EUROPEAN PARLIAMENT

Technology options for feeding 10 billion people

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

Summary

Science and Technology Options Assessment

STOA

Technology options for feeding 10 billion people

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

Summary

IP/A/STOA/FWC/2008-096/Lot3/C1/SC6-SC8

September 2013

PE 513.513

The STOA project 'Technology options for feeding 10 billion people - Recycling agricultural, forestry & food wastes and residues for sustainable bioenergy and biomaterials' was carried out by the Institute for European Environmental Policy.

AUTHORS

Bettina Kretschmer, Project Leader, IEEP
Allan Buckwell, IEEP
Claire Smith, IEEP
Emma Watkins, IEEP
Ben Allen, IEEP

STOA RESEARCH ADMINISTRATOR

Lieve Van Woensel
Science and Technology Options Assessment (STOA)
Directorate for Impact Assessment and European Added Value
Directorate General for Internal Policies, European Parliament
Rue Wiertz 60 - RMD 00J012
B-1047 Brussels
E-mail: lieve.vanwoensel@europarl.europa.eu

LINGUISTIC VERSION

Original: EN

ABOUT THE PUBLISHER

To contact STOA or to subscribe to its newsletter please write to:
STOA@ep.europa.eu
This document is available on the Internet at:
http://www.europarl.europa.eu/stoa/

Manuscript completed in July 2013.

DISCLAIMER

CAT BA-03-13-493-EN-C
ISBN 978-92-823-4738-6
DOI 10.2861/33312

This document is the Layman's summary of the STOA study 'Technology options for feeding 10 billion people - Recycling agriculture, forestry & food wastes and residues for sustainable bioenergy and biomaterials'. The full study and an Options Brief related to the topic are available on the STOA website.

Abstract of the study

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.

TABLE OF CONTENTS

1 INTRODUCTION

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 being fed to animals to provide transport and traction power. 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, paper and textiles. In this sense, the growing policy discussion of the 'bioeconomy' 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 of the bioeconomy focus on advanced conversion technologies that are able to process diverse feedstocks to produce liquid and gaseous transport fuels for use in both road transport and aviation. Wood is the traditional resource for the construction and furniture industries and many 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.

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

Biorefinery: 'the sustainable 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 study is carried out in the frame of the STOA Project 'Technology options for feeding 10 billion people'. With regards the policy context, it is strongly related to 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).

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)

The analysis in this report centres on the following three topics related to the European bioeconomy that are addressed in the subsequent chapters of the report:

The report systematically examines the **waste and residue streams** and tries to quantify how much material will be available, and how easily and reliably. This is followed by an explanation of **the range of technologies** available, and under development, to transform these waste and residue streams into useful products, and the nature and potential markets for these products. The rationale for being interested in wastes and residues is threefold. First, some of these materials have largely been considered a nuisance, and a challenge for disposal without polluting the environment. It is highly attractive therefore to be able to switch mind-set and see such materials as useful feedstocks or raw materials. Second, the recent experience of the development of certain renewable energy sources, particularly biofuels from food and feed crops such as cereals, oilseeds and sugar, has stimulated concern that new biorefinery processes must as far as possible be based on non-competing wastes and residues to minimise impacts on food availability and prices. The third interest in the bio-based economy is based on the notion that it is (or should be) fundamentally based on biological processes energised by renewable, current, solar power rather than by the stock of fossil fuel. This should, in principle, be far less polluting, particularly in terms of greenhouse gases (GHG). However, this cannot be taken for granted, and so the study looks carefully at the sustainability credentials of biorefinery technologies, especially at their climate protection performance and their potential impacts on biodiversity, water and soil.

The report concludes with a summary *strengths, weaknesses, opportunities and threats* (SWOT) analysis of biorefinery development and a brief consideration of the policies, in use or necessary, to stimulate the sustainable development of bioenergy and biomaterial production from wastes and residues.

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

The report considers three streams of bio-resources: food wastes, crop residues and forest residues[1].

2.1 Food waste – estimates of potential and barriers to mobilisation

Food waste will primarily be used for energy purposes in the form of biogas obtained through anaerobic digestion. Unfortunately, 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 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 the Commission study therefore do not include food waste from agricultural production.

There are many different causes of food waste in Europe. In the **manufacturing/production** sector, much food waste is largely unavoidable (eg bones, carcasses, certain organs), although technical malfunctions (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 buy-one-get-one-free 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). Causes of **household** food waste also include cultural factors as well as lack of knowledge on how to use food efficiently, food being undervalued by consumers, personal food preferences (eg discarding apple skins, potato skins, bread crusts), lack of forward planning, misinterpretation or confusion over food date labelling, suboptimal storage and packaging, incorrect portion sizes, and socio-economic factors (eg single person households create more food waste) (European Commission, 2010).

Because the physical composition of different waste streams is so different, the sheer mass of waste is not very revealing. It is more useful to focus attention on the energy potential of the material. 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. 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).

[1] The main report explains why other resource streams such as animal manure and human sewage waste have not been considered.

Applying the standard formulae for the dry matter content and its calorific value the European Commission's estimate of 89 million tonnes of total food waste would generate 0.22 Exajoules (EJ). This represents around 2.2 per cent of total EU electricity use of 9.96 EJ in 2011[2].

Dietary preferences and food cultures are very different around the EU so the estimates of food waste arisings expressed per capita have a very wide range between the EU Member States varying from below 80 kg in Greece, Malta, Romania and Slovenia to over 300 kg in Cyprus, Belgium and the Netherlands. However, definitional and measurement issues suggest such numbers are interpreted with caution.

Four factors contribute to the difficulty of mobilising food waste across the European Union. First, the **absence of a harmonised definition** inhibits the establishment of robust and reliable estimates and forecasting to inform effective EU and national level policy-making and action on the issue[3]. 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 has the potential to reduce significantly the amount of food waste generated adding to the uncertainty about the future potential volume of this waste stream, which can inhibit investment. Correspondingly, if the utilisation of food waste became an attractive business option, perversely it could cause environmental damage as it might work against these efforts to reduce waste. There is no doubt that the first best solution to waste is not to create it in the first place, this is firmly the strategy of the waste hierarchy set out in the Waste Framework Directive.

2.2 Agricultural crop residues – estimates of potential and barriers to mobilisation

The study was restricted to crop residues. These arise on farms including 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 (Elbersen *et al*, 2012)[4]. By far the largest source of crop residues is the straw and stover from grain crops (wheat, barley and maize). There is a wide range from 0.8 to 2.64 EJ of energy potential from these residues, summarised in Table 1 below. It can be seen that this source is between four and 12 times larger than the estimated energy value of food waste. These estimates suggest that crop residues could provide between 8 and 27 per cent of total electricity consumption[5]. The wide range is explained by differences in definitions and what is included in the estimation (eg some exclude woody materials), and in particular for straw by the assumed extraction rates. This latter factor is very important as the

---

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

[3] An EU funded project, EU FUSIONS, is currently working towards proposing a definition of food waste in late 2013 (http://www.eu-fusions.org/).

[4] 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.

[5] EU final electricity consumption in 2011 was 9.96 EJ according to Eurostat (Eurostat code B_101700, label 'final energy consumption').

incorporation of crop residues in the soil is part of maintaining soil fertility and especially soil organic matter (SOM).

Table 1: Estimates of the energy potential of agricultural crop residues

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)			
Straw range	0.82 - 1.83		
Rettenmaier *et al* (2010) estimated ranges agricultural residues:			
for 2010-2019	0.8 - 3.57		
for 2020-2029	1.02 - 3.2		

Source: Own compilation based on the cited studies.

There are essentially two challenges to mobilising these crop residues. **Transport costs** are high because these residues are highly dispersed and they 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 SOM with knock on effects for wider soil functionality, soil biodiversity and erosion risk.

It is possible, that biorefineries producing higher value products such as platform chemicals could afford to pay higher prices for biomass than bioenergy plants. However, energy sector modelling[6] 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.

2.3 Forestry residues – estimates of potential and barriers to mobilisation

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[7]. These by-products of the processing industry are already mostly utilised in a variety of uses such as fibreboards and panels,

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

[7] 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).

and so are not considered further here. As with agricultural residues, definitions of forest residue categories differ across studies[8].

When considering forest biomass potentials to meet energy (or other) demands, it is important to understand the relative assumptions and definitions that are considered within different studies. This is particularly important in relation to sustainability, which may refer to a business concept of sustainability, ie the long-term potential of a forest to meet demands irrespective of environmental impacts, or it may relate to an assessment of potentials that are environmentally benign[9]. 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).

The range of estimates of energy from forest residues shown in Table 2 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.

Table 2: Summary of results for selected forestry residue estimates, in EJ/year

EUwood (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 pot. 2010	HIGH 2030	MEDIUM 2030
0.80	1.25	0.82
Rettenmaier *et al* (2010) Stemwood + primary forestry residues:		
Min-max 2010-2019	0.51 - 2.70	
Min-max 2020-2029	0.66 - 2.70	
BNEF (2010) Existing and energy uses subtracted		
2020	0.09	

Source: Own compilation based on the cited studies

The first impediment to mobilising these considerable resources is the need for a better understanding of sustainability impacts to determine appropriate extraction levels. But then the high costs of extraction will be a factor along with technical issues such as limited accessibility (for example due to slope and distance) for harvesting of forest biomass. In addition, there is in many Member States a highly fragmented ownership of forests which already results in under-management. With greater incentives this might be overcome but still may need institutional development, such as co-operation and use of contractors to exploit the resource. Further uncertainties about achievable extraction rates for forest residues are created by uncertain future climate impacts, such as extreme weather and storm events affecting forest stands.

[8] 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.

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

As with crop residues, 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 twelve per cent of total EU final energy consumption (46.19 EJ in 2011), or 15 to 55 per cent of electricity consumption in the EU (9.96 EJ in 2011). These magnitudes are however subject to considerable estimation issues so should only be taken as broad approximations. Also not all this bioresource 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 will be explored in more detail in Chapter 4, the sustainability of these pathways is far from assured.

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, products will be limited by 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 and its price has a crucial influence on what can be produced.
2. **Market demand** – While the number of products which can be derived from biomass are numerous, the market for bio-based products varies; from bulk energy and chemicals to speciality chemicals which may only be needed in a few tonnes of product. A key decision is therefore determining the products for which there is a demand. In turn, for some products this is highly dependent upon policy decisions, for example for biofuels, for others it depends on consumer demand for 'green' products and for others the commercial demand for specialised molecules from the chemical industry.
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 or will be produced in reality. This in turn 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 (Holladay *et al*, 2007).

After a brief summary of the range of biomass conversion technologies in section 3.1, the following section includes discussion of the issues of costs and commercial maturity.

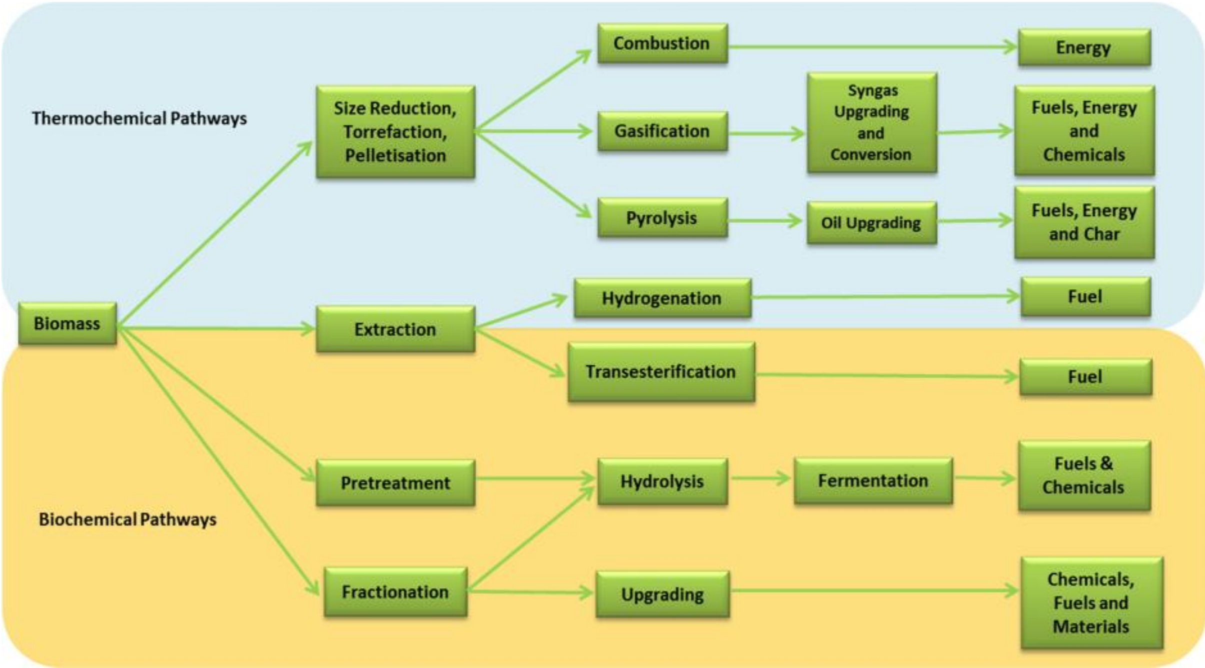
3.1 Conversion technologies – thermochemical and biochemical routes

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 or biochemical pathway. These processes are illustrated in Figure 1 below. This also shows the range of products which can be produced from each of the pathways.

Broadly there are three thermochemical conversion technologies, all characterised by requiring considerable process heat:

- **Hydrogenation** is a process which adds hydrogen (at high temperature in the presence of catalysts) to convert vegetable and animal oils into a high quality product which can be directly used as a fossil fuel substitute;
- **Gasification** is the breakdown of the carbon contained within a biomass material at high temperature and in an oxygen-limited environment. This forms a gas known as synthesis gas (syngas) which is a mix of hydrogen and carbon monoxide and from which a wide variety of chemicals, fuels and energy forms can be derived;
- **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.

Figure 1: Overview of thermochemical and biochemical conversion pathways for biomass



Source: Own compilation

There are broadly three biochemical conversion pathways which utilise biological agents such as yeasts, bacteria, algae, and enzymes to extract or convert to the required products.

- **Transesterification** is a process involving alcohols and acids to produce esters which are intermediaries en route to producing fossil fuel replacements and a variety of polymers (plastics);
- **Fermentation** is a biological process using yeasts or other micro-organisms to convert sugars into a large range of chemicals and products;
- **Fractionation** is a separation process (can precede fermentation) in which a certain quantity of a feedstock mixture is divided up in a number of smaller quantities (fractions) in which the composition varies according to a gradient, eg the viscosity of oils.

The full report explains each of these processes 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 current and future markets for bio-based materials is reviewed under the three headings:

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.

1. Macromolecules

Woody, or 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 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. 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.

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. One example is the established use of cellulosic fibres as a replacement for products such as cotton and cellophane. Another example is the development of Skalax, a biodegradable barrier material derived from the hemicellulose material xylan, found in a wide range of agricultural by-products such as the husks and hulls of cereals. Skalax is an additive approved for food contact applications. A third example is the development of higher quality materials from lignin such as that derived from biomass fractionation. This could involve pyrolysis oil derived lignin to be used in the production of polyurethane adhesives for the wood-based panels industry.

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. These 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 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.

There are a number of routes by which biofuels can be produced from biomass using thermochemical approaches. These include biofuels produced by the 'biomass to liquids' (BTL) route, pyrolysis and others. These fuels may be used as a partial or full substitute for petrol (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 'advanced' biofuels. The full report documents where the active commercialisation of advanced biofuels is underway at pilot, demonstration or full commercial scale. As of October 2012 in the EU, there were three plants in operation (none of them at commercial scale), four under construction and four which had ceased operation (see Figure 2 on the next page).

Figure 2: 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, planned plants are shown in orange, yellow are plants under construction and red represents projects which have stopped.

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 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. The most promising prospects of useful chemicals derived from this route are hydrogen (for ammonium for fertilisers), methanol to produce formaldehyde for the construction industry and many others. An interesting example is the GreenSky project operated in London between British Airways and Solena. This will take municipal solid waste (previously destined for landfill) plus agricultural and waste woody material, and subject it to Solena's high temperature gasification process to derive a synthesis gas and thence aviation fuel, diesel and naphtha. BioSNG is a comparable venture to produce a natural gas substitute from biomass.

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. Major high value compounds derived from pyrolysis oil include phenols, organic acids, furfural, hydroxymethylfurfural and levoglucosan (de Jong *et al*, 2012, de Wild *et al*, 2011).

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. 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.

Several countries in Western Europe are active in the commercialization of advanced biofuels based on either fermentation or anaerobic digestion of biomass, some are still at pilot or demonstration scale but others are at commercial scale. As of October 2012, there were 13 plants in operation, four plants under construction, and two plants had ceased operation (See Figure 3).

Figure 3: 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.

State of the current market and future prospects

In summary, **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[10], 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. The full report lists the current commercial plants in Europe and elsewhere in the world producing 18 different groups of bio-based chemicals (Table 14) and the plants in development for another 11 bio-based chemicals (Table 15).

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). 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[11]. 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 to be derived 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 research and development (R&D) activity into developing bio-based chemicals from waste materials.

Future prospects for a biorefinery industry based on wastes and residues: 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 concerns about environmental impacts (taken up in the following chapter) and the effects of the increased demands for agricultural crops on the level and volatility of food prices.

[10] 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/.

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

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.

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. 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.

4 ASSESSING THE SUSTAINABILITY OF BIO-BASED PRODUCTS

Sustainability is usually conceived as having economic, social and environmental dimensions. The economic sustainability, or commercial viability, of the exploitation of wastes and residues have partly been considered alongside technical feasibility in the assessments reviewed in Chapter 3. This chapter focuses on the environmental sustainability of a selection of bioenergy and biomaterial technology pathways and compares the bio-based products with their 'traditional' counterparts. This assessment first looks at relevant Life-Cycle Assessments (LCAs) conducted for bio-based pathways that compare the relative merits of bio-based products to traditional products. It then reviews wider environmental impacts of bio-based products which are usually not covered in LCAs. This includes water, soil and biodiversity impacts at different stages of the supply chain, including important sustainability concerns linked to the mobilisation of the wastes and residues.

There is a considerable body of literature on the environmental impacts of bioenergy and especially on conventional biofuels. The conclusions are that it is far from clear that they are carbon neutral, let alone generate large GHG savings, compared to fossil based fuels especially if Indirect Land Use Change (ILUC) effects are taken into account. The focus of this chapter is on the emerging evidence on impacts from advanced bioenergy and other biorefinery technologies that are less well understood at present. Some lessons seem to have been learned from the errors made in the promotion of biofuels as sustainability is being addressed during the early stages of the development of the bioeconomy. Also, another approach to embrace sustainability is contained in emerging initiatives to establish certification schemes for bio-based materials such as the US National Institute for Standards and Technology's 'Building for Environmental and Economic Sustainability' (BEES)[12] framework, and in research projects evaluating sustainability aspects, such as in the EU funded BIOCORE project[13].

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 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, illustrated in Figure 4.

The prioritisation first distinguishes between energy and the many non-energy uses of biomass discussed in the previous chapter, then between the utilisation of wastes and residues as opposed to food products, and finally between different energy use pathways. 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 form a given volume of biomass. Put simply, biomass can end up in bulk applications where high volumes of biomass are needed to

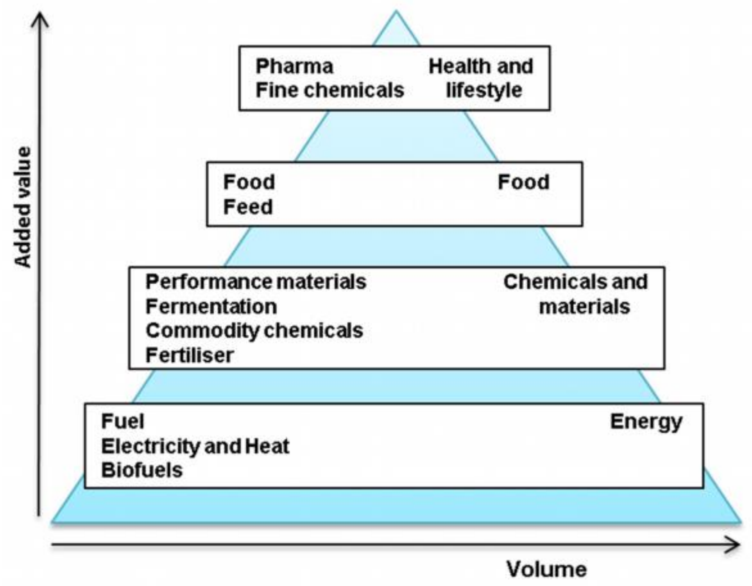
[12] http://www.nist.gov/el/economics/BEESSoftware.cfm

[13] http://www.biocore-europe.org/page.php?optim=a-worldwide-sustainable-concept

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 research findings indicate that biomaterial use does not unambiguously and always outperform solid and gaseous biomass use for electricity and heat production but a meta-analysis of LCAs indicates that when biomass is used in a cascading way, an additional 10 to 20 tonnes CO_2-equivalent/hectare can be abated on average (Carus *et al*, 2010). This highlights the importance of cascading biomass use suggesting that where applicable, non-energy and energy uses for biomass materials should be combined over time.

Figure 4: The biomass value triangle



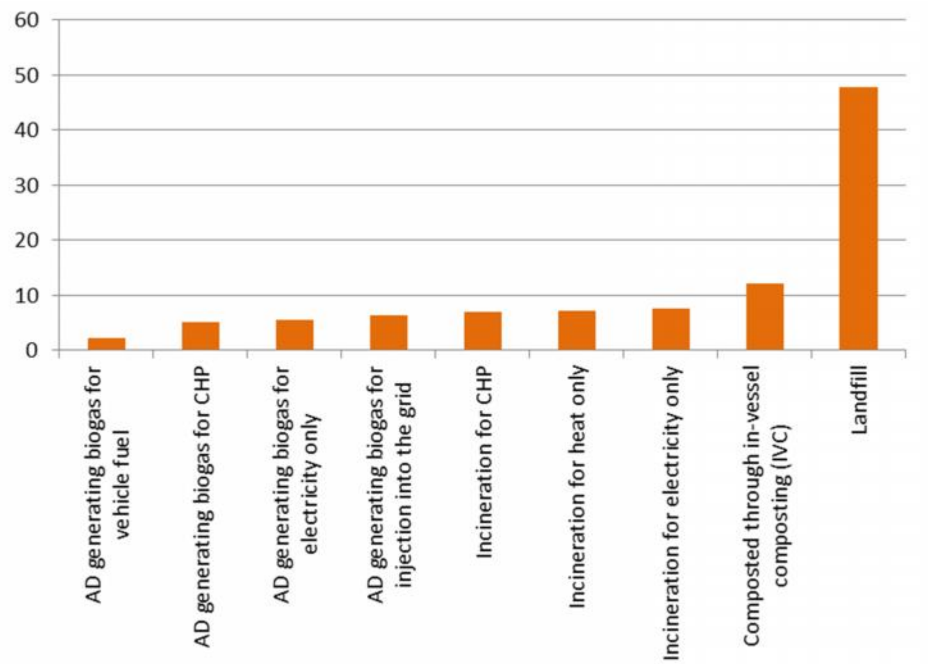
Source: Adapted after Eickhout (2012), based on

4.2 Review of greenhouse gas LCAs

The methodology of life-cycle assessments has undergone considerable development (see Pawelzik *et al*, 2013, and European Commission, 2013). There is no single way of conducting them and there are difficult questions whether it is more appropriate to use attributional LCAs (which look at impacts directly attributable to the different stages of the process, or consequential LCAs, which look more widely at consequences of decisions at different stages on second and higher order impacts. There are often complicated decisions on how to allocate GHG emissions between main and co-products (eg based on economic or energy values), and further complications arise on how to treat co-products of biomass processing, as residues or as a valued by-product. Also, it is necessary to emphasise again that a key indirect effect which cannot be overlooked when utilising waste and residue streams is the consequence of diverting these materials from their previous non-marketed route. The key examples of this are two of the biggest material streams being considered in this study, straw and forest residues.

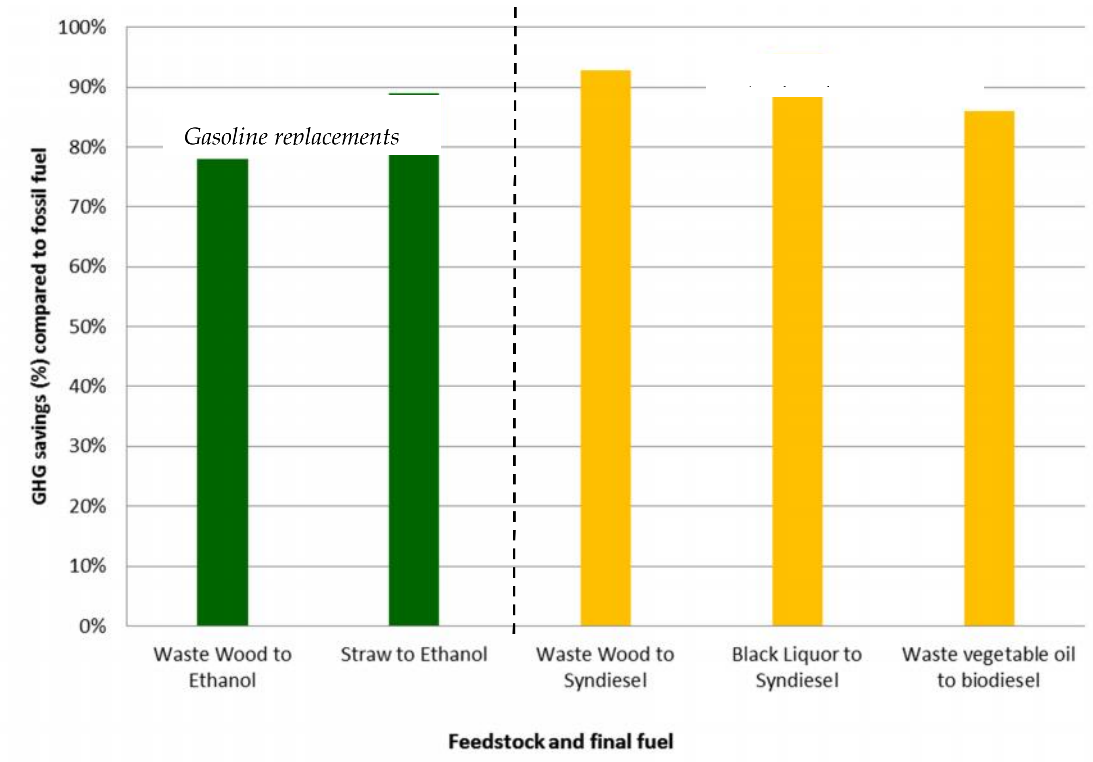
An indication of the results from studies comparing LCAs is provided in Figure 5 for different treatments for biowaste – showing the superiority of AD over other pathways, and in Figure 6 for advanced biofuels – showing the additional GHG savings potential associated with advanced biofuel pathways. Finally, Table 3 provides interesting insights into the aggregate GHG savings potential from bio-based products, showing 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).

Figure 5: Climate change costs in Euro/tonne of biowaste treated in different ways



Source: Derived from Arcadis and Eunomia, 2010. **Note**s: 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. As shown in the figure, 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 6: 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.

Table 3: 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)

4.3 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.

Soil: the main consideration for soil 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 (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'[14].

In agriculture, 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 (C:N ratio). This is particularly true in areas where local conditions mean the straw cannot decompose quickly (Kretschmer *et al*, 2012). However, in other areas of the EU 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.

Forestry soils account for around twice the amount of organic carbon found 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. Like agricultural land, residues (including leaves, branches, bark and stumps) 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[15] species. Changes to harvesting patterns and increases in residue extraction rates can have a negative impact on many of these factors. For example, 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).

---

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

[15] ie relating to dead or decaying wood

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[16] (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.

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 should avoid the majority of such impacts and therefore generally will have a lower 'water footprint'[17] 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.

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.

Biodiversity: less is known about the impacts on biodiversity of the processing pathways for agricultural residues under examination here. 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).

For forest biodiversity, there is a broad 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. 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.

Other environmental issues: the disposal of bio-based materials is potentially a contentious issue. To take bio-plastics for example, some are **biodegradable** whilst others are not. 'Bio-based' simply refers to the use of material from renewable resources, whereas 'biodegradable' refers to biodegradability at

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

[17] See Hoekstra and Chapagain (2007) for a discussion of the water footprint concept.

the end-of-life phase. 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. With a recent study suggesting that composts from mixed waste containing biodegradable plastics may hinder plant growth (Kopec *et al*, 2013), there is a definite need for more research in order for policy to promote the optimal waste management practices for bio-plastics.

Regarding **air quality** impacts there is some evidence of stratospheric ozone depletion associated with bio-based materials compared to their conventional counterparts. However, these are found to largely result from N_2O emissions associated with fertiliser application in the cultivation of crops. This therefore offers a further potential benefit 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).

Finally, any use in biorefineries of toxic chemicals which may have harmful impacts on human health are further aspects that have to be closely monitored (Essel and Carus, 2012).

4.4 Summarising the environmental credentials of bio-based products

The main lessons are as follows:

- It is imperative to maintain monitoring of the situation. The Bioeconomy Observatory proposed by the European Commission could be a useful body to ensure that any future policy stimulus for these technologies is conditional upon firm evidence of positive environmental outcomes.
- Bio-based products, their production, use and disposal, should not be considered automatically sustainable *per se* but should be subject to scrutiny.
- Because strong negative environmental impacts are associated with crop cultivation then using wastes and residues as feedstock should offer comparative benefits. However, these cannot be assured without careful analysis of the impacts on existing uses of the wastes and residues which will be displaced. It is strongly recommended that the use of wastes and residues be accompanied by a set of safeguards to ensure their sustainability.
- Because there are so few commercial plants in operation for advanced biofuels and bio-based materials, robust LCAs for these processes are not yet available.
- However, there is some 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 (Albrecht *et al*, 2010; Hermann *et al*, 2007, Bos *et al*, 2010). This questions the current policy framework that gives significant support to bioenergy but not to other biomass using product pathways.
- A key sustainability concern is 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 into a stronger tool for the promotion of advanced biofuels.

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[18]. 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.

[18] 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 is a summary of the main Strengths, Weaknesses, Opportunities and Threats facing the use of food wastes and crop and forestry residues for material and energy substitution in Europe.

<table>
<tr>
<td>STRENGTHS
• 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.</td>
<td>WEAKNESSES
• 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.</td>
</tr>
<tr>
<td>OPPORTUNITIES
• 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;
• 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).</td>
<td>THREATS
• 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;
• 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.</td>
</tr>
</table>

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 GHG emissions, water, soil and biodiversity compared with 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 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 appropriate policy framework to encourage the optimal development of the use of wastes and residues is treated at greater length in Chapter 5 of the full report. Suffice to say here that it is emphatically *not* recommended that the EU repeats for biomass use in the wider biorefinery sector the mistakes it has made for biofuels policy based on policy mandates and targets. 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 integrated set of objectives and principles for the efficient use of Europe’s bio-resources for food, energy and material use

The final points to be made concern the necessity that environmental safeguards are in place to minimise the risk of over-utilising wastes and residues with resulting long-term damage, particular to soil fertility.

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.

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 would be to extend 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 and bio-based products would be a logical step 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 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.

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 the waste and residues used as raw material in biorefineries 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, it should be seen as reducing uncertainty about necessary environmental performance. This greater predictability of the environmental ground rules should be beneficial for attracting investment and ensuring the long-term viability of the sector. Indeed, given the experience with first generation biofuels, the lack of well-based and understood sustainability criteria are a barrier to the sector's development. There is a chance to overcome this barrier now and to avoid it arising in the case of the wider biorefinery sector.

6 REFERENCES

- Albrecht, J, Carrez, D, Cunningham, P, Daroda, L, Mancia, R, László, M, Raschka, A, Carus, M, Piotrowski, S (2010) *The Knowledge Based Bio-Economy (KBBE) in Europe: Achievements and Challenges*. Full report. Available at: http://sectie.ewi-vlaanderen.be/sites/default/files/documents/KBBE_A4_1_Full%20report_final.pdf.
- Bacovsky, D, Ludwiczek, N, Ognissanto, M, Wörgetter, M (2013) *Status of Advanced Biofuels Demonstration Facilities in 2012*. Report to the IEA Bioenergy Task 39. Available at: http://demoplants.bioenergy2020.eu/files/Demoplants_Report_Final.pdf.
- Bloomberg New Energy Finance [BNEF] (2010) *Next-generation ethanol and biochemicals: what's in it for Europe?* Available at:
- http://www.bioenergy.novozymes.com/files/documents/BNEF_report_nextgeneration_biofuels.pdf.
- Bos, H, Meesters, K, Conijn, S, Corré, W, Patel, M (2010) *Sustainability aspects of biobased applications: Comparison of different crops and products from the sugar platform*. Report 1166, Wageningen UR Food & Biobased Research: Wageningen. Available at: http://edepot.wur.nl/170079.
- Carus, M, Carrez, D, Kaeb, H, Ravenstijn, J and Venus, J (2011) *Level Playing Field for Bio-based Chemistry and Materials*. Nova-Institute Policy paper on Bio-based Economy in the EU, nova-Institut für politische und ökologische Innovation GmbH: Hürth.
- CBD (1992) Convention on Biological Diversity, United Nations.
- Craswell, E T and Lefroy, R D B (2001) The role and function of organic matter in tropical soils. *Nutrient Cycling in Agroecosystems* 61(1-2), 7-18.
- Curry, N and Pillay, P (2011) Biogas prediction and design of a food waste to energy system for the urban environment, *Renewable Energy*, doi:10.1016/j.renene.2011.10.019.
- DBFZ and Oeko-Institut eV (2011) *Environmental impacts of the use of agricultural residues for advanced biofuel production*, commissioned by WWF; unpublished.
- de Jong, E, Higson, A, Walsh, P, Wellisch, M (2012) *Bio-based Chemicals: Value Added Products from Biorefineries*. Report for IEA Bioenergy Task 42 Biorefinieries. Available at: http://www.ieabioenergy.com/LibItem.aspx?id=7311.
- de Wild P J, Reith H and Heeres, H J (2011) Biomass pyrolysis for chemicals. *Biofuels* 2(2), 185-208.
- Detzel, A, Kauertz, B, Derreza-Greeven, C (2013) *Study of the Environmental Impacts of Packagings Made of Biodegradable Plastics*, ifeu – Institut für Energie und Umweltforschung, Heidelberg, Germany. Available at: http://www.umweltdaten.de/publikationen/fpdf-l/4446.pdf.
- EEA (2010) *The European Environment. State and Outlook 2010*, Biodiversity. EEA: Copenhagen.
- EEA (2013). *EU bioenergy potential from a resource‑efficiency perspective*. EEA report N°6/2013, EEA: Copenhagen.
- Eickhout, B (2012) *A strategy for a bio-based economy* (based on a study by Jonna Gjaltema and Femke de Jong), Green European Foundation, Green New Deal Series volume 9. Available at:
- http://gef.eu/uploads/media/A_strategy_for_a_bio-based_economy.pdf.
- Elbersen, B, Startisky, I, Hengeveld, G, Schelhaas, M-J, Naeff, H and Böttcher, H (2012) *Atlas of EU biomass potentials. Deliverable 3.3: Spatially detailed and quantified overview of EU biomass potential taking into account the main criteria determining biomass availability from different sources*. Available at: http://www.biomassfutures.eu/work_packages/WP3%20Supply/D_3_3__Atlas_of_technical_and_economic_biomass_potential_FINAL_Feb_2012.pdf.
- European Commission (2013) *Bio-economy and sustainability: a potential contribution to the Bio-economy Observatory*. European Commission, JRC, Institute for Environment and

Sustainability, Available at: http://publications.jrc.ec.europa.eu/repository/bitstream/111111111/27454/1/lb-na-25743-en-n.pdf.

- European Commission (2012) Innovating for Sustainable Growth: A Bioeconomy for Europe (Communication from the Commission to the European Parliament, the Council, the European Economic and Social Committee and the Committee of the Regions). Brussels, 13.2.2012. COM(2012) 60 final.
- European Commission (2010) Preparatory study on food waste across EU 27. Available at: http://ec.europa.eu/environment/eussd/pdf/bio_foodwaste_report.pdf.
- Essel, R and Carus, M (2012) *Meta Analysis of 30 LCAs, Bio-based plastics convince with high climate protection and low use of fossil resources*, based on: 'Meta-Analyse von Ökobilanzen für bio-basierte Polymere in der Produktion von Proganic', nova Institut GmbH, Hürth, Germany.
- Evans, G (2007) *International Biofuels Strategy Report*. NNFCC: York.
- Evans, G and Smith, C (2012) Biomass to Liquids Technology. In: Sayigh, A (Ed) *Comprehensive Renewable Energy*, Elsevier, Oxford, 155-204.
- E4Tech (2009) *Review of the potential for biofuels in aviation*. Report for the CCC, E4Tech: London.
- Forest Europe, UNECE and FAO (2011) *State of Europe's Forests 2011. Status and Trends in Sustainable Forest Management in Europe*. Ministerial Conference on the Protection of Forests in Europe, Oslo.
- Hansen, K, Stupak, I, Ring, E, Raulund-Rasmussen (2011) The impact of forest management on soil quality. In *Papers on impacts of forest management on environmental services*. Raulund-Rasmussen *et al* (Eds). EFI Technical Report 57, 2011, 56-89.
- Hart K, Allen B, Lindner M, Keenleyside C, Burgess P, Eggers J, Buckwell A (2013) *Land as an Environmental Resource*, Report Prepared for DG Environment, Contract No ENV.B.1/ETU/2011/0029, Institute for European Environmental Policy (IEEP): London.
- Helmisaari H-S and Vanguelova E [Eds] (2012) Proceedings of the Workshop W6.1 Forest bioenergy and soil sustainability at EUROSOIL Congress 2nd July to 6th July 2012, Bari, Italy. Available at: http://www.oecd.org/tad/crp/Forest-Bioenergy-Soil-Sustainability_Proceedings.pdf.
- Hermann, B G, Blok, K and Patel, M K (2007) Producing Bio-Based Bulk Chemicals Using Industrial Biotechnology Saves Energy and Combats Climate Change. *Environmental Science & Technology* 41(22), 7915-7921.
- Hiederer, R, Michéli, E, Durrant, T (2011) *Evaluation of BioSoil Demonstration Project – Soil Data Analysis*. EUR 24729 EN. ISBN 978-92-79-19320-0; DOI:10.2788/56105.
- Hoekstra, A Y, Chapagain, A K (2007) Water footprints of nations: Water use by people as a function of their consumption pattern. *Water Resour Manage* 21, 35-48.
- Holladay, J E, Bozell, J J, White, J F and Johnson, D (2007) *Top Value Added Chemicals from Biomass: Volume II – Results of Screening for Potential Candidates from Biorefinery Lignin*. Report for the US Department of Energy, Available at: http://www1.eere.energy.gov/biomass/pdfs/pnnl-16983.pdf.
- IPCC (2003) *Good Practice Guidance for Land Use, Land-Use Change and Forestry*. Penman *et al* (Eds). Intergovernmental Panel on Climate Change (IPCC). ISBN 4-88788-003-0.
- Jones, A, Panagos, P, Barcelo, S *et al* (2012) *The State of Soil in Europe. A contribution of the JRC to the European Environment Agency's Environment State and Outlook Report – SOER 2010*. Report EUR 25186 EN, European Commission Joint Research Centre: Ispra.
- Keegan, D, Kretschmer, B, Elbersen, B and Panoutsou, C (2013). Cascading Use: A Systematic Approach to Biomass beyond the Energy Sector. *Biofuels, Bioproducts and Biorefining* 7(2), 193–206.

- Kopec, M, Gondek, K and Baran, A (2013) Assessment of respiration activity and ecotoxicity of composts containing biopolymers. *Ecotoxicology and Environmental Safety* 89, 137-142.
- Kretschmer B, Allen B and Hart K (2012) *Mobilising Cereal Straw in the EU to feed Advanced Biofuel Production*. Report produced for Novozymes. Institute for European Environmental Policy (IEEP): London.
- MCPFEE, European Commission, UNECE/FAO (2010) Good practice guidance on the sustainable mobilisation of wood in Europe. 39pp.
- Pawelzik, P, Carus, M, Hotchkiss, J, Narayan, R, Selkec, S, Wellisch, M, Weiss, M, Wicke, B, Patel, M K (2013) Critical aspects in the life cycle assessment (LCA) of bio-based materials – Reviewing methodologies and deriving recommendations. *Resources, Conservation and Recycling* 73, 211–228.
- Rettenmaier, N, Schorb, A, Köppen, S *et al* (2010) *Status of Biomass Resource Assessments* (Version 3). Deliverable 3.6 of the Biomass Energy Europe (BEE) project, IFEU: Heidelberg.
- Scarlat, N, Dallemand, J F and Martinov, M (eds) (2008) *JRC Scientific and Technical Reports - Proceedings of the Workshop 'Cereals straw and agriculture residues for bioenergy in European Union New Member States and Candidate Countries'*, 2 - 3 October 2007, Novi Sad, Serbia.
- Spath, P and Dayton, D (2003) *Preliminary Screening – Technical and Economic Assessment of Synthesis Gas to Fuels and Chemicals with Emphasis on the Potential for Biomass-derived Syngas*, NREL Technical Report NREL/TP-510-34929. Available at: http://www.nrel.gov/docs/fy04osti/34929.pdf.
- Tiessen, H, Cuevas, E et al (1994) The role of soil organic matter in sustaining soil fertility. *Nature* 371(6500), 783-785.
- Turbé, A, De Toni, A, Benito, P, Lavelle, P, Lavelle, P, Ruiz, N, van der Putten, W H, Labouze, E and Mudgal, S (2010) *Soil biodiversity: functions, threats and tools for policy makers*. Bio Intelligence Service, IRD, and NIOO, Report for European Commission (DG Environment).
- Weiss, M, Haufe, J, Carus, M, Brandão, M, Bringezu, S, Hermann, B and Patel, M K (2012) A Review of the Environmental Impacts of Bio-based Materials. *Journal of Industrial Ecology* 16(S1), S169-S181.
- Werpy, T and Petersen, G (2004) *Top Value Added Chemicals from Biomass: Volume I – Results of Screening for Potential Candidates from Sugars and Synthesis Gas*. Report for the US Department of Energy. Available at: http://www1.eere.energy.gov/biomass/pdfs/35523.pdf.
- WWF (2012) *Smart use of Residues – Exploring the factors affecting the sustainable extraction rate of agricultural residues for advanced biofuels*. WWF Briefing Paper by Lübbeke, I and Anderson, J, WWF-World Wide Fund For Nature: Brussels. Available at:
- http://awsassets.panda.org/downloads/wwf_smart_use_finale_version.pdf.

This document summarises the findings and conclusions of the STOA study 'Technology options for feeding 10 billion people - Recycling agriculture, forestry & food wastes and residues for sustainable bioenergy and biomaterials'.

An 'Options brief' related to this study is 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:

This is a publication of the
Directorate for Impact Assessment and European Added Value
Directorate General for Internal Policies, European Parliament

PE 513.513
DOI 10.2861/33312
CAT BA-03-13-493-EN-C
ISBN 978-92-823-4738-6

ISBN 978-92-823-4738-6

9 789282 347386

14769