

Source: Based on nova-Institut (2012); GreenChems Blog (http://greenchemblog.wordpress.com/); de Jong *et al* (2012). **Note**: Chemicals in shaded rows are explored in a series of 'practical examples' below.

The tables above show that the location of biochemical production plants varies by product and by the scale of the plant. For many large scale products, especially those based on hexose sugars (for example lactic acid and ethanol production), the commercial plants have been located in areas close to abundant sugar processing, notably in Brazil and Thailand where both the feedstock and processing infrastructure is easily available. In other cases, the location of plants has been influenced by government policies, synergies with downstream chemical using industries and financial incentives and new opportunities have developed over time.

Several screening exercises have been carried out to ascertain which chemicals have the greatest economic potential in particular regions. Two comprehensive reports have attempted to elucidate the chemicals with the greatest potential, namely the US Department of Energy 'Top Value Added Chemicals from Biomass' study (Werpy and Petersen, 2004 and Holladay *et al*, 2007) and the EU's 'Biotechnological Production of Bulk Chemicals from Renewable Resources' (BREW) study (Patel *et al*, 2006). As shown in Table 16, several of these chemicals overlap.

Table 16: Bio-based Chemicals with the Greatest Potential for the Global and EU markets

Carbon Number	DOE Report	BREW Report
C2		Ethanol
		Acetic Acid
C3	Glycerol	Lactic Acid
	3-Hydroxypropionic Acid	Glycerol
		3-Hydroxypropionic Acid
		1,3 Propanediol
		Acrylic Acid
C4	Succinic Acid	Succinic Acid
	Fumaric Acid	Fumaric Acid
	Malic Acid	Aspartic Acid
	Aspartic Acid	1-Butanol
	3-Hydroxybutyolactone	1,4 Butanediol
C5	Glutamic Acid	Xylose
	Itaconic Acid	Arabinose
	Levulinic Acid	Xylitol
	Xylitol	Arabinitol
	Xylonic Acid	Levulinic Acid
		Furfural
C6	2,5 Furan Dicarboxylic Acid	Sucrose
	Gluaric Acid	Glucose
	Sorbitol	Sorbitol
		5-Hydroxymethylfurfural
		Adipic Acid

Source: NNFCC, 2009, p28

More recently, the EU sponsored FP7 BIO-TIC project has identified five bio-based product groups (rather than distinct chemicals) that have the potential to be produced in the EU, are able to substitute for non-bio-based alternatives and help improve EU competitiveness[98]. These are:

- Non drop-in bio-based polymers (PLA and PHA);
- Chemical building blocks (platform chemicals – with a focus on succinic acid, isoprene, furfural, 1.3-PDO & 3-HPA);
- Bioethanol (2nd generation biofuels from waste) and bio-based jet fuels;
- Bio-surfactants;
- CO_2 as a bio-based feedstock.

It is notable that few of these are indicated specifically from waste materials. Several bio-based materials are already produced from wastes and residue materials, for example xylose, furfurals. Nevertheless, there is a growing R&D activity into developing bio-based chemicals from waste materials, as shown in the practical example on ethanol below.

Practical examples

The three examples outlined below all consider the production of bio-based plastics from plant sugars, but differ in the conversion technology used, the end use application and in the development status. Two examples consider commercial processes for the fermentation of sugars, one considers the production of lactic acid, which could be used in the production of compostable flexible packaging, and the other, the fermentation of sugars to produce ethanol, which as well as producing a fuel can also produce a chemical which could be used in the production of recyclable rigid packing materials. The third considers a catalytic route for producing a component of recyclable rigid packaging materials which is at the pilot scale of development.

Box 15: Furanics – A catalytic route to fuels and chemicals from sugars

Avantium, a Netherlands-based chemicals company, are developing catalytic routes for the conversion of plant based sugars to furanic building blocks. Whilst fermentation can take days, catalytic conversion can take seconds, thus improving the economics.

One of the key furanic building blocks is 2,5-Furandicarboxylic acid (FDCA) which is produced through a three-step process. FDCA can be used in conjunction with Bio MEG (see ethanol example below) to produce PEF, a completely bio-based alternative to PET. Indeed, Avantium has signed development partnerships with The Coca-Cola Company and Danone to further develop and commercialise these 100 per cent bio-based bottles. FDCA can also be used in a wide range of industrial plastics, including bottles, textiles, food packaging, carpets, electronic materials and automotive applications. Avantium are currently at the lab to pilot plant scale of development, but plan to have a first industrial plant (50,000 tonnes per year) by 2015.

Source: Own compilation based on http://avantium.com/yxy/YXY-technology.html and sub-pages

[98] http://suschem.blogspot.be/2013/03/bio-tic-identifies-five-breakthrough.html

Box 16: Lactic acid – A gateway to plastics and more

Lactic acid (2-hydroxypropionic acid) is a bulk chemical with a global market size of around 300,000 to 400,000 tonnes per year (NNFCC, 2010b). Bio-based lactic acid is formed by the fermentation of sugars. At present, these use food based materials, starch, tapioca and sugarcane, but there is no reason why lignocellulosic sugars could not be used in the future.

Lactic acid has a wide range of different applications, ranging from pH stabilization, use in the food industry, solvents and as a raw material for the production of polylactic acid (PLA). PLA can be used in a range of applications including the production of biodegradable shrink-wrapped films, rubbish bags and rigid plastics. PLA made up 16 per cent of bio-based plastics in 2011, but will only make up 5.1 per cent by 2016. Current production is around 180,000 tonnes, but a production capacity of over 800,000-950,000 tonnes is expected by 2020[99]. Growth in demand for PLA is currently outstripping growth in EU supply[100].

There are several producers world-wide including Natureworks, Futerro, a collaborative venture between Galactic and Total, HiSun and Tong-Jie-Lang who are producing PLA at variety of scales. The largest producer is NatureWorks, who have a capacity of 155,000 tpa in the USA and expect to have a 155,000 tpa plant in Thailand by 2015. The other producers have a current capacity of between 1,500 and 10,000 tpa[101]. The majority of PLA is currently derived from food crops; Asia Pacific is expected to take the lead, given the abundance of cheap feedstock, such as tapioca, sugar cane and sugar beet, for lactic acid production[102].

Source: Own compilation based on sources cited

Box 17: Ethanol – a fuel, but also so much more

Ethanol is a bulk chemical and had a global market size of around 61 Mt per year in 2008. It can be produced from the steam cracking of crude oil or bio-based ethanol can be produced through the fermentation of sugars. The vast majority is derived from biomass (NNFCC, 2010a).

Ethanol can be used to synthesise a range of other chemicals including ethylene, ethyl acetate and acetic acid. These can, in turn, be used as building blocks to a range of other valuable chemicals, for example ethylene can be used in the production of polyethylene plastics (LLDPE, LDPE and HDPE) or oxidised to ethylene oxide, which is used in the production of ethylene glycol amongst other uses[103]. Monoethylene glycol (MEG) is predominantly consumed in the production of polyester polymers (polyethylene terephthalate, also known as PET).

Bio-based plastics from ethanol are a rapidly growing sector. These non-biodegradable, but fully-recyclable plastics are already found in a wide range of different applications; for example, bio-PET produced is used by Toyota Tsusho in vehicle seat covers, floor carpets[104], the plant-based bottles developed by Coca Cola and Pepsi. However, the renewable component of bio-PET is only around 30

[99] http://www.nova-institut.de/pdf/12-08-06_pr_market_study_bioplastics_nova.pdf

[100] http://www.prweb.com/releases/lactic_acid/polylactic_acid/prweb9369473.htm

[101] http://www.nova-institut.de/pdf/12-08-06_pr_market_study_bioplastics_nova.pdf

[102] http://www.prweb.com/releases/lactic_acid/polylactic_acid/prweb9369473.htm

[103] Ibid

[104] http://greenchemicalsblog.com/2012/10/26/toyota-tsushos-bio-pet-rolls-out/

per cent by weight (the monoethylene glycol component), with the remainder (purified terephthalic acid) derived from fossil components. The Plant PET Technology Collaborative, formed by the large household brands Coca Cola, Nike, Ford, Heinz and Proctor and Gamble, aims to accelerate the development and use of 100 per cent based PET in their products[105]. Bio-based PET already makes up 40 per cent of the global bioplastics production capacity. According to the trade association 'European Bioplastics', by 2016, partially bio-based PET will account for 80 per cent and bio-based polyethylene will account for 4 per cent of the total bioplastics production capacity[106].

The largest producers worldwide are Braskem, Petrobras and Dow Mitsui who manufacture bioethanol in Brazil from sugar cane. However, while the majority of bioethanol is currently derived from food crops, it can be produced from waste and residue materials. Pepsi Co. for example, are investigating a closed loop approach where the wastes and residues from their food processing industries (including orange and potato peelings, oat hulls) are used in the production of bio-PET, whilst the thermochemical conversion of wastes, followed by the biological fermentation of syngas to ethanol, could be another way to use wastes and residues in bio-based chemicals production (see section 3.1.1) (NNFCC, 2010a).

Source: Own compilation based on sources cited

3.2.4 Discussion

The bio-based chemicals industry is developing rapidly, both in the EU and globally. Many of the chemicals already produced or planned for the near future are derived from plant sugars, either through catalytic and chemical transformation, or through fermentation by bacteria and yeasts. While some are already produced from lignocellulosic materials, particularly the pentose derived chemicals xylose, furfural, and arabinose, the larger scale commodity chemicals are currently produced from the simpler hexose sugars found in the sugar and starch food crops such as sugar cane, wheat, maize and sugar beet. The use of these products creates two sets of concerns. First, the environmental effects of any direct and indirect land use change associated with using new or existing cropland area for non-food uses. These land use changes may be associated with biodiversity loss, and significant additional greenhouse gas emissions if it involves deforestation or ploughing up of previously uncultivated land. The second major concern is the effects of the increased demands for agricultural crops on the level and volatility of food prices.

Wastes and residues offer a potential route to overcome the concerns over using food materials for non-food purposes. Indeed, glycerine, a co-product of the biodiesel industry, is already a significant feedstock for many bio-based chemicals (such as propylene glycol), in part due to its low price. The use of lignocellulosic materials and other wastes is, however, less well developed, except for bioethanol production, albeit one which is being driven by the biofuels industry, and which may be adopted by the chemicals industry in the future. There is a growing recognition of the benefits of using wastes and residues for the production of bio-based chemicals where appropriate to do so. As shown in the ethanol 'practical example' in the previous section, Pepsi Co is investigating the use of wastes and residues from their food processing industries for the production of bio-PET. Other examples under investigation by companies include the production of PHA from greenhouse gases by Newlight and Biomer[107], the production of polyols from CO_2 by Novomer[108], and the production of

[105] http://www.coca-colacompany.com/press-center/press-releases/formation-of-the-plant-pet-technology-collaborative-ptc

[106] http://en.european-bioplastics.org/wp-content/uploads/2012/10/PR_market_study_bioplastics_ENG.pdf

[107] http://greenchemicalsblog.com/2012/11/11/pha-bioplastic-update/

propylene from syngas by Coskata and Total[109]. The FP7 projects EcobioCap[110] and SYNPOL[111] are investigating feasibility of producing PHAs for biodegradable plastics (eg for packaging) from food by-products and a range of biowastes, respectively. The BIOCORE FP7 project is investigating routes to producing organic acids, aromatics and olefins from lignin. These are key building blocks for commonly used thermoplastics (such as polyurethanes, polyolefins, PVC) and producing adhesives, resins, and feed ingredients.

While the use of lignocellulosics for the production of bio-chemicals may be, in theory, attractive, it has some significant technical and economic drawbacks. Indeed, the overall growth of the market greatly depends on the continued adoption of biodiesel to provide steady glycerine production and the market growth of new glycerine-based intermediate chemicals. This is problematic, especially for the EU where there is uncertainty over the future of conventional biofuels such as biodiesel. The concerns are principally the sustainability credentials of such biofuels. This is an important matter because the biodiesel route acts currently as a significant source of affordable glycerine. Apart from the sustainability concerns associated with biodiesel production, this highlights one of the key issues associated with the production of chemicals from biomass, that is unless there are policy or economic benefits associated with a particular feedstock, processors will choose to use the simplest sugars (ie sugars from food crops), due to their ease of use, low cost and existing infrastructure. Moreover, at the current time, mandates in the EU are distorting the market in favour of biofuels, discouraging the scale of investment needed to incentivise the biorefinery sector (Carus, 2011).

Technical issues associated with using lignocellulosic materials also need to be overcome in order to develop a lignocellulosic waste and residues to chemicals capability. One of the key issues here is the heterogeneity of many wastes and residues. For example, lignocellulosic biomass is made up of both pentose and hexose sugars. Pentose sugars are harder for microorganisms to breakdown during fermentation than hexose sugars. Therefore, it is necessary to develop systems to improve the fermentation of pentoses in mixed hexose/pentose feedstocks and to develop systems to separate and ferment and then utilise pentose sugars. This is certainly possible using molecular biology, but will require a sustained research effort. One of the most attractive routes for heterogeneous feedstock streams such as mixed wastes and residues, and potentially of great interest to the EU as a whole, is perhaps the use of hybrid thermochemical / biochemical approaches whereby the feedstock is gasified to form a syngas which can then be converted to chemicals using microorganisms which can ferment syngas to economically interesting chemicals. This approach is already being developed for both fuel ethanol (for example by Coskata and Ineos Bio) and several other companies, for the production of PHA, polyols and propylene.

[108] http://greenchemicalsblog.com/2013/02/22/novomer-produces-co2-based-polyols/

[109] http://www.icis.com/blogs/green-chemicals/2011/12/coskata-looking-at-bio-propyle.html

[110] http://www.ecobiocap.eu/

[111] http://www.synpol.org/

4 ASSESSING THE SUSTAINABILITY OF BIO-BASED PRODUCTS

Sustainability is usually conceived as having economic, social and environmental dimensions[112]. The economic sustainability, or commercial viability, of the bio-economy developments considered in this report have partly been considered alongside technical feasibility in the assessments reviewed in Chapter 3. In this chapter, the focus is the environmental sustainability of a selection of bioenergy and biomaterial technology pathways and how the bio-based products compare with their 'traditional' counterparts. Environmental sustainability issues are reviewed given the emphasis on GHG mitigation and wider environmental benefits as part of the bioeconomy discourse. The sustainability assessment covers two important areas:

- A review of the relevant LCAs (life-cycle assessments) conducted for bio-based pathways that compare the relative merits of bio-based products to traditional products;
- A review of assessments looking at wider environmental impacts of bio-based products which are usually not covered in LCAs (as recognised, for example, in a recent JRC report, JRC-IES, 2011) such as water, soil and biodiversity impacts. This considers impacts at different stages of the supply chain, including important sustainability concerns linked to the mobilisation of wastes and residues.

There is a considerable body of literature on the environmental impacts of bioenergy and especially on first generation biofuels, summarised in Box 17. The focus of this chapter is therefore the emerging evidence on impacts from advanced bioenergy and other biorefinery technologies that are less well understood and communicated at present. It seems that there has been some learning from the errors made in the promotion of biofuels as sustainability is being addressed during the early stages of the development of the bioeconomy in order to understand better potential environmental impacts. Another approach to embrace sustainability is seen in emerging initiatives to establish certification schemes for bio-based materials, these are reviewed in Box 19.

Box 18: The literature on the environmental impacts of bioenergy and biofuels – a rapid reading guide

This is no attempt to provide a comprehensive review but rather to point out some of the key studies and primarily review studies in the rapidly expanding literature on the environmental performance of (conventional) biofuels and bioenergy:

Summary studies:
A study performed by the European Academies Science Advisory Council (2012) introduces the EU policies relevant to the development of biofuel use, and explores the impacts of biofuel production on GHG emissions and other environmental dimensions such as biodiversity, water resources availability and soil quality. Another recent summary study done by Chatham House (Bailey, 2013) with a UK focus summarises the consequences of expanding biofuel use in relation to environmental, social and economic sustainability.

[112] Some social repercussions of biofuels and bioenergy use especially for developing countries have been investigated in a range of publications: ActionAid (2012), Ecofys *et al* (2012) and Oxfam (2012) consider biofuel related impacts; Wunder *et al* (2012) address impacts of (mainly woody) biomass use in the EU on developing countries). Kretschmer *et al* (2012) review the literature on the agricultural commodity price impacts of biofuels use.

GHG profile of biofuels and ILUC:

An early study that highlighted the risks associated with biofuel use leading to indirect land use change was by Searchinger *et al* (2008). Numerous studies have investigated the ILUC effects associated with biofuel use in the EU since. A 'prominent' one is the 'IFPRI' study (Laborde, 2011) prepared for the European Commission from which ILUC emission factors have been included in the Commission's ILUC proposal. Further studies were prepared for the Commission's impacts assessment[113], one of them comparing assumptions, modelling approaches and results across different models (Edwards *et al*, 2010). Another approach to quantify ILUC is based on historical data (Overmars *et al*, 2011). There is also a broad US focused literature; one example worth mentioning is by Hertel *et al* (2010) who investigate the combined effects of EU and US biofuel mandates.

GHG intensity of bioenergy:

Bowyer *et al* (2012) investigate the GHG intensity of bioenergy and question the assumption underlying current bioenergy policies in Europe that the use of bioenergy is carbon neutral and delivers significant GHG savings (see also section 4.2.1). Likewise, the European Commission's Joint Research Centre (JRC, 2013) conducted a 'critical literature review' on carbon accounting in the area of forest bioenergy equally challenging the carbon neutrality assumption. Both studies contain extensive references to the wider literature.

Biodiversity impacts:

A CBD paper (2012) explores impacts of biofuel scale up on biodiversity and discusses assessment tools and mitigating measures. Bertzky *et al* (2011) developed a methodology to evaluate the biodiversity impacts associated with ILUC. An earlier attempt to estimate the biodiversity impacts of ILUC is by Hellmann and Verburg (2010) using a spatially explicit analysis and demonstrating that indirect effects of European biofuel policy on biodiversity are much larger than the (easier to observe) direct effects. Marelli *et al* (2011) combine ILUC modelling results with a spatially explicit modelling tool to *inter alia* study biodiversity impacts (via a mean species abundance indicator).

Soil, water and air impacts:

Diaz-Chavez *et al* (2013) have investigated the impacts of biofuel consumption on soil, water and air quality in the main producer countries both in the EU and externally in a study for the European Commission.

Source: Own compilation

Box 19: Examples of sustainability schemes and other initiatives to address the sustainability of biomaterials

Building for Environmental and Economic Sustainability (BEES): The first comprehensive assessment framework that was developed for bio-based materials, by the US National Institute of Standards and Technology (NIST)[114]. It is implemented through the BEES Online webtool. This is designed as a practical, flexible and transparent tool to be used by designers, builders and product manufacturers. It is based on actual environmental and economic performance data and follows

[113] http://ec.europa.eu/energy/renewables/studies/land_use_change_en.htm

[114] Developed by Lippiatt, B, Landfield Greig, A and Lavappa, P; documentation available at: http://www.nist.gov/el/economics/BEESSoftware.cfm.

international LCA standards, most notably the ISO 14040 series of standards, in order to analyse all stages relevant to the life of a product: raw material acquisition, manufacture, transportation, installation, use, recycling and waste management. Its original purpose is for the assessment of building products (over 230 are covered in the database); a second application is developed to asses over 100 bio-based products, in the context of the USDA BioPreferred Program[115] (a product labelling and public procurement programme)[116].

BIOCORE project: The FP7 funded BIOCORE project (on-going at the time of finalising this report) conducts relevant research on optimising biomass supply chains for biorefineries both in economically and environmentally sustainable ways. Biomass sources considered are ligno-cellulosic feedstocks including straw, forestry residues and Short Rotation Coppice. The project aims to 'provide a multicriteria evaluation of the sustainability of the entire value chain'[117].

Global-Bio-Pact project: This FP7 funded project concluded in January 2013. It conducted a 'global assessment of biomass and bioproduct impacts on socio-economics and sustainability'. Based on a range of case studies of different biomass value chains across the globe, the project proposed a set of criteria and indicators for both, biomass production and conversion chains in order to cover the whole life cycle of bioenergy and bio-products. These fall into the categories 'Basic information' 'Socio-economic' and 'Environmental' indicators[118].

ISCC PLUS certification scheme: The ISSC PLUS scheme is an extension of the existing ISCC EU scheme, which is one of the 14 (at the end of June 2013) certification schemes recognised by the European Commission as proof of compliance with the Renewable Energy Directive's (RED) sustainability criteria. The scheme has been extended to also offer certification to food, feed, bioplastics and solid biomass/SRC. The scheme's standard consists of the six principles of the existing ISCC EU on former land use, responsible biomass production, safe working conditions, respect for human, labour and land rights, compliance with applicable regional or national legislation and good management practices. These principles are further specified through a detailed list of criteria against which suppliers are to be assessed. A set of documents spell out special provisions for the different bio-based pathways and for different aspects of the certification process, for instance the GHG requirements. These do not spell out in detail yet comparators, ie lifecycle emission values for traditional products, against which the lifecycle emissions of bio-based products would be compared, apart from providing values for biofuels and bioliquids used for heat, electricity and transport[119].

LCA to go project: This is another FP7 funded project that develops easy-to-use web-based LCA tools for use by small and medium-sized enterprises (SMEs) for a range of product categories, among them bio-based plastics. The project has identified a number of different bio-based plastics as most promising and relevant from a SME point of view. Establishing eco-profiles of the different products

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[115] http://www.biopreferred.gov/, see also Box 24.

[116] http://www.globalbioenergy.org/fileadmin/user_upload/gbep/docs/2007_events/tfGHG_Wash2007/BEES_for_State_Dept_GBEP.pdf

[117] More information is available at: http://www.biocore-europe.org/page.php?optim=a-worldwide-sustainable-concept. The relevant BIOCORE deliverables are expected for the end of August 2013 according to *pers comm* with one of the project collaborators.

[118] More information is available at http://www.globalbiopact.eu/ as well as http://www.globalbiopact.eu/images/stories/publications/d8_2_final.pdf on the indicators specifically.

[119] Further information including the documentation of the standard and all accompanying documents can be found at: http://www.iscc-system.org/en/iscc-system/iscc-plus/.

suggested that a range of environmental impacts beyond global warming potential are to be considered, among them water footprint and land use[120].

PROSUITE project: Another FP7 funded project that develops methods and tools for the sustainability lifecycle assessment of current and future technologies, at different stages of maturity. Five 'impact categories' are considered, these are impacts on human health; social well-being; prosperity; natural environment; and on exhaustible resources. In order to test the framework develop and gather stakeholder feedback, four technology case studies are being conducted. One of them is considers biorefinery technology and in particular bio-based resins for paint, bio-based PVC and anaerobic digestion[121].

Source: Own compilation

4.1 Resource efficient use of biomass via cascading

The resource efficient use of biomass is essential given the anticipated scale-up of biomass to be used for energy purposes and bio-based products along with the growing demand for food and feed. Resource efficiency as a guiding principle when using biomass for energy in particular is highlighted by the EEA (EEA, 2013). An important part of this drive for resource efficiency is to utilise wastes and residues as potential feedstock sources instead of dedicated energy crops. Apart from striving to get most from available biomass and hence land and water resources by putting wastes and residues to productive use, another relevant consideration is to prioritise waste and residue sources and to combine several biomass applications in a cascade of uses.

In conducting the prioritisation, it is necessary first to distinguish between energy and non-energy uses of biomass in general, then between the utilisation of wastes and residues as opposed to food products, and finally between different energy use pathways. Non-energy uses of wastes and residues include the conversion into bio-based materials as discussed in this report. Assessing the sustainability of all these pathways must also take into account that some of the wastes and residues to be used as feedstocks were previously used in ways which provided direct environmental benefits. Prime examples are the use of straw as a soil improver, the retention of forestry residues in forests to benefit biodiversity and carbon stocks (discussed in section 4.3.1), and the composting of food waste instead of recovering its energy value via anaerobic digestion.

There is no doubt that one of the strong motivations for the interest in the bioeconomy and the substitution of fossil-based fuels and material with bio-based products concerns the need to contain climate change by reducing greenhouse gas emissions. Therefore, an important consideration in determining the merits of using a particular feedstock for energy or non-energy purposes is the level of the lifecycle GHG savings per unit of biomass that can be attained by replacing traditional, mainly fossil-based feedstocks. Another consideration is the availability of low-carbon fuel alternatives (eg Keegan *et al*, 2013, Kretschmer *et al*, 2013, Ros *et al*, 2012). In order to prioritise some energy uses over others, energy system modelling is an appropriate tool to take into account the availability of other low-carbon alternatives in the heat, electricity and transport sectors and indeed in different regions of Europe.

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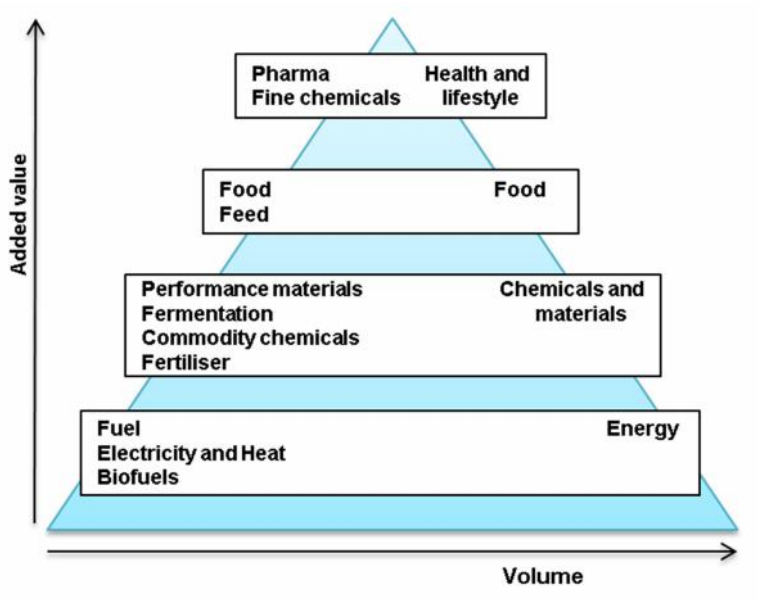
[120] More information is available at: www.lca2go.eu; technical report summary bio-based plastics: http://www.lca2go.eu/files/re/D_2_1_ExecutiveSummary.pdf

[121] More information is available at: www.prosuite.org; information on the bio-refinery case studies being conducted: http://prosuite.org/c/document_library/get_file?uuid=4f0942de-6d11-4729-8a9d-1cfe9d0d396c&groupId=10136.

An additional consideration when prioritising uses is the economic value added that may be derived from a given volume of biomass. Put simply, biomass can end up in bulk applications where high volumes of biomass are needed to generate a unit of value added – these include bioenergy but also some biomaterial uses – or in high-value applications where relatively small volumes of biomass generate high-value products. This is illustrated in the biomass value triangle (Figure 15).

Figure 15: The biomass value triangle



Source: Adapted after Eickhout (2012), based on http://www.biobasedeconomy.nl/themas/bioraffinage_v2/

It is difficult to make a case for or against a certain biomass use pathway without being able to employ encompassing economic modelling tools. We are aware of one meta-analysis of LCA studies that brings together results of various lifecycle analyses comparing potential GHG emission savings on a per hectare basis (Carus *et al*, 2010). Its authors conclude that savings derived from material biomass uses are at least in the order of magnitude of savings from conventional biofuels and in most cases higher than that. Biomaterial use does not seem to unambiguously outperform solid and gaseous biomass use for electricity and heat production but the authors indicate that when biomass is used in a cascading way, an additional 10 to 20 tonnes CO_2-equivalent/hectare can be abated on average.

This finding highlights the concept of cascading biomass use as an aspect worth highlighting, stipulating that where applicable, non-energy and energy uses for biomass materials should be combined over time. Cascading is envisaged as a tool to optimise resource use; optimal biomass use through cascading is most relevant for woody (ligno-cellulosic) material that can be used in the pulp, paper and board industry, with energy recovery following recycling loops within these sectors[122].

[122] Mantau (2012) provides valuable insights into the implementation of the cascading use principle in the wood-based industries, visualising the different recycling loops and providing volume estimates for the European forestry and wood-industry sector. The concept of cascading is explained in a range of earlier and more recent imports, including Sirkin and Ten Houten (1994); Østergård *et al* (2010) and Keegan *et al* (2013).

The following sections will highlight in more detail LCA performance of different use pathways and discuss impacts of alternative uses on soils and biodiversity.

4.2 Review of greenhouse gas LCAs

This section reviews relevant LCAs for bioenergy in order to assess the GHG performance of promising technology pathways and compare the derived products to their traditional fossil-based counterparts. It starts with a discussion of challenges for, and shortcomings of LCAs followed by separate sub-sections addressing LCAs for bioenergy and in particular advanced biofuel pathways, and then for other bio-based products.

4.2.1 Biomass LCAs – challenges and shortcomings

This section summarises some general and frequently encountered challenges for and shortcomings of LCAs. The development of LCAs for bio-based materials is under continuous development. A methodological framework is offered by Pawelzik *et al* (2013), for example. Also the Joint Research Centre has been calling for advancing LCAs in this area by providing 'comparative life-cycle based assessment of example bio-based products and their [entire] supply chains' (European Commission, 2013).

Choice of LCA type – attributional versus consequential LCA

A range of LCA related publications discusses the choice between attributional versus consequential LCAs (or ALCA and CLCA). We will not go into the details of this discussion but only outline the broad differences between the two categories following Pawelzik *et al* (2013) who provide further references. ALCAs study the direct impacts *attributable* to the different stages (production, use and disposal) of the lifecycle of a product, making use of average data and average assumptions about the state of a technology and other parameters. The system boundaries are typically more narrowly defined. Based on their design, ALCAs are able to provide results with higher certainty than consequential LCAs (Pawelzik *et al*, 2013).

CLCAs provide more comprehensive information on the consequences of decisions taken at the different stages of the lifecycle of a project. This can take into account more complex secondary and higher order impacts. The system boundaries are hence wider. Instead of using average data as in the case of ALCAs, CLCAs typically study changes *at the margin*. Pawelzik *et al* (2013) explain this using the example of replacing grid power by power generated from the combustion of waste biomass originating from a biorefinery process. Whereas ALCA would calculate GHG savings from this substitution by assuming that power of average grid carbon intensity is replaced, CLCA would take into account the carbon intensity of the marginal source of power replaced, requiring investigation of what this would most likely be. This more comprehensive framework comes with a lower level of certainty, however. Indeed, scenario analysis is often necessary in order to reflect this degree of uncertainty when studying likely future consequences (Pawelzik *et al*, 2013). For the example of biofuels, this may include different sets of assumptions about future crop yields, the degree to which farmers would replace traditional feed with biofuel by-products or the degree to which new oil palm plantations would encroach onto peatland as opposed to other land, to name a few examples often highlighted in the ILUC debate.

Allocation of GHG emissions to co-products

Another important debate with significant bearing on LCA results is the way in which GHG emissions are allocated between the biofuel or biomaterial production and any co-products that arise. The significant effects of applying different methods of allocating lifecycle GHG emissions between the main product and co-products have been demonstrated for biofuels (Whitaker *et al,* 2010). These different methods include allocation based on energy content, on economic value or system

expansion. Likewise, significant implications arise for bio-based products. An example is provided by the production of Polylactic Acid (PLA) from wheat or sugar beet, where the differences in GHG emissions per kg PLA can be up to 70 per cent depending on the method chosen (Essel and Carus, 2012). The same study, focusing on crop-based pathways, found that emissions are lowest when allocating GHG emissions between products and co-products in line with the mass of product and co-product. (This concurs with findings in Mortimer *et al*, 2009). This implies in turn that emissions are *highest* when allocation is based on mass for *residue*-based pathways. This conclusion concurs with the findings of a LCA study for ethanol produced from corn stover in Canada (Whitman *et al*, 2011). The lowest GHG impact for the corn-stover based ethanol pathway studied was found when applying system expansion.

In the debate on conventional biofuels, allocating some emissions of the production of biofuel crops to the co-product arising that can replace traditional feed (such as DDGS or oilseed cake) improves the LCA performance of those biofuels. Therefore, whether residues are treated as a residue, or as a by-product is an issue of particular relevance to this study, particularly with regard to the consequences this will have for the allocation of GHG emissions from the crop cultivation stage. The RED follows an energy allocation method, and excludes residues from this allocation. Energy allocation can be justified on the grounds that the primary interest in the process is to produce energy. So the relevant energy content of both the main and co-product are critical to the measurement sought as part of the LCA. In the case of the RED, this is the lifecycle emissions of alternative sources of energy for transport. Naturally, the energy based allocation is less suited for bio-based materials. For these products, mass or economic value-based allocation or the so-called 'system expansion' approach might be more helpful. The latter implies widening the LCA analysis to include co-products and by-products. This has merits, especially considering cases where the co-product would otherwise be produced via conventional, often petrochemical based technologies (Pawelzik *et al*, 2013).

The system expansion approach implies extending the scope of the LCA to those products that would be replaced by the co-product arising from the main process of interest. This means that the GHG emissions embodied in, for example, the petrochemical based products replaced would be considered as a credit in the overall assessment. It would also imply taking into account the effects of residue extraction on soil carbon. Such effects are clearly locally specific and therefore difficult to deal with in generic LCA studies; they are nevertheless important considerations that should be taken into account, as highlighted in section 4.3.1. Another potential way forward would be allocation based on economic value. An economic value allocation would reflect changes in the marketing of residues. For example, increased demand, or reduced availability, for straw would increase its price, or in other words its economic value, and would close the gap between the main and co-product from wheat cultivation. This would result in a rising share of cultivation emissions being allocated to straw.

Other issues that influence the GHG profile of bio-based fuels and other products

Land use emissions: This issue is of less immediate relevance given the focus of this study on wastes and residues. It is mentioned nevertheless for its important role in the debate on the sustainability of bio-based materials and advanced biofuels, where many players voice concerns about repeating past mistakes made in the conventional biofuels sector. When dedicated crops are used as the feedstock in advanced conversion technologies, direct and indirect land use change may occur, which should be accounted for in LCAs. In this light, the IEA highlights that 'understanding land use change issues is as important for 2nd technologies as it is for 1st generation' (2008). One way of looking at land requirements is the concept of land use efficiency, which can provide valuable insights from a resource efficiency perspective (Pawelzik *et al*, 2013). Land use efficiency is defined to measure the avoided environmental impact (eg non-renewable energy use, NREU, or GHG emissions) per unit of

land use[123]. It allows for a comparison between a bio-based material and its petrochemical counterpart; or between several bio-based materials that are compared to the same petrochemical counterpart. This last point alludes to the importance that the reference (petrochemical) material has for the results in land use efficiency. This indicator therefore needs to be applied with caution and different bio-based pathways can only be compared to each other when their petrochemical reference material is the same (Pawelzik *et al*, 2013).

Other indirect impacts: While wastes and residues are promoted precisely in order to avoid ILUC effects associated with the use of dedicated crops, there are nevertheless indirect effects that must be taken into account. A critical determinant of sustainability is the potential indirect effects of diverting wastes and residues away from existing uses (Kretschmer *et al*, 2013). PBL (2012) highlight that some of the apparently more favourable LCA results for waste-based streams are based on the assumption that no existing uses of these resources are being replaced. To the extent that this is not so, the emissions calculated are likely to be an understatement. A methodology for evaluating indirect displacement effects in the context of a LCA has been proposed in a UK study, further introduced in the next section (Brander *et al*, 2009).

The GHG intensity of forest biomass: Burning forest biomass for energy purposes releases CO_2 emissions, just as when coal, oil or other fossil fuel sources are combusted. In fact, emissions from biomass per unit of energy generated are even higher given the lower energy density of wood compared to coal or oil. Bowyer *et al* (2012) explain why bioenergy is nevertheless considered a renewable, low-carbon energy source while revealing the inherent flaws. The main underlying presumption is that the CO_2 that is released when woody biomass is burned is re-absorbed during tree growth. This assumption deserves close scrutiny, especially in relation to the time sequence of emissions and any compensating carbon take-up and storage. Burning biomass releases emissions now and increases the concentration of GHG in the atmosphere. Meanwhile, the compensating carbon storage occurs over a much longer time frame because trees grow slowly; this results in a carbon debt in the short to medium term. Whether or not a bioenergy reliant system compared to the reference energy system (for example fossil fuel) will ever decrease emissions, and 'pay back' this carbon debt, depends mostly on the prevailing forest management practices and on the reference energy system. Several studies reviewed by Bowyer *et al* (2012) claim that it will take decades to re-pay the carbon debt. Bioenergy will have a better chance to reduce overall emissions in the medium and long term if the reference is heavily reliant on coal and other emission-intensive energy sources, but less so if the reference is dominated by natural gas or even other, truly low-carbon renewable energy sources such as wind or solar power. The chances of a better outcome for the climate are higher in the case of undermanaged forests that are not already managed at their optimal yield. They are also better for forest residues than for using roundwood or stumps.

Meanwhile, GHG emission accounting in the energy sector relies on the assumption that changes in forest carbon stocks as well as the emissions from the combustion of biomass are accounted for in the land use, land use change and forestry (LULUCF) sector. However, this accounting framework is not completely implemented. First, not all countries from which the EU may import biomass for energy have signed up to the Kyoto Protocol. Second, the design of accounting rules for LULUCF emissions have been very weak in the first commitment period. Third, the emissions from the combustion of biomass were completely omitted from the accounting framework (Bowyer *et al*, 2012).

[123] Taking the example from Pawelzik *et al* (2013) to express it as a formula, using NREU as a measure of environmental impact: Land use efficiency = $(NREU_{PCHEM} - NREU_{BIO\text{-}BASED}) / (LAND_{BIO\text{-}BASED} - LAND_{PCHEM})$

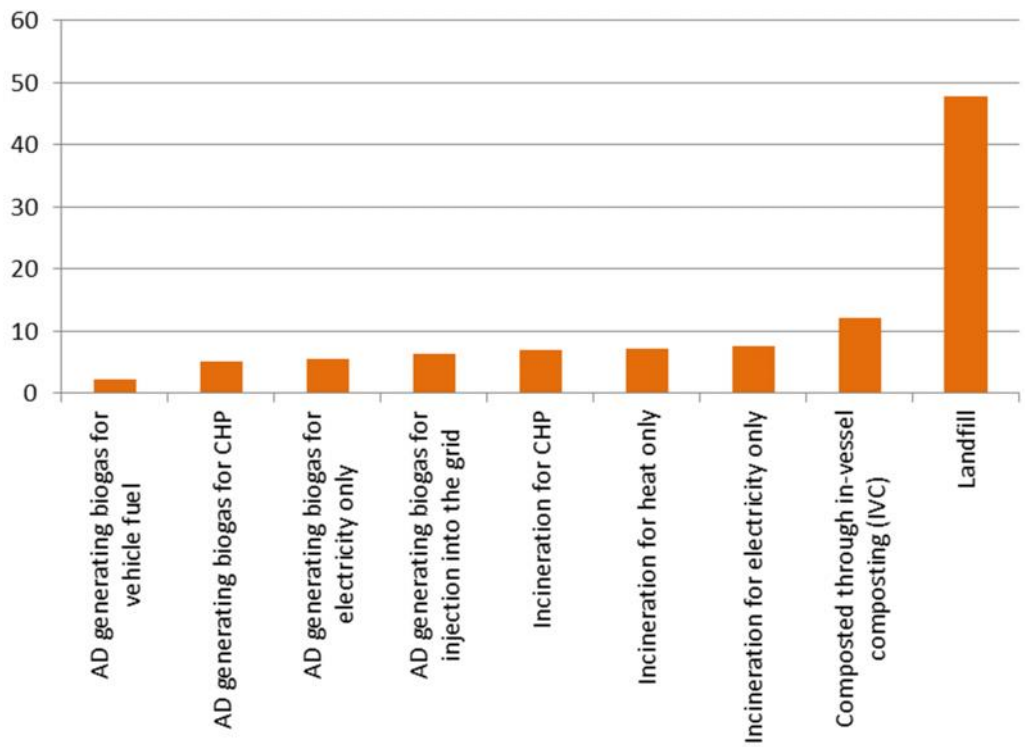
4.2.2 LCAs of bioenergy and in particular advanced biofuels

This section reviews LCAs for the advanced conversion technologies introduced in section 3.1. It starts by discussing the relative GHG profile of different food waste treatment methods to determine whether anaerobic digestion (AD) can be superior to composting, an alternative waste processing method that is further up the waste hierarchy as set out in the Waste Framework Directive (WFD).

LCA performance of different food waste treatment methods

AD was recognised (in Arcadis and Eunomia, 2010) as the recycling technology that potentially yields the highest benefits in terms of GHG emission reductions for food waste. The study used the Czech Republic as a case study to monetise the climate change costs for one tonne of biowaste treated in different ways. The model used to calculate the costs accounts for and monetises all CO_2 emissions, including those generated from the biogenic carbon contained within biowaste which are typically excluded from lifecycle analysis. As shown in Figure 16 below, the outcome suggests the following preference hierarchy for biowaste treatment: AD (*biogas for vehicle fuel* > *for CHP* > *for electricity only* > *for injection into grid*) > incineration (*for CHP* > *for heat only* > *for electricity only*) > composting through In-vessel Composting (IVC) > landfill.

Figure 16: Climate change costs in Euro/tonne of biowaste treated in different ways



Source: Derived from Arcadis and Eunomia, 2010

A study by Phong (2012) found that AD had lower GHG emissions than composting, although the post-treatment of solid digestate from AD (composting, tunnel composting or open windrows) is acknowledged as an important source of GHG emissions from AD plants. The overall CO_2 equivalents were 118kg/tonne for composting, 76kg/tonne for AD, 97kg/tonne for AD with tunnel composting of solid digestate and 506kg/tonne for AD with open windrow composting of solid digestate. Friends of the Earth (2007) suggested that in the UK, treating 5.5 million tonnes of food waste through AD rather than in-vessel composting (which tends to use equal weights of food waste and garden waste mixed together) would save 0.25 million tonnes CO_2 equivalent or more each year (if the displaced source is gas-fired electricity generation). It appears that this calculation relates to large-scale composting from

collected waste; the paper also acknowledges that amongst the different types of composting, home composting is preferable (because it avoids transport emissions from collections, uses the waste where it is generated, and replaces artificial fertilisers and peat in household gardens).

A 2011 Government review of waste policy in England (Defra, 2011) stated that AD was the best currently available treatment option for food waste, offering the greatest environmental benefit (followed by composting and then incineration with energy recovery). The review predicted that there could be around 5 million tonnes of food waste available for AD by 2020, which would save a total of 386,000 t CO_2e in GHG emissions. An AD Strategy and Action Plan published around the same time (DECC and Defra, 2011) concurred that AD is generally preferable to composting, because it produces both biogas and a biofertiliser, which together offset more GHG emissions than producing compost. The Strategy does, however, acknowledge that composting remained the best option for co-collected food and garden waste, or separately collected woody garden waste.

Review of advanced biofuels LCAs

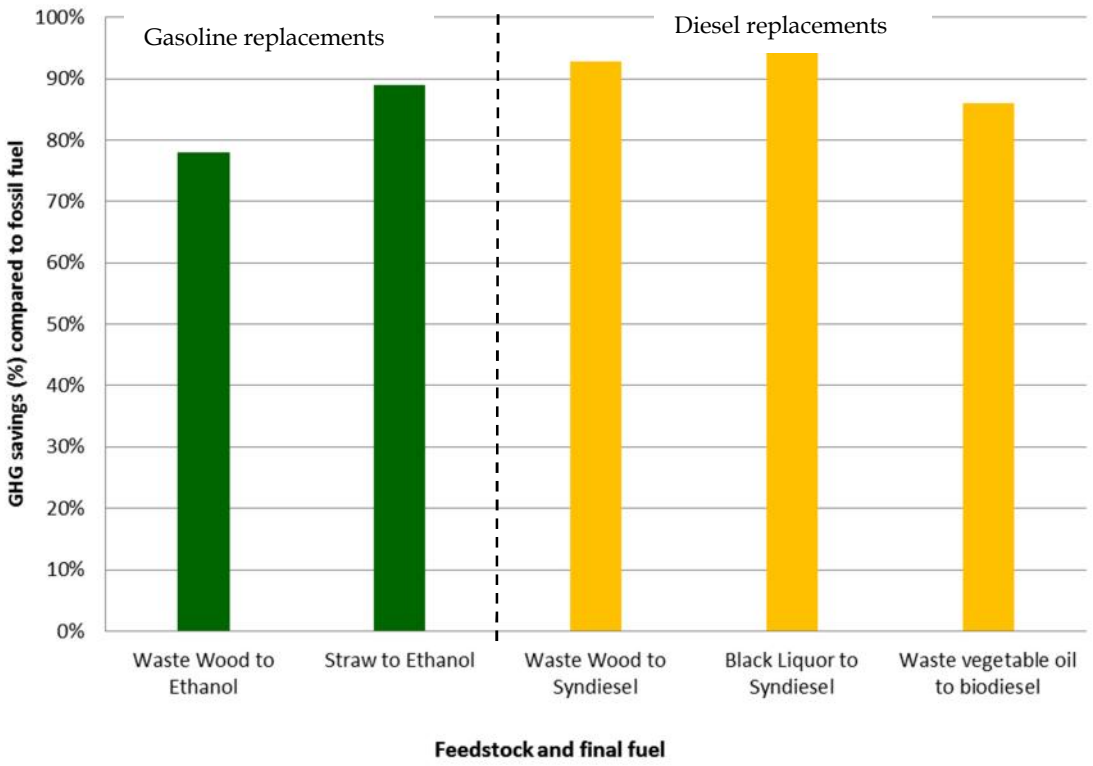
The reduction of GHG emissions is one of the principal drivers for the production and use of biofuels. The lifecycle emissions of biofuels are relatively well studied. However, this does not apply to advanced conversion routes to the same extent as to conventional biofuels. The use of advanced technologies to process waste materials can significantly improve GHG savings compared to conventional fuels. At the same time, with little commercial scale experience of advanced biofuel production, an assessment of their lifecycle emissions is more difficult as little 'real-world' data are available (IEA, 2010). The IEA (2011) has compiled results based on a review of 60 LCA studies, comparing relatively broad categories of advanced biofuels to different conventional biofuel pathways, including diesel, petrol and gas (replacement) fuels. Their overview shows that advanced biofuels tend to achieve higher potential GHG savings over fossil fuels than conventional biofuels. However, the results are not presented at sufficient level of detail to enable a distinction between different feedstock-conversion route combinations. Also, the system boundaries underlying the reviewed LCA studies exclude emissions from indirect land use change and, also due to the lack of feedstock-specific information on the advanced biofuel side, potential soil carbon stock changes from residue extraction. There is consequently no clear picture emerging on the relative preference of conversion routes from the IEA (2011) study.

A detailed set of lifecycle emissions for a range of biofuel pathways is provided by the JEC consortium (Edwards *et al*, 2011). LCA data available for the conversion routes introduced in section 3.1 are shown in Figure 17. According to this, all pathways show very high saving potential compared to fossil fuels of 75 to 95 per cent. With regard to the treatment of residues, the JEC analysis considers additional fertiliser application and resulting emissions as a result of the removal of residues and hence minerals from soils. Other impacts on soil quality including soil carbon are not considered. The value reported for UCO derived biodiesel is taken from a different source but seems in line with new JEC results. These are due to be published in summer/autumn 2013 as the JEC version 4 release. Most notable updates with regards the biofuel LCAs are in relation to fertiliser provision and use, N_20 field emissions and crop transport distances. These updates show significant changes of emissions from the cultivation of crops and are hence of less relevance for advanced pathways based on residues. The new set of figures will also include new pathways including biodiesel produced from tallow and used cooking oil[124]. A very important caveat for the LCA results currently available relates to the treatment of soil carbon stock changes. The Renewable Energy Directive ignores these for waste and residue

[124] Following a presentation on 'JEC Well-to-Tank (WTT) Study: Early Results from Version 4' given by Jean-François Larivé, representing CONCAWE and JRC team, at an event held by the JEC consortium on 13 May 2013 in Brussels; available at: http://iet.jrc.ec.europa.eu/about-jec/.

pathways, which are considered zero emission up to their collection[125]. This is a significant shortcoming as emissions from soil carbon stock changes can be substantial, as is discussed in section 4.3.1 below. A solution would be to extend the system boundaries of the RED GHG methodology by taking into account changes in soil carbon stock from agricultural or forestry residue extraction.

Figure 17: Well-to-wheels GHG emissions from different feedstocks and biofuels



Source: Own compilation based on data from Edwards *et al* (2011); waste vegetable oil value from http://www.biomassenergycentre.org.uk/portal/page?_pageid=75,163182&_dad=portal&_schema=PORTAL.

Notes: Bars on the left hand side of the dotted line denote savings compared with fossil gasoline; bars on the right hand side compared with fossil diesel.

A UK study explored the indirect GHG effects of using wastes, residues and by-products for biofuels and concludes that these can be negative or positive depending on the feedstock (Brander *et al*, 2009). One of the feedstocks considered is the use of municipal solid waste (MSW) for biogas. The indirect effect of diverting MSW away from landfill and towards anaerobic digestion is a significant reduction of GHG emissions (0.5 t CO_2e for one tonne of residual MSW diverted). The same magnitude is found for food waste diversion (even higher savings are reported for garden waste and paper, 0.78 t CO_2e and 0.97 t CO_2e, respectively). These findings concur with the result reported in the previous section that AD is a beneficial waste management option for food waste. At the same time, it should be noted that the choice of landfill as the comparator is the worst case possible; AD outperforms less strikingly other waste management options such as composting (Figure 16 above). Another feedstock studied is wheat straw, for which small indirect emissions are found from the displacement of existing uses (defined as a set of existing uses prevailing in the UK, such as soil improver, animal bedding,

[125] Directive 2009/28/EC, Annex V

mushroom growing, combustion and further specialist uses, whose relative importance is varied across scenarios). An indirect GHG effect of 0.0074 $tCO2_e$ per tonne of wheat straw used is estimated for a 'most likely' scenario, resulting in a minor reduction of GHG savings compared to petrol of one percentage point (see also section 4.2.2 for further discussion and evidence on SOC impacts). It is noted that indirect effects are inherently depending on local and regional conditions and prevailing uses and that 'geographically specific factors' would be required to enable the inclusion of indirect effect in LCAs.

Another relevant study considered the environmental performance of using corn stover for ethanol production in the USA (Kim and Dale, 2005). This suggests that corn ethanol production systems where additional ethanol is produced from stover outperform conventional corn ethanol systems (where stover remains on soils) on a global warming impact criterion. Note that all these systems are based on no-tillage practices, widespread in the USA. They acknowledge the reduction of soil carbon, which in their analysis is counterbalanced by the increased ethanol production and hence fossil fuel replacement and by the energy recovered from lignin-rich fermentation residues used to displace fossil energy. Planting winter cover crops, which allows for a higher stover removal rate, increases the climate benefits of the system. The stover using systems perform somewhat worse than the conventional corn ethanol production system on an acidification criterion (attributed to higher fuel use given the harvesting of residues and the planting of winter cover crops).

The figure above clearly points at significant savings achievable, having in mind all the caveats mentioned. At present, however, LCA figures for advanced biofuels should be treated with caution as technologies continue to evolve. The evidence base should be strengthened over the years to come with further estimates becoming available. Currently, the International Council for Clean Transportation (ICCT)[126] is performing LCAs for a selected number of advanced biofuel pathways produced from biological wastes, agricultural crop residues and forestry residues as part of a project coordinated by the European Climate Foundation (ECF)[127]. This work will take into account soil carbon losses as well as emissions associated with displacing existing uses of wastes and residues (following the methodology proposed in Brander *et al*, 2009). While highly relevant in the context of this study, these results will not be available before autumn 2013.

Issues that influence LCA results

The following summarises some of the important determinants that will influence LCA performance of different (advanced) biofuel pathways and are therefore important to understand. ***Biomass (pre-)processing steps necessary for conversion***: some technologies rely on dry feedstocks to ensure a high output quality and high conversion efficiency. Examples are many of the thermochemical gasification and pyrolysis routes. Biomass drying can have detrimental GHG impacts depending on the drying process and in particular the energy used. Further conversion steps require process energy as well and the choice of this energy in both biochemical and thermochemical production routes will have an important bearing on the overall GHG profile of the biofuel. A further parameter of interest is the occurrence of any excess energy generated by the system and the GHG intensity of the (conventional) energy that this would replace. In this context, Stephenson (2010) modelled the conversion of Short Rotation Coppice (SRC) willow to bioethanol and showed GHG savings of 70-90 per cent of gasoline, whereas Budsberg (2012), again using willow, demonstrated GHG savings of 120 per cent. Budsberg explains these differences as being the result of the greater use of coal as an energy source in the USA in the latter study where the use of residues from the conversion process for energy would displace a greater amount coal in the grid. Similarly, Hsu (2012) investigated the use of forest residues for

[126] http://www.theicct.org/

[127] http://www.europeanclimate.org

pyrolysis, showing 65 per cent GHG emissions savings compared to conventional petrol. However, as grid electricity and natural gas account for some 81 per cent of emissions, the displacement of these energy sources, either through a) using biomass in place of fossil fuels to produce process energy or b) using co-products from the conversion process, would significantly improve the GHG balance of this system (Hsu, 2012).

The use of co-products and residues from the production process may significantly improve the GHG savings from both biochemical and thermochemical conversion routes. The production of mixed alcohols through thermochemical approaches can, for example, produce ethanol (which can be used as a fuel) and various other higher alcohol products. These can then be sold and generate revenue for a biorefinery[128]. In replacing alcohols derived from natural gas, they can therefore induce beneficial environmental impacts (Mu *et al*, 2010). In some cases, however, the use of co-products and residues may be detrimental to the use of the feedstock for biofuel production. For example, the high efficiency conversion of biomass sugars to bioethanol reduces the amount of residues which can be used as an energy source. Indeed, the greater GHG savings in Budsberg (2012) compared to Stephenson (2010) was attributed by Budsberg (2012) as partially due to the greater amounts of residues assumed in that paper.

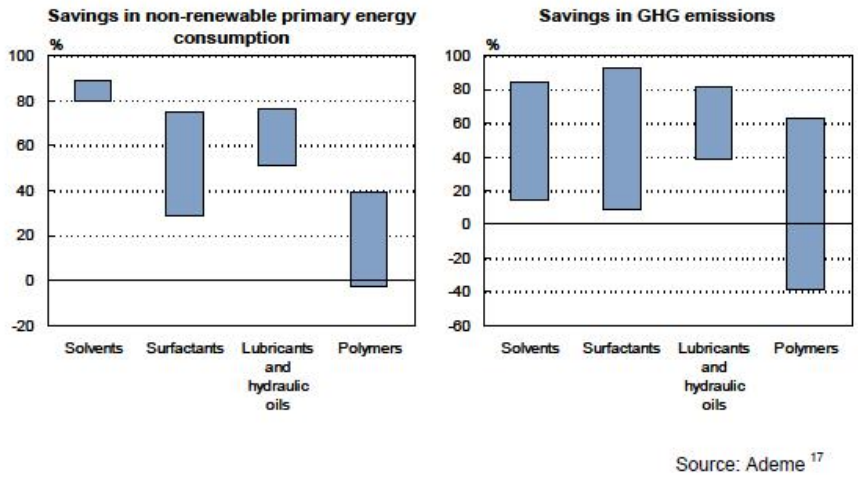
4.2.3 LCAs of bio-based materials

Potential savings in GHG emissions from use of biomass to produce bio-based materials has been shown by a number of LCAs to be high as compared to fossil fuel equivalents on a per unit basis. One study cites an average savings potential of 45 per cent compared to fossil based equivalent materials (Albrecht, 2010, in de Jong *et al*, 2012). However, GHG savings clearly vary depending on the conventional material being replaced and on a number of other key factors including: the feedstock used, the technology used in the various stages of the process, the level of non-renewable energy use (NREU) to name a few. Taking into account these parameters, certain ***categories of bio-based materials*** show more potential for GHG savings than others. It should be noted that many of the studies reviewed focus on LCAs for bio-based products produced from crops (eg maize and sugar cane). These are therefore of limited relevance for the purpose of this study. They are cited given the lack of studies focusing on residue-based biomaterial pathways and because they nevertheless contain conclusions of wider applicability.

A study by ADEME (2004) analysing 67 bio-based products found solvents, surfactants and lubricants have in general more potential than polymers to save fossil energy use but as shown in Figure 18, there is significant savings potential both in NREU and in GHG emissions for all categories of bio-based products. With regards GHG emissions, a wide range of results, particularly for polymers has been found. In the 'BREW study' (Patel *et al*, 2006), NREU savings associated with bio-based products are estimated at 30 per cent, with larger savings of up to 75 and 85 per cent possible for pathways based on lignocellulosic feedstock or sugar cane, respectively.

[128] Mixed alcohols may include significant amounts of higher alcohols with longer chain lengths than ethanol.

Figure 18: Benefits of bio-based products compared to fossil-based products: Savings in non-renewable primary energy consumption and GHG emissions per functional unit

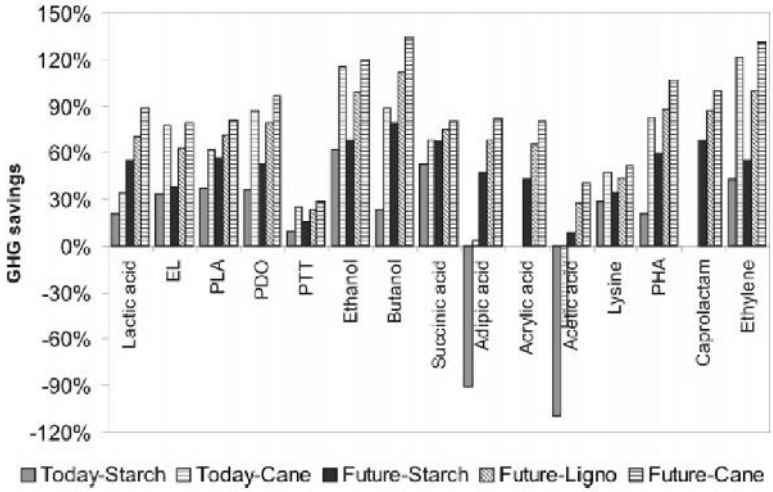


Source: Europa Innova *et al*, 2010 (citing Ademe, 2004)

Within the various categories above, ***specific types of bio-based products*** have been shown more favourably than others. Assuming current production technologies, adipic and acetic acid are found to increase emissions, as shown in Figure 19, but these represent a minority. The figure illustrates the large impact of the assumed technological state and (in most cases less important), the feedstock used. Acrylic acid, ethanol, ethylene, PDO, and PHA are highlighted as the products with the highest GHG savings potential (Hermann *et al*, 2007). Indeed, specifically PLA and PHA have been shown to have favourable results in several studies (Essel and Carus, 2012). Having conducted a meta-analysis, Essel and Carus (2012) find unambiguously positive results for PLA and PHA/PHB in terms of fossil resources used when compared to petro-chemical equivalents. The greatest GHG savings are found compared to Polycarbonate: for PLA, average GHG savings are 4.7kg CO_2/kg, for PHA average savings were 5.8kg CO_2/kg. When compared to polypropylene (PP) savings were considerably less but still positive. Again, all studies reviewed are for crop-based pathways, rather than based on residues and wastes. The one exception is a study looking at the use of corn stover for PHA production[129].

[129] It should be noted furthermore that for both PLA and PHA, only six studies were suitable to be considered in the meta-analysis, a rather unsatisfactory data basis according to the authors. It is also highlighted that all studies but one considered 'cradle to gate' emissions only.

Figure 19: GHG emission savings per tonne of bio-based chemical compared with their petrochemical counterparts for current and future technology cradle-to-grave



Source: Hermann *et al*, 2007

A Dutch study (Bos *et al*, 2010) is highlighted here for its inclusion of land use efficiency. The aim of this study was to compare PLA, PE and ethanol (as both a chemical feedstock and a petrol replacement) with their fossil fuel based counterparts considering NREU as well as GHG emissions. They look at both savings achievable per unit of product as well as per hectare. It turns out that while PE leads to the highest NREU savings per tonne, the higher bio-based product yield per tonne of biomass implies that savings per hectare of cropland are highest for PLA. Similarly, PLA leads to the highest GHG savings per hectare (the lowest savings are achieved by ethanol for transport fuel use). Given that these results are driven by the input data on bio-based product yield per tonne of biomass, they are relevant for residue based pathways alike. Given the range of existing uses of residues, extracting highest value per tonne of residue is paramount from a resource efficiency perspective.

Other parameters highlighted are the use of co-product (energy recovery versus leaving them on field are the choices investigated) as well as the uptake of excess heat generated during the process, which impact results significantly. A final point to flag is that the authors call their conclusions on GHG savings 'premature' as neither DLUC nor ILUC has been taken into account (Bos *et al*, 2010).

Having discussed the relative merits of individual pathways, bringing this information together with the future market outlook for different bio-based products provides interesting insights into the ***aggregate GHG savings potential from bio-based products***. These calculations were done in a study for the IEA Biorefinery taskforce (de Jong *et al*, 2012). As shown in Table 17, there may be important discrepancies between a ranking of products based on their per unit savings potential compared with their aggregate savings potential. The savings per unit of product for bio-ethylene, for example, are less than half that of caprolactum[130]. However, the aggregate demand for bio-ethylene is projected to be much higher in terms of volume, with projected production levels more than 25 times higher (100m tonnes per year for ethylene as opposed to 3.9 tonnes per year for caprolactam), resulting in total worldwide GHG savings of 246 million tonnes CO_2eq per year, compared with a total of 20 million tonnes CO_2eq per year for caprolactam, due to the far lower production level.

[130] Used for the synthesis of Nylon 6, a widely used material with uses in industrial components, textiles, strings for musical instruments etc.

Table 17: Future GHG savings per tonne and annual savings for bio-based chemicals assuming a complete replacement of fossil based chemical by biobased chemical

Product	GHG savings (t CO_2/t of product)	Installed world capacity (mil. t/year)	Annual GHG savings (mil. tonne CO_2/year)
Acetic acid	1.2	8.3	9.6
Acrylic acid	1.5	2.9	4.4
Adipic acid	3.3	2.4	7.9
Butanol	3.9	2.5	9.6
Caprolactam	5.2	3.9	20.0
Ethanol	2.7	2.6	7.1
Ethyl lactate	1.9	1.2	2.2
Ethylene	2.5	100.0	246.0
Lysine	3.6	0.6	2.3
Succinic acid	5.0	1.4	6.8
1,3-propanediol	2.9	-	-
PHA	2.8	57.0	160.0
PLA	3.3	11.1	36.5

Source: de Jong *et al*, 2012, p13 (citing Hermann *et al*, 2007)

Other bio-based substances not included in the de Jong *et al* (2012) report also show high potential GHG savings on both a life cycle basis and in terms of overall GHG savings potential market wide. For example, the US firm ADM carried out on its own LCA for bio-propylene glycol (PG) and found there to be an overall reduction in GHG emission of 80 per cent compared to conventional PG. ADM also said that its new facility is capable of producing 25 per cent of the US demand for PG, however, this is yet to be realised[131].

However, increasing the volume of bio-materials manufactured from a particular feedstock can itself be counter productive in certain cases, reducing potential GHG savings from the use of such a bio-based material or biofuel. This has been highlighted by Whitman *et al* (2011) in an LCA analysis for bioethanol production from corn stover in Quebec, Canada. The study found that where the percentage removal of stover increased from the field to produce the ethanol, the GHG savings decreased due to loss of SOM. However, such an effect will vary by region and can be mitigated with safeguards in place (Kretschmer *et al*, 2013). Nevertheless, it does highlight a potential trade-off between the scale of production from a particular (limited) feedstock and GHG savings even from residues.

Issues that influence LCA results

In addition to the aspects mentioned in section 4.2.1, an important consideration for LCAs of bio-based products is the treatment of **biogenic carbon storage**. Unlike bioenergy where the carbon contained is emitted to the atmosphere at the moment of combustion, bio-based products store carbon during their lifetime. This is what the concept biogenic carbon storage refers to, identified as a critical parameter in LCAs comparing the GHG emissions of bio-based materials with those of petrochemical materials (Pawelzik *et al*, 2013). There are different approaches of accounting for carbon storage, the most important distinction being between 'cradle-to-grave' and 'cradle-to-factory gate' accounting

[131] http://www.icis.com/blogs/green-chemicals/2011/05/adms-glycerin-based-pg-onstrea.html

approaches. The former grants the bio-based product a GHG credit for the delay in emitting carbon and hence radiative forcing, depending on the lifetime of the product[132]. The latter ignores the lifespan of a product and would if applied in the strict sense not grant any credit for carbon storage, however, hybrid approaches exist. Whether or not biogenic carbon should be accounted for remains controversial. An important consideration relates to the future level of atmospheric CO_2 concentration. With higher future levels, delayed CO_2 release resulting from biogenic carbon storage may aggravate global warming disproportionately due to higher atmospheric CO_2 concentrations in the future. Nevertheless, Pawelzik *et al* (2013) recommend accounting for storage via a step-wise approach whereby one would first calculate cradle-to-gate emissions and subsequently apply a credit for carbon storage in line with the ILCD Handbook (EC JRC, 2010). In this way, LCA results would reflect emissions resulting from both the use phase and the disposal route chosen.

As for advanced biofuels, ***process energy use*** is an important determinant of LCA performance. A UK study investigating the energy used in converting sugar beet and wheat grain into five bio-based chemicals (Mortimer *et al*, 2009) revealed the high energy input required for such processes. In the case of biobutanol produced via the ABE (acetone-butanol-ethanol) process for example, the energy input requirement for the fermentation stage alone was found to be approximately 22,000 MJ per tonne ABE produced. This single stage of processing is shown to exceed the total energy requirement for all the cultivation, harvesting and transport stages involved in bringing an agricultural residue feedstock such as corn stover to the factory prior to processing[133]. In addition, there are significant additional process energy requirements for pre-processing of biomass feedstocks in order to obtain fermentable sugar prior to the fermentation process as well as for subsequent separation processes such as distillation. In all cases, heat energy requirement greatly exceeds electrical energy requirement. All this highlights the significance of the choice of process energy (ie from renewable or fossil sources) and whether CHP is used or not. With regard to specific production stages, in the production of butanol, for example, fermentation and extractive distillation require most energy input. For polyethylene (LLDPE), the polymerisation (of ethylene) is the most energy intensive stage of the process. For PLA, both the production of crystallised lactic acid as well as the conversion of lactic acid to PLA are the most energy intensive stages (Mortimer *et al*, 2009).

Another aspect worth highlighting is the **efficiency and integration of the biorefinery facility**. Efficiency of the processes inherent to the operation of biorefineries is a key parameter with an important bearing on LCA results. A report by the World Economic Forum (WEF, 2010) stresses the importance of efficient processes both for the economics and the sustainability of biorefinery operations. An optimal biorefinery takes an integrated approach that strives to maximise the recycling of heat or other process energy and the regeneration of catalysts needed for the conversion of biomass to refined products. GHG performance can be optimised by putting residues accruing from the process to good use such as for energy generation, any excess of which would be exported to the grid.

Properties of bio-based materials compared to their traditional counterparts

To conclude this section, we discuss the comparability of bio-based materials to conventional, typically petrochemically based counterparts. Given the numerous applications and materials that abound, it is difficult to give a comprehensive overview; instead some of the materials discussed as

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[132] This is the recommended approach of the European Commission's guide to LCAs, the ILCD Handbook (EC JRC, 2010).

[133] Comparison with results from a study by Whitman *et al* (2011) where the total energy requirements for the sum of cultivation (including herbicide and pesticide use), harvesting and transport stages for corn stover feedstock were shown to range from 265MJ to 1442MJ per tonne dry stover. These energy input variations were dependent on level of stover collection and other variables (Whitman *et al*, 2011).

part of this report and their properties are highlighted. Furthermore, whether or not bio-based and petrochemical materials are one-to-one substitutable may not always matter. Keegan *et al* (2013) note that despite the fact that many petrochemicals may not be easily substituted by bio-based alternatives directly given differences in the inherent composition of their building blocks plant biomass and crude oil, the particular characteristics of bio-based products can also present distinct advantages: For example, the highly-oxygenated nature of biomass can reduce the need for toxic reagents to oxygenate petroleum-derived compounds. It is furthermore noted that the pharmaceuticals industry can benefit from the stereochemical purity of many plant-derived compounds, reducing the cost and complexity of purification methods otherwise needed (citing Ragauskas *et al*, 2006).

Some bio-based materials are chemically identical to their conventional counterparts, implying that they display identical properties. This includes **bio-PET** and **bio-PE** (partially or fully bio-based plastics). A range of bio-based plastics (PP, PE, PVC, PS and PUR) are in fact attributed a high potential for technical substitution of petrochemical based plastics. The substitution potential is more limited for some high-end plastics that have specific properties, which may include oxygen barrier or moisture barrier functions as well as engineered plastics (Dobon, 2012). **Bio-based ethanol** and petrochemical ethanol are chemically identical as well with identical properties.

PLA is found to be a very suitable packaging material that benefits in particular from two properties, its transparency and its water resistance. It further has particular gas barrier properties. A typical feature of PLA film is its crackling sound. A potential shortcoming of PLA material is that it does not very quickly resume its original form once deformed. PLA used as fibre is characterised by good moisture regulating properties, making it a suitable material for use in matrasses, as filling material as well as for clothing and carpets. Further characteristics of PLA include that it can be blown into shape (for plastic bottles) and that it can be foamed (Bolck and Bos, 2010b).

Cellulose fibres used in textiles have beneficial properties that include good moisture absorption; they can also be easily coloured. When used as a film (cellophane), it is valued as a packaging material for its properties that include strength, clarity and chemical resistance. Its glossy appearance makes it furthermore attractive for applications such as decoration material, handles for tools and similar applications (Bolck and Bos, 2010a).

4.3 Wider environmental impacts

A range of wider environmental considerations apart from GHG emission savings are relevant when judging the potential for a sustainable bio-based economy. The following sections highlight soil, water and biodiversity as important to take into account. 'Other' impacts are considered separately. Many of these non-climate environmental impacts result from competing existing uses for the residues considered here.

4.3.1 Soil

The increased removal of both agricultural crop and forestry residues can influence soil properties, such as soil organic matter, soil structure and soil biodiversity. These represent significant environmental pressures given that many European soils are already degraded. Research from different parts of Europe suggests that levels of soil organic carbon (SOC), the main constituent of soil organic matter (SOM), are declining on agricultural land (Jones *et al*, 2012). There is evidence that soil organic carbon in European forests has seen slight increases in some places but data are uncertain (Jones *et al*, 2012, citing Hiederer *et al*, 2011; Forest Europe *et al*, 2011). Generally speaking, EU-wide

monitoring of SOC is complicated, one reason being the 'lack of geo-referenced, measured and harmonised data on soil organic carbon'[134].

Impacts on soils associated with crop residue extraction

Of particular interest in the context of this report are the impacts of residue removal on soil carbon stocks. Kretschmer *et al* (2012) and WWF (2012) review the soil impacts of removing cereal straw, the most important agricultural crop residue in Europe, as was seen in section 2.2[135]. Straw has been traditionally used as a soil improver, typically combined with manure in mixed farming systems[136]. The ploughing-in of straw can benefit soil structure and allow the build up soil carbon. In addition to ploughing-in, there are also significant environmental benefits that result from leaving cut crop residues such as straw and stover on the surface of the soil. These include increased water retention and decreased evaporation; reduced soil erosion from wind and water; more stable soil temperatures and more humid soil surface conditions, all of which could help to maintain soil fauna and biological activity on and in the soil.

The risk of potential negative impacts on soil function and quality as a result of straw removal varies greatly and they differ on a regional and even a farm scale. These risks depend on many factors including the local climatic and soil conditions as well as the level of incorporation of straw into the soil and the resultant humus balance prior to residue removal. In some instances, good levels of soil humus availability may mean removal of the straw would not have any detrimental impacts on soil carbon levels. In some areas, for example, in parts of Southern and Eastern Europe, removal of straw for bio-based products and bioenergy use may in fact be beneficial, where there is a risk of loss of soil fertility from over incorporation of straw into the soil affecting the balance of Carbon to Nitrogen ratio (C:N). This is particularly true in areas where local conditions mean the straw cannot decompose quickly (Kretschmer *et al*, 2012).

In other areas of the EU, however, such as in the Czech Republic, where there has been a decrease in availability of manure due to a decline in the livestock industry, or in Slovenia, where the soils are of particularly poor quality, straw plays an important role as a soil improver (Scarlat *et al,* 2008). In these areas, diversion of straw from such a use could have negative impacts on soil function and quality.

The management methods used to incorporate straw and the overall impact on GHG emissions are highly interrelated. For example, Davis *et al* (2010) found that when straw is simply incorporated into the soil without any other additional management, SOC content increased but this was offset to some degree by additional release of N_2O (resulting from nitrogen release from the straw) and changes in water holding capacity. However, when minimum tillage was used in addition to straw incorporation the effects were additive with an overall greater increase in carbon sequestration. The energy used in machinery and field management would need also to be taken into account in order to provide a full picture of the GHG balance under different management regimes.

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[134] http://eusoils.jrc.ec.europa.eu/ESDB_Archive/octop/octop_download.html

[135] The risks of negative impacts on soil function and carbon content were also evaluated in a recent IEEP report on advanced biofuels (Kretschmer *et al*, 2013) where a series of potential advanced biofuel feedstocks were examined. Apart from straw, another crop residue considered were maize cobs. These have a low nutrient value relative to other stover components (notably leaves and stems) and decompose slowly, meaning that they are thought to be less valuable as a source of soil organic material and nutrients. This in turn might imply reduced risks for soils from diverting them to energy or other uses, an aspect that requires verification, however.

[136] Another important use is for animal bedding. See Kretschmer *et al* (2012) for an overview table of existing on and off-farm uses.

There are alternatives to the use of straw to ensure soil quality, including fertility as well as erosion control. These include the application of manure and slurry, commercial (largely fossil fuel based) fertilisers, green manure and the planting of cover crops. The application of artificial fertilisers in lieu of straw may of course induce additional emissions and therefore make it unlikely that straw would be considered a sustainable feedstock for biofuels or bio-based materials.

There is no commonly agreed method to track soil carbon development in the EU currently. One relatively simple method is the calculation of soil carbon following the IPCC (2006) Tier 1 method that uses default values provided for different land use and vegetation systems. Given the importance of soil properties and local climatic and biophysical conditions, it is suggested that the 'only reliable method' to track changes in soil organic carbon over time is through a 'comparison of laboratory analysis of soil samples' (Jones *et al*, 2012). WWF (2012) suggest developing a standard method for Europe, for example using humus balance methods, to ensure the sustainable use of agricultural residues for biofuels. Humus balance methods tend to take into account more detailed information on the impacts of different cultivation systems and for different crops. They have been applied in a study looking into the impacts of straw removal on SOC in Northern Germany (Zeller *et al*, 2012)[137]. Despite the regional focus, several observations are worth noting as they are applicable to the wider European context in demonstrating the significance of SOC changes and the challenge of allocating them in LCAs. Additional emissions from cultivating wheat grain as a result of straw removal are estimated to be of the order of 10g CO_2-eq/MJ. As a comparison, the same study calculates cultivation emissions for wheat grain from diesel, fertiliser and pesticide use as well as N_2O emissions to be 23g CO_2-eq/MJ. Looking at the effect on straw 'cultivation' emissions, these are 0.23g CO_2-eq/MJ when humus balance changes are ignored, increasing to 27g CO_2-eq/MJ when applying the VDLUFA[138] humus balance method[139].

These additional emissions are clearly significant, especially when compared to the default LCA emission value for straw ethanol from the RED (which ignores emissions prior to collection) of 13 g CO_2/MJ[140]. An example from Denmark further highlights the potentially significant impacts, which are at the same time uncertain due to continued controversy about the right accounting methods (Box 20). Whitman *et al* (2011) highlight the considerable negative impact on SOC in the case of full stover removal and the importance of taking this into account, even when the application of fertiliser can compensate for the loss of nutrients such as phosphorus (P) and nitrogen (N). For example, when manure is applied in order to compensate for the nutrient loss from stover removal, the application of enough manure to fully replace lost P and N levels will only reduce the soil carbon loss by approximately four per cent due to the low C:P and C:N ratio for manure as compared to stover. Similarly, the application of synthetic fertiliser can disguise the underlying loss of soil carbon (Whitman *et al*, 2011).

The potential of including emissions arising from soil carbon stock changes in LCA analysis is seen critically, however, at least when referring to the humus balance method. This is because this method is designed to assess humus changes within different crop rotations, or for different farming system (such as traditional wheat growing without straw removal versus wheat growing with straw removal

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[137] The humus balance methods used for determining soil carbon stock changes are the so-called VDLUFAu and VDLUFAo (developed by VDLUFA, 2009), as well as the dynamic HE-method (developed by Hülsbergen, 2003).

[138] Verband deutscher landwirtschaftlicher Untersuchungs- und Forschungsanstalten (VDLUFA). *Translated as the Association of German Agricultural Investigation and Research Institutions*.

[139] Additional emissions are primarily the result of carbon loss (24.8g CO_2-eq/MJ), the remainder being associated with the application of fertiliser to substitute for nitrogen loss (1.95g CO_2-eq/MJ).

[140] Directive 2009/28/EC, Annex V

for renewable energy production), taking into account all products derived from the system instead of following a product focused approach (eg straw ethanol) as is typical in LCA. The importance of the wider system would call for a 'system expansion' approach to study lifecycle GHG emissions (Zeller *et al*, 2012). Another challenge is the significant differences resulting from the application of different humus balance methods.

Box 20: Emissions from straw removal – an example from Denmark

Petersen *et al* (2013) examined and quantified the impact of straw removal for the bioenergy industry on Danish soils using an LCA study. This differed from the IPCC Tier 1 approach (IPCC, 2006) to quantifying soil humus in several ways, including the use of a 100cm soil depth as opposed to the IPCC methodology which recommends using 30cm soil horizon. This study highlighted the large difference in the results obtained when quantifying soil carbon stock change, depending on the time perspective used, with a 20 year time horizon resulting in much higher figures for carbon released as compared to the longer timescales used in some LCAs (such as 30 or 100 year time horizons). Petersen *et al* found that for Danish soils, calculated additional CO_2 release from lost soil carbon as a result of straw removal for bioenergy use was found to be 781 kg CO_2 per tonne of straw carbon when using a 20 year time perspective. This is approximately four times higher than when using a 100 years time horizon (198 kg CO_2 per tonne of straw carbon).

To exemplify these figures, we broke them down to emission per MJ ethanol (using figures for bioethanol yields provided by industry contacts). This was found to equate to an additional CO_2 emission of approximately 49.5g to 61.9g CO_2 per MJ ethanol produced over a 20 year time horizon, or between 12.5g and 15.6g CO_2 per MJ ethanol produced if the 100 year time horizon is used. The choice of time horizon is ultimately subjective, however, with many LCAs using the 100 year time horizon but with other approaches favouring a 20 year time perspective, such as the PAS 2050 standard[141] when used for calculating land use change emissions. Petersen *et al* recommend the 100 year time perspective to be used for LCA of products. However this could be contested, for there is a widely recognised need to mitigate GHG emissions to meet shorter term climate targets to 2030 and 2050. Meeting such targets would be influenced by emissions and sequestration of biogenic carbon over a much shorter timescale than 100 years.

Source: Own compilation

Impacts on soils associated with forest residue extraction

Forestry soils account for around twice the amount of organic carbon found in forests compared to the above ground biomass. There is a wide range of factors that influence SOC and SOM in EU forests, including acidification, nitrogen deposition, management approach (including residue management), and differences in soil horizon profiles. Here we focus on the impact of residue extraction on soils[142]. Like agricultural land, residues[143] form an important and interlinked relationship with forest soils, helping to stabilise and increase SOC and SOM, contribute to regulation of carbon to nitrogen ratios, reduce erosion events and provide nutrients for soil biota and Saproxylic[144] species. Changes to

[141] PAS 2050 is the internationally applicable British standard on product carbon footprints, developed in 2008 and updated in 2011. It uses broadly the same quantification approach as the Greenhouse Gas Protocol (developed in 2011, http://www.ghgprotocol.org/).

[142] For a broader description of the state of soils under EU forests see Forest Europe *et al*, 2011.

[143] including leaves, branches, bark and stumps.

[144] ie relating to dead or decaying wood

harvesting patterns and increases in residue extraction rates can have a negative impact on many of these factors (see Box 21).

The export of nutrients from forest systems during harvesting can be substantial leading to a decrease in soil quality (Raulund-Ramussen *et al,* 2007; Merino *et al*, 2003; Augusto *et al,* 2002; Jacobson *et al*, 2000; Glatzel, 1990), have an impact on natural regeneration of understory vegetation, and in some cases limit the future production potential of a forest stand (Alam *et al,* 2012; Helmisaari *et al*. 2011; Hansen *et al,* 2011[145]; Walmsley *et al,* 2009; Raulund-Ramussen *et al,* 2007; Smith *et al,* 2000). The increasing use of branches and tops (including needles) for wood fuel contributes significantly to the depletion of soil nutrient levels and organic matter composition in some areas[146]. Although these residue fractions only amount to a small proportion of the total weight of the tree, they have a much higher nutrient concentration per unit weight than roundwood or stems. Thus, the increase in nutrient export might be significant, with up to six times the removal of nitrogen and phosphorous seen under intensive biomass removal (including stumps and roots) compared to harvesting of stems only (Helmisaari *et al,* 2011; Hansen *et al*, 2011)[147].

Increased harvesting intensity can reduce the level of carbon sequestered in particular forest stands particularly where extraction exceeds the net annual timber increment or the accumulation of woody biomass (Raulund-Ramussen *et al,* 2007; Smith et al, 2000). In these situations, forests can change from being a carbon sink to a carbon source (Loustau and Klimo, 2011). A growing trend in residue management is the removal of stumps. Stumps are removed to decrease root rot infection in the new stand, and to harvest biomass for energy (Hansen *et al*, 2011). The removal of stumps from forest stands has an overall negative impact on SOC levels under forests influencing the overall carbon benefits of their use towards renewable energy generation targets (Bowyer *et al*, 2012). Stump extraction can also be a highly disruptive and damaging process seen in some cases as comparable to intensive site preparation measures such as ploughing and harrowing (Hansen *et al*, 2011) with likely increases in erosion risk and sediment transport to adjacent waters (Egnell *et al*, 2007 cited in Hansen *et al* 2011). Site preparation processes, including stump removal can also be highly energy demanding. Depending on the nature of the preparation this could lead to increased GHG emissions.

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[145] It has been reported that retention of harvest residues on the area has improved tree growth in the short-term and long term effects may be comparable to the effect of intensive harvesting (Chen and Xu, 2005; Mendem *et al*, 2003).

[146] However, good practice guidelines for harvest residue extraction recommend to apply this only twice during a forest rotation and advocate application of wood ash to compensate for the nutrient losses (Hart *et al*, 2013 citing: Aronsson and Ekelund, 2004; Skogsstyrelsen, 2008).

[147] There is a substantial difference in the size of nutrient removals, depending on the size and age (Ranger *et al*, 1995) of tree species and density of the trees at the time of cutting (Angusto *et al*, 2000; Glatzel, 1990; Perala and Alban, 1982; Cole and Rapp, 1980) site productivity, harvesting intensity, and nutrient concentration level in the biomass (Stupak *et al,* 2007 cited in Hansen *et al*, 2011).

Box 21: Impacts of increased residue extraction in North Karelia, Finland

North Karelia is one of the forerunners in the use of renewable energy in both Finland and Europe with 38 per cent of woody biomass used for heat and power generation (Regional Council of North Karelia, 2011; UNECE, 2012). As part of a wider study (see Hart *et al,* 2013) a *bioenergy scenario*[148] was modelled to look at potential future impacts on ecosystem services in the region.

As the most cost-effective biomass resource for energy comes from harvest residues, the scenario included a change to the management of the forest stand towards a longer rotation[149], which is expected to result in better quality and higher value timber (for timber products), and an increase in harvest residue volumes (tops and branches) that could be used for energy production. This change in management is predicted to increase biomass extraction by 48 per cent.

Despite being seen as sustainable in economic supply terms, trade-offs with other ecosystem services were evident. The total proportion of old forest would decrease from four per cent to 2.8 per cent and there are expected to be negative impacts on biodiversity from reduced deadwood and a reduction in small mammal numbers. Water and soil run off rates are predicted to increase and there is expected to be an increase in the amount of carbon lost from the forest system, both from soils and above ground biomass. Despite the increase in woody biomass feedstock to meet renewable energy production targets, the loss of carbon may impact on the overall ability of North Karelian forests to aid in the reduction of GHG emissions and improve carbon sequestration, particularly if significant quantities of tree stumps are extracted (see for example Wihersaari, 2005). This scenario shows some of the potential trade-offs that take place when provisioning services are prioritised over regulating and cultural services across the whole forest.

Source: Adapted from Hart *et al*, 2013, Chapter 6

Of course the extraction of forest residues is part of a broader approach to forest management and will thus vary across the EU, along with the impacts of any such approach. Good practice guidelines do exist for forest management in the EU such as the European Commission's good practice guidance on the sustainable mobilisation of wood in Europe (MCFEE *et* al, 2010) and the good practice guidelines for land use and land use change in forestry[150] (IPCC, 2003) as well as Member State guidelines. Although these guidelines mention forestry residues explicitly, none of those reviewed here provide a quantified proportion of residues that could be sustainably extracted. This reflects the implicit variation in forest types, climatic conditions, soil types and management approaches across the EU and even within some forest stands. A discussion of existing guidelines in relation to forest bioenergy and soil sustainability was undertaken as part of the EUROSOIL Congress (Helmisaari and Vanguelova, 2012). Amongst the conclusions of this workshop it was pointed out that '*the effects of forest bioenergy harvesting on soils are species-, site- and practice-specific, and therefore each country or region must apply local scientific knowledge or expert opinion, and consider the ecological conditions and management in the guideline development for that country/region*'.

[148] The *bioenergy scenario* was defined by the stakeholders in a way to improve the economic performance of biomass utilisation.

[149] It should be noted that t extension of the rotation length is feasible in this region because of the low felling rates over the past two decades. In many other regions in Europe it would not be possible to simultaneously increase biomass extraction and extending rotation lengths.

[150] Which includes calculation values for estimating carbon balances for different biomass fractions.

4.3.2 Water

The most important water related impacts from the production of biofuels and bio-based products relate to the cultivation of feedstock (IEA 2010; Eickhout, 2012; Weiss *et al*, 2012). Therefore, bio-based products derived from wastes and residues avoid the majority of such impacts and therefore generally will have a lower 'water footprint'[151] (Hoekstra and Chapagain, 2007) compared to those derived from dedicated crops. However, negative impacts may ensue from the increased extraction of residues from both cropland and forests with regard to water erosion and water holding capacity as a result of changes in soil structure (see also Box 21).

For processes based on residues and dedicated crops alike, the production of bio-based products and fuels from wastes and residues still involves the consumptive use of water at various stages of production. This may be due to water use in production of process energy or from the use of water to dilute process chemicals. Although such process related water consumption is far lower than cultivation consumption, local impacts on water quality and availability should nevertheless be monitored and will vary by conversion technology, feedstock and regional freshwater availability. For technologies such as pyrolysis, water use is a closed process and is only related to the feedstock cultivation, resulting in a low water footprint if residue and waste derived feedstock are utilised. In the case of lignocellulosic bioethanol production, biochemical routes have been shown to result in higher water consumption than thermochemical routes, consuming over four litres of water per litre ethanol produced, more than double that of the thermochemical processes examined. This is due to the lime, nutrients and sulphuric acid used in the biochemical conversion of certain lignocellulosic materials (Mu *et al*, 2010; Wu *et al*, 2009).

However, quantifying process water consumption in this way does not necessarily encapsulate all significant water related impacts. An alternative approach to the 'water footprint' methodology was advocated by Pfister *et al* (2009) whereby the impacts from freshwater consumption are measured by considering impacts on the state of ecosystems, resources and human health, taking regional water availability into account. As advanced biofuels are hardly operating on commercial scale currently, such environmental and health impacts, relating to freshwater consumption, are not yet completely understood. As a result, there is a need to monitor them closely and improve technologies over time.

With regard to water quality, eutrophication is often the factor for which bio-based materials typically perform worse than their conventional counterparts (Detzel *et al*, 2013, Europe Innova *et al*, 2010, Weiss *et al*, 2012). But this is mostly due to emissions and effluents created by crop cultivation so this provides a further argument for pursuing pathways based on wastes and residues. A potential indirect impact on water quality may result from using residues, however. With the displacement of crops residues such as straw as a soil improver, additional application of nitrogen fertiliser and manure may result in consequent water quality impacts from leachate and ammonia effluents.

4.3.3 Biodiversity

The increased removal of agricultural crop and forestry residues can have negative biodiversity impacts, although the full implications are not well understood currently. This is therefore an area where continued monitoring and future research are needed to ensure that agricultural and forestry residue potentials are exploited within sustainable limits.

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[151] The water footprint was devised as a method of quantifying water impacts. It is calculated as the total volume of blue water (freshwater from lakes, rivers, and aquifers), green water (rainfall) and grey water (water needed to dilute aquatic pollutants) used in a particular situation. It does not, however, take into account local impacts of water use and pollution on the environment, human health or biodiversity.

Potential impacts of agricultural residue extraction on soil faunal, floral and fungal assemblages are closely related to the above discussion on soil organic matter impacts. There is little clear-cut evidence on likely impacts. What is clear is that soil fauna including invertebrates and those species dependent on invertebrates for food, depend largely on SOM as their main habitat. SOM often constitutes hotspots of soil activity and is fundamental in maintaining fertile and productive soils (Tiessen, Cuevas *et al*, 1994; Craswell and Lefroy, 2001, as cited in Turbé *et al*, 2010). A reduction of fresh organic matter is consequently associated with negative impacts on organisms living in the upper and lower soil horizons (WWF, 2012). At the same time, there is little evidence for a direct link between residue extraction and soil biodiversity. This can be explained by the range of other factors that influence soil biota, including climate, temperature and moisture, soil texture and soil structure, salinity and pH. Singling out the impacts of residue extraction from this wider set of influences is an area that requires further research (Kretschmer *et al*, 2012).

Mitigating measures can be adopted, such as maintaining appropriate stubble heights when harvesting cereal straw and planting cover crops to provide alternative winter fodder, many of which are available for support, or recommended as best practice, under agri-environmental schemes through the CAP. Cover crops have wider benefits for lowering erosion risk, improving soil quality and providing additional habitat for certain species. At the same time, the right management of cover crops and stubbles is crucial. Timing is particularly important with cover and food availability critical for certain species during the period between mid-winter and spring, where species such as farmland birds, suffer from a lack of available food known as the 'hungry-gap' (eg Siriwardena *et al*, 2006).

Similar to cropland, changes in the structure of forests soils may induce harmful effects on soil biodiversity. One particular issue is the removal of deadwood, which is an important habitat for Saproxylic species (Raulund-Rasmussen *et al*, 2011). The State of Europe's Forests report has observed increasing levels of deadwood in European forests in most regions. At the same time, it expresses concern about future increases in harvesting intensity triggered by demand for energy wood. A subsequent reversal in the trends observed is likely to lead to negative biodiversity impacts (Forest Europe *et al*, 2011). Box 22 discussed this at the example of the Czech Republic.

Box 22: FERN report of forest biomass in the Czech Republic

With many studies focusing on the GHG implications of using forest biomass, a report produced by FERN and Friends of the Earth Czech Republic (2012) is of particular interest. It considers the wider environmental impacts of extracting forest residues and presents methodologies that could be of interest to other EU countries. The aim of the methodologies reviewed is to define forest areas where residue extraction is deemed sustainable, taking into consideration nutrient cycling, acidification and topology parameters, and also if the forest lies within a protected area. One study using these parameters identified just 19 per cent of the total forested area as available for sustainable residue extraction.

The report furthermore stresses the importance of leaving deadwood, because this is required by 20 per cent of forest biodiversity. A study investigating the impacts of slash removal on biodiversity found that this led to changes in species composition, with generalist species crowding out forest species. Also, the report highlights the importance of including soil carbon stocks when calculating the GHG balance of bioenergy sourced from forest residues. At the same time, reduced soil carbon stocks from clear-felling and residue extraction can have a negative impact on water and nutrient cycles.

Source: Own compilation

Generally speaking, there is a trade-off between the use of forests to supply predominantly provisioning services (timber and other wood products as well as wood for energy) and the role of forests to supply important regulating and cultural ecosystem services as well as biodiversity (see also Box 21). Despite some improvements, more than half of the species and almost two thirds of the habitat types of Community interest (protected under the EU Natura 2000 framework) in forest ecosystems continue to have unfavourable conservation status (EEA, 2010). Therefore, any mobilisation of forest residues must respect the needs to improve conservation status in EU forests.

There is some scope for positive impacts as well, depending on the status of the forest and its management. Positive biodiversity impacts may occur where forests are currently undermanaged, as is the case for a significant share of UK forests. The removal of conifers from planted ancient woodland sites (PAWS), removal of invasive alien species from woodlands and water courses, as well as scrub removal and grassland mowing may trigger such positive biodiversity impacts (Kretschmer *et al*, 2010). Ensuring a balance between managing forests for biomass harvesting whilst respecting their importance as an ecosystem is therefore critical to the sustainable management of this natural resource.

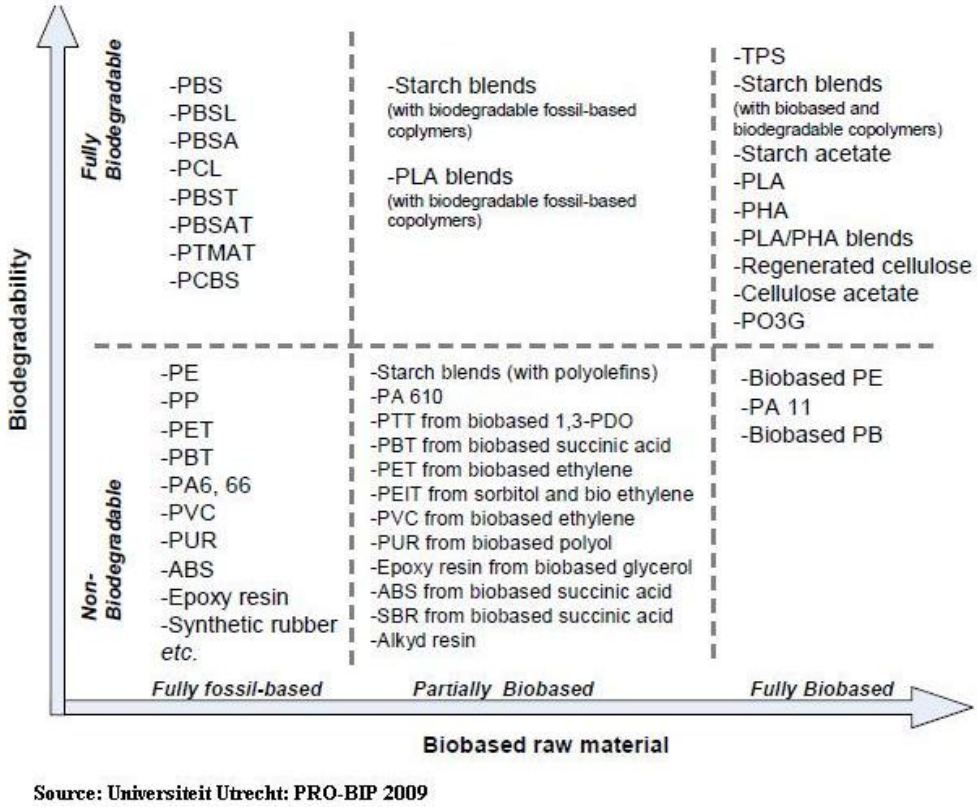
4.3.4 Other Impacts

This section discusses a few other issues that are touched upon in the literature to then conclude the review of environmental impacts. These include disposal of bio-based materials, air impacts and finally health impacts.

Disposal of bio-based materials

The disposal of bio-based materials is a contentious issue; bio-plastics are particularly relevant in this respect and are still a young, developing technology. Some bio-based materials are biodegradable whilst others are not; 'bio-based' simply refers to a composition using material from renewable resources, whereas 'biodegradable' refers to biodegradability at the end-of-life phase (see Figure 20 for an illustration of the biodegradability and bio-based content of a range of bio-plastics). For example, beverage bottles from partially or fully bio-based PET or PE, which are expected to gain significant market shares, are not biodegradable (Detzel *et al*, 2013). Furthermore, 'compostable' refers to material that is degradable due to a biological process occurring during composting and does not produce toxic residues for water, soil, plants or living organisms; this means that not all biodegradable material is compostable. As a result, not all bio-based materials are suited to the same waste stream or treatment technique (composting versus other recycling). The situation is further complicated by the fact that many products are only partially bio-based.

Figure 20: Current and emerging (partially) bio-based plastics and their biodegradability



Source: Universiteit Utrecht: PRO-BIP 2009

Source: As indicated and taken from the Green Chemicals Blog, http://greenchemicalsblog.files.wordpress.com/2012/10/bioplasticcategories-utrecht1.jpg.
Note: several of the materials mentioned in this figure are introduced in the glossary.

An Ad-hoc Advisory Group for Bio-based Products, appointed by the European Commission to contribute to the Lead Market Initiative for Bio-based Products, made recommendations with respect to bio-based products in 2011. This included a priority recommendation for bio-based plastics certified as compostable (according to standard EN 13432) to gain unhindered access to bio-waste collection, but also to allow bio-based plastics to enter all waste collection and recovery systems (including composting, recycling and energy recovery depending on the type of plastic and compliance with applicable standards) (Ad-hoc Advisory Group for Bio-based Products, 2011). This approach is strongly supported by the bioplastics industry (European Bioplastics, 2012).

A recent private agreement amongst businesses in Switzerland has reached consensus that there should be restricted acceptance of bio-plastics in biowaste treatment plants (to guarantee good quality compost and digestate), that only bags designed for the collection of biowaste are allowed without restrictions, and that other bio-plastics may only be composted if they originate from a defined source (eg events or companies) that have an advance agreement with the biowaste treatment plant accepting the waste (European Bioplastics, 2013).

Recent research reviewing current disposal practices of bio-based plastics in Germany revealed that insufficient information is available currently, rendering appropriate waste management difficult. It appears that while a larger share of bio-based packaging materials is being recovered, this is mainly through incineration (for energy recovery) and some through thermal recycling. Composting in contrast does not constitute a significant disposal route currently (Detzel *et al*, 2013). Another recent study has concluded that composts from mixed waste containing biodegradable plastics may hinder plant growth. Composts with an 8 per cent content of biopolymers led to seed germination and root

growth that was inhibited twice as much as composts without biopolymer content, and the presence of biopolymers can dilute the dry mass of solid organic matter which may limit the compost's usefulness (Kopec *et al*, 2013). These findings create further uncertainty for defining the quality of compost, and in turn the optimal waste management practices for bio-plastics. It is evident that more research would be beneficial in order to ensure a solid evidence base for future policy in this area.

Air impacts

In a review of LCAs of bio-based materials it was found that seven studies indicate an increase in stratospheric ozone depletion associated with bio-based materials compared to their conventional counterparts. These are found to largely result from N_2O emissions associated with fertiliser application in the cultivation of crops, displaying once more the potential benefits from using wastes and residues. Results on photochemical ozone formation are inconclusive, suggesting very tentatively such bio-based materials perform better than conventional materials (Weiss *et al*, 2012; Essel and Carus, 2012).

The potential for fugitive emissions from (bio-)chemical processes is furthermore mentioned along with a potential increase in particulate emissions arising from biomass crushing and grinding operations prior to further conversion. These, however, can be and are mostly controlled by deploying baghouses or filtering systems (Europe Innova *et al*, 2010).

Health impacts

The use of toxic chemicals in the production process of bio-based materials some of which may have harmful impacts on human health are further aspects that have to be monitored (Essel and Carus, 2012). An example is that in the production of PHA, workers may be exposed to possibly carcinogenic chemicals (such as chloroform, methylene chloride, and 1, 2-dichloroethane). In the production of PLA, a tin-based chemical is used that is thought to have potentially toxic effects on the hormonal system (Alvarez-Chavez *et al*, 2012).

These examples serve to warn that a perception that 'bio-based' automatically means natural and sustainable *per se* is unwarranted. It is also pointed out, however, that there are likewise many potential harmful impacts from conventional production processes, in which instances bio-based materials can perform better displaying reduced toxicity (Jering *et al*, 2010).

4.4 Summarising the environmental credentials of bio-based products

The literature on the environmental performance of advanced biofuels as well as of bio-based products is expanding, possibly signalling a real intention to avoid the compelling concerns that are dominating the discussion around the sustainability of conventional biofuels. It is too early to come to assess with certainty the relative merits and shortcomings of one pathway or the other. Some general observations emerge rather clearly, though.

- While there is the potential to reap substantial benefits from pursuing conversion routes leading to the production of advanced biofuels, bio-based plastics or other products, there are risks involved. This calls for continued monitoring of the situation. While a range of technical questions arise and will arise continuously that need to be addressed by appropriate research efforts, the Bioeconomy Observatory proposed by the European Commission in its Bioeconomy Communication as a panel of experts could be a useful body to ensure that any future policy stimulus is conditional upon firm evidence of positive environmental outcomes.
- In this context, it is also important to note that bio-based products of any form should not be considered automatically sustainable *per se*. This refers to their production and potential impacts resulting from the pathway, but also to the way in which they are used and the longevity of different products. These aspects needs critical evaluation, especially in relation to the necessity of certain forms of packaging, be it bio-based or not.

- A range of the environmental impacts found for bio-based materials as well as advanced biofuels relate to the crop cultivation stage. These are highlighted in LCAs or other assessments that consider pathways based on dedicated crops. This strongly supports the approach of this report to zoom in on the potential of using wastes and residues as feedstock. Doing so can avoid to a large extent the cultivation stage impacts described by various authors. However, this is not to say that the use of wastes and residues is sustainable *per se*. For many of the commonly proposed waste and residue sources there is a range of existing uses, which will be displaced. So these potential indirect effects must be taken into account, as for example stated in Kretschmer *et al* (2013)[152]. It is strongly recommended that the use of wastes and residues be accompanied by a set of safeguards to ensure their sustainability.
- LCAs of advanced biofuels and of bio-based materials still face a range of challenges. These include common challenges already discussed in relation to conventional biofuels such as the proper allocation of co-products, which refers back to a discussion of the selection of the correct system boundaries. Further challenges are related to the fact that many bio-based production pathways are yet to be demonstrated on commercial scale, so that real-life data to underpin analyses is currently unobtainable.
- Keeping the previous points on persisting challenges in mind, a range of studies have found that using biomass for bio-based materials rather than burning them for energy recovery (for heat and electricity or after conversion to transport fuels) leads to higher GHG savings in many cases (Albrecht *et al*, 2010; Hermann *et al*, 2007, Bos *et al*, 2010). This puts into question the current policy framework that gives significant support to bioenergy but not to other biomass using product pathways.
- One extremely important sustainability consideration relates to the impact of residue removal on soils and in particular soil carbon stocks and its knock on effects, given that bio-based fuels and products are commonly promoted as a way to mitigate GHG emissions. The GHG accounting framework of the Renewable Energy Directive excludes soil carbon stock changes arising from residue extraction, as these are considered 'zero emission' up to their collection. As demonstrated by the evidence compiled here and elsewhere, this is a point that needs urgent remedy, especially with the RED developing potentially developing into a stronger tool for the promotion of advanced biofuels.

[152] A summary of their findings on the existing uses of a range of wastes and residues and the impacts potentially ensuing from displacing those is found in Annex 4.

5 THE FUTURE FOR A BIO-BASED INDUSTRY IN EUROPE PROCESSING WASTES AND RESIDUES

Having reviewed potentials available from selected waste and residue pathways, both biochemical and thermochemical conversion routes, their technological development status and resulting products as well as a range of sustainability issues relevant in the context of using wastes and residues for bioenergy and biomaterials, this chapter concludes the report with a presentation of the strengths and weaknesses of the biorefinery sector and the threats and opportunities facing it[153]. The final section of this chapter offers some policy recommendations.

A few points that are relevant to all the biomass resources discussed in this report are worth summarising upfront. First, speaking of a new use of what was formerly considered a waste product turns a waste disposal problem into a question of raw material availability. What was formerly considered a liability which had to be disposed of with least cost, now becomes an asset which has to be mobilised and then efficiently utilised and transformed. This immediately means that waste becomes the wrong word setting up wrong thinking.

Second, it is often the case that some of this waste material had alternative uses – whether they were marketed or sold as such and had a discoverable value or not. This certainly applies to many agricultural wastes or residues like straw, or forest and wood processing 'wastes'. In these situations, the new technology or new set of environmental, economic or policy factors which creates the drive to mobilise the material creates competition with the existing uses. Rational resource use dictates that the now probably scarce, and certainly scarcer than formerly, resource will, or should, be allocated between traditional and new uses such that the marginal revenue in each use is equated, ie normal economic allocation rules now come into play.

Of course the new uses are likely to start at a low level and generally speaking they involve processing large-volume low-value materials so economies of scale are likely. Hence, it may take some time before the new uses can compete on level terms with traditional uses. This might, in some circumstances, warrant infant industry assistance to get these processing routes established. These will most likely be contested by the traditional users whose raw material prices are likely to rise.

Third, as the new uses have effectively shifted out the demand for the raw materials, this could further worsen the terms of trade with non-market ecosystem services. That is, the supporting, regulating and cultural ecosystems services, and the biodiversity which underpins these, for which land managers are not rewarded by the market, are likely to suffer further neglect at best or reductions at worst.

[153] Over the coming years, more such analysis is expected to come forward, in particular as part of the Bioeconomy Observatory who will provide a series of 'SWOT snapshots' evaluating 'bio-economy research and development capacity of the EU today and the perspectives for 2020 and 2030' (European Commission, 2013).

5.1 SWOT analysis of a European bio-refinery industry based on wastes and residues

The following table summarises the findings of this section in brief while the subsequent sub-sections elaborate on each of the four dimensions[154].

Table 18: Summary SWOT analysis of a European bio-refinery industry based on wastes and residues

STRENGTHS	WEAKNESSES
• Offers the possibility to turn waste streams into valuable resources, and improve sustainability of agriculture and food production; • Potential for 'green' jobs and economic activity if sustainability concerns addressed; • Many conversion technologies have been developed and Europe is believed to hold a strong position in biorefinery research; • The sector is believed to have great potential, one highlight being the potential to produce simultaneously both bio-based chemicals and energy in biorefineries; • Bio-based plastics with strong development potential identified.	• Commercial demonstration of technologies lags behind, *inter alia* due to high costs, financing constraints and a current lack of demand-pull effect; • Sustainability risks exist even for an industry based on wastes and residues, given prevailing existing uses and environmental functions; • Availability of sufficient biomass constrained by logistical, technical, economic and environmental factors, and seasonality; • Wastes and residues tend to be bulky, low value per tonne, heterogeneous and diffuse; their processing in biorefineries therefore tends to be expensive, putting them at a cost disadvantage.
OPPORTUNITIES	**THREATS**
• The sector's significant potential to create jobs and economic growth makes it an attractive target for decision making in times of economic downturns; • The on-going revision of EU biofuel policy in an attempt to mitigate ILUC by moving towards biofuels from wastes and residues may provide a stimulus to the wider biorefinery sector; • The Bioeconomy Communication as a high-level policy initiative with the potential to stimulate decision making by industry and European and national policy makers;	• Policy determination to reduce wastes in the food chain which should increase future raw material costs; • The current political focus on bioenergy and biofuels (promoted through renewable energy targets) puts bio-based material uses at competitive disadvantage; • The lack of sustainability criteria for biomaterials (or even for solid biomass energy) in light of the on-going discussion on conventional biofuels may undermine trust in the sector;

[154] Several stakeholders from industry, policy and academia (see Annex 5) were consulted on a draft version of this SWOT diagram along with further questions aimed at validating key findings summarised in this chapter.

• The Biobased PPP could develop into a promising initiative helping *inter alia* bring about large-scale demonstration; • Private sector initiatives to move towards bio-based sourcing (notably in the food packaging industry).	• The lack of technical standards for bio-based products may complicate market penetration; • Lack of public awareness as regards bio-based products; • The oil price (and development of unconventional fossil sources) is an important determinant of the profitability of many bio-based operations but its development is outside of the sector's control.

Source: Own compilation based on the sections below and sources referenced

5.1.1 Strengths

A range of technologies exist for the conversion of agricultural and forestry residue material into a wide range of bio-based chemicals that find application is many different spheres of the economy including daily life and speciality applications. Available evidence on the sustainability of bio-based materials, while pointing out some potential negative impacts that need continued monitoring, shows that the displacement of petrochemical based materials by bio-based ones can generate significant GHG savings. Where technically feasible, GHG savings can be augmented by cascading biomass use to benefit first a range of high value material uses, down through lower value uses, and usually with energy recovery at the base of the cascade. On top of these environmental benefits, the importance of the current and growing bio-based sector for jobs and economic activity is highlighted (WEF, 2010; European Commission, 2012, 2013). It appears that there is a potential for 'green' jobs and economic activity if sustainability concerns are properly addressed.

For a range of conversion routes, relevant technologies have been developed or are in the process of development and Europe is believed to hold a strong position in biorefinery research. Some have been demonstrated at pilot scale whilst others are well established at commercial scale. This includes the use of the biomass macromolecules cellulose, hemicellulose and lignin, for which a range of commercial applications exist, as well as a range of bio-based chemicals and polymers from sugar-based biochemical conversion routes. European countries are also active in the commercialisation of advanced biofuels, including via thermochemical routes (eg the use of municipal solid waste in the planned London based GreenSky facility) and more so via biochemical routes, where the two only plants worldwide that process lignocellulosic material operate in Europe (given the status of information available).

Based on the LCA studies reviewed, some ***bio-based products that appear particularly promising*** can be singled out. These include many bio-plastic building blocks, such as PLA and PHA that have yielded favourable results in several studies (Essel and Carus, 2012). Acrylic acid, ethanol, ethylene, PDO and again PHA are highlighted in another study as those with the highest GHG savings potential (Hermann *et al*, 2007). Considering market development potential, again PLA, bio-based 'drop-in'[155] PET, the polymers PE/PP and (to a lesser extent) PHA are displaying the largest growth rates (nova-Institut, 2013). This concurs with another study that counts among the most promising bio-plastics PLA, PHA, bio-based PE (Dobon, 2012)[156]. An IEA report sees the bio-chemical sector at a

[155] ie identical to its petrochemical counterparts and therefore one-to-one substitutable

[156] Some industry contacts consulted see PHA lower down the list with regard to market development potential.

'tipping point, with production expected to double in the upcoming years, driven in particular by growth in the drop-in bio-based chemicals sector and also by the production of platform chemicals (de Jong *et al*, 2012).

The other great strength of the use of wastes and residues is that they are clearly ***preferable from a sustainability point of view***. The direct use of land in thus avoided and hence the risk of ILUC with knock on effects in terms of GHG emissions and on biodiversity is mitigated. Apart from mitigating the potential for indirect emissions, emissions from the crop cultivation chain are avoided as well, as long as it can be considered that the use of crop residues does not drive crop cultivation. When LCAs conducted have found that bio-based materials may perform worse than fossil-based materials on several environmental parameters, this was indeed explained by environmental impacts resulting from the crop cultivation stage, impacts that can be avoided when using wastes and residues. The potential for very resource efficient closed-loop systems implemented as part of biorefineries is also mentioned. Yet despite this promising potential, sustainability challenges remain, as discussed in the next section.

5.1.2 Weaknesses

While a range of technologies are available, their ***commercialisation is often lagging***. The biorefinery industry is at the critical stage of making the jump from successful pilot demonstration to first-of-its-kind plants and to successful commercial activity. The European bio-based sector is active when it comes to investment in pilot and demonstration scale facilities, but the large investments in commercial-scale plants are concentrated in other world regions, most notably Asia and North and South America (Carus, 2012; WEF, 2010). The most important factor mentioned in this respect is that costs (especially capital but also operating costs) remain high for many technologies. The EU credit crisis also imposes financing ***constraints***. It is suggested also that, the EU sector suffers from a lack of funding for large demonstration plants and a fragmented R&D funding landscape (WEF, 2010)[157]. Another explanation for the slow development of this sector is the lack of a stable market demand that could increase investor confidence and provide the ground for increasing production capacity.

Sustainability is a key challenge and ***sustainability risks exist even for an industry based on wastes and residues***. This is because many of the wastes and residues have a range of prevailing existing uses and environmental functions. Also, the understanding and monitoring of a range of environmental parameters is unsatisfactory currently. Apart from uncertain LCA results, one key challenge are the system boundaries of LCAs and whether or not they address such important issues as soil organic carbon. The loss of SOC and related soil functionality as a result of excessive residue extraction is a significant environmental concern. The situation is exacerbated by policy frameworks, notably the Renewable Energy Directive's GHG accounting framework, explicitly considering residues 'zero emission' up to their collection, hence dismissing potential negative impacts for soil carbon that can be significant. SOC impacts are admittedly difficult to trace and to regulate, as they require consideration of the local biophysical and climatic conditions. In other words, a broad-brush approach by which EU policy would mandate uniform maximum extraction rates does not seem feasible. Instead, farmers and forest owners must draw on local knowledge in order to determine the appropriate extraction rates at the local level. Rural Development Programmes or other support tools could be possible means of supporting this process. It is also unclear as to whether an industry can be build exclusively based on wastes and residues. The ***supply of some of these, in particular cereal harvesting residues, is***

[157] See also 'Bio-based chemical companies face difficult stock market conditions in 2013' (17 January 2013), http://www.icis.com/Articles/2013/01/21/9632874/bio-based+chemical+companies+face+difficult+stock+market+conditions+in.html.

seasonal and hence intermittent, possibly requiring additional supply of energy crops – which would trigger sustainability concerns related to increased cropland requirements – or storing of residues – likely to increase costs further.

Apart from these environmental barriers mentioned, ***the collection of wastes and residues is constrained by a range of logistical, technical and economic factors***. Transporting of bulky and low density residues is feasible over relatively short distances only, which requires a careful siting of biomass processing plants. Enhanced efforts to develop 'densification techniques', such as briquetting and pelletising, are another way to possibly expand sourcing radii (WEF, 2010). Farmers may be reluctant to give up established existing uses and practices related to residues even in situation where extraction for industrial purposes would be environmentally sustainable and economically viable. Likewise, forest management may be hindered by fragmented ownership structures. The lack of suitable machinery for harvesting of residues both on fields as well as in forests can limit residue potential further. With regard to the processing of food waste, typically through anaerobic digestion, a lack of separation of food waste from other types of waste is a major barrier that would most effectively be overcome by source separation and separate collection of waste streams. Any infrastructure build up in this sector is rendered difficult due to the diffuse sources of food waste, however.

A further very important weakness of the current biorefinery sector alluded to above is the current focus on sugar and starch crops instead of lignocellulosic biomass. This can be explained by the ***higher costs of processing of wastes and residues in biorefineries***, especially at the pre-treatment stage, putting them at a cost disadvantage (NNFCC, 2009; Paulová *et al*, 2013). Indeed the pre-treatment stage is called the 'key bottleneck in the bioprocessing of lignocellulose biomass' (Paulová *et al*, 2013), partly explained by high energy consumption. It can be assumed that in the absence of policy or economic benefits associated with a particular feedstock, processors will choose to use the simplest sugars (ie sugars from food crops), due to their ease of use, low cost and existing infrastructure. Certainly, it is difficult to see how the cellulosic sugars derived from biomass fractionation could be used for fermentation processes given the cost of this compared to the cheaper pre-treatment technologies, unless the other fractions, hemicellulose and lignin, can be commercialised (NNFCC, 2009). The economic viability is further reduced due to outstanding technical issues, such as the ability to deal with the heterogeneity of many wastes and residues.

5.1.3 Opportunities

With regard to the feedstock basis, there is currently no clear preference for the use of wastes and residues, a fact that is best exemplified at the biofuel sector, where conventional biofuel production based on arable crops (sugar, starch and oilseed crops) dominates. The currently ***on-going revision of EU biofuel policy in an attempt to mitigate ILUC may provide a stimulus***, however, in the sense that advanced biofuels from wastes and residues are considered increasingly as a potential solution. As some of the technological pathways (or at least stages thereof) to produce biofuels and bio-based chemical building blocks are similar or even identical, this could turn out to be a push factor for the entire biorefinery sector.

The ***Bioeconomy Communication as a high-level policy initiative*** could stimulate wider interest in the bioeconomy and all its related sectors and economic activities. It is envisaged to trigger decisions by the relevant industry stakeholders as well as policy makers (at European and national level) to advanced the biorefinery industry. To build the evidence base for such decision making, the Bioeconomy Observatory is being set up currently by the Commission's Joint Research Centre with

the aim to ultimately collect, analyse and disseminate data for the three pillars research and innovation, markets and competitiveness, and policy interaction[158]. Currently, the 'bioeconomy discourse' seems to interest mainly those and is shaped mainly by those industrial groups with a direct stake in the development of the sector (Keegan *et al*, 2013). There is a lack of public awareness among consumers about what 'bio-based' means and what potential benefits can derive from it. Industry representative point out that while the bioeconomy is a framework for putting facilitating framework conditions in place and ease financing constraint, concrete actions still need to be delivered on the ground in order to deliver on the goals of the Communication. The public-private partnership 'Biobased PPP' (co-financed under Horizon 2020) could help in the large-scale demonstration and commercialisation of bio-technologies (see Box 23).

Box 23: Horizon 2020 and the Biobased PPP

Horizon 2020 is Europe's financial instrument for implementing the Innovation Union, a flagship initiative targeted at ensuring Europe's global competitiveness. The framework spans over the period 2014 to 2020 and is aligned with the policy priorities of the Europe 2020 strategy and the activities developed by the European Innovation Partnerships (EIP)[159]. One of the social priorities targeted by the framework refers to delivering secure, clean and efficient energy, which encompasses also the provision of alternative fuels (European Commission, 2011b).

Another area of contribution of Horizon 2020 represents its support to the realisation of the biobased industry's objectives, for example, by means of co-funding for the 'Biobased PPP' (also known under the working title Bridge 2020[160]). This is a Public-Private Partnership established between the European Commission and the Biobased Industries Consortium (BIC). The overall objective of the Biobased PPP is to the promote the use of advanced feedstock for biorefineries, while also setting up biobased value chains, starting from mobilization and supply of sustainable feedstock, towards the utilization of biobased products, and to the consolidation of new markets. In order to achieve this, the Biobased PPP focuses on the implementation of several types of initiatives including whole value chain demonstration programmes that include the development of supply chains and explore ways of providing a secure and sustainable supply of lignocellulosic biomass (including wastes and residues) through integrated agricultural and forestry value chains and flagship projects that support the upscaling of bio-technologies (Biobased for Growth, 2012).

Source: Own compilation

There is a considerable optimism about the bioeconomy's ***potential to create jobs and economic growth*** (for example de Jong *et al*, 2012; European Commission, 2013, citing CSES, 2011, Biobased for Growth, 2012; nova-Institut, 2013; WEF, 2010). However, the realisation of these economic benefits is associated with large uncertainty and should be treated with caution. Continued monitoring will be a way to shed more light on potential positive economic impacts. This monitoring is indeed envisaged as part of the Bioeconomy Observatory. Nevertheless and despite the uncertainties, the emphasis on growth and jobs could make it attractive for policy makers to focus on decisions to advance the bio-based industries in times of economic difficulties.

[158] http://europa.eu/rapid/press-release_IP-13-113_en.htm

[159] http://ec.europa.eu/research/innovation-union/index_en.cfm?pg=eip

[160] http://bridge2020.eu/about/

An example of the ***potentially important role of private sector initiatives*** is the recent growth in bio-PET to become the most important bio-based polymer 'due to an initiative by one big brand-owner' (nova-Institute, 2013). This refers to The Coca Cola company's decision to move towards 100 per cent bio-based PET bottles. Such initiatives by global brand owners are considered very important to reach out to many consumers and increase the visibility of and trust in bio-based products.

5.1.4 Threats

One rather obvious threat to the development of a bio-refinery sector based on wastes and residues is that policies intend to significantly reduce waste, especially food waste. This highlights the importance of developing a sound information bio-resources data base so that all parties are aware of the developments in the generation and use of these bio-resources.

Another potential threat to the development of bio-based product routes is the ***unbalanced encouragement of some bio-based pathways at the expense of others***. The prime example of this is the strong incentives being given through the Renewable Energy Directive in favour of (conventional) biofuels and bioenergy. This discourages the scale of investment needed to incentivise the biorefinery sector (Carus *et al*, 2011; CEPI, 2011). In this way, bio-based material uses are at a competitive disadvantage.

The ***lack of sustainability criteria for biomaterials*** (or even for solid biomass energy) in light of the on-going discussion on conventional biofuels may undermine trust in the sector's development (WEF, 2010; European Commission, 2013). This calls for increased understanding of the lifecycle emissions and other environmental impacts of wastes and residue pathways, which includes a better tracking of soil organic carbon development facilitated by common EU guidelines, for example.

On a similar note, the ***lack of common standards for bio-based products*** may hinder their widespread market uptake European Commission, 2013, citing CSES, 2011). Standardisation is needed to convey information on important product characteristics such as 'bio-based content, technical performance, life-cycle environmental impact and biodegradability'. Several mandates exist to develop relevant standards, brought about by the Lead Market Initiative and the establishment of the European Ad-hoc Advisory Group for Bio-based Products (European Commission, 2013).

The general ***lack of public awareness*** of bio-based products may also further harm the development potential of the industry. This can be overcome by labelling initiatives or, as mentioned above, through initiatives taken by big brand owners.

Because the principal alternative substrates for bio-resources are fossil fuels, ***oil and natural gas prices are an important determinant of the profitability of many bio-based operations***. This is certainly the case for any low-carbon (energy) technology and is also evidenced by Bos *et al* (2010) in the case of bio-PE production over time, which clearly boomed in times of high oil prices and hence higher costs for the petrochemical counterparts. Until recently, it was generally expected that declining fossil fuel reserves over time would bring about systematically higher oil prices in the future, and this would provide a boost to bio-based alternatives. However, the rapid development of new sources of fossil energy, notably shale oil and gas, may postpone the point at which fossil fuels become more expensive than bio-based alternatives. These oil and gas price developments are exogenous, that is beyond the control of the bio-based sector. This turns it into a threat to the sector's development and economic viability.

5.2 In conclusion and the way forward

Advanced biofuels and innovative bio-based pathways based on wastes and residues show considerable potential and should be further developed especially as Europe is already seen by some as having a lead in relevant technologies. There are sound infant industry arguments in addition to

the market failure arguments which justify further collective action to stimulate the development of this sector. However, there are also considerable uncertainties for investors and indeed all market participants and thus a major task is to ensure good transparency and better information concerning the availabilities of the waste and residue streams, the opportunities for processing and the benefits to consumers. In addition, because, by definition, bio-based economic developments necessarily interact with ecosystems there has to be visible assurance that the bio-products are indeed environmentally preferable, with respect to greenhouse gases, water, soil and biodiversity than their fossil-based counterparts. There are persisting uncertainties surrounding the continued availability of wastes and residues, the environmental viability of the sourcing of feedstock, and also the sustainability of the bio-based products resulting from a biorefinery processes. ***The conclusion is thus that encouragement should be given to this sector, but with enhanced transparency of all aspects of its development, and with equally strong sustainability safeguards.***

The scale of the potential developments is considerable. The evidence reviewed suggests that the development of the food wastes and the crop and forestry residue streams considered in this report together could account for between three and 12 per cent of current total EU final energy consumption (1.55 EJ - 5.56 EJ out of the total 46.19 EJ/year). Since there is no meaningful way of putting a figure to the volume of the vast array of bio-based products that could be produced, these figures are offered as the crudest of indicators of orders of magnitude for potential energy generation, and the report explains the great uncertainties about mobilising and utilising such magnitudes of bio-resources. Also, it must be noted that it may well be that producing energy from such resources is not the most efficient way of utilising them. There might be far greater value realisable by decomposing the resources into a cascade of more valuable intermediate chemicals and products.

Given this potential, the main barriers and challenges remain to be overcome are:

- reliable and cost competitive availability of biomass and, linked to this, the environmental and technical challenges to mobilising waste and residue resources;
- proven technologies at commercial scale by crossing the innovation gap between demonstration and full commercialisation;
- adequate financing to do so by setting up large (commercial) scale demonstration or first of its kind plants;
- sufficient market demand to facilitate investments and make the step towards commercialisation; and
- predictable and stable longer-term policy framework, and for bio-based materials in particular, the public support available for using biomass in the energy sector that is not matched by similar measures for other bio-based products.

The next sub-section discusses options to help overcome these challenges before the report concludes by highlighting the need for environmental safeguard to address sustainability concerns.

5.2.1 Towards overcoming technical and economic challenges

Successfully mobilising waste and residue feedstocks

Targeted policy measures, such as the many instruments in Member States' Rural Development Programmes, could play a role in helping to overcome some of the technical and economic barriers when sourcing ***agricultural crop and forestry residues***. Wider extension services and advice for forest managers, improved organisation and increased cooperation between forest owners are further measures. Existing tools for example as part of RDPs can also be used to provide incentives and advice to increase the management of currently undermanaged forests. Likewise, cooperative arrangements of farmers organised in producer groups or associations are of form of improving the supply chain functioning that may be supported under RDPs.

With regard to ***food waste***, a harmonised definition of food waste across Europe would be a first step to enable the compilation of better statistical data of food waste volumes in Member States. This in turn would improve the evidence base to inform policy and investor decisions on the use of food waste for energy recovery. The lack of EU wide separation of food waste from other types of waste is a major barrier. Enhanced efforts in Member States to source separate and collect food waste are needed to increase available volumes and therefore improve waste management. Legislative requirements in Member States would usefully be revisited with regard to their impacts on using food waste as a co-substrate with manure and slurry in anaerobic digestion. This seems to be a promising way of putting two waste streams to good use by reducing the need for other co-substrates along with animal wastes, such as maize with knock on effects on land use and other harmful impacts linked, for example, to fertiliser use.

Overall, a ***regional approach to biomass development*** is recommended to take into account regionally or locally relevant sustainable limits of residue availability and link these to the siting of bioenergy or biorefinery plants, including pre-treatment facilities.

Moving from demonstration to commercialisation – the role of public policy

Several requirements need to be met to make the step across the innovation gap towards commercialisation. The need for further research is mentioned such as to reduce costs of proven technologies. Capital expenditure for biorefinery plants are often high and there may be a need for grant giving bodies such as the European Commission to focus attention on developments that promise to be more cost-effective and possible to operate at smaller scales to reduce investment needs (and eventually feedstock needs, hence making it more feasible to use locally available waste and residue biomass).

Another way to increase the potential for economic viability would to increase attention on biomass components beyond fermentable sugars, for instance by increasing attention on developing applications that give value to lignin and xylose.

There is a warranted role for some public money to ***provide finance and other assistance*** for setting up large scale demonstration or first-of-its-kind plants, for example as part of public-private partnerships, as anticipated as part of the 'Biobased PPP' (Box 23). The justification is to help set up new industries which will take some time to achieve the scale economies enabling them to compete with established fossil-based industry, and at the same time to realise the provision of public goods in the form of reduced GHG emissions and other pollution. However, this is not to imply that public financial assistance is always justified. Other policy options that do not involve the use of public money but help create a market demand should be also considered[161]. Several mandates exist to develop relevant standards, brought about by the Lead Market Initiative and the establishment of the European Ad-hoc Advisory Group for Bio-based Products (European Commission, 2013) which are worth pursuing further. Having in place standards for bio-based products would facilitate a public procurement programme another option worth considering to create a market for bio-based products (Box 24 introduces the US BioPreferred programme). The introducing of a (EU wide) label for bio-based products, endorsed by high-level politicians to increase its visibility among consumers, would be a further measure to help create a market and to increase public awareness among consumers about 'bio-based' products. Outside of the sphere of public policy, the role of global brand owners is highlighted for its potential to create a 'demand pull' and facilitate new production capacity at the same time as increasing wider consumer awareness.

[161] Many of which have been put forward as part of the lead market initiative, see Ad-hoc Advisory Group for Bio-based Products (2011).

Box 24: USDA BioPreferred Programme

The United States Department of Agriculture (USDA) launched the BioPreferred programme in 2002 to promote and stimulate the development of bio-based products ranging from industrial supplies to personal care, such as fibre-based materials, bio-plastics, surfactants, bio-solvents, bio-lubricants, bio-chemicals, inks, enzymes and cosmetics. The project has two components: the public procurement initiative and the voluntary labelling scheme, which was added in February 2011.

The public procurement initiative supports the purchase and use of product categories with a minimum of seven per cent bio-based content by federal agencies and their contractors[162]. Further, the voluntary BioPreferred Labeling Programme offers an option for companies to test and certify their products for renewable resource content. The overall objective of this initiative is to inform consumers, and to help manufacturers market their materials and finished products with a 25 per cent minimum bio-based content. In order to qualify for the 'USDA Certified Biobased Product' label, a Life Cycle Assessment needs to be carried out by an independent third-party organisation[163].

By the end of 2011, BioPreferred programme certified more than 500 products[164] and is deemed to mark its contribution to expanding the knowledge base and supporting the development of the emerging biobased industry. At the same time, the programme makes available Life-Cycle Assessment data for biobased products, which may be used for informing and better shaping policy decisions[165].

Source: Own compilation

Given its currently high level of dependence on policy decisions playing a key role in shaping the future market, the demand by the biorefinery industry for a ***supportive and stable policy framework*** has a stronger basis than in many other sectors. There is concern among the bio-based material sector about the level of public support available for using biomass in the energy sector that is not matched by the measures in place for other bio-based products outside the energy market.

It is, however, *not* recommended that fair terms of competition in Europe are achieved by following for biomass the example of the policy mandates and targets used in the case of biofuels for road transport use. That experience is not one to repeat. Adequate sustainability criteria were not developed for conventional biofuels before they were put in place and subsequently it has been proposed that the targets are changed. Instead, a level-playing field could be created by phasing out support for volume targets in the transport sector in particular. The proposal by the Commission and the current legislative process to amend the Renewable Energy Directive in order to address the risks associated with indirect land use change is a chance to do just that. There needs to be an urgent discussion about the role of biofuels and bioenergy as part of renewable energy policy post-2020. Indeed, whilst the next steps for the development of renewable energy policy towards 2030 are being considered, there could be a case made to legislate biofuels and all forms of bioenergy outside of that framework and to consider working towards a 'Bio-resources Directive' which provides a more

[162] http://www.cereplast.com/biopreferred-procurement-vs-labeling-program-the-united-states-department-of-agriculture%E2%80%99s-promotion-of-biobased-products/

[163] following ISO 9001 guidelines, see http://www.biopreferred.gov/files/45174_BP_Fact_Sheet_HR.pdf

[164] According to 2011 data, a total of 25,000 products that could potentially carry the 'USDA Certified Biobased Product' label were identified, Ibid.

[165] http://www.ndcee.ctc.com/task_descriptions/N_0488_0532.pdf

integrated set of objectives and principles for the efficient use of Europe's bio-resources for food, energy and material use.

A further practical measure that could be implemented within the framework of sustainability criteria in the RED would be incentives to use end-of-life biomass for energy purposes, for example by allowing Member States to grant enhanced support for those biomass resources that have gone through cascading uses. This would be a way to promote cascading use, which would ultimately benefit non-energy bio-based applications that would be available for later energy recovery. A major pitfall underlying current renewable energy policy is the assumption that burning biomass for heat and power generation is carbon neutral (see for example Bowyer *et al*, 2012). Rectifying this assumption would deliver a strong case for favouring material use over bioenergy (Keegan *et al*, 2013).

At the same time, creating a level playing field between fossil and biomass resources would be a helpful step forward and one with multiple benefits when implemented through the removal of environmentally harmful subsidies (EHS) for fossil resources[166] or through appropriately taxing the use of non-renewable and polluting resources such as fossil fuels (Keegan *et al*, 2013).

5.2.2 Towards ensuring environmental sustainability

The analysis in this report has stressed in particular the impacts of intensified extraction of agricultural and forestry residues on soil quality, primarily through its impacts on soil carbon. This can have undesirable knock-on effects for water quality and biodiversity. In the case of food waste, valuing the former 'waste' as a resource bears the risk of counteracting on-going waste prevention efforts, which, apart from its wider resource efficiency benefits, is the option with the highest GHG savings potential. The report also explored available lifecycle analyses investigating the carbon footprint of different advanced biofuels and of other bio-based products. Advanced biofuels clearly show a high GHG saving potential compared with fossil fuels, clearly exceeding savings that are achievable by most conventional biofuels. Also other bio-based products show considerable saving potentials compared to their counterparts produced based on fossil raw material. At the same, the current evidence base in the form of existing LCA studies is not impressive and available meta-analyses point out this shortcoming. A further shortcoming that will be overcome with time is the lack of widespread commercial scale facilities and hence a lack of 'real life' data on which to base LCAs. Possibly most importantly in the context of the present study, however, is the widespread ignorance in LCAs of soil carbon impacts when studying the carbon footprint of forest or agricultural residue based pathways.

An assessment of the wider environmental impacts of, for example, bio-based plastics is furthermore challenging due to the varying potential scenarios according to which such materials are used and how they are disposed of at the end of their lifetime. If, for example, the increased availability of bio-based plastic wrapping in the food industry leads to more plastic wrapping used overall, this could be expected to have an unfavourable overall impact. With regard to disposal, ensuring that bio-based products are treated by appropriate waste management techniques is needed to maximise environmental performance. It was shown that there is still uncertainty with regard to the compostability and in turn the optimal waste management practices for bio-plastics. More research would be beneficial in order to ensure a solid evidence base for future policy in this area.

Suggestions have been made to address some of these challenges. A first aspect that emerges is the need for continued monitoring, as the information base for many (environmental) assessments is often thin at best. In order to obtain the necessary evidence on the environmental preferability of biofuels

[166] See Withana *et al* (2012) for an overview of EHS in Europe and recommendations towards their phase out.

and bio-based materials, the development of environmental indicators, such as soil and water quality, and biodiversity status need to be monitored. Part of such monitoring can follow exiting resource efficiency indicators developed by the JRC (European Commission, 2013). This may require the development of EU-wide guidance, for example for the monitoring of soil carbon stocks to evaluate appropriate levels of residue extraction. Some of this could be achieved as part of the Bioeconomy Observatory. With regard to soil carbon, rural development programmes (RDPs) are seen as an important facilitator to train land managers in the appropriate methods and guide them towards sustainable residue management both on agricultural land as well as in forests.

It is vital that environmental safeguards are developed to accompany the use of the waste and residue resources reviewed here in order to prevent harmful disruptions of existing uses of wastes and residues. These should be implemented as part of extending sustainability criteria for biofuels to solid and gaseous forms of bioenergy and eventually to bio-materials. As part of advancing the bioeconomy, the Commission would be advised to start the dialogue on sustainability criteria early in the process by engaging the relevant stakeholders and come to informed conclusions[167]. Safeguards needed at the feedstock sourcing stage include (following Kretschmer *et al*, 2013; also Annex 4):

- For ***food waste***, respecting the waste hierarchy is essential. Otherwise, there is a strong risk that by increasing the value of food waste going into bio-refineries this works against efforts to reduce waste. Respecting the waste hierarchy means that deviations would need to be justified based on technical feasibility, economic viability or environmental protection. It requires cooperation across policy domains on the EU and lower governance levels, particularly departments responsible for waste and renewable energy policies, to ensure that the resource efficiency benefits associated with avoiding food waste in the first place are valued above any energy recovery. AD operators could be required to demonstrate the availability of unavoidable food waste when setting of AD plants for food waste processing. While this might be challenging in the case of household sources, it is a reasonable requirement when sourcing from retailers who can be checked against having in place waste prevention and reduction policies that take priority over the marketing of food waste to AD operators.
- For ***agricultural crop residues***, the top priority is to avoid depleting soil carbon and other nutrients. For this purpose:
    - Appropriate safeguards could require biorefinery operators to conduct humus balance assessment in the relevant region prior to installing plants and to ensure that their sourcing of agricultural residues does not impact negatively on soil carbon and other soil nutrients through continued monitoring.
    - Strengthening environmental requirements in relation to soil organic matter as part of the cross compliance provisions of the Common Agricultural Policy would be a strong safeguard against unsustainable residue sourcing. More positively, this should be accompanied by the CAP's Rural Development Policy using advice and support measures for farmers to enable them to assess sustainable residue extraction levels.
    - An important safeguard is the extension of the Renewable Energy Directive's GHG accounting framework to include soil carbon stock changes. Given the RED only applies to biofuels, an extension of sustainability criteria to other forms of bioenergy

[167] These would involve discussing outstanding challenges related for instance to way in which LCA approaches can be applied to bio-based materials where the end-use and hence fossil comparator is hard to define.

and bio-based products would be the logical parallel measures needed to protect soil carbon.

- For ***forestry residues***, sustainable residue extraction rates are best ensured as part of clear and comprehensive measures put in place in Member States for the sustainable management of forests and woodlands. In addition, the need for sustainability criteria that go beyond the biofuel sector and are comprehensive in considering carbon stock changes in soil and the overall forest carbon stock as mentioned above is valid also for forest residues. There are a range of existing uses for forest residues, such as in the paper and pulp, the fibre board and for composting and soil mulch processing. Again, a valid safeguard would be to require biorefinery operators to investigate the sustainable sourcing of residues and also the likely displacement effects on other industries and their GHG implications.

Third, in order to maximise GHG savings per available biomass, the cascading use concept should be considered as a tool to maximise the value extracted from biomass, in situations where this is technically feasible.

In conclusion, any policy recommendations targeted at the development of biorefinery pathways must be underpinned by clear evidence that the relevant bio-based pathways contribute towards meeting climate change mitigation targets by delivering GHG benefits or other defined environmental benefits compared to the traditional products they replace. This includes a monitoring of the displacement effects where waste and residues are used as raw material in biorefineries that have existing uses. Monitoring in this sense would involve investigating the GHG impacts associated with the alternatives that would fill the gap triggered by the displacement. The Bioeconomy Observatory should be set up with the clear goal of providing the necessary evidence in all these respects.

All this should not be understood as an attempt to limit the development of a bio-based industry in Europe by imposing additional burdens. Instead, reducing uncertainty on environmental performance and ensuring favourable outcomes by introducing appropriate safeguards would be seen as a long-term benefit to the viability of the sector. Indeed, some highlight the uncertainty about the sustainability of bio-based products and the lack of sustainability criteria as a barrier to the sector's development, especially in light of the on-going discussion on conventional biofuels and the high degree of public scepticism. Given the need for and sometimes challenges associated with attracting financing to make the leap from pilot and demonstration plants to commercial scale operations, investor certainty is key.

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ANNEX 1 ADDITIONAL INFORMATION ON AGRICULTURAL RESIDUES POTENTIALS

This annex contains additional information complementing Section 2.2.1 of the report.

BEE project review of agricultural residues

Box 25: Details on the BEE project review of agricultural residues and organic wastes potentials (Rettenmaier *et al*, 2010)

Number of studies reviewed: Detailed analysis of 21 studies on European level and two on global level. Further nine studies on regional / national level analysed.

Horizon: Mostly 2020 or 2030 (the two global studies provide 2050 estimates, different estimates provided for present/past/near future situations.

Types of potential / constraints: Technical potential estimated in the majority of studies, some report economic, implementation and/or sustainable potential. Different constraints to the technical potentials are considered across studies, most notably accounting for food and feed production, other uses, environmental constrains and costs.

Calibration to compare EU-level studies: Rettenmaier *et al* (2010) include a calibration exercise of selected twelve European studies (selected inter alia on the grounds of covering a sufficient number of countries) in order to obtain EU-27 estimates for all these studies and therefore make results for the whole EU comparable[168].

Only seven studies of the twelve that form part of the calibration exercise report results for agricultural residues. Out of those, five studies do not specify which agricultural residues are considered (though one study out of those five reports separated results for manure). Thrän *et al* (2006) is the only study with a highly detailed representation of residues, distinguishing residues from woody, starchy, sugar, oil and other crops as well as manure.

Main difficulties / sources of variation:

- Different geographical coverage across studies;
- Resource categories covered with diverging level of detail, as well as differences in the classification of certain wastes and residue streams;
- Different conversion factors for biomass to energy yield used (eg depending on assumptions about moisture content of biomass). Adjustments could be made within the forestry sector but not for agricultural residues given the large variances between feedstocks within that latter category. For forestry estimates, results from studies assuming absolute dry matter were revised downward to reflect a certain moisture content assuming a lower conversion rate of 10 MJ/kg.

[168] See Section 3.2 in Rettenmaier *et al* (2010, p25) for the calibration procedure explained in detail.

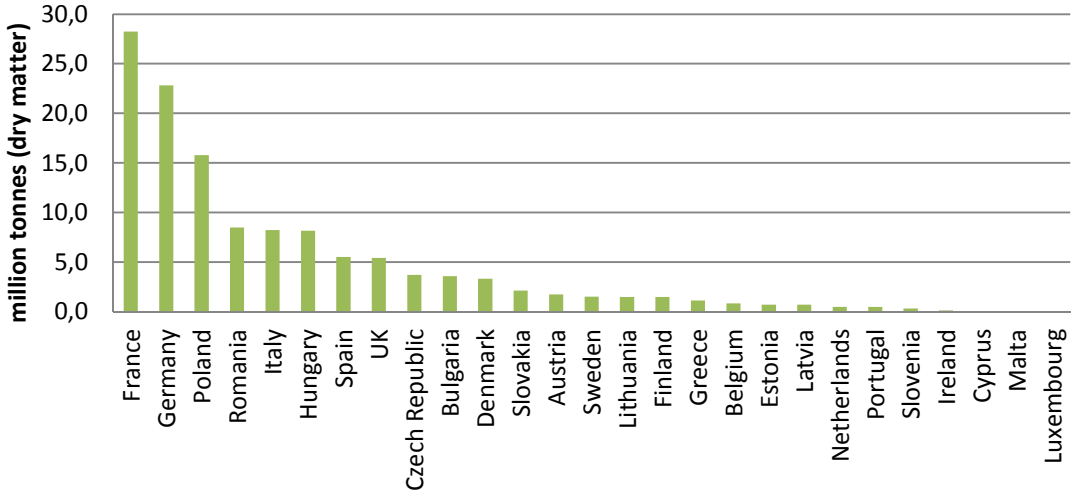
Additional information on agricultural residue potentials

Table 19: Assumptions and overall potential of biomass residue sources (as in BNEF, 2010)

Agricultural residues	Forestry residues	Municipal solid waste
Based on the 12 main EU food crops. Calculated based on 1990-2008 FAO data for area harvested and yields and linear projection to 2020. Main assumptions: • *Harvest index*: Ratio of food weight over total crop weight; differentiated per crop, typically one third (the remainder are residues); • *Recoverability index**: 25 per cent, ie 75 per cent of residues left on the ground; • Recovered residues are split further into: 10 per cent for power generation, 20 per cent for animal husbandry and 70 per cent for bioproducts; • Linear projections of production volumes, based on yield increases that are linearly extrapolated from 1990 to 2008 data in the *base case*; yield exceeds the historic trend by 5 per cent in the *bull scenario*.	Based on historical annual production data from 1990-2008 for 'sawn wood (sawn timber), plywood, fibreboard, chemical wood pulp, mechanical wood pulp and pulpwood'. Main assumptions: • Wood residues used in the wood panel industry and the paper industry are subtracted to yield potential for energy recovery; • 80 per cent of bioenergy potential is used for power generation.	Based on EEA data on waste generation and Eurostat population data. Main assumptions: • All countries with a landfill MSW shares >10 per cent reduce landfilling by 2.14 per cent annually until 2020. • Biodegradable part of MSW considered, 'organics, paper and paper board, and wood waste', assumed to amount to 57 per cent of landfilled MSW; • In the base case, 75 per cent of this is converted into bioproducts (100 per cent in bull scenario).
Total available biomass residues in 2020 in million tonnes (bull scenario in brackets)		
180 (212.6)	6.2	39 (51.4)

Source: Kretschmer *et al* (2012), Table 1. **Note**: *Defined as 'percentage of the crop weight that can realistically be recovered after harvesting' (BNEF, 2010, p21).

Figure 21: EU-27 straw potential in million tonnes (dry matter) for 2020



Source: Based on results from Elbersen *et al* (2012). The figures are based on results of the CAPRI model for 2020 and Biomass Futures elaborations. **Note**: According to a Polish report, the 2008 surplus straw potential (15 per cent of all available straw) per year is around 4.5 million tonnes, much below the estimated 2020 potential in 2020 as displayed in Figure 3 above (http://www.4biomass.eu/document/file/Poland_final_1.pdf). The 2020 figure of over 15 million tonnes could be an overestimation but certainly reflects large anticipated yield increases.

Table 20: Comparing results for agricultural residue potentials from BNEF and Biomass Futures to BEE project review

	BNEF (2010)*	Elbersen et al (2012)		BNEF (2010)*	Elbersen et al (2012)		BNEF (2010)*	Elbersen et al (2012)	
	Million tonnes			Mtoe			EJ		
	2020	2004	2020	2020	2004	2020	2020	2004	2020
Straw		59	127		23	49		0.96	2.06
Wheat straw	74			29			1.21		
Barley straw	26			10			0.42		
Rye residues	6			2			0.10		
Maize stover	18			7			0.29		
Sugar beet residues	38			15			0.62		
Sub-total	162			63			2.64		
Sub-total without sugar beet	124			48			2.02		
Other agricultural residues	18	24	26	7	9	10	0.29	0.39	0.42
Total (agricultural residues)	180	83	153	70	32	59	2.93	1.35	2.49
Rettenmaier *et al* (2010) ranges of *total agricultural residue* estimates for comparison:									
Min-max for 2010-2019							0.8 - 3.57		
Min-max for 2020-2029							1.02 - 3.2		
DBFZ and Oeko-Institut (2011) range of *straw estimates* for comparison:									
Min-max of straw estimates	50-110						0.82-1.83		

Source: Own compilation based on the cited studies. **Notes**: *all BNEF (2010) figures are for the 'base case'. All BNEF figures converted from Mt to Mtoe by a factor of 0.39, used by Elbersen *et al* (2012) for straw and other agricultural residues. Conversion factor from Mtoe to EJ: 0.04187 (as used eg in Rettenmaier *et al*, 2010). Straw in Elbersen *et al* (2012) includes the cereals wheat, rye, oats and barley as well as rice, and maize, sunflower and rapeseed

ANNEX 2 ADDITIONAL INFORMATION ON FORESTRY RESIDUES POTENTIALS

This annex contains additional information complementing Section 2.3.1 of the report.

BEE project review of forestry residues

Box 26: Details on the BEE project review of forestry residues potentials (Rettenmaier *et al*, 2010)

Number of studies reviewed: 21 European or global studies are reviewed. Ten studies focusing on Germany were reviewed as the basis for a case study.

Horizon: The time horizon of the resource projections across the different studies varies substantially, but most include 2020 estimates and several include do not only report estimates for one point in time but for several points, eg in ten-year intervals (2010, 2020, 2030). Most studies do not go beyond 2030.

Types of potential / constraints: All of the studies report technical potentials. Out of the eleven studies selected for the calibration (see below), two are classified as 'technical, economic potential'. Eight studies out of the seven include some forms of constraints, mostly environmental but also constraints on implementation and recovery rates.

Calibration to compare EU-level studies: Rettenmaier *et al* (2010) include a calibration exercise of selected twelve European studies (selected inter alia on the grounds of covering a sufficient number of countries) in order to obtain EU-27 estimates for all these studies and therefore make results for the whole EU comparable[169].

Eight studies are selected for the calibration of the forestry sector results to EU-27 level. Seven of those report results on stem wood and primary residues and one other study reports total forestry sector results. Out of those eight, four report separate results on secondary forestry residues.

Main difficulties / sources of variation:

- Different approaches (resource-focused, demand-driven, wood balance approach);
- Different scenario assumptions, eg about intensity of harvesting, existence or stringency of sustainability constraints (the definition of the latter is found to be largely 'subjective');
- Different categorisation of forest biomass sources. It is noted in the context of stemwood and primary forestry residues that more detailed sectoral studies yield a narrower range of results than 'umbrella studies' (ie studies that look at biomass potentials not only from forestry, but also from the agriculture and waste sectors);
- Furthermore the definitions of the different categories are not always clear and results are reported in different units.

[169] See Section 3.2 in Rettenmaier *et al* (2010) for the calibration procedure explained in detail and Section 4.3.2.2 for its application to the forestry sector.

Summary of EUwood results on forest biomass potentials

In 2010, the results of the EUwood study conducted for the European Commission were published (Mantau *et al*, 2010). The ***aim of the study*** was to assess different scenarios of future wood supply available for energy use and meeting EU renewable energy targets. The work is based on demand and supply balances provided by the Wood Resource Balance[170]; EUwood presents historical balances for 2005 and 2007 and extrapolated balances for 2010, 2020 and 2030. Whereas the 2010 results are presented as the balance of likely biomass supply, figures for 2020 and 2030 are interpreted as estimates of potential that are subject to uncertainty. Three scenarios are designed to showcase the different potential development paths, a ***low, medium and high mobilisation scenario***, distinguished, for example, by different mobilisation rates and sustainability constraints[171]:

- High mobilisation scenario: strong focus on using wood for energy; strong development of the forest sector including the set up of new cooperations among forest owners, further mechanisation and technology transfer; environmental impacts deemed less important which is reflected in less restricting biomass harvesting guidelines and permission to use fertilisers.
- Medium mobilisation scenario: new forest owner cooperations and mechanisation however resulting in more limited growth in biomass mobilisation; existing biomass harvest guidelines are deemed appropriate and are disseminated to other countries; (some) protection of forests to protect biodiversity; permission to apply fertiliser to a limited extent.
- Low mobilisation scenario: environmental concerns are at the forefront leading to strict biomass harvesting guidelines; fertiliser use is not permitted; strong limits on harvesting due to protection of forests for biodiversity conservation; mechanisation of harvesting but with limited effect on harvesting intensity.

While the focus of the EUwood study is on wood resources available for meeting renewable energy targets specifically, its results are nevertheless relevant in the context of the present study that considers the potential for both bioenergy and biomaterials. This is because EUwood reports results for total woody biomass potentials, irrespective of their eventual use. When presenting wood resource balances, the demand analysis in EUwood only takes into account 'traditional' material uses (most importantly saw mill, pulp and panel industries), so novel uses in the plastics and chemical industry (such as wood plastic composites and the use of cellulose in the clothing industry) are outside the scope. This implies that the potentials estimated to be available for the energy sector can be interpreted as estimates of potential for the wider bioeconomy, ie energy and (novel) biomaterials.

Looking at the ***results for 2010 displaying the likely current supply balance***, the bulk of the EU wood resource is from forests (70 per cent compared to 30 per cent other woody biomass in 2010) and within forest biomass from stemwood (coniferous and non-coniferous). Forestry residues account for 17 per cent of the total forest biomass potential and 12 per cent of the overall potential supply in 2010. Landscape care wood accounts for 6 per cent of the overall potential supply in 2010.

Looking at the ***balance between potential supply and demand*** (forecasted based on GDP projections and taking into account EU renewable energy targets), the EUwood study finds that the potential outweighs demand in 2010 by about 170 million m^3 (994 million m^3 potential versus 826 million m^3 demand). Looking at the 2020 and 2030 projected balances, Mantau *et al* note that '[in] the medium

[170] Methodology to bring together information on physical wood supply with the different sources of demand for wood developed by Mantau (2005) (see also Box 3).

[171] See Mantau *et al* (2010, pp57-58) for a more detailed explanation of the scenarios.

mobilisation scenario potential demand will overtake potential supply between 2015 and 2020' given the significant demand increase from the energy sector (2010, p22). It is noted furthermore that the balance between energy and material demand would be swapped with energy outstripping material demand at some point between 2015 and 2020, leading to a drop of material demand from 55.5 to 43.5 per cent out of the total wood potential. Projected increases in demand from the energy sector are driven by rapidly increasing demand for biomass from power plants in particular (household demand remains almost flat over the period 2010 to 2030).

In terms of the wood resources, the share of other woody biomass increases towards 2030, which is explained by the growth in wood using industries while the forest biomass remains fairly stable considering the relatively short time span in light of long rotation periods in forestry. The sustainability constraints imposed in the different scenarios influence the results strongly. In particular the potentials from logging residues and stumps are reduced strongly with stricter sustainability concerns that limit such intensive harvesting practices.

Table 21: Wood Resource Balance results for EU-27 and selected biomass categories

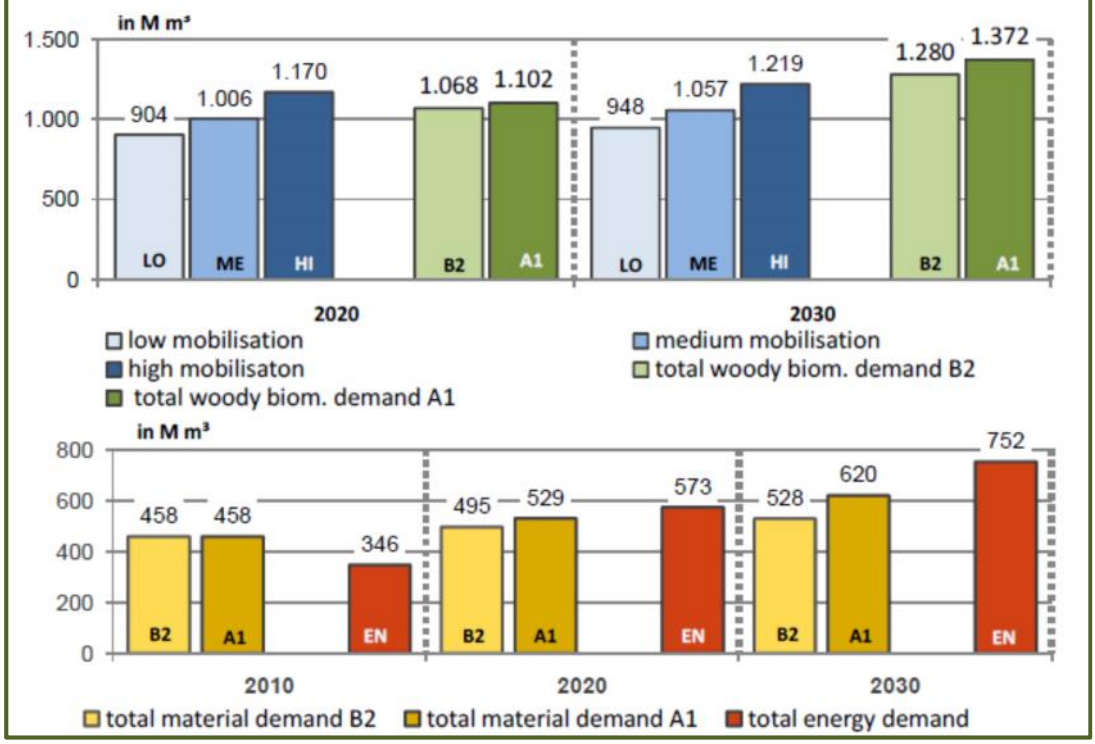
	2010	2020	2030	2010	2020	2030
	million m^3			EJ*		
Stemwood (C)	362	357	356	3.15	3.11	3.10
Stemwood (NC)	182	178	181	1.59	1.55	1.58
Forest residues	118	120	120	1.03	1.04	1.05
Bark	24	23	23	0.21	0.20	0.20
Landscape care wood (use)	59	66	74	0.51	0.58	0.64
Subtotal	744.30	744.00	753.90	6.49	6.49	6.57
Sawmill by-products (POT)	87	96	108	0.76	0.84	0.94
Other ind. res. reduced (POT)	30	35	42	0.26	0.30	0.36
black liquor (POT)	60	71	85	0.53	0.62	0.74
solid wood fuels (POT)	21	44	54	0.18	0.38	0.47
post-consumer wood (POT)	52	59	67	0.45	0.51	0.59
Subtotal	249.60	304.40	355.30	2.18	2.65	3.10
Total	994	1048	1109	8.67	9.14	9.67

Source: Mantau *et al* (2010). **Notes**: *Conversion factor: 1 million m^3 = 8.72 PJ. The figures in the table are for the medium mobilisation scenario. In the case of landscape care wood (LCW), 'use' refers to 'potential that is or will be used' determined again according to a high, medium and low scenario, but this time accounting for different demand levels with constant supply; shows that under neither of the scenarios the full LCW potential becomes utilised due to high 'procurement costs' associated with small volumes of biomass from scattered locations and of low density (Mantau *et al*, 2010, Chapter 5)

Box 27: EUwood fact sheet on Wood Resource Balance results for EU 27

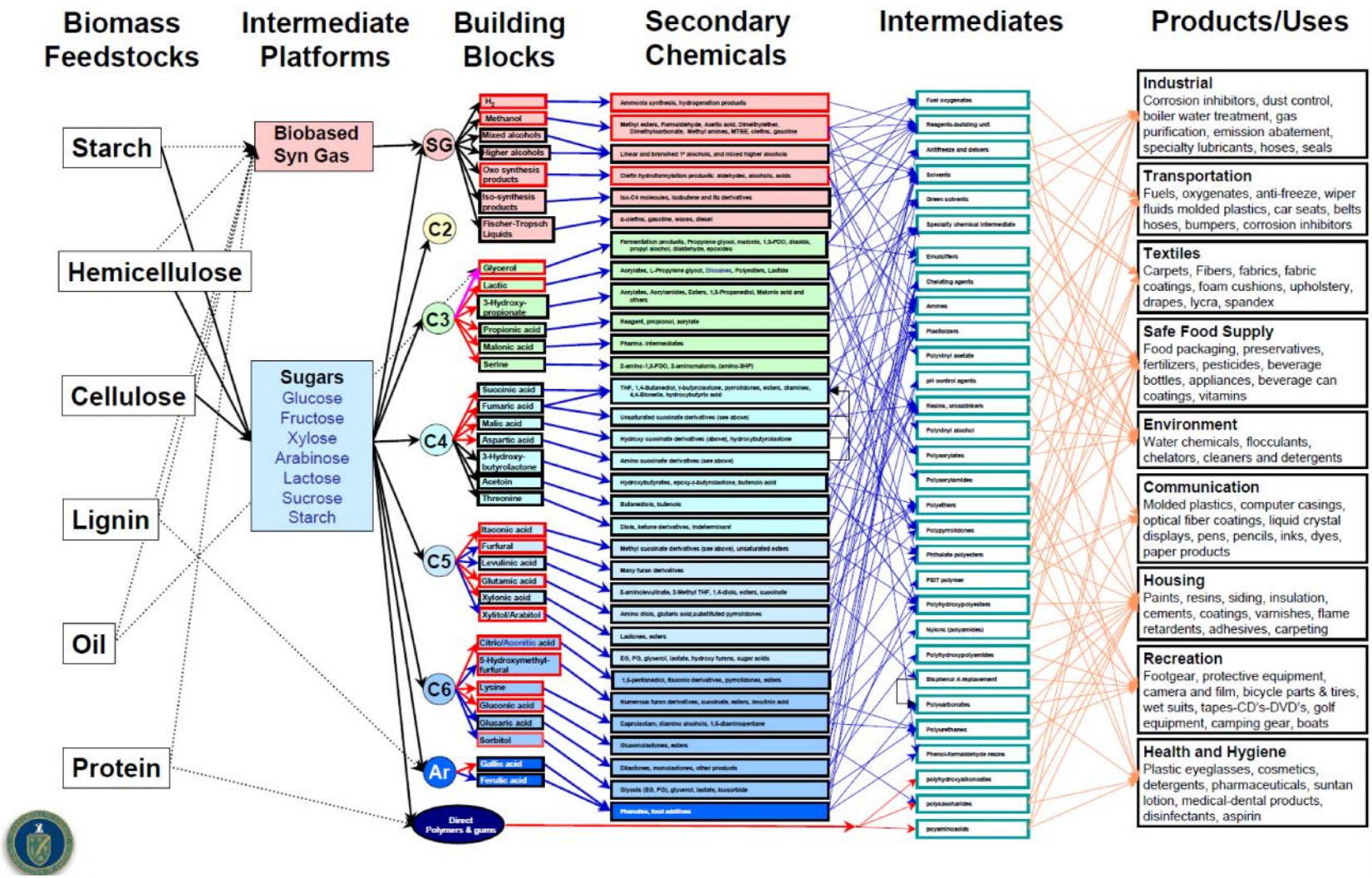
Wood Resource Balance							
Region	EU27			IPCC Scenario:			A1
potential	2010	2020 M m³	2030	2010	2020 M m³	2030	demand
stemwood C, ME	361,8	356,8	355,7	196,4	218,5	246,7	sawmill industry
stemwood NC, ME	182,3	178,1	181,0	11,4	14,2	17,3	veneer plywood
forest residues C+NC, ME	118,0	119,8	120,3	143,3	168,4	200,3	pulp industry
bark, C+NC, ME	23,7	23,3	23,4	92,3	110,1	135,7	panel industry
landsc. care wood (USE) ME	58,5	66,0	73,5	14,8	17,6	19,8	other material uses
				20,9	43,5	53,6	producer of wood fuels
sawmill by-products (POT)	86,6	96,0	107,8	85,5	98,3	113,9	forest sect. intern. use
other ind. res. reduced (POT)	29,7	34,9	41,7	83,2	242,0	377,1	biomass power plants
black liquor (POT)	60,4	71,3	84,9	23,2	68,8	81,5	households (pellets)
solid wood fuels (POT)	20,9	43,5	53,6	154,5	163,2	150,6	households (other)
post-consumer wood (POT)	52,0	58,7	67,3	0,0	0,8	29,0	liquid biofuels
total	993,9	1.048,4	1.109,4	825,5	1.145,4	1.425,4	total

Wood Resource Balance (without solid wood fuels)							
Region	EU27			IPCC Scenario:			A1
potential	2010	2020 M m³	2030	2010	2020 M m³	2030	demand
forest woody biomass	686	678	680	458	529	620	material uses
other woody biomass	287	327	375	346	573	752	energy uses
total	973	1.005	1.056	805	1.102	1.372	total



Source: Mantau *et al* (2010, p31) **Notes**: C refers to coniferous/softwood; NC refers to non-coniferous/hardwood; ME refers to 'medium mobilisation scenario'; POT refers to '"real" availability under given constraints'; USE refers to 'potential that is or will be used'

ANNEX 3 BIO-BASED PRODUCTS OVERVIEW



Source: Werpy and Petersen, 2004, p11 (go there for improved readability)

ANNEX 4 WASTES AND RESIDUES: EXISTING USES, RISKS OF DIVERTING THOSE AND SAFEGUARDS REQUIRED

Feedstock name and definition	Examples of existing uses	Examples of risks of diversion of existing uses	Environmental safeguards
Biomass fraction of mixed municipal waste: Food waste and green waste (ie garden waste) as well as biodegradable plastics and non-separated card and paper	Composting, in compliance with waste management policy. Animal feed in some cases.	Might counteract efforts to prevent, re-use and recycle waste.	Adherence to waste hierarchy: prevention > re-use > recycling or composting > energy recovery > disposal (landfill or incineration without energy recovery).
Biomass fraction of industrial waste: Various waste streams including paper, cardboard, wood from packaging and transport; industrial food waste	Recycling of waste paper and cardboard in the paper and pulp industry; of waste wood in the board industry; composting of food waste.	Diversion of paper and cardboard may destabilise pulp and paper industry recycling loops. Might counteract efforts to prevent, re-use and recycle waste.	Cooperation between policy makers to ensure adherence to waste hierarchy.
Straw: Straw refers to the dry stalks of crops that remain following the removal of the grain and chaff during the harvesting process and can encompass cereal straw, maize stover, oilseed rape straw.	Livestock bedding, animal feed, mulch for vegetable growing, mushroom growing, compost. Left on field or ploughed in to reduce erosion, improve nutrient content, help maintain soil organic carbon level.	Straw removal impacts on soil functionality, reduction of soil organic matter; potential impacts on fauna from changes to stubble heights and straw management; animal welfare impacts when no suitable alternatives employed.	Compulsory investigation of soil humus balance, strengthening of CAP cross compliance requirements relating to soil organic matter, guidance to farmers on sustainable straw use and including soil carbon in GHG accounting framework (in the RED).
Grape marc and wine lees: 'Grape marc' (pomace) is residue remaining after the pressing of grapes. 'Wine lees' are the precipitated sediment remaining in the vessels used in wine production.	Pressing produces Ripasso and piquette wines and the marc can be distilled to produce 'grape marc spirits' (eg Grappa). Production of grape seed oil and other culinary ingredients. Soil mulch; peat or perlite substitute.	Impacts on the food and wine industry particularly on liqueur and grape spirit production (small-scale producers). Displacement of marc by peat and synthetic fertiliser with associated environmental impacts.	Measures to ensure sufficient supply to traditional and small-scale spirit producers. Integrated production pathways, enabling continued supply of useful by-products.
Nut shells: Nut shells are the outer hard casing of nuts. The largest source of nutshells in the EU is from almond, walnut and hazelnut production.	Walnut shells used as soft abrasive media in manufacturing processes. Nut shell used by cosmetics industry and for fuel in biomass boilers. Further uses include: composting, packing material.	The displacement of walnut shells from industrial processes may lead to increased use of silica, with associated human health risks including silicosis. Increased fossil fuel use in substitution for nutshell use in biomass boilers.	Unclear. Safeguards would need to ensure that sufficient quantities are available for current use as a blasting media and for other industrial applications where it has displaced more harmful media.

Husks: Husks (hulls) are the protective outer coating of seeds, nuts, grains or fruit.	Maize husks used as constituent of high energy silage or substrate for anaerobic digestion (AD). Wheat husk used in high fibre bran pellets (animal feed). Olive husks can be composted or used as a solid biomass fuel.	Conversion to liquid biofuels as opposed to onsite combustion to provide heat or power may lead to an increase in on-farm use of fossil fuels. Current fodder uses may have to be substituted.	There is a need for better understanding of the relative emission saving potentials of using husks as a biofuel feedstock as opposed to fodder use or other forms of energy processing.
Cobs: A cob is the central, fibrous core of a maize ear to which kernels or grains are attached. Isolated cobs are a by-product from the harvesting of grain maize kernels for food, chemical or biofuel use.	Maize cobs left in the field to decompose or harvested for energy and heat production. Also used as forage material for livestock (as silage) or for the production of platform chemicals. Used for polishing and other manufacturing processes.	Risk for soils thought to be limited as relatively low nutrient value. Heat and power would require substitution with other forms of biomass, other renewables or fossil fuels.	Strengthen environmental safeguards through cross compliance (Common Agricultural Policy) in the form of specific requirements in relation to soil organic matter. Include soil carbon in GHG accounting framework (in the RED).
Bark, branches, leaves, saw dust and cutter shavings: Includes both primary woody residues, such as bark, branches and leaves as well as processing residues such as saw dust and cutter shavings. Primary residues can also include woody biomass on non-forest land, such as prunings and cuttings from permanent crops (eg olives, vine) and orchards.	Saw dust and cutter shavings: pellets; fibreboard and paper production; composting, mulch and soil protector; animal bedding. Bark, branches and leaves: natural decompostible material left in forests, small scale wood fuel. Chemicals from bark used in the pharmaceutical industry. Some cork used in drinks industry and for flooring.	Higher extraction rates of forestry residues can negatively impact on forest carbon balances and biodiversity. Diversion from existing uses where wood remains as solid component (ie fibreboard) risks negative impacts on carbon balances.	Ensure extraction rates of bark, branches and leaves permit adequate quantities to remain in forests at sustainable levels; that suitable alternatives are available for compost and soil mulch; and that the paper pulp industry is not deprived of feedstock resulting in demand for higher-grade wood, with consequential diversion from other industries.
Used cooking oil (UCO): UCO is typically collected from catering establishments and industrial food processors as food production waste. Domestic household collection is also possible where the infrastructure exists.	Biofuels; combustion; animal feed; small amounts used by the oleochemical industry.	Increasing UCO collection and utilisation, especially from domestic properties, can result in environmental benefits eg prevention of water contamination and drain blockages and diversion from landfill.	Ensure that oils are not simply fried to make them 'used' and qualify for extra incentives for wastes and residues.
Animal fats (Category 1 and 2): Tallow products are from rendered	Tallow use depends upon its category. Lower category materials (Cat 1 and 2),	Utilisation of tallow for biodiesel production versus energy generation	Cat 3 tallow, used in feed and oleochemicals industry should not be

animal fats obtained by the crushing and heating of animal by-products. Three categories of tallow are defined by the Animal By Products Regulations (ABPR), with category 3 being the highest quality and lowest health risk.	used for heat in rendering process. Higher category materials (Cat 3) used in the production of animal and pet foods and in the oleochemical industry (eg soap, cosmetics, detergent and lubricants).	may have some effects on GHG savings if fossil fuels are used as an energy source in place of tallow. This could be overcome by using other renewable energy sources in place of the tallow.	utilised for biodiesel or downgraded to Cat 1 due to incentives (else increased palm oil use may substitute). A robust chain of custody and use of chemical markers within Cat 1 and 2 tallow should be able to prevent this.

Source: Adapted from Kretschmer *et al* (2013)

ANNEX 5 LIST OF INTERVIEWEES

Last name	First name	Organisation
Bothmer Kerckow Peters	Philipp v. Birger Dietmar	FNR (German specialist agency renewable resources)
Burton	Freya	Director HR and Communications at LanzaTech
Cobror	Sandro	M&G Chemtex
Lecoq	Eveline	European Commission DG Research & Innovation, Unit E2, Research Programme Officer
Mokkila	Kosti	Director, Technology, Biofuels at UPM - The Biofore Company
Needham	Andrew	Commercial Director at BIOGEN UK
O'Donohue	Michael	INRA; BIOCORE Project coordinator
Plan	Damien	European Commission Joint Research Centre, Unit A2 Responsible for Bioeconomy Observatory development
Scharathow	Roland	European Bioplastics, Deputy Managing Director Policy Affairs

This document is the final report of the STOA study 'Technology options for feeding 10 billion people - Recycling agriculture, forestry & food wastes and residues for sustainable bioenergy and biomaterials'.

A 'Study summary' and an 'Options brief' related to this study are also available.

The STOA studies can be found at:
http://www.europarl.europa.eu/stoa/cms/studies
or requested from the STOA Secretariat: STOA@ep.europa.eu

or accessible via this QR code:

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