An assessment of the potential for the establishment of lignocellulosic biorefineries in the UK

Final Report

Reference: UY/PROC/415

E4tech (UK) Ltd for LBNet[1]

04th October 2016

[1] LBNet, a BBSRC Network in Industrial Biotechnology and Bioenergy (BBSRC NIBB)

Table of Contents

List of figures

List of tables

List of acronyms

ABE	Acetone-Butanol-Ethanol
AFEX	Ammonia fibre explosion
AD	Anaerobic digestion
APP	Advanced Plasma Power
APR	Aqueous phase reforming
BBIA	Bio-based and Biodegradable Industries Association
BBSRC	Biotechnology and Biological Sciences Research Council
BDC	Biorenewables Development Centre
BDO	1,4 butanediol
bioSNG	Bio-synthetic natural gas
BMW	Biodegradable municipal waste
BTX	Benzene, toluene, xylene
BTG	Biomass Technology Group
CAGR	Compound annual growth rate
CCC	Climate Change Committee
CHP	Combined heat and power
CNG	Compressed natural gas
CO	Carbon monoxide
CPI	Centre for Process Innovation
C&I	Commercial and Industrial
DECC	Department of Energy and Climate Change
DfT	Department for Transport
DME	Dimethyl ether
EPSRC	Engineering and Physical Sciences Research Council
ETI	Energy Technology Institute
FCC	Fluid catalytic cracking
FDCA	2,5-furandicarboxylic acid
FiT	Feed-in tariff
FT	Fischer-Tropsch
GM	Genetically modified
GSK	GlaxoSmithKline
HDPE	High-density polyethylene
HMF	Hydroxymethylfurfural
3-HPA	3-hydroxyl propionaldehyde
IB	Industrial biotechnology
IBIoIC	Industrial Biotechnology Innovation Centre
IBLF	Industrial Biotechnology Leadership Forum
IEA	International Energy Agency
IP	Intellectual property

LABs	Linear alkyl benzene sulfonate
LC	Lignocellulosic
LCA	Life cycle assessment
LLDPE	Linear low-density polyethylene
MBT	Mechanical biological treatment
MEG	Monoethylene glycol
MTHF	Methyltetrahydrofolate
MSW	Municipal solid waste
NASA	National Aeronautics and Space Administration
NNFCC	National Non-Food Crops Centre
PE	Polyethylene
PEF	Polyethylene furanoate
PET	Polyethylene terephthalate
PF	Phenol formaldehyde
PDO	Propanediol
PHAs	Polyhydroxyalkanoates
PLA	Polylactic acid
PTT	Polytrimethylene terephthalate
PVC	Polyvinyl chloride
RDF	Refuse derived fuel
RHI	Renewable heat incentive
RO	Renewable obligation
SME	Small and medium enterprises
SRC	Short rotation coppice
THF	Tetrahydrofuran
TRL	Technology readiness level
UK	United Kingdom
US(A)	United States (of America)
WGS	Water gas shift

List of units

Unit	**Definition**
ha	hectare
Mha	Million hectare
kg	Kilogram
t	Tonne (metric)
Mt	Million tonne
tpa	Tonnes per annum
ktpa	Kilo tonnes per annum
Mtpa	Million tonnes per annum
MW	Megawatt
MWh	Megawatt hour
Mlpa	Million litres per annum
t/ha/yr	Tonnes per hectare per year

E4tech (UK) Ltd
83 Victoria Street
London SW1H 0HW
United Kingdom
Tel: +44 20 3008 6140
Fax: +44 20 7078 6180

Incorporated in England and Wales
Company no. 4142898
Registered address:
60-62 Old London Road
Kingston upon Thames KT2 6QZ
United Kingdom

www.e4tech.com

Executive Summary

There is a significant opportunity for the UK to tap into a biorefinery products market valued at £262 billion in 2014 and growing at an estimated 14% per annum to 2020. This is coherent with the United Kingdom's greenhouse gas emissions reduction target of 80% by 2050.

Commercial scale solutions are urgently required to decarbonise the economy, especially for the transport sector which accounts for one third of UK greenhouse emissions[2]. Lignocellulosic biofuels produced without detrimental land use change impacts provide a sustainable solution to meeting the demand for liquid transportation fuels whilst reducing carbon emissions. The opportunity to replace liquid fossil fuels with low carbon lignocellulosic biofuels will open broader opportunities for producing renewable chemicals and materials that enable a circular economy and are more sustainable than fossil-based products. The potential scale of this activity provides significant scope for innovation, which the UK is strongly placed to capitalise on through world leading academic and commercial capabilities at lab and pilot scale. Also, the (bio)fuels, chemicals and chemicals-using sector in the UK provide a strong base on which to build commercial scale biorefining activities in the coming years.

In addition to technical capabilities, the establishment of lignocellulosic biorefineries requires available and sustainable feedstocks, viable business models across the entire supply chain, suitable locations with potential for business clustering and downstream users, and a supportive policy framework. This study assessed the potential of four feedstock-specific scenarios for UK biorefineries, which were identified at an LBNet scoping workshop in April 2016. These included the co-location of a lignocellulosic biorefinery with a biomass power station, a straw biorefinery, a municipal waste biorefinery and a dedicated perennial energy crop biorefinery. The report highlights the potential opportunity provided by each scenario, discusses gaps and barriers to realising their potential, and the conditions under which they would be viable. A set of high-level conclusions can be drawn from the assessment of the four scenarios.

Co-location of a biorefinery next to a biomass power station is appealing due to the existing feedstock supply chains, potential scale of operation and integration with existing power generation activities. Commercial competitiveness of this scenario will depend on feedstock costs, and may be challenging as the technology for wood pellet conversion is less mature than for feedstock such as straw, and scales and business models of power generation and biorefining are substantially different.

Straw is an attractive feedstock because conversion technologies are relatively mature and it has a relatively low cost, although the potential for supply may be limited in the UK. Straw is the only feedstock, among the four scenarios, that has been used in commercial scale facilities globally and for which there is a UK lignocellulosic ethanol plant in the design phase. Existing supply chain experience with straw for power generation could be helpful in making use of regional concentrations of this feedstock in the UK.

[2] Including surface transport, aviation and shipping (CCC, 2013)

Producing bio-based products from UK Municipal Solid Waste (MSW) is a favourable scenario with respect to sustainability, feedstock costs and waste policy objectives. A MSW-based biorefinery demonstration plant could support existing UK actors in their path to commercialisation and give the UK a potential competitive advantage in this area. Realising this opportunity will require identifying sites with available and accessible feedstock that is not already contracted to competing uses.

A biorefinery based on perennial crops is attractive from the perspective of having a dedicated feedstock, but poses significant challenges in terms of engaging farmers to grow the crops, establishing dedicated supply chains, and potentially dealing with land use change issues. Overcoming these issues will require careful planning, including finding sufficient land with high yield potential in proximity of the plant, as well as public sector support in establishing the feedstock supply chain. The timescales involved in getting this infrastructure in place are long.

There is already a wide range of biorefinery research and development activities in the UK at lab or pilot scale that can be used to springboard the development of a commercial sector. While continued support of basic and applied research relevant to the area remains important, the sector would benefit from greater emphasis on commercialisation and scale up of activities. Galvanising pre-commercial activity could be achieved through a “UK Biorefinery Demonstration Competition” that would stimulate the UK biorefinery community to address the scale up challenge, potentially in collaboration with international players. Policy that supports the development of sustainable biofuels, biochemical and biomaterials is critically important to encouraging commercial deployment and investment in this sector. Targets discussed for advanced biofuels in the context of the RTFO will send important market signals and additional government support could come from the use of procurement programs along the lines of the US “BioPreferred Program”. Finally, the establishment of a “UK Biorefinery Forum”, that would complement the existing “Industrial Biotechnology Leadership Forum”, would provide a vehicle for biorefinery actors to elaborate activities and actions in support of the sector and set a direction of travel for the UK biorefining sector.

1 Introduction

Biorefining typically refers to the integrated production of materials, chemicals, fuels and energy from biomass or bio-based feedstocks. The focus of this report is specifically lignocellulosic biorefineries, which are those that use lignocellulosic biomass feedstocks such as agricultural and forestry residues, non-food energy crops or solid biogenic waste (see Figure 2-1), and can include biological, chemical and thermochemical conversion processes[3]. This report explores UK opportunities in biorefining by describing the range of options and their relevance to the UK, and by assessing a number of potentially attractive biorefinery scenarios.

The value of the biorefinery scenario is linked to highly efficient extraction, fractionation and conversion processes that convert all portions of the available biomass feedstocks into useful outputs. The drivers for biorefining include the opportunity to diversify feedstock supply, provide products with environmental performance, and possibly technical and economic performance as well, and the opportunity to build an internationally competitive sector. The valorisation of biomass and wastes for the production of materials, chemicals, fuels and energy provides an opportunity to reduce the demand for finite fossil resources, avoiding the negative environmental, price variability and security of supply concerns associated with their use. It also provides an opportunity for economic growth through valuable IP and domestic production.

The global market for biorefinery products was estimated in 2014 at £262 billion[4] and is expected to grow rapidly, at an annual average growth rate of 14%, in the period to 2020 (PRNewswire, 2016). While biological routes have the largest market share at slightly above 50%, thermo-chemical routes are expected to have the largest growth rates in the period to 2020. The US has the largest market share, estimated at 72%. Commercial scale lignocellulosic biorefineries are operational in the US, Canada and Italy for the production of ethanol or methanol as a fuel, and many countries are investing in innovation and pursuing opportunities in the biorefinery area. While certain biorefinery product pathways, or parts thereof, are mature, there is still plenty of innovation possible because of the variety of feedstocks and products. The UK has a strong academic base in the area and some innovative SME activity, and the potential to generate additional value from UK-based IP is substantial.

On the national level, the waste bioeconomy opportunity is being explored by a cross Whitehall working group following a House of Lords report on “Waste or resource? Stimulating a bioeconomy” (House of Lords, 2014). In Scotland, Scottish Enterprise has specifically identified biorefining as an opportunity to build on existing industrial and academic capabilities to improve the competitiveness of industries in Scotland (Scottish Enterprise, 2015). This could be true for the whole of the UK. Innovation is already being supported by Research Councils, InnovateUK and government departments - DfT’s Advanced Biofuels Demonstration Competition is aiming at demonstrating three lignocellulosic biofuel production plants. These include Celtic Renewables’ process to produce n-butanol from whisky production by-products, Nova Pangea’s thermolysis process and Advanced

[3] Feedstocks such as food waste or algae are not included in this report as they are not the focus of the LBNet network, but could in a different context form part of a biorefinery.
[4] Using the average 2014 exchange rate 1 GBP = 1.65 USD

Plasma Power's plasma clean-up process for syngas. But, to benefit from the biorefinery products market will require sustained and growing effort and investment, which need to be targeted at products that are likely to be viable and where the UK can be competitive.

This report reviews the biological and thermo-chemical biorefinery options (Chapter 2) and the market for potentially interesting biorefinery products (Chapter 3), and evaluate four potentially attractive biorefinery scenarios (Chapter 4). The final section (chapter 5) will provide a synthesis and recommendations including the implications for policy makers.

2 Technology assessment

2.1 Introduction

The technology assessment reviews the status of technologies for the conversion of lignocellulosic biomass to valuable fuels and chemicals, and the technical barriers that need to be overcome to progress towards commercial deployment. It discusses key potential products, their development status and highlights related UK capabilities.

For the conversion of lignocellulosic biomass the key technology platforms are illustrated in Figure 2-1. These include pre-treatment of lignocellulose to separate the various components (sugars and lignin), and subsequent conversion of sugars via fermentation or catalytic processes; biomass gasification with subsequent conversion of the syngas via catalysis or syngas fermentation; and biomass pyrolysis and with subsequent conversion and/or upgrading of the pyrolysis products.

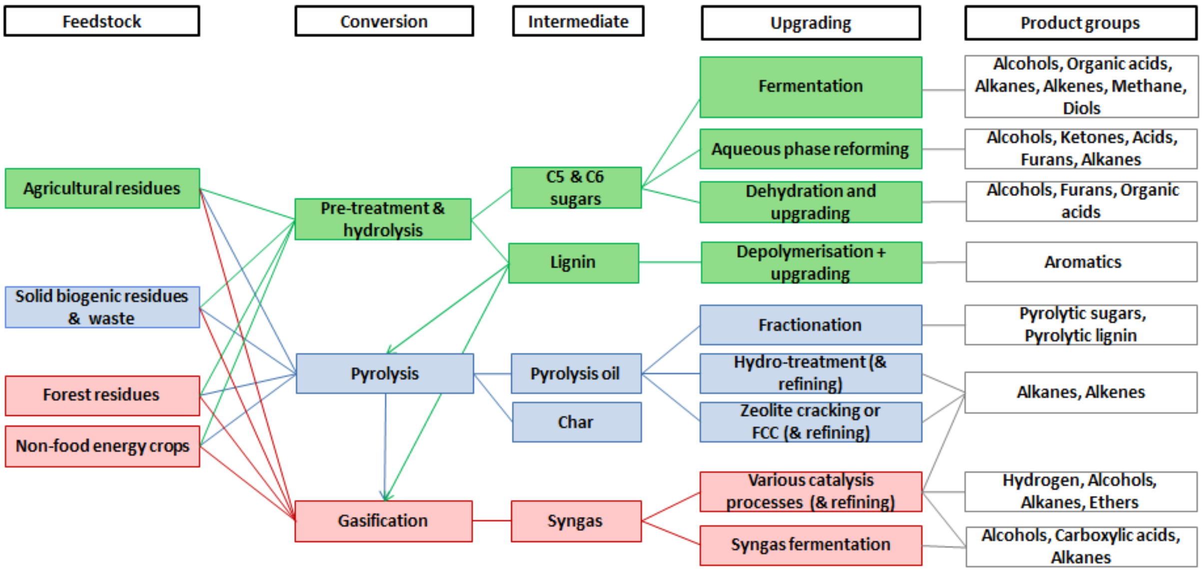


Figure 2-1 Overview of considered feedstock conversion and upgrading technologies

The development status is expressed in terms of the technology readiness level (TRL). TRL was first introduced by NASA, and is a relative measure of the maturity of evolving technologies on a scale of 1 to 9. As shown in Table 2-1, TRL 1 indicates basic research on a new invention or scenario, while TRL 9 represents a fully commercialised technology.

TRL definitions are not necessarily inferred by plant capacity, because of the enormous potential difference in markets. For example, at the same capacity a small demonstration plant in one market could count as a first commercial plant in another. Annual production or production capacity for a specific product is therefore only an indicator for the level of commercialisation.

Table 2-1 TRL definitions
(European Commission, 2014)

TRL	Plant stage	Definition
1	Basic research	Principles postulated and observed but no experimental proof available
2	Technology formulation	Scenario and application have been formulated
3	Applied research	First laboratory tests completed; proof of scenario
4	Small scale prototype	Built in a laboratory environment ("ugly" prototype)
5	Large scale prototype	Tested in intended environment
6	Prototype system	Tested in intended environment close to expected performance
7	Demonstration system	Operating in operational environment at pre-commercial scale
8	First of a kind commercial system	Manufacturing issues solved
9	Full commercial application	Technology available for consumers

2.2 Pre-treatment, hydrolysis and lignin recovery

2.2.1 Technology description

Lignocellulosic biomass may be converted to a very wide range of chemicals via pre-treatment and hydrolysis, and subsequent downstream processing such as fermentation. Lignocellulosic biomass is mostly comprised of three primary components: lignin, hemicellulose, and cellulose. The composition ratios differ by feedstock, but a fairly typical range for each component is shown in Figure 2-2. Due to the integrated chemical structure of lignocellulose the feedstocks must be pre-treated to separate the cellulose (C6 sugars), hemicellulose (C5 and C6 sugars) and lignin (phenols) fractions (Figure 2-2), and then hydrolysed to break down the cellulose and hemicellulose into simple sugars.

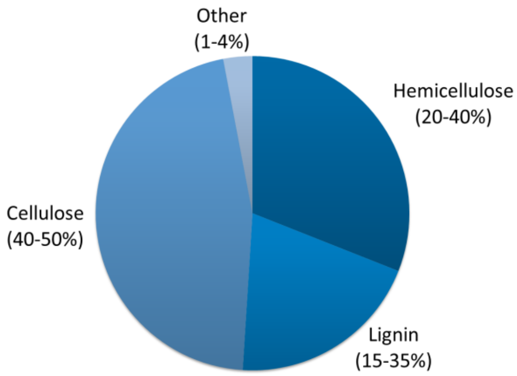


Figure 2-2 Typical composition of woody biomass

Hydrolysis is a process whereby the depolymerisation of the carbohydrate polymers (typically cellulose and varying levels of hemicellulose) produces free sugars. This may be initiated by chemical treatment, typically acid, or by enzymes.

Pre-treatment and hydrolysis are crucial initial steps for both anaerobic and aerobic fermentation pathways as well other catalytic conversion processes. Pre-treatment options include physical/mechanical, chemical, and biological processes, or a combination thereof (Figure 2-3). The most widely used technology currently is steam explosion, followed by enzymatic hydrolysis. The steam explosion decreases the size of the biomass and begins to break down the hemicellulose and lignin. The process has a high energy demand, and leads to the creation of by-products that inhibit downstream fermentation. Other pre-treatment options, which are at varying levels of commercialisation (TRL), are shown in Figure 2-3, and discussed further in the sections below. With the exception of concentrated acid hydrolysis, all pre-treatment technologies require a subsequent hydrolysis step to produce fermentable sugars from the cellulose (together with varying levels of hemicellulose which remain after pre-treatment) (Harmsen *et al*., 2010).

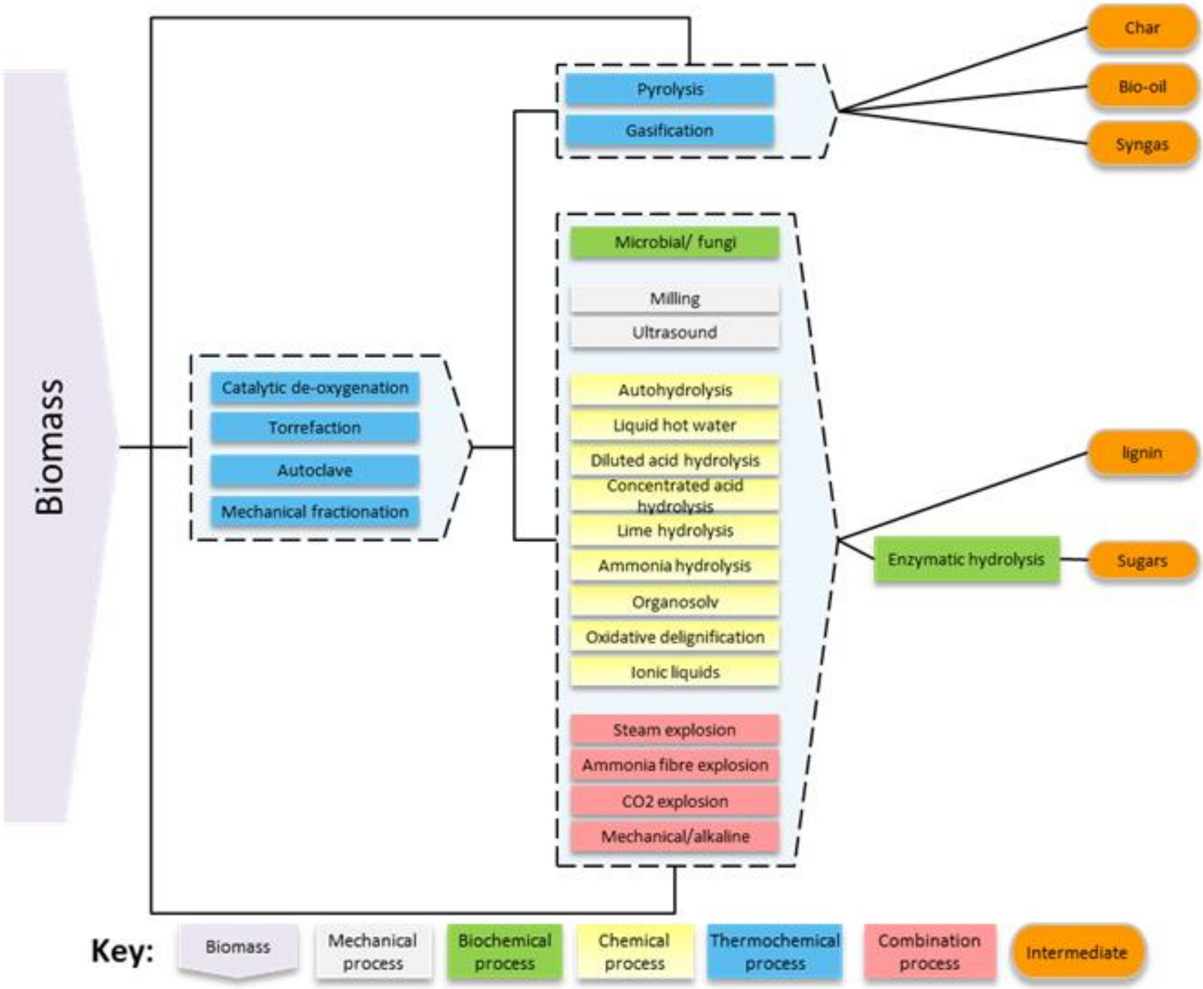


Figure 2-3 Overview of pre-treatment and fractionation processes for biorefinery feedstocks (E4tech *et al*., 2015)

In a biorefinery lignin recovery typically occurs at two points in the process, either following fractionation during pre-treatment or later following carbohydrate conversion. Recovery which occurs late in the process is likely to produce lignin suitable for low-value markets (for example heat and power - as is mostly the case today), while earlier recovery from pre-treatment will likely yield lignin suitable for high-value products (such as aromatics, carbon fibre, plastics and thermoplastic elastomers, polymeric foams and membranes, and fuels).

The structural and chemical features of recovered lignin are important in determining their suitability to specific products and applications. A number of commercial pre-treatments that target lignin separation, and produce high quality lignin streams (so-called technical lignins), have been developed by the pulping industry. However, in a biorefinery a wider range of pre-treatments, which typically focus on extraction of sugars, are used and the impact on the lignin produced varies widely. High value lignin, for example, is obtained from the organosolv process – which yields a sulphur-free high purity lignin with low molecular weight, and also produces residual high-quality cellulose for hydrolysis. Ionic liquid pre-treatment also produces a sulphur-free lignin which retains most of its structural features. Low value lignin is obtained from dilute acid or hydrothermal pre-treatment, which alter the physical and chemical structure of the lignin.

2.2.2 Products

There are different pre-treatment technologies for different feedstocks as well as purposes. Overall, the main outputs of pre-treatment are the individual components of biomass, primarily cellulose, hemicellulose and lignin, followed by hydrolysis of celluloses to produces simple sugars (C6 and C5). Technologies will need to demonstrate value on aspects such as energy, costs, quality and production, and inhibitors, in order to be successful.

2.2.3 Development status

A number of pre-treatment technologies have been developed to pilot, demonstration and first commercial scale. With the exception of concentrated acid hydrolysis, these technologies hydrolyse the hemicellulose to varying degrees, but require additional enzymatic hydrolysis for the cellulose and remaining hemicellulose to produce fermentable sugars. The most notable of these are briefly mentioned below.

- **Steam explosion** (TRL 7-8) is the most common pre-treatment technology in use industrially. Key industry players using this process include Abengoa (USA, commercial-scale plant on hold due to restructuring), and BetaRenewables (Italy, world's first commercial-scale advanced ethanol plant). The technology is licensed by Biochemtex to other companies under the name PROESA. Also using this are Inbicon, BioGasol, and Andritz.
- **Dilute acid** pre-treatment (TRL 7-8) is also used by a number of companies, including Blue Sugars (USA, ethanol demonstration plant), Cobalt Technologies in cooperation with Rhodia and Andritz (Brazil, building a demonstration plant), and POET-DSM (USA, commercial-scale plant). SEKAB and Iogen also use this pre-treatment.
- DuPont (Danisco) applies **alkaline** pre-treatment (TRL 5-7) for their biomass pre-treatment at their first commercial plant in Nevada, Iowa, which produces ethanol from lignocellulosic biomass (corn stover).
- Inbicon in Denmark produces ethanol from straw by **autohydrolysis** (TRL 4-6) at demonstration scale.
- **Organosolv** (TRL 4-6) is used by Chempolis (Finland, demonstration scale), CIMV (France, pilot plant), Lignol (Canada, pilot plant) and Bio-Sep (UK, pilot plant).
- Several companies are in the process of commercialising **concentrated acid hydrolysis** (TRL 4-5), including Virdia (demonstrated at pilot scale), and Weyland (Norway, pilot scale). TNO, the Dutch organisation for Applied Scientific Research, and BlueFire also use strong acid pre-treatment.
- Other pre-treatment options are at a lower TRL: AFEX (TRL 3-5), supercritical pre-treatment (TRL 2-4), ionic liquid pre-treatment (TRL 2-3), and microbial/fungi pre-treatment (TRL 3-4).

2.2.4 Technical barriers to development and deployment

The pre-treatment and hydrolysis that is often required to process lignocellulosic feedstocks is one of the most expensive processing steps in the conversion process, and the delignification of raw material is a technically difficult task.

Technical challenges in existing pre-treatment processes include **inadequate separation of cellulose and lignin** - which decreases cellulose accessibility and the efficacy of subsequent hydrolysis, **high use of chemicals and/or energy**, and **high costs** for enzymes and capital costs – which limit scale-up.

Further, many pre-treatment pathways are **developed for a specific feedstock**, and both pre-treatment conditions and enzymes may require modification for use with an alternative lignocellulosic feedstock.

In hydrolysis, aqueous acids often **destroy many of the unlocked sugars** in the process (Lin & Tanaka, 2006). Dilute acid hydrolysis takes place at high temperatures, which may lead to the **creation of inhibitors** that negatively impact the downstream fermentation process (Chiaramonti *et al*., 2012). **High enzyme costs**, which make up a significant part of overall production costs, present a further challenge, but have fallen markedly in recent years as dosage requirements and pre-treatment techniques improve, and lignocellulose enzyme production moves towards commercial scale.

Research and demonstration activities are focused on converting biomass into its constituents in a market competitive and environmentally sustainable way. Table 2-2 provides a summary of the barriers and development needs of major pre-treatment pathways for lignocellulosic biomass. A relative comparison between the barriers is not made here, however the TRL of the technology provides an indication of how limiting these barriers may be.

Table 2-2 Barriers and needs for lignocellulosic biomass pre-treatment technologies
(adapted from E4tech *et al*., 2015; Harmsen *et al*., 2010; Garcia *et al*., 2014)

Pre-treatment	Key barriers	Development needs
Steam explosion *(TRL 7-8)*	Often catalyst needed to optimise pre-treatment Formation of inhibitors and toxic compounds	Development of new catalysts Developing microorganisms more tolerant to inhibitors
Dilute acid pre-treatment *(TRL 7-8)*	Degradation by-products (salts) and inhibitors Corrosion	Developing microorganisms more tolerant to inhibitors Reducing intensity of pretreatment New enzyme developments
Alkaline pre-treatment (e.g. dilute ammonia, NaOH, lime) *(TRL 5-7)*	Residue formation Need to recycle chemicals Enzyme adjustment needed	New enzyme development Recovery and reuse of chemicals
Concentrated acid hydrolysis *(TRL 4-5)*	High chemical use and capex Corrosion and toxic hazard Degradation by-products (salts) and inhibitors	Recovery and reuse of chemicals Developing new catalysts More tolerant microorganisms
Auto-catalysis/ hydrothermal *(TRL 4-6)*	Higher operating temperature Inhibitor formation	Develop methods to add value to lignin
Organosolv treatment *(TRL 4-6)*	High capital and operating costs Solvent may inhibit cell growth	Develop methods to add value to lignin Recovery and reuse of chemicals

Pre-treatment	Key barriers	Development needs
Ammonia Fibre Explosion (AFEX) ***(TRL 3-5)***	High cost due to solvent	Recovery and reuse of chemicals
Supercritical (CO_2) pre-treatment ***(TRL 2-4)***	Does not affect lignin and hemicelluloses Very high pressure, high capex	Develop methods to add value to lignin Improve process technology
Ionic liquids ***(TRL 2-3)***	Expensive technology and recovery required	Develop methods to add value to lignin Recovery and reuse of chemicals Develop process technology
Microbial/fungi ***(TRL 3-4)***	Time consuming Some saccharide losses	Development of robust microorganisms
Mechanical milling	High energy consumption Poor sugar yields	Process integration, combine with mild chemical treatments

Overall lignin separation technology is no longer a key technical challenge, however it is important to note that the differing lignin levels of feedstocks, and thus lignin produced by the various processes (which impacts lignin structure), means that their suitability for various markets and applications depend strongly on their structure-related properties.

2.2.5 UK capabilities

The UK has a handful of industrial actors developing pre-treatment and hydrolysis technologies. **Plaxica**, based in Wilton, have developed a pre-treatment to accompany their proprietary Versalac technology, to transform industrial waste sugar streams for downstream processing (Plaxica, 2016). They have also developed an extractive hydrolysis technology which they have tested continuously for 3,500 hours at pilot scale and plan to scale-up to commercial scale of around 70-80 ktpa (Marshall, 2016, pers. comm., 23 August). **Advanced Extraction Technology Ltd**, based in East Yorkshire, is developing their sub-critical water technology, as a replacement for organic solvents, to treat waste material from existing biofuel manufacturing processes as well as other sources of waste biomass such as agricultural residues (AET, 2016). Plant capacity is unknown, but it is estimated that this technology is at lab-scale. **Wilson Bio-Chemical**, previously Wilson Steam Storage, specialise in steam-treatment to breakdown biogenic materials through their autoclave technology. They are also looking at various lab-based process engineering and systems biology projects to hone the initial autoclaving process and optimise enzymes for use in the fermentation stage (Wilson, 2016). **Bio-Sep**, based in Melton Mowbray, has developed a modular ultrasonic organosolv process applicable for the fractionation of a wide range of lignocellulosic feedstocks. This technology is at pilot plant scale, but has been modelled to processing capacity up to 50 ktpa (Bio-Sep, 2016). There also appears to be relevant market demand for further technology development. For example, pharmaceutical giant **GSK** is working with Scotland's Industrial Biotechnology Innovation Centre (IBioIC) to generate fermentable sugars from locally available waste streams such as timber waste. GSK will use this sugar to replace corn-based glucose in their processes, and burn remaining plant material to produce heat and electricity for the site (Altenergymag, 2016).

The UK also has a strong focus on academic and industrial collaborations to provide proof of scenario and overcome technical barriers to commercialisation. Some examples of this include (LBNet, 2016a; LBNet, 2016b):

- **Fiberight | University of Southampton**: Improve the yield of sugar obtained from the use of enzymes for MSW. Enhancing enzymatic hydrolysis.
- **Johnson Matthey | University of York**: Developing processing alternatives for conversion of poppy straw into valuable products. The academic team will optimise the pre-treatment and hydrolysis, while the industrial partner will explore catalytic conversion alternatives.
- **SERE-Tech Innovation | University of York**: Looking at the potential for pre-treatment with ultrasonic equipment, focussing on for pre-treatment of straw for ethanol production.
- **Croda | University of Bath**: Project aiming to develop a pilot scale multi-product biorefinery by coupling a recently developed one-step microwave process for the depolymerisation of bio-wastes with Metschnikowia pulcherrima yeast to produce 2-phenylethanol, arabinitol and lipids.
- **Advanced Microwave Technologies | University of Edinburgh**: Develop a novel pre-treatment to break down lignin using microwaves and enzymes, increasing the amount of aromatic feedstock chemicals from the lignin without reducing fermentable sugars. They are testing this process with Scottish Sikta Spruce.
- **Biome Technologies | Imperial College London**: Investigating conversion yields and biocompatibility of ionic liquids as solvents for carbohydrates, to produce bio-based polymers.
- **Novozymes** is also working with several UK companies and universities on enzymes.

2.2.6 Summary

The development of pre-treatment and hydrolysis technology is essential to the production of lignocellulosic sugar-based biofuels and bio-based chemicals. There are multiple options, at different stages of development, the most advanced of which is steam explosion. The UK has a small but developing SME community focused on the development of pre-treatment technologies, particularly those at early TRL levels such as organosolv and ionic liquids. Many of these SMEs are also working on collaborations with UK universities to leverage their research expertise and overcome the most important technical barriers. The success of these technologies (and partnerships) could be vital to the long-term competitiveness of a local value chain, as they provide the first key step to downstream technology developers looking at fermentation.

The presence of organisations that support these SMEs in their development is also important. Notably the Centre for Process Innovation (CPI), the Biorenewables Development Centre (BDC) and the Industrial Biotechnology Innovation Centre (IBioiC) are supporting a number of SMEs mentioned in this report (not only in pre-treatment) to scale-up their technologies and overcome key technical and non-technical barriers. Such initiatives contribute to the UKs competitive position and are critical to maintain.

2.3 Fermentation

2.3.1 Technology description

The most common biochemical conversion process is the microbial fermentation of sugars to produce alcohols, organic acids, alkenes and lipids, using yeast, bacteria or fungi. Products may be produced extracell, where they are separated from the fermentation broth, or intracell, where products must be extracted from the cells. There are several types of process integration (depending on which sugars are used), which then differ for downstream processing and are modified according to technology requires.

2.3.2 Products

A list of primary products that may be directly produced from the microbial fermentation of sugars is shown Figure 2-4. In many cases the primary product is of commercial interest, but it is also possible to produce a wider range of bio-based chemicals and polymers by further transformation, often by established chemical process. Figure 2-4 is shown only as a summary, and further details about the market are found in *Chapter 3 Market assessment*.

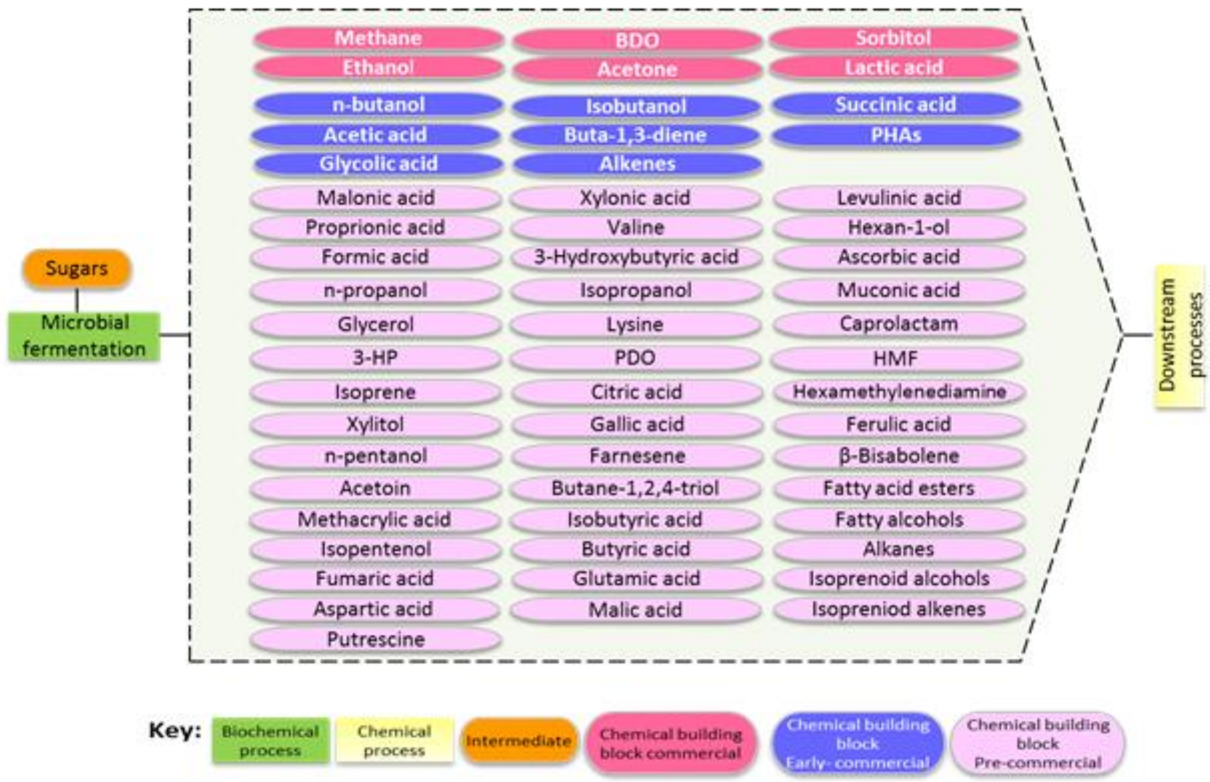


Figure 2-4 Primary products from the microbial fermentation of sugars
(E4tech *et al.*, 2015)

2.3.3 Development status

There is a significant range of TRLs across the various fermentation products (see *Chapter 3 Market Assessment*). However, at present the most widely used fermentation product is ethanol, which is commercially available. Other commercially available fermentation products include BDO, sorbitol, methane, acetone and lactic acid. Products such as n-butanol, a high profile liquid biofuel and chemical building block, butanol, and succinic acid, are in early commercialisation. It is important to note however that **very few of these products are currently produced from lignocellulosic sugars**.

Globally there are multiple first-of-a-kind commercial scale **lignocellulosic ethanol** plants (TRL 8), many of which have recently become operational or are ramping up to full scale operation. These include Beta Renewables in Italy (60 ktpa), GranBio (64 ktpa) in Brazil, Shangdong Longlive (50 ktpa) in China, and Poet-DSM (60 ktpa) and DuPont (90 ktpa) in the USA. Smaller demonstration scale plants include Clariant in Germany (1 ktpa) and Fiberight, who have an MSW-based demo plant (0.3 ktpa), but have shelved plans for converting a mothballed ethanol plant in Blairsville, USA, focussing instead on using the waste for biogas for CNG. It plans to resume ethanol plans in future. These plants currently use the lignin they produce for power (and/or heat), but are considering the potential for lignin-derived chemicals (such as aromatics, terephatalic acid and phenols) in future (Beta Renewables, 2013).

Bio-based basic and speciality chemicals include established products with a history of bio-based production (such as citric acid), recently introduced products (such as succinic acid), and products currently in the demonstration or pilot stage of development (such as FDCA). An analysis of these shows that those with the highest TRL (such as lactic acid, acetic acid, itaconic acid etc.) have a strong manufacturing presence in Asia (typically China), whereas most R&D and pilot plants (for products such as 3-HPA, adipic acid, malic acid etc.) are located in Europe and North America. The majority of commercial production and R&D currently utilise starch or sugar derived from sugar and starch crops.

2.3.4 Technical barriers to development and deployment

The fermentation process can be initiated by either yeast or bacteria. A number of technology challenges are common across fermentation processes - including **insufficient concentration of solids** for fermentation, **microorganism toxicity effects**, **increasing desired end product yields** from the fermentation broth, and **lowering energy demand** during product separation. Inhibitory substances (such as acetic acid and furans) produced during pre-treatment strongly inhibit growth and fermentation performance, and present a significant hurdle for large-scale lignocellulose-based bioprocessing (Unrean, 2016). The removal of inhibitors (by physical or chemical means) adds significant additional cost to the overall process, increases water usage and separation energy, and causes loss of sugars (Liu and Blaschek, 2010). The use of inhibitor-tolerant microorganisms in the fermentation or optimising the process to minimize inhibitory effects is required to improve process efficiency. Thus, greater engineering of microorganisms to improve selectivity, tolerance to inhibitors or minimisation of inhibitory effects, and yield represent necessary areas for innovation – but due to metabolic constraints improvements are difficult.

Creating an integrated fermentation and downstream separation process and technology options (e.g. advanced reactors with “in-situ” product removal) could also present a means to increase yields and reduce capital costs. The product separation stage (e.g. distillation) typically has a significant energy demand, in order to accommodate purity requirements for downstream processes. Separation techniques which have lower energy requirements or may be more effective at separation are in development but require further demonstration and upscaling to prepare for commercial application. Cost effective separation remains a key challenge.

2.3.5 UK capabilities

Europe and the US have a number of key industry players operating or planning pilot, demonstration and first commercial plants for a range of lignocellulosic biofuels and biochemicals. The UK has **no lignocellulosic ethanol demonstration or commercial plants** under development, but does however have (lignocellulosic) n-butanol developers. **Green Biologics**, headquartered in Abingdon, is developing the Clostridium microbial strains for use with lignocellulosic biomass. They are currently repurposing a 62 ktpa corn ethanol plant to produce n-butanol and acetone, and have secured distribution agreements with Texas-based Nexeo Solutions and Acme-Hardesty. Green Biologics are also part of the ButaNexT project which is focussing on biobutanol from lignocellulosic feedstocks. **Butamax** produces butanol from sugars and starches, and is planning lignocellulosic plants in future. They were operating a demonstration facility in Hull, however this has been mothballed. Scottish-based **Celtic Renewables** produce butanol from whisky production by-products (draff and pot ale), but have no known plans to use lignocellulosic biomass.

Fiberight, together with the Centre for Process Innovation (CPI), have also initiated a joint project to further develop Fiberight's waste to sugar technology, with the aim of eventually rolling out a string of UK plants, including Teesside.

Biocatalysis and microbial development is fundamental for many processes and products using or derived from biological feedstocks, and has the potential to help the UK to further advance in R&D through to manufacturing. **CHAIN Biotechnology** has developed a unique fermentation technology platform for Clostridium, for a wide range of biotechnology applications (CHAINBiotech, 2016). As part of the Innovate UK IB Catalyst Late Stage feasibility project, **ReBio Technologies** is demonstrating performance of proprietary Geobacillus technology on sugars derived from landfill waste (CPI, 2015). Key biocatalysis and process development actors include **Ingenza,** focused on microbial strain improvement, synthetic biology, fermentation and bioprocess development, and **C-Tech Innovation**, working on biocatalysis and microbial processes for conversion of biomass to biofuels (such as hydrogen, methane and butanol).

Biocatalysis and synthetic biology is also an area with a strong academic base, including the Centre of Excellence for Biocatalysis, Biotransformations and Biocatalytic Manufacture (CoEBio3) based at the University of Manchester, The Centre for Bioactive Chemistry at Durham University, and The Green Chemistry Centre of Excellence at York University.

There are further **strong collaborations between industry and academics in the UK**. A large consortium of industrial actors - **Lucite International, Green Biologics, CPI, Ingenza** and **Chain Biotechnologies**, and academic actors - **University of Nottingham, University College London**, and **University of Cambridge** are working on an IB Catalyst funded project, ConBioChem. The project aims to produce a continuous fermentation process to provide stable and robust production microbes, a balance between microbe and product generation, new manufacturing processes and process controls that select for high-level production. Several other industrial players have partnered with academic institutions through the IB Catalyst programme, which has been vital for sector development, for example **Marlow Food** and **Heriot-Watt University**, **ReBio Technologies** and the

University of Bath, and **GSK** and the **University of Strathclyde**. These projects cover a range of topics from lab-scale development of new products from fermentation processes to optimising the yield and use of by-products from established industrial processes. **GSK**, in an IBioIC-funded project, is working with the **University of Edinburgh** on a project that aims to use synthetic biology principles to develop a new biochemical route to an important starting material for antibiotics manufacture using biocatalysis and metabolic engineering (IBioIC, 2016b).

2.3.6 Summary

The use of fermentation for ethanol production is a well-established commercial process, now applied to lignocellulosic sugars. Other advanced biofuels and bio-based chemicals, particularly butanol, remain at an earlier level of technology readiness and still face significant technical and non-technical challenges.

Figure 2-4 shows the broad range of products available from fermentation, and highlights the opportunity for the UK to further develop any number of these based on existing industry and academic capabilities. Together with this opportunity, the UK has a number of competitive aspects upon which to capitalise and build global competitiveness. There are existing fermentation technology developers, such as Green Biologics, Butanext, Celtic Renewables, Fiberight and recent acquisition Itaconix. Key products already under development by these developers include n-butanol, isobutanol, lactic acid and itaconic acid. There are already existing UK-based chemical companies making use of biorefinery products, such as PLA. There is world-class expertise in microorganisms, biocatalysis and synthetic biology, with companies such as CHAIN Biotechnology, ReBio Technologies, Ingenza and C-Tech Innovation. And, the UK has a strong academic and science base, and universities such as Manchester, Durham and York have dedicated biocatalysis, synthetic biology and fermentation centres working together with industrial actors to overcome technical barriers associated with the development of biofuels and bio-based chemicals. Companies such as Green Biologics, Celtic Renewables and CHAIN Biotechnology are key examples of successful commercial spin-outs from academic research. These strengths provide a good base for demonstration and further product development. However, more investment is needed to move these technologies to commercialisation via demonstration projects. For example, a biorefinery equivalent of the DfT £25 million Advanced Biofuel Demonstration Competition which aims to support the development of a domestic advanced biofuel industry.

2.4 Catalytic conversion of sugars

There are a number of chemical (e.g. acid dehydration of xylose to furfural) and thermochemical (e.g. aqueous phase reforming to BTX and a mix of other ketones, furans, acids and paraffins) processes which may be used to convert sugars (mainly C5 and C6) to liquid biofuels and biochemicals. The main technologies considered in this section are the dehydration to furfural process, and aqueous phase reforming – as these two processes are the most developed at present.

2.4.1 Technology description

Dehydration (to furfurals) and upgrading

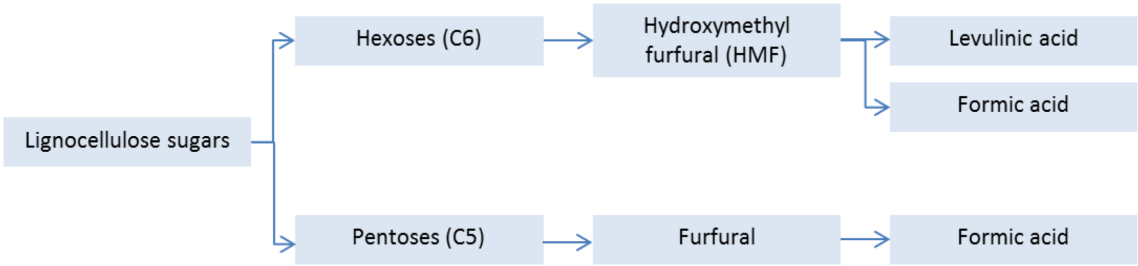


Figure 2-5 Acid-catalysed dehydration of sugars to new products

Hydroxymethylfurfural (HMF) is a key intermediate biochemical, and so-called 'sleeping giant[5], and is produced through a dehydration reaction from hexose. The production of HMF is generally more efficient and selective from ketoses (e.g. fructose) rather than aldoses (e.g. glucose) (Wang *et al.*, 2012). Both reactions are complex and include a number of side-reactions such as isomerization, dehydration, fragmentation, and condensation – which play a significant role in the selectivity of HMF. The reaction primarily uses acid catalysts, such as mineral acids, heterogeneous acids, and salts. A similar dehydration process with pentoses yields furfural. In furfural production, aqueous-acid/mineral acid catalytic solutions have been primarily used to date, however environmental and health concerns, low yields and poor selectivity have led to research of other options (such as bi-phasic[6] or autocatalytic[7] systems) (Dashtban *et al.*, 2012; Machado *et al.*, 2016). Typical recovery rates, for crop residue feedstocks, are relatively low (E4tech *et al.*, 2015). However, recent advancements (such as SupraYield) have shown furfural yields of 50 – 70% (Dashtban *et al.*, 2012).

Furfurals show high chemical functionality and reactivity - making them relatively simple to catalytically upgrade to a variety of value-added products (Davda *et al.*, 2005). For example, through catalytic hydrogenation HMF and furfural can be upgraded to 2,5-dimethylfuran and other liquid alkanes – many of which have high octane numbers and good miscibility with gasoline (Centi *et al.*, 2011). Levulinic acid, produced from HMF, is a valuable platform chemical because it can react as both a carboxylic acid and a ketone – allowing for a wide array of downstream derivatives (including tetrahydrofuran, succinic acid, and methyltetrahydrofuran). Other key downstream products include formic acid, biodiesel components, chemicals, and monomers for polymers.

Perhaps the most well-known example of the above is the **Biofine process** – originally developed by Biofine Inc., and also used today by GFBiochemicals. This two stage process uses a novel dual reactor design, which facilitates high throughput and high yields to produce levulinic acid, and by-product formic acid, as well as tars and a carbon-rich char mixture that can be further processed or used elsewhere. While there are also fermentation processes for the production of levulinic acid, the chemical process is more commercially developed.

[5] Furanics are often referred to as 'sleeping giants' due to their significant potential, as intermediate chemicals, for the production of bio-based plastics and chemicals (IEA, 2013).
[6] Aqueous biphasic / two-phase systems are alternatives for traditional organic-water solvent extraction systems. They occur when certain solutes cause an aqueous solution to fully separate into two aqueous phases
[7] In autocatalysis, the chemical reaction is catalysed by one of its products (i.e. a product is also a reactant)

Aqueous phase reforming to hydrocarbons and hydrogen

Aqueous phase reforming (APR) is a thermochemical catalytic process that produces hydrocarbons (typically light alkanes) and hydrogen from biomass-derived sugars and polyols (such as sugar alcohols). The process takes place at relatively mild conditions (typically 200 - 260°C, and 10-50 bar) (Fernanda Neira D'Angelo, 2014) using a heterogeneous catalyst, and in aqueous or liquid phase. The low process temperatures reduce the energy requirements of the process considerably, and also reduce undesirable side reactions. Further, the liquid conditions mean that there is no need to remove water from the feedstocks – again reducing cost and energy input.

To date the process has focused primarily on the production of hydrogen, due to advantages over other hydrogen producing methods (such as reduced energy requirements, improved chemical safety, decreased CO production, etc.). Alkanes are produced as a by-product of this process, however the process can be modified (via feedstock selection, catalyst composition, reaction conditions, and reactor design) (Davda *et al*., 2005) to favour alkane production. The APR and catalytic process for hydrocarbon production is shown in the figure below.

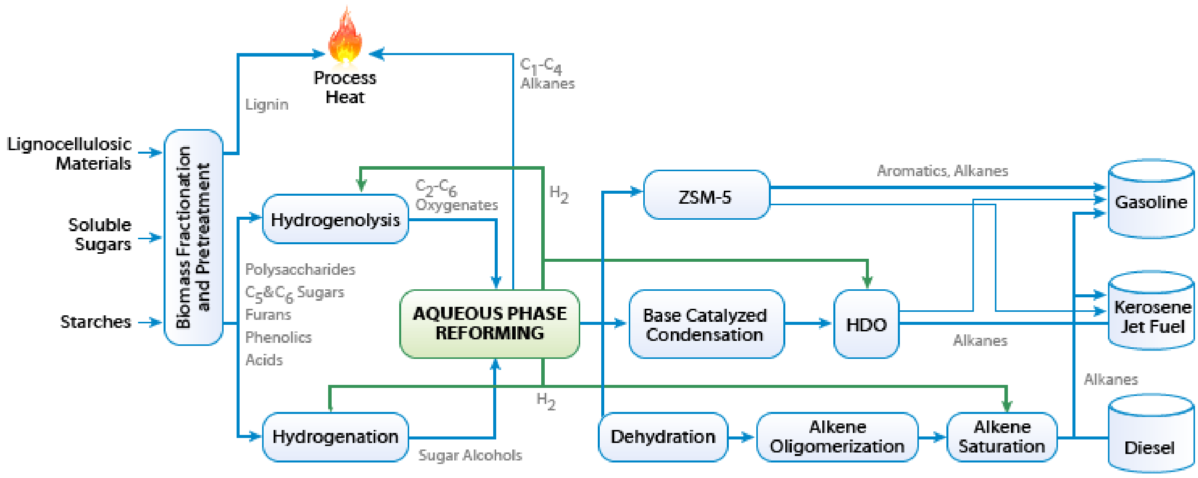


Figure 2-6 Catalysis of lignocellulosic sugars
(NABC, 2011)

There is also research ongoing around one pot[8] acid hydrolysis and APR (to produce hydrogen).

The predominant APR process currently available is Virent's **BioForming**® technology, which combines APR with catalytic processing (similar to petroleum refining) to produce drop-in gasoline, diesel, jet fuel and aromatic chemicals (such as bio-paraxylene, a building block for bio-polyester). Virent, now a subsidiary of Tesoro, has a 30 tpa pilot plant for drop-in fuels, together with a 25 tpa demonstration plant and a 10 tpa bio-paraxylene demonstration plant in Madison, USA (Lerner, 2015; Virent, 2010). Virent has formed a strategic consortium, including UK-based Johnson Matthey, for the commercialisation of their BioForming technology (Virent, 2016).

[8] Single /one pot synthesis is where several chemical reactions take place in a single reactor

Catalytic hydrodeoxygenation to liquid alkanes

Recent developments have shown that it is possible to convert raw woody biomass directly to liquid alkanes, in a high yield process. Using a multifunctional catalyst[9], cellulose, hemicellulose and lignin fractions in solid woods were converted into hexane, pentane, and alkylcyclohexanes respectively (Xia *et al*., 2016). This process requires no feedstock pre-treatment, which could result in significant energy savings. Other similar research is ongoing for other single phase mediums and catalysts (Matson *et al*., 2011). No industrial activity is taking place yet.

Direct conversion of cellulose to hexitols

Another research-stage novel route is the catalytic conversion of cellulose to hexitols (such as sorbitol, mannitol etc.). In this process hydrolysis of cellulose and subsequent hydrogenation of glucose takes place in a single pot to produce hexitols. This serves to simplify the reaction process and increase product yields due to increased stability. Research is underway looking at homogeneous catalysts (Wang *et al*., 2016), and heterogeneous and bi-functional catalysts (Song *et al*., 2015; Pang *et al*., 2012), as well as the reaction conditions to increase yield (Xie & Gathergood, 2012).

2.4.2 Products

There are many fuels, chemicals and polymers which are possible end products for lignocellulosic chemical pathways. A few notable products are shown in the table below. Many of these are platform chemicals, and applications include a broad range from polymers, polyesters and polyurethanes, to food, fragrances, cosmetics, agricultural products, solvents, and fuel additives.

Table 2-3 Potential products from chemical processing of lignocellulosic sugars

Feedstock	Potential products
C6 sugars	HMF, levulinic acid, formic acid, sorbitol, glucaric acid, 2,5-FDCA, THF, MTHF
C5 sugars	Furfural, levulinic acid

2.4.3 Development status

Dehydration (to furfurals) and upgrading

Currently China, South Africa, and the Dominican Republic are the major producers of furfural and its derivatives. Using agricultural residues as feedstock, over 300 ktpa is produced between them. The market is expected to increase to around 490 ktpa in 2021 (BCC Research, 2016). Commercial producers in these countries include over 200 companies in China, Illovo Sugar (South Africa), and Central Romana (Dominican Republic).

There are a number of actors and projects globally producing HMF and levulinic acid:

- The **Biofine** process, developed by Biofine Inc. (later Biofine Renewables LLC), operated a pilot facility in Maine, USA and an industrial-scale facility in southern Italy. It is unclear whether this is still in operation.
- **GFBiochemicals** is operating the world's largest commercial-scale levulinic acid plant in Caserta, Italy. Commercial-scale production began in 2015 (using starch feedstock) at 2 ktpa (2/3 of the

[9] Pt/NbOPO4

world production capacity), with plans to scale up to full capacity of 10 ktpa by 2017. Levulinic acid could replace fossil-based phthalate plasticisers (as demand increases for renewable, phthalate-free plasticisers) with a global demand of 6 Mtpa in 2012 (FMI, 2016; ICIS, 2012). GFBiochemicals full scale plant would represent 0.2% of this demand. They also aim to switch to cellulose-based feedstock in 2016.

- US-based green chemistry firm **Segetis** was recently acquired by GFBiochemicals. Segetis' technology focused on conversion of levulinic acid into intermediates and speciality chemicals used in fragrances, cleaners, plasticisers, acrylate polymers etc. The company operates a biobased levulinic acid pilot plant in Minnesota.
- **Bio-on** has announced a collaboration with sugar company Eridania Italia to produce levulinic acid from sugar by-products, using a novel fermentation technology.
- **Avantium** operates a furanics pilot plant based on their YXY platform to produce methyl levulinate, FDCA and PEF, in the Netherlands. The plant has a capacity of 40 tpa.
- **CIMV** operates a pilot lignocellulosic biorefinery in France, which fractionates the components of wheat straw. Hemicelluloses are converted to xylitol, furfural, and furfuryl alcohol, cellulose to bleached pulp, and lignin to resins and adhesives.
- **Corbion Purac** has developed a 2-step process for FDCA production, which entails chemical dehydration of C6 sugars to HMF, followed by a biotransformation of HMF to FDCA.
- **AVA Biochem** is producing HMF at its demonstration Biochem-1 facility in Muttenz, Switzerland with a production capacity of 20 tpa.

Aqueous phase reforming to hydrocarbons and hydrogen

- **Virent** operates a 30 tpa demonstration plant in Madison, USA to produce drop-in fuels from conventional and lignocellulosic feedstocks, as well as a 25 tpa demonstration plant and a 10 tpa bio-paraxylene demonstration plant. Virent are working closely with The Coca-Cola Company on bio-based polyethylene terephthalate (PET) for plastic bottles.
- **BTG** is a consortium partner in the European Commission funded SusFuelCat[10] project, which is focusing on catalysis and process optimisation for aqueous phase reforming of biomass to hydrogen (or a hydrogen alkane combination).
- **Shell** operates a 30 tpa pilot plant in Houston, USA to produce drop-in biofuels using technology licenced from Virent. The plant is focused on testing non-food feedstocks.

2.4.4 Technical barriers to development and deployment

There are a number of technical barriers and development needs which are specific to products, however in general catalytic conversion of sugars is **challenged by the purity of lignocellulosic sugars** used in processing, which is impacted not only by inherent biomass composition but also pre-treatment. Sugar purification technologies, such as chromatography, have high costs that may be unfeasible for scale-up. A high quality sugar stream is required to improve selectivity and reduce by-products, and to enhance catalysis and prevent catalyst poisoning. Moreover, **new catalyst developments for improved selectivity and lower inhibitor impacts** are also necessary. The optimisation of reactor designs will also go a long way to reducing costs and improving yields.

[10] Sustainable fuel production by aqueous phase reforming – understanding catalysis and hydrothermal stability of carbon supported noble metals

Dehydration (to furfurals) and upgrading

Important technical challenges to commercialisation are focussed predominantly on reducing unwanted by-products, purities and improved separation and purification techniques, together with catalyst improvement (selectivity, cost and recyclability). The key barriers for each product are listed in Table 2-4.

Table 2-4 Barriers and needs for lignocellulosic biomass catalytic dehydration technologies (adapted from E4tech *et al*., 2015)

Product	Barriers	Development needs
Levulinic acid *(TRL 6-8)*	Unwanted salts, humins deposition Equipment acid corrosion Difficult to recycle catalysts 5-HMF instable intermediate	Improve or develop new separation and purification techniques Improve production economics
Furfural *(TRL 6-7)*	Expensive to remove impurities (in particular humins), other alcohols and organic acids Further process optimisation needed	Improve or develop new separation and purification techniques
HMF *(TRL 3-5)*	Expensive catalysts, toxic solvents, high pressure, costly extraction Low yields, decomposes to levulinic & formic acid	Develop ways of stabilise the product Improve or develop new separation and purification techniques Develop new catalysts for glucose dehydration

Aqueous phase reforming to hydrocarbons and hydrogen

Catalyst challenges, shown in the table below, are a key barrier to commercial aqueous phase reforming. While catalyst choice is very specific to the desired product (for example hydrogen versus alkanes) selectivity (especially to liquid hydrocarbons) is a challenge, together with catalyst tolerance and poisoning during liquid phase, and catalyst durability and lifetime. Catalyst innovation is required to address these challenges, as well as reduce costs for scale-up. Further challenges to scale-up include improved (multiphase) reactor design, and process issues such as design and heat integration (BCIWG, 2011; Wei *et al*., 2014).

Table 2-5 Barriers and needs for lignocellulosic biomass aqueous phase reforming technology (adapted from E4tech & TUHH, 2016)

Barriers	Development needs
Low selectivity to liquid hydrocarbons – current production has large gaseous yields and wide range of aromatics	Improve selectivity to desired product
Catalyst lifetime is short due to deactivation and coking	New or optimised catalysts with higher lifetimes at given process conditions

Barriers	Development needs
Very limited testing and low yields when using lignocellulosic sugars (C5 sugars), due to less homogeneous feedstock and impurities introduced from the LC biomass pre-treatment	Adaptation of the catalysts to improve tolerance and conversion of C5 structures

2.4.5 UK capabilities

Biome Bioplastics is undertaking a feasibility study on the production of polyesters from HMF using straw feedstocks (Kovacs-Schreiner, 2015).

Plaxica have developed a chemical-based technology, Versalac, to produce lactic acid. Another technology, Optipure, produces low cost polymer-grade D-lactic acid and L-lactic acid, which may be used in the production of PLA. Due to the low cost of oil, together with difficulty sourcing adequate feedstocks, Plaxica has placed their Versalac technology on hold, and are focussing instead on their extractive hydrolysis technology which they have tested continuously for 3,500 hours at pilot scale and plan to scale-up to around 70-80 ktpa. Their target market also falls largely outside of Europe, and they are in the process of licensing their technology to large overseas customers from 2017/18. However, they continue to develop their lactic acid technologies with the aim of reintroducing these in future (Marshall, 2016, pers. comm., 23 August). The UK however, does have several chemical companies which actively source PLA: Paragon Print & Packaging, Lake Chemicals & Minerals, Amcor Food Packaging, and Sidaplax. Further expansion of this market pull could create an opportunity for UK-based supply of lactic acid and PLA, however this is already a competitive market globally.

Johnson Matthey PLC, a speciality chemicals company, is a consortium partner in the EC funded SusFuelCat (SusFuelCat, 2016) project (discussed under Development status). They have also recently announced a strategic consortium with Virent for the commercialisation of their BioForming technology (Virent, 2016). Their globally renowned catalysis knowledge and expertise provides an important supply chain platform for the UK.

Based on funding received from organisations such as LBNet[11], BBSRC, and Innovate UK, a few academic and industrial collaborations, to provide proof of scenario and overcome technical barriers to commercialisation, include the following. This list is not exhaustive, but provides relevant examples of active collaboration:

- **Fiberight | Aston University**: As part of InnovateUK's IB Catalyst Late Stage feasibility project, Fiberight are working with Aston University to produce of levulinic acid using heterogeneous catalysts (CPI, 2015).
- **Biome Technologies | University of Liverpool; University of York**: Explores the manufacture of aromatic chemicals from cellulose to be converted into bioplastics and tested.
- **BASF| University of Huddersfield**: The collaboration worked on the development of a biocatalytic manufacturing process for the production of bio-acrylamide. BASF operate bio-acrylamide production facility in Bradford.

[11] LBNet is funded by the BBSRC

- **Circa Group| University of Huddersfield, University of York**: Developed the process for the production of a bio-solvent, Cyrene, from a cellulosic feedstock.

2.4.6 Summary

There are a number of chemical and thermo-chemical processes which may be used to convert C5 and C6 sugars to liquid biofuels and biochemicals. The dehydration to furfural process and aqueous phase reforming are some of the most developed at present. The production of HMF and FDCA, so-called 'sleeping giants' of bio-based chemicals, are currently underway by a number of global companies such as Avantium, Ava Biochem and Corbion. There has been no major UK competition in this space, however Biome Bioplastics is working at lab scale on the production of HMF and downstream polyesters. Other companies developing other catalytic conversion chemicals include Plaxica, who are operating a pilot plant in Wilton, and Johnson Matthey and Fiberight (together with Aston University). Johnson Matthey is also working together with Virent to commercialise production of BioForming ® technology (to produce bio-paraxylene), which they will market and licence out together. The UK has a strong catalysis base, both in academia at universities such as York, Liverpool and Huddersfield, and with industry players such as Johnson Matthey and Velocys, upon which to call for development of a biorefinery.

2.5 Valorisation of lignin

Lignin is a complex amorphous heteropolymer, which to date has been used primarily in low grade fuel (heat and power) applications due to its ease of use in gasification. It is a key by-product of the pulping industry, and also increasingly produced by 2nd generation bioethanol production. Many of the conversion processes to produce fuels and high value chemical products are focused on doing so from cellulose/hemicellulose derivatives, however there is an opportunity for biorefineries to make better use of lignin in chemicals, fuels and materials to replace oil-based equivalents. Indeed, the advent of lignocellulosic biorefineries will produce more lignin than is required by the plant's heat and power demands, thus there is increasing focus on the role of lignin in additional value-added products to fully utilise technical lignin resources.

2.5.1 Technology description

Lignin may be valorised to various high-value products, including aromatics (BTX, phenols), polymers and other materials. Broadly speaking the value-added uses for lignin are for materials, as a drop-in fuel feedstock, and high-value chemicals. Typical routes for lignin valorisation are shown in Figure 2-7. However, because of the highly heterogeneous and complex properties of different technical lignins, there is no "one-size-fits-all" solution for catalytic downstream processing (Rinaldi *et al.*, 2016).

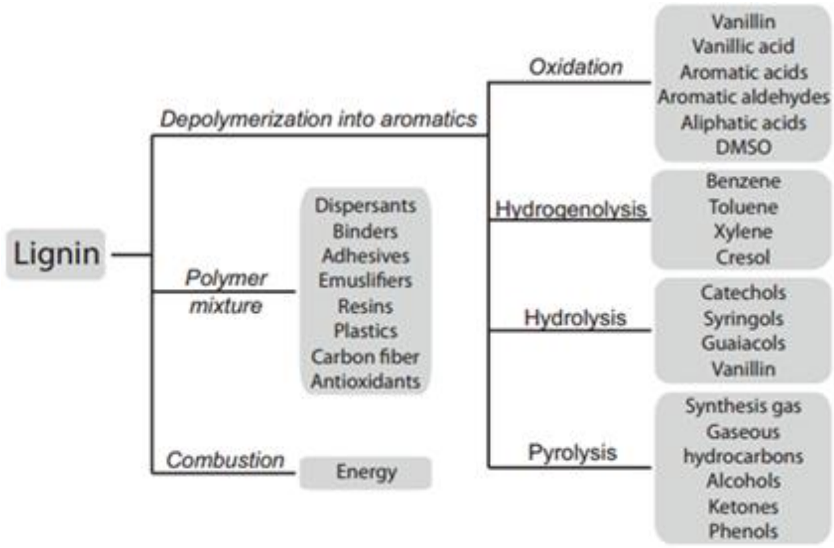


Figure 2-7 Potential routes for lignin valorisation and corresponding products
(adapted from Werhan, 2013)

Given the aromatic nature of lignin the production of aromatic chemicals via depolymerisation is a key focus of lignin valorisation. Lignin depolymerisation is possible via a number of established methods, which can be broadly classified based on the severity and selectivity of the processes. Multiple strategies for depolymerisation and upgrading are possible, including thermochemical treatments, biological depolymerisation, and homogeneous and heterogeneous catalysis (Ragauskas *et al*., 2014). “Mild” depolymerisation pathways (oxidative, reductive and redox-neutral) use highly selective reagents and catalysts while “harsh” procedures utilise concurrent thermal and catalytic reactions.

The selectivity of catalysts determines the aromatic-derived substrates for conversion (Linger *et al*., 2014). For example, the simplest products – BTX mixtures – typically use transition metal catalysts in hydrogenolysis and hydrodeoxygenation upgrading. Oxidative processes to produce aromatic acids and aldehydes for example, typically use oxidative fungal and bacterial enzymes. Other catalysts include homogeneous and heterogeneous alkaline catalysts.

For some material applications, it is required that the technical lignin properties (macroscopic or microscopic) are able to forego major treatment, although some physical or chemical treatment may be introduced. Thus no further depolymerisation is required and processing is simpler (Rinaldi *et al*., 2016). Catalytic pyrolysis and upgrading is covered in section 2.6.

2.5.2 Products

Lignin is well suited, in the short term, to gasification processes. However, it is also potentially suited to a number of value-added applications. In particular, lignin is particularly suited to aromatic building blocks and due to its intrinsic aromatic structure – replacement of petroaromatics, as well as various polymers (Strassberger *et al*., 2014). Lignosulphonates are used in many applications (such as cement, polymers and resins), but to date vanillin is the only chemical commercially produced. These and other potential applications are shown in the Table 2-6.

Table 2-6 Lignin products and application
(adapted from VTT, 2016)

Product	End use
Aromatics (including BTX - benzene, toluene, xylene)	Flavouring agent (e.g. vanillin), aromatic aldehydes, syringaldehyde Various petrochemical products LABs – surfactants, cosmetics
Phenol formaldehyde (PF) resins	Mainly wood adhesives, moulding compounds, laminates, insulation
Polymers (e.g. polyurethanes)	Foams, elastomers, paints, adhesives
Polymers (e.g. thermoplastic composites)	Plastic composites, coatings, carbon fibre, hot melt adhesives, asphalt
Surface active agents	Dispersants, emulsifiers, detergents & foaming agents
Fuels	

2.5.3 Development status

Lignin depolymerisation and valorisation also has links to a number of biofuel actors. Most notable of these is **Borregaard**, who operate a commercial scale advanced biorefinery in Norway. The biomass feedstock is separated into cellulose, which is converted to 2G bioethanol, and lignosulphonates, which are converted to vanillin. Borregaard are also developing their BALI technology at a demonstration plant (Biorefinery Demo), focussing on conversion of bio-based lignin products and sugars to bioethanol and advanced biochemicals. **Biochemtex**, in partnership with Valmet, recently announced a project to combine LignoBoost lignin extraction technology with Moghi (patented technology which converts lignin into biofuels and biochemicals), for the production of bio-based PET[12] (Valmet, 2016).

There are also a number of research partnerships which are complete or underway, and provide a key proving ground for future technology commercialisation. These include LigniVal (part of BioRefine 2007-2011) – which aimed to develop methods to modify lignin and other aromatic process side-stream components into materials applicable for composites, coating adhesives and barriers, LIBRA (Biocore) – which is looking at a viable valorisation route for lignin from lignocellulosic-based industries, and CatchBio, BioValue, EuroBioRefand SupraBio amongst others.

2.5.4 Technical barriers to development and deployment

Lignin depolymerisation and valorisation have a number of key challenges to address, many of which are based on the structural features of technical lignin. The first of these is analytics and the characterisation of lignin. Lignin is diverse and highly heterogeneous (there are no repetitive bonding patterns or repetitive units), and thus the nature of lignin carbohydrate linkages is not completely understood. Moreover, current degradation analytics techniques are often laborious to perform, subject to errors and accompanied by a high degree of uncertainty, and produce results of questionable value (Crestini, n.d.). These analytical problems, together with the heterogeneity of

[12] Polyethylene terephthalate – a thermoplastic polymer

lignin chemical structure and morphology itself, means that current quantitative characterisation still presents a technical barrier to more widespread use of lignin.

The second challenge is that of processing. Due to their heterogeneous structure, technical lignins often exhibit unexpected behaviour and may display poor levels of desired reactivity. Depolymerisation (to oligomers and monomers), and the use of enzymes, is applied to improve reactivity (Vishtal & Kraslawski, 2011). There is a strong focus on reactor development, in particular combining the reaction and separation steps of processing. Further technological progress is also required on the different catalytic steps, in order to obtain a selective and clean final product following lignin depolymerisation and valorisation. In particular, catalytic steps that require further improvement include dealkylation and hydrodeoxygenation. Hydrodeoxygenation often incurs catalyst deactivation, which is driven by high coke formation, hydrothermal instability and catalyst sintering (Ragauskas *et al.*, 2014). New catalysts, as with other technologies, that are suited to lignocellulosic biomass feedstocks are required. However, upstream pre-treatment, which may impart impurities to the lignin stream, also plays a role in catalyst stability and lifetime (Rinaldi *et al.*, 2016).

Finally, hydrocracking, hydrodealkylation and hydrodeoxygenation processing steps all utilise significant volumes of hydrogen, which is typically from a non-renewable source.

2.5.5 UK capabilities

Apart from **Biome Bioplastics**, there are no industrial actors in lignin valorisation in the UK. However, there are strong academic capabilities and research groups at universities, notably the Department of Chemical Engineering at Imperial College London, University of Warwick, University of York and University of Dundee (LBNet, 2016a; LBNet, 2016b). Biome Technologies has partnered with the University of Warwick’s Centre for Biotechnology and Biorefining to explore the use of novel lignin-degrading bacteria and enzymes to extract aromatic feedstock chemicals for the production of bioplastics (Biome Bioplastics, n.d.).

2.5.6 Summary

Lignin is produced in significant quantities by the paper and pulping industries, and use of it is already well established albeit for largely low value applications. However, the burgeoning biofuel and biochemical industry, which looks increasingly towards lignocellulosic feedstocks will also produce large volumes of lignin and look to create maximum value from this. The use of lignin valorisation in cellulosic biorefineries faces technical challenges both upstream and downstream, many caused by the heterogeneous and complex nature of lignin. These challenges are being tackled by academia and industry, and a number of significant research projects, such as that between Biome Technologies and the University of Warwick, are underway. While the use of lignin from biofuels and chemicals is not yet commercial, development is underway by global players such as Borregaard and Biochemtex. The UK has with Biome Plastics one industrial actor in lignin valorisation and Imperial College London, the University of York, Warwick, and Dundee have academic capability in the field.

2.6 Pyrolysis platforms

2.6.1 Technology description

Pyrolysis produces a liquid bio-oil, a mixture of syngas and charcoal, through a thermal decomposition in the absence of oxygen at around 500°C (IEA Bioenergy Task 34, 2012). Two types of pyrolysis can be distinguished based on different residence times in the pyrolysis reactor: fast and slow. The liquid, gas and solid fractions are different in the two pyrolysis types. In the former, the bio-oil fraction is maximised to be used in power, heating or upgraded to transport fuels. In the latter, the production of bio-char is maximised to substitute solid biomass or coal. Bio-oil provides more opportunities for a biorefinery than the other outputs used in power or heating; we will therefore focus on fast pyrolysis and the upgrading of bio-oil.

Outputs

Fast pyrolysis produces gases which are then condensed to pyrolysis or bio-oil, a dark brown viscous liquid. Pyrolysis oil can be used in some heat and power applications and gasification directly, but upgrading is required for more advanced heat and power applications and transport fuels as well as chemical building blocks due to high acidity, viscosity and other unfavourable characteristics (Stevens, 2009). Using pyrolysis oil in gasification reduces the clean-up requirements of the syngas as alkali metals are retained in the char and tars are reduced (Bridgewater, 2009). Besides upgrading, pyrolysis oil could be fractionated to separate it into pyrolytic lignin, pyrolytic sugars and a watery phase containing smaller organic components (BTG, 2016).

Scale

Current and planned commercial scale plants are in the range of 20 to 40 Mlpa (EMPYRO, 2015; Ensyn, 2016). Besides the large plants, pyrolysis has the option to be built at small scale near the feedstock, as a pre-treatment and densification option followed by upgrading in a larger scale plant.

Upgrading

The choice of upgrading technology determines the end product. Both hydrotreatment and zeolite cracking are followed by refining processes and thus conventional refinery products while the gasification of pyrolysis oil leads the range of syngas products discussed in section 2.7. Besides gasification, pyrolysis oil can either be upgraded through integration into a conventional oil refinery, or in a standalone upgrading process. The two most common upgrading steps are hydrotreatment (or hydrocracking) and catalytic processes (zeolite cracking or fluid catalytic cracking (FCC). The hydrotreating step uses a catalyst at high pressure to remove oxygen through reacting with hydrogen as water and catalytic processes use a catalyst to reject oxygen as CO_2 (Bridgewater, 2011). Both can be integrated into a conventional refinery or be operated in a standalone process. A stand-alone facility can be optimised for pyrolysis oil characteristics while the integration into a conventional oil refinery allows an operation at large scale while benefiting from lower capex. The other main process is using pyrolysis oil in a gasification plant as discussed in section 2.7. Pyrolysis biorefineries could thus be co-located next to conventional biorefineries, for example in the Humber area in the UK.

2.6.2 Products

Pyrolysis oil fractionation produces pyrolytic lignin, pyrolytic sugars for fermentation (to ethanol for example) as well as organic acids and mono-phenolics (BTG, 2016). These could be upgraded or sold to chemical companies who use intermediate chemicals. The upgrading process can lead to gasoline, diesel, kerosene or naphtha or the range of gasification products as described in section 2.7.2.

2.6.3 Development status

Current production capacity of fast pyrolysis is still limited and three companies are operating a fast pyrolysis plant at early commercial stage (TRL 7-8): Ensyn in Canada, Fortum in Finland and BTG in the Netherlands (Karatzos *et al.*, 2014; Lehto *et al*., 2014). Ensyn is constructing another 38 Mlpa project in Quebec, which besides providing pyrolysis oil to the heating markets will also provide feedstock for refineries, and is planning another two plants in Brazil and in Georgia, USA (Ensyn, 2016). The BTG EMPYRO project is operational in the Netherlands, aiming to produce 20 Mlpa and the pyrolysis oil is used for heating (EMPYRO, 2015). The Fortum project in Finland is operational since late 2013, but is only targeting heating markets (Fortum, 2016). BTG are however piloting several upgrading steps such as fractionation, hydrotreatment and gasification which would be interesting for a biorefinery.

Nova Pangaea Technologies is another player that fractionates lignocellulosic materials through a pyrolysis process producing lignin and pyrolysis oil. They are currently operating a pilot plant at 160 tpa and constructing a 8000 tpa[13] biomass input demonstration facility in Teesside (NovaPangea, 2016).

A few other companies have, due to limited uptake markets, economic and technical difficulties stopped their operations. These include KiOR in the US, Dynamotive in Canada and Pyrogrot in Sweden (NER300, 2014; Mufson, 2014).

Upgrading

Pyrolysis upgrading technology to produce transport fuels or chemical building blocks is taking longer to scale up looking at the development over the last five years. However, a few companies and academics are working on this process. The main actor looking at pyrolysis oil upgrading is Envergent, a joint-venture of Ensyn and Honeywell UOP (Envergent, 2016). In the UK Future Blends is working on fast pyrolysis and upgrading, but currently only at small pilot scale. Overall, upgrading projects are currently only at the pilot to small demonstrations stage, TRL 4-5, and would require significant additional funding and development to overcome the technical barriers mentioned in the next chapter and reach commercial scale (Carbon Trust, 2016).

2.6.4 Technical barriers to development and deployment

As several early commercial plants producing pyrolysis oil for heat and power applications are in operation, most technical barriers relate to the upgrading process, the quality of the pyrolysis oil impacting the upgrading and improving yields of pyrolysis oil:

[13] Assuming to be 8000h operational per year.

- The yields of pyrolysis oil are strongly impacted by feedstock ash; an optimisation of the process is required to reduce feedstock ash, increase yields and thus improve economics
- Pyrolysis oil is unstable, has high viscosity, acidity and water content, characteristics that make downstream processing very challenging. This is being addressed by technologies for pyrolysis oil stabilization, such physical separation as developed by Aston University and NREL and the separation of acetic acid in the EMPYRO project (IRENA, 2016)
- Further barriers relate to catalysts being deactivated through pyrolysis oil with high water and oxygen contents, low lifetime, stability and high cost of catalysts
- Using pyrolysis oil in conventional refining requires the removal of significant amounts of oxygen which has been tested by Ensyn in collaboration with Petrobras in a fluid catalytic cracking (FCC) process (IRENA, 2016).

2.6.5 UK capabilities

The UK has strong capabilities in pyrolysis; however the focus has been on producing pyrolysis oil. Apart from pilot scale work of Future Blends (and possibly Cynar) the UK does not have any actors working on pyrolysis oil upgrading to advanced biofuels or chemical building blocks and all large fast pyrolysis plants are outside the UK.

Cynar developed a technology that recycles end-of-life plastic waste into low sulphur diesel, kerosene and light oil, but the current status of their operations is unclear. Future Blends is developing a technology to produce biofuels and biochemicals through fast pyrolysis (PYNE, 2015). The company was set up under the auspices of the Carbon Trust Pyrolysis Challenge and has 2 operating rigs at pilot scale near Oxford.

Several technologies utilising waste to generate energy through pyrolysis are also available in the UK. Torftech operate a pilot plant capable of running in both pyrolysis and gasification modes. Feed trials have been conducted for a range of renewable and waste feedstocks including; waste wood chip, straw, sewage sludge and refuse derived fuel (RDF) (PYNE, 2015). 2G BioPOWER is currently developing a project in the UK to convert used tires into renewable oil and carbon black that will be re-used in rubber goods manufacture. There are a number of companies in the UK focusing on producing bio-liquids from waste. The focus lies however on the heat and power market rather than an integrated biorefinery (PYNE, 2015).

2.6.6 Summary

Fast pyrolysis to produce a liquid bio-oil as main output can be used as a cleaner input in the gasification process, be fractionated into pyrolytic lignin and sugars, upgraded in a standalone process or through integration into a conventional oil refinery. The pre-treatment has the advantage of lower contaminant levels and higher syngas quality, but comes at a significant additional cost. Integration into a conventional oil refinery brings the advantage of large scale and using existing infrastructure, but an efficient integration still represents a major barrier. However, while fast pyrolysis is at early commercial scale, the upgrading step is currently only demonstrated at lab scale, taking longer than expected to scale up and would require at least another 10 years to reach commercial viability. The quality of the pyrolysis oil makes downstream processing currently very difficult and its high water and oxygen contents often deactivate catalysts which already have a low lifetime and high cost.

The situation looks very similar in the UK with capabilities on fast pyrolysis, but very limited activity on the upgrading side. However, all commercial scale fast pyrolysis plants are outside the UK.

2.7 Gasification

2.7.1 Technology description

Biomass gasification and upgrading can represent an alternative thermochemical-route for a biorefinery to the biological routes described above. It is a process in which a biomass material or solid waste is converted into synthesis gas (also known as syngas), by being subject to elevated temperature and pressure. The main components of the 'syngas' are hydrogen and carbon monoxide, usually with smaller amounts of nitrogen, carbon dioxide, methane, other hydrocarbons and tars, organic compounds and metallic contaminants. The feedstock composition and gasification conditions mainly influence the proportions of these species. After any required cleaning and conditioning steps, syngas can then be used to produce heat, electrical power and/or a range of chemicals, including liquid and gaseous fuels. For chemicals, liquid or gaseous fuels, the end product is produced through catalytic conversion or syngas fermentation. The specific syngas clean-up and conditioning step requirements are determined by the energy conversion process, end product and are strongly influenced by the type of gasifier. A wide variety of feedstocks can be used in gasification, but the gasifier as well as the upgrading technology needs to be adapted to each feedstock as it influences the syngas quality and might harm the catalyst. Depending on the gasifier type (and excluding fixed bed gasifiers) the size can range from around 0.01 Mtpa to 2 Mtpa of feedstock input[14].

Syngas upgrading technologies

The four main catalytic conversion routes, methane synthesis, Fischer-Tropsch synthesis, methanol synthesis and mixed alcohol synthesis all share many similarities, including suitable gasifier types, syngas quality requirements and only differ significantly in the final synthesis step (and hence the resulting end products). Dimethyl ether can be produced through upgrading of methanol and hydrogen through a water-gas-shift reaction (WGS). In the catalytic conversion step, the hydrogen (H_2) and carbon monoxide (CO) in the syngas are reacted over a catalyst to form various hydrocarbon chains of different lengths. The type of catalysts, pressure and temperature conditions vary with each catalysis reaction. An upgrading step after the catalysis is often needed to recycle unused syngas and take out any other unwanted components to purify the desired end product.

Syngas fermentation is very different to the catalytic conversion routes. Syngas is anaerobically fermented by micro-organisms into ethanol or other products, before product upgrading. Other alcohols or organic acids could also be produced, for example butanol and acetate. In contrast to catalytic conversion, syngas quality requirements are much less strict, economies of scale are different due to the fermentation step, and the fuel production step relies on low temperature and pressure biological processes.

[14] Assuming 8000h of operation and pellets with an LHV of 17.1 GJ/t as feedstock.

2.7.2 Products

Based on the catalytic conversion upgrading the following products can currently be produced: hydrogen, methane, methanol, DME, diesel, gasoline, aviation fuels, and naphtha, and a mixed range of C2-C6 range of alcohols. Syngas fermentation can lead to a variety of products from low carbon fuels to commodity chemicals, specialty chemicals and single cell proteins. Current commercial-scale processes are focused on the production of ethanol. Ongoing research is targeting a range of products including higher alcohols, ketones, and diols, organic acids, alkenes, and amines (C1Net, 2016). Other target molecules include fatty acids, terpenoids, aromatic compounds, polyhydroxyalkanoates (PHAs), and medium to long chain alkanes.

2.7.3 Development status

The development status discussion below focuses on gasification projects that produce chemicals or fuels. Even though a handful of developers already offer commercial biomass gasification in the power and heat markets, industrial experience with biofuel and chemical applications is at a much earlier stage. The status of the gasifiers is included in the catalytic conversion or syngas fermentation description.

Catalytic conversion

A large variety of catalytic processes exist and catalysts are proven in a fossil fuel context, but using catalysts with biomass derived syngas is not proven. Enerkem is the only commercial-scale plant (TRL 8), at 100 ktpa waste input, operating a catalytic conversion process based on a commercially available catalyst using solid waste derived syngas (Lane, 2014). The current status of several other catalytic conversion plants using biomass derived syngas is at lower TRL levels or is unclear, e.g. E.ON bioSNG plant in Sweden. The GoBiGas project in Sweden producing methane is operational with interruptions since 2014 and can be evaluated at TRL 6-7 (Goeteborg Energi, 2015). Two first-of-a-kind commercial-scale FT plants are currently in the planning stage in the US, one by Fulcrum Biofuels at 38 Mlpa Nevada using MSW feedstocks and one by Red Rock Biofuels at 61 Mlpa in Nevada using woody feedstocks (Fletcher, 2015; Flagship ventures, 2015). However, given no commercial operation FT-Diesel synthesis is only at TRL 5-6. Only the Enerkem technology could be implemented in a UK biorefinery today to produce methanol, other upgrading technologies require further development.

Syngas fermentation

There are currently two developers working on syngas fermentation routes, Ineos Bio and Lanzatech. Lanzatech have so far focused on the conversion of steel mill waste gases (not syngas), with pre-commercial activities in China, rather than using lignocellulosic feedstocks. Ineos Bio has constructed a first commercial-scale plant in Florida, gasifying MSW and palm fronds. Calaysta, a UK/US-based company, works on the fermentation of methane (rather than syngas) at a demonstration scale of 10 ktpa (Calysta, 2016). Based on the commercial-scale demonstration plant operated by Ineos Bio the TRL can be estimated at 7-8.

2.7.4 Technical barriers to development and deployment

Technical barriers relate to the gasification, catalytic conversion and syngas fermentation stage and can be very technology specific given the variety of gasifiers, catalytic conversion technologies and syngas fermentation options.

For the gasifier high quality, homogeneous feedstocks are required by the more established gasification systems in order to operate reliably and efficiently. A homogenous pellet feedstock could be well suited for example. In general, this could be overcome either through biomass feedstock specifications, or gasifiers such as plasma gasifiers designed to handle heterogeneous feedstocks such as waste, or pre-treatment technologies such as fast-pyrolysis to improve feedstock quality (IRENA, 2016). A high quality syngas is required by most downstream processes, and therefore the raw syngas must be cleaned. High level of tars can clog heat transfer equipment and pipes when they condense during cooling processes and inhibit syngas fermentation (IRENA, 2016). This can lead to failure of equipment as well as reduced efficiency.

For the catalytic conversion (apart from syngas to methanol), one of the main barriers is the poisoning and inhibition of catalysts as well as their high costs and short lifetime. New catalyst materials, structures and production methods and process intensification are being trialled to improve catalyst performance (IRENA, 2016). Scaling down the catalytic conversion process to a suitable size for a biomass supply chain such as energy crops or wheat straw with limited feedstock supply would represent another challenge.

One of the main technical barriers of syngas fermentation is the inhibition of fermentation organisms by the fermentation products which requires that the process is carried out at high dilution leading to higher energy consumption in the product recovery. In addition, other bacteria can disrupt the syngas fermentation too, impacting yields (IRENA, 2016).

2.7.5 UK capabilities

With Advanced Plasma Power the UK has one significant player on gasification and a number of smaller scale companies operating in the biomass gasification field, currently mainly with a focus on syngas use in heat and power. Most activity in the UK on catalytic conversion of syngas is currently focused on hydrogen and methane outputs both using Advanced Plasma Power Technology. Since 2016 Advanced Plasma Power operates a pilot plant in Swindon (APP, 2015). The Gasplasma process produces hydrogen-rich syngas which could be refined through a water-gas shift reaction to obtain pure hydrogen (APP, 2016). In the second project APP works with National Grid, Progressive Energy and Carbotech. They have been awarded funding to build a bioSNG demonstration plant using 7.500 tpa of RDF (WMW, 2015; National Grid, 2015). Another larger scale catalytic conversion project, the Tees Valley 49MW one with AlterNRG plasma gasifiers[15], was mothballed by Air Products in April 2016 as they discontinue their waste to energy business due to design and operational challenges (Air Products, 2016). Globally, methanol catalysis is most advanced in comparison to other catalytic upgrading technologies, but no activities are taking place in the UK. Advanced Plasma Power would be a UK company that could form an important part of a MSW based biorefinery using gasification.

[15] Gasifiers operating at 1500-5000C and atmospheric pressure where the biomass comes in contact with an electrically generated plasma producing very high quality syngas.

With ZuvaSyntha focused on syngas fermentation to manufacture butadiene, of which it produces approximately 10 Mtpa, the UK has one actor working on syngas fermentation. The company uses renewable resources, such as the low cost C1 feedstocks syngas and methanol (Zuvasyntha, 2016). A major academic UK capability is on syngas (or other C1 feedstocks) fermentation including C1Net and the Synthetic Biology Research Centre at the University of Nottingham working on the gene manipulation of Clostridia (SBRC, 2016).

2.7.6 Summary

The development status and UK capabilities for the biomass gasification and syngas catalytic and fermentation upgrading routes depend strongly on the technology route. Globally, the only commercial-scale gasification to advanced biofuels or biochemical plants are Enerkem's MSW to methanol plant and Ineos Bio's syngas fermentation plant. Both companies would have to be attracted to the UK. There are no large biomass gasification players in the UK, and the most significant activities in the UK are the planned bioSNG demonstration plant and another GasPlasma plant to produce hydrogen. Both are using waste feedstock and could form a central part of a thermo-chemical waste based biorefinery in the UK. However, they are currently focusing on hydrogen and methane production. Other UK companies such as Velocys and Johnson Matthey are working on improving one of the key technical barriers, the performance and costs of catalysts. A better integration of the gasifier with the upgrading process and improvement in clean-up costs are crucial to improve syngas quality to make it better suited to the catalyst requirements.

3 Market assessment

The different technologies, downstream conversion and upgrading processes discussed in *Chapter 2 Technology assessment* provide a platform for the production of a wide variety of biofuel and biochemical products. Many of these products are at a low TRL and some years away from commercialisation, while development of others has been recognised and supported. For example the US Department of Energy and the IEA Bioenergy Task 42 Biorefinery report, have highlighted up to 20 products of specific interest due to the current industry activity, and potential market size (IEA, 2013; US DoE, 2004). Most of these products are produced via biochemical conversion pathways, and are primary fermentation products (Table 3-1).

Table 3-1 Bio-based chemical products of specific interest globally

Ethanol	Lactic acid	Furans	Glycerol
n-butanol	Levulinic acid	HMF	1,3-Propanediol (PDO)
Iso-butanol	Succinic acid	Furfural	
Sorbitol	Fumaric acid	FDCA	
Xylitol	Malic acid	Algal lipids	
Hydroxypropionic acid (3-HPA)	Itaconic acid	Isoprene	

Figure 3-1 shows the TRL achieved for each of these key products, and their most important derivatives, allowing a visible comparison of which products are nearest commercialisation. Some of the products illustrated in Figure 3-1 span several TRLs, and this represents the status of different production routes, these may include the conversion of lignocellulosic feedstock (in the case of n-butanol and ethanol), or direct and indirect pathways via intermediate products (for example BDO).

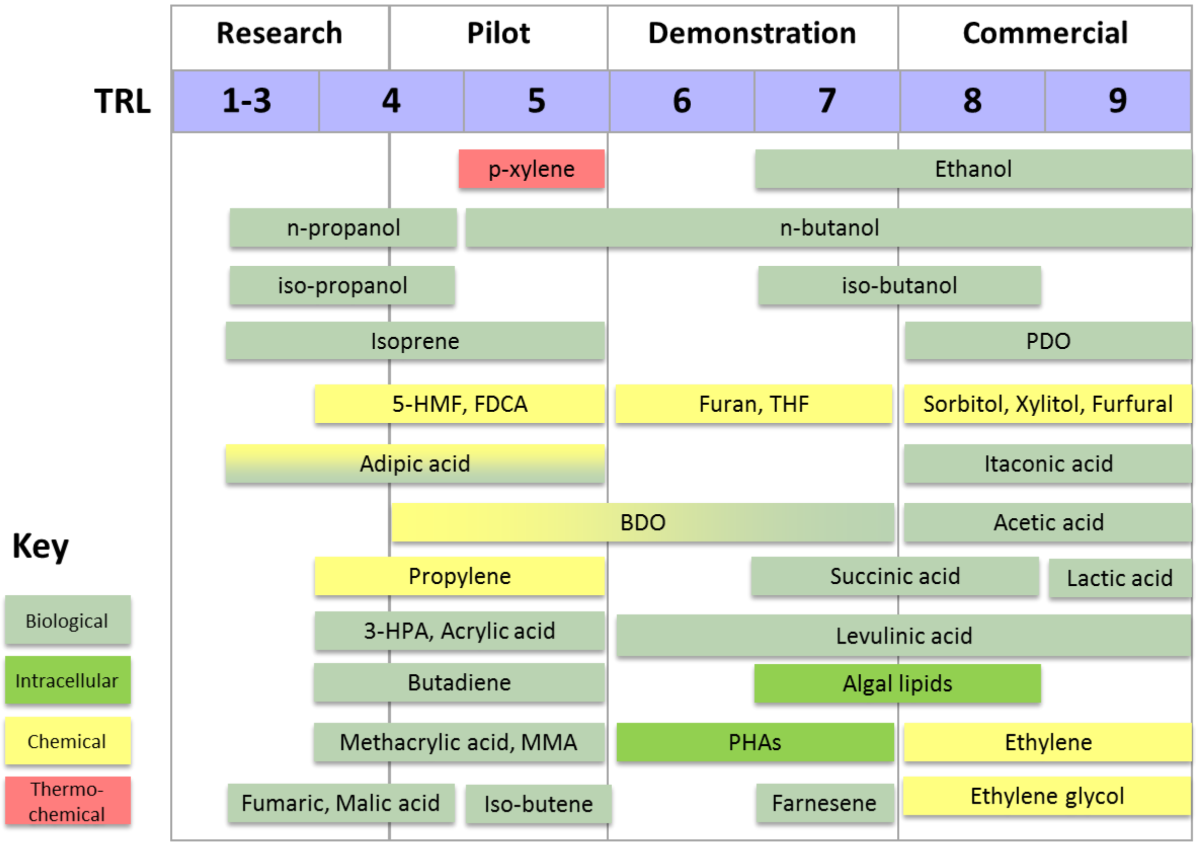


Figure 3-1 Current development status of key bio-based chemicals

In the market assessment provided in Table 3-2, we give a brief overview of some key primary products focussing on those closest to market and currently produced at commercial scale (albeit not specifically with lignocellulosic feedstocks), including current market size and price, and potential growth. Table 3-2 also identifies the main producers and regions, in order to illustrate the competitive landscape for existing (or potential) UK actors.

There are a number of fermentation-based products which are already well established– most notably ethanol, including commercial-scale lignocellulosic production. Large increases in non-fuel demand for ethanol is possible, if demand for bio-based versions of PE and PET grow, along with n-butanol. Others include PDO and lactic acid (and derivative PLA), as well as farnesene – which has no fossil-based substitute. Growth in lactic acid and PHAs could result from demand for new materials with enhanced functionality.

Growth in demand for levulinic acid, which has applications in pharmaceuticals, pesticides, cosmetics, food additives and as a critical building block for fuel additive MTHF, and succinic acid, a drop-in replacement for fossil-based succinic acid and near drop-in for adipic acid for use in resins, plasticisers and polymers, is expected, albeit from low current volumes, as new derivatives and new routes to existing products become available. These products command very high prices, and their costs may decrease as technologies move to commercialisation and production costs are reduced.

Besides these fermentation-based products, pure streams of CO2 produced in biorefineries can be captured for additional synthesis.

While the UK has a strong academic base upstream, and a strong chemical industry downstream, it does not yet have any commercial-scale globally competitive bio-based chemical producers for the key bio-based products mentioned above. Current players working at pre-commercial scales, noted in Table 3-2, include Green Biologics, Celtic Renewables, Butamax, Plaxica, Biome Technologies, CHAIN Biotechnologies, ReBio Technologies and Fiberight. The UK has a strong base of multinational chemical companies, who are increasingly focused on bio-based chemicals. These include BASF, who recently opened a bio-acrylamide manufacturing plant in Bradford, and Croda, who produce a range of bio-based fatty acid building blocks.

Due to the status of development and the number of technology developers, the availability of information is limited. However, the world market size and product value may provide an indication of which target molecules are most attractive. The status of development of the products listed in Table 3-2 is based on sugar and starch feedstocks, are so not necessarily indicative of lignocellulosic sugars. Given the early stage of lignocellulosic feedstock use, very little reliable cost information is available.

Table 3-2 Market assessment of key bio-based products
(adapted from E4tech *et al*., 2015)

Product	Status	Producers/ developers *(UK companies in bold)*	Leading regions	Uses	Areas of growth	Price ($/t)	Global market size based on production (2013/14) (ktpa)
Ethanol	Established commercial product, technologies for the conversion of lignocellulose at early commercial and demo stage	Many, large scale producers include POET, ADM, Beta Renewables and IneosBio No LC ethanol UK producers	US, Europe, Brazil	Predominantly fuel. Industrial uses – as a solvent, building block for chemical synthesis including ethylene.	In addition to the growth in biofuel demand, the production of ethylene and MEG represent large potential market growth - the global ethylene market represents 188 Mt of ethanol	815	71,310 Industrial use ~6, and food and drink ~3
n-butanol	Commercial production via the ABE process in China. High yielding processes at demo/pilot	**Celtic Renewables, Green Biologics,** Cathay Industrial Biotech, Shi Jinyan, Butalco, Cobalt/Rhodia, Solvert	China, Europe, UK & US (demo higher yielding routes)	As a solvent in industrial applications and consumer products (e.g. paints)	Very large increase in new applications - transport fuel and C4 building block	1,890	590
Isobutanol	Early commercial	Gevo, **Butamax**	UK, US	Industrial uses - cleaners & coating solvents, isobutyl esters, extractant for pharmaceutical products, textiles, cleaners & polish additive, gasoline additive, agricultural chemicals. Biofuel	Isobutyl acetate, biofuels	1,721	105
PDO	Commercial	DuPont Tate & Lyle Bio Products, Metabolic Explorer, Zhangjiagang Glory Biomaterial Co, Zouping Mingxing Chemical Co	US	Manufacturing of polytrimethylene terephthalate (PTT), polyurethane, cosmetics, personal care	Existing markets	1,760	128

Product	Status	Producers/ developers *(UK companies in bold)*	Leading regions	Uses	Areas of growth	Price ($/t)	Global market size based on production (2013/14) (ktpa)
Itaconic acid	Commercial	DSM, Chengdu Lucky Biology Engineering Industry Co, **Itaconix, Lucite International Group**, Nanjing Huajin Biologicals Co, Qingdao Langyatai Group Co	Asia, Europe	Adhesives, sealants, finishing agents, paints and coatings	Speciality polymers	1,900	41
Acetic acid	Via methanol commercial, via fermentation at pilot scale	Wacker Chemie, SEKAB, ZeaChem, Phtanol with AkzoNobel	Europe, US	Solvents, polymers		617	1,357
Succinic acid	Commercial, early a number of first commercial facilities in development	Bioamber, Myriant, Reverdia (DSM/Roquette), Succinity, BASF/Purac Other: PTT Chem / Mitsubishi CC	Europe, US	Current applications include polyurethanes, as a food additive, and as a pharmaceutical precursor	Largest potential - production of PBS, a biodegradable polymer. May also substitute maleic anhydride, and as a precursor for BDO, THF and GBL	2,940	38 Expected to grow rapidly
Lactic acid	Commercial	Cargill, Corbicon Purac, Galactic, Henan Jindan, **Plaxica**. [PLA producers - NatureWorks, Hisun, Futerro, Synbra]	Asia, Europe, UK	Production of PLA and lactate solvents. For use in biodegradable packaging and personal care products. *UK chemical companies using PLA include Paragon Print & Packaging; Lake Chemicals & Minerals; Amcor Food Packaging; Sidaplax*	Biodegradable packaging, strengthened by the development of material with improved thermal properties.	1,450	472
Acetone	Commercial	**Green Biologics**, Cathay Industrial Biotech	Europe, US, UK	Paints, coatings, adhesives, inks, pharmaceutical and food applications. Intermediate to produce monomers, polymers, aldol chemicals & cellulose acetate	Existing markets	1,400	174

Product	Status	Producers/ developers *(UK companies in bold)*	Leading regions	Uses	Areas of growth	Price ($/t)	Global market size based on production (2013/14) (ktpa)
BDO	Demonstration	Genomatica, **Johnson Matthey**, BASF, M&G, Novamont Global Biochem, Dupont, Purac, DSM, Mitsubishi Chemicals, Myriant	US, UK	Precursor to polyurethane, THF, polybutylene terephthalate, and GBL. With applications as solvents, footwear and textiles including spandex.	Existing markets	>3,000	3.0
PHAs	Commercial (early limited producers, and demonstration)	Tianjin GreenBio Materials, Metabolix Explorer, Meridian plastics, Biomer, Bio-on, KNN	China	Biodegradable polymers	Biodegradable polymers, based on novel functionality		Production capacity 100 – 130 in 2013
Farnesene	Demonstration	Amyris	US	Moisturiser emollients, durable easy-cast tyres, and jet fuel properties consistent with C15 iso-paraffin	Cosmetics, flavours and fragrances, tyes, base oils and lubricants, diesel and jet fuel	5,581	12
Sorbitol	Commercial	Large number including American International Foods, ADM, Cargill, Roquette	US, France, movement towards Asia	Major uses in the production of vitamin C and as a sweetener. Other uses - personal care products, in the chemical and biochemical industries and pharmaceuticals	In oral care products, and food applications	650	164
Xylitol	Commercial	Danisco/Lenzing, Xylitol Canada	China	Sweetener	Existing markets	3,900	160
Ethylene	Commercial (early limited number of producers although high potential for expansion)	Braskem	Brazil	Production of polyethylene, LLDPE and HDPE	Mainly the production of polymers - PE, PVC and polystyrene, and also as a C2 building block	1,300-2,000	200 Braskem predict current demand for bio-based PE at 600

Product	Status	Producers/ developers *(UK companies in bold)*	Leading regions	Uses	Areas of growth	Price ($/t)	Global market size based on production (2013/14) (ktpa)
Ethylene glycol	Commercial	Global Biochems, Gruppo M&G, India Glycols, Greencol Taiwan Corporation, Novepha	Asia	Chemical intermediate for production of PET. Other uses include dewatering agent, antifreeze, coolant & heat transfer agent	Existing markets - PET and fibre production (CAGR 5.4% and 5.1% respectively)	1,300-1,500	425
Levulinic acid	Commercial, early limited number of producers	Avantium, Biofine Technology, GFBiochemicals/ Segetis	Europe, US, China	Precursor to MTHF (fuel additive), and DALA (pesticide), Diphenolic Acid (DPA), and ethyl levulinate. Minor uses in nylons, synthetic rubbers & plastics	Largely the production of fuel additives and drop-in transport fuels. Additional potential as a platform chemical.	6,500	3.0
HMF	Commercial	**Biome Bioplastics**, AVA Biochem	Europe, UK	Polymers, resins, coatings, paints, varnishes, artificial fibres, and additives. PET.	Replacing PET via the intermediate of FDCA	>2,655	0.02

4 Scenarios

Based on a workshop organised by LBNet in April 2016 four scenarios based on location and feedstock combinations were selected. The key reasons for selecting these scenarios are explained in Table 4-1.

Table 4-1 Scenario overview and key reasons for their selection

Scenario 1: Co-location of a lignocellulosic biorefinery with a biomass power station	**Scenario 2: Straw biorefinery in Eastern England**
Synergies with existing feedstock supply and power plant equipment and infrastructure.	Localised, sustainable and comparatively low cost feedstock. Existing experience with use in biorefineries. Possible synergies with 1G ethanol production.
Scenario 3: MSW-based lignocellulosic biorefinery	**Scenario 4: Dedicated biomass crop biorefinery in the west of the UK**
Localised, negative cost feedstock that is potentially widely available.	Domestically grown resource that could complement feedstocks such as straw.

4.1 Scenario 1: Co-location of a lignocellulosic biorefinery with a biomass power station

4.1.1 Scenario introduction

Co-locating a lignocellulosic biorefinery with a major biomass power station can provide at least two advantages over a stand-alone biorefinery.

Firstly, co-location would offer large-scale quantities of feedstock through optimised supply chains. Large bioenergy producers will already have secured a long-term supply of lignocellulosic feedstock. They will also have optimised their supply chains for imports in the form of specialised biomass handling facilities at nearby ports and accompanying rail infrastructure, which the lignocellulosic biorefinery could exploit. This would allow for ease of access to shipping routes for exports, and to companies interested in bulk quantities of sugar or platform chemicals. In addition, if the biorefinery were able to scale up sufficiently to draw on a large power producers' feedstock supply, the economies of scale achieved could significantly reduce production costs

Secondly, a co-located biorefinery could lower capex costs by avoiding the need to build new CHP boilers. Biorefineries require large amounts of heat and steam to process the biomass which adds both capital and operating cost. Previous work by E4tech has found that the CHP can constitute as much as 25% of total capital cost for lignocellulosic biorefineries (E4tech internal, 2015). We therefore assume in this scenario that co-location also implies the power station converting one of its units to CHP for integration with the biorefinery. The power station could therefore supply large amounts of power and waste heat to the biorefinery and also substitute pellets with low-cost lignin contributing to the full valorisation of the biomass input to the biorefinery. In this case the lignin would have to be dried and pulverised before combustion in the boiler. Depending on the pre-treatment process, the biorefinery could develop the lignin further for chemical production or sell it on to other companies in high-value markets.

A possible location for such an operation would be next to Drax in the Humber region, which already imports significant amounts of pellets and has converted two 660 MW coal boilers to biomass and retrofitted another similar sized unit for co-firing. Lynemouth power station in the North East is another possible location as it recently received EU state aid approval for converting its 420 MW unit from coal to biomass. The planned biomass power plant by MTG in Teesside or a UPM pulp and paper mill in Irvine could be other possible locations (Chronicle, 2016). This scenario study will discuss the opportunities, barriers and viability of co-locating a lignocellulosic biorefinery next to a power station, using Drax as an example, from the perspective of feedstock supply, regional clusters, UK capabilities and overall viability. Figure 4-1 illustrates the main potential interdependencies and opportunities between Drax and the biorefinery.

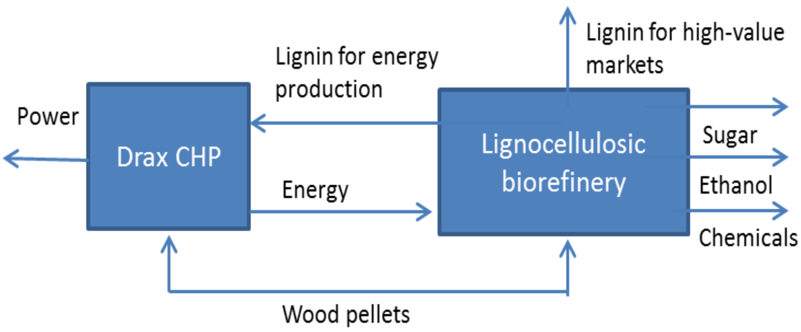


Figure 4-1 Main scenario interdependencies and flows

4.1.2 Feedstock assessment

Feedstock scale and supply

Figure 4-2 Map of Humber region and Drax power station (red circle)

Pelletised wood is an attractive lignocellulosic feedstock both in terms of its stable characteristics and availability. Wood pellets for the co-located biorefinery would be imported at one of the nearby ports at Port of Tyne, Immingham or Hull which have been optimised for handling large quantities of biomass. Port of Tyne alone has a handling capacity of 2 Mtpa of pellets. Drax has also optimised its rail infrastructure to carry 50% more biomass from the ports to the power station compared to traditional freight trains (Drax, 2013). The UK government also granted £130 million to improving access to the ports (UK Trade & Investment, 2015). Drax currently imports 7.65 Mtpa of certified sustainable wood pellets with each dedicated biomass boiler combusting 2.75 million tonnes/year (E4tech estimation, 2016)[16].

This is far above the size range for first-of-a-kind lignocellulosic ethanol plants which currently operate at scales between 117 ktpa – 285 ktpa (E4tech Advanced Biofuel Database, 2016). Depending on market demand for lignocellulosic chemicals and fuels, however, we may expect this size range to increase. Due to economies of scale the cost of sugars from lignocellulosic biomass improves significantly with the size of biomass input as seen in Figure 4-3. The infrastructure capacity surrounding Drax's site in Humber would clearly enable these scales from a feedstock perspective - in particular since alternative unsubsidised uses for wood pellets in the future, after the closure of various UK support schemes in the mid-2020s, could be limited in heat and power.

[16] The remainder is combusted in the co-firing plant currently running at 83% biomass.

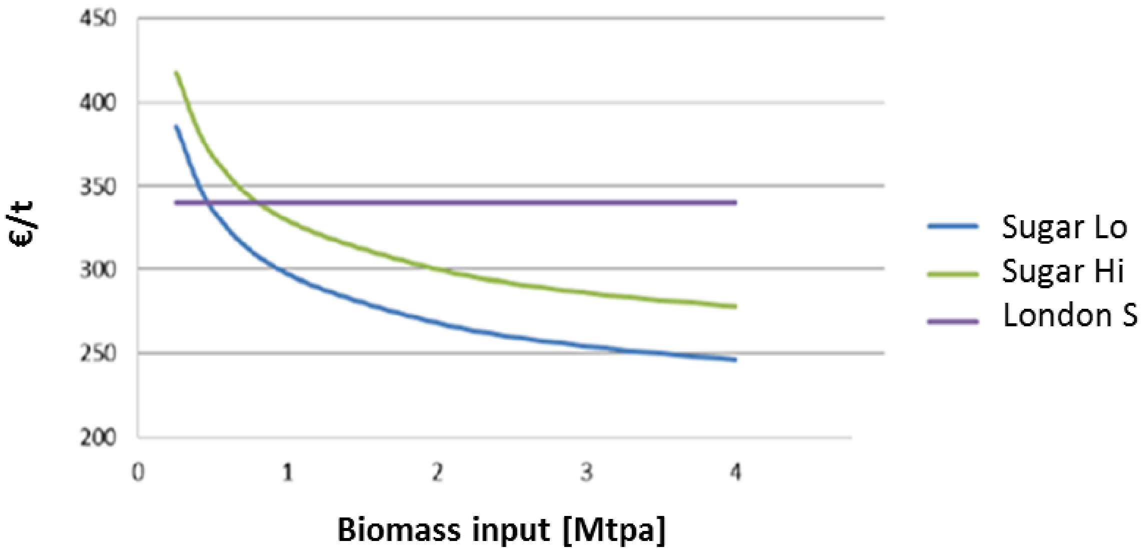


Figure 4-3 Biomass prices in the scenarios
Sugar Lo (EUR/t) = EUR 100/tonne. Sugar Hi (EUR/t) = EUR 130/tonne
(Biobased Delta, 2016)

A biorefinery not co-located with a plant the size of Drax would need to run on a mixture of locally sourced feedstock or invest capital in establishing similar import infrastructure elsewhere to reach similar scale, thereby increasing overall feedstock and capital cost. **Access to large quantities of pellets from a mature supply chain is therefore one of the key benefits of this scenario and in particular from the viewpoint of achieving economies of scale.**

Despite their availability, pellets are costly on a per tonne basis. Bulk European imported EN plus certified A1 pellets used for power and heat generation sold at £121/t in April 2016 (Argus Media, 2016).[17] In previous financial modelling E4tech conducted for clients in the lignocellulosic ethanol space, a price of £47/t was used for other feedstock such as wheat straw and corn stover. This modelling found that at a feedstock price of £121/t the investment in the lignocellulosic ethanol plant assessed would have a negative net present value. While there were several site specific assumptions underpinning these results, it suggests that the high cost of wood pellets may be a barrier to the economic viability of the co-located biorefinery. On the other hand, the valorisation of the lignin (either by selling to Drax or to other higher value markets), the potential for high value chemical production, and the economies of scale and infrastructure synergies allowed for by Drax's mature wood pellet supply chain and energy production facilities may very well make up for the high feedstock cost on a £/t basis. It may also be that wood pellets only require pre-treatment with low grade heat as the lignin may well have been melted during the pelletising process – this would further reduce energy and capital costs.

[17] We could expect Drax's pellets to cost less than this due to the optimised import infrastructure and likely long-term supply contracts. The EN*plus* scheme is a global certification scheme designed to assure a high quality of wood pellets produced for energy applications.

4.1.3 Regional cluster assessment

While abundant feedstock supply is important, access to regional markets and knowhow downstream is also key to assessing the overall attractiveness of co-locating a biorefinery in the Humber region. Another benefit to this scenario is that **chemicals manufacturing in the UK is to a large degree concentrated in the northern region and UK Trade & Investment identified the Humber Estuary around Drax as one of the key chemical clusters in the UK**. There are several active companies in the Humber region with expertise including petrochemical refining and chemicals for a range of uses such as surface treatments and agrochemicals (UK Trade & Investment, 2015). **Croda** is one that produces natural products, consumer goods and industrial chemicals for coatings and polymers. Several other chemical companies are based there such as **Air Products, BOC, BASF, Knauf, Airedale Chemicals, and Novartis** (UK Trade & Investment, 2015). The Humber region is a fast growing chemical base in the UK with investment having exceeded £1 billion since 2007 (UK Trade & Investment, 2015). If producing ethanol, the product could be sold to either of the ConocoPhillips or Total oil refineries on the South Humber Bank for blending into petrol – both of these are located about an hour's drive from Drax and together make up 27% of UK refining capacity (UK Trade & Investment, 2015). As Drax is located on a commercial waterway connecting to the Humber region, transport via barges or pipelines is also a possibility. The strategic location of these refineries close to ports also allows for access to export markets. In addition, **Vivergo**, a joint venture between DuPont and AB Sugar, currently operates one of the largest first generation bioethanol plants in the UK at the Port of Hull which offers further knowhow and infrastructure in the region.

Although not in the immediate Humber cluster, there are several regional companies also producing plastics and paper based packaging which could utilise the bio-based chemicals. The Bio-based and Biodegradable Industries Association (BBIA) is the UK trade association for companies producing biodegradable polymers and finished bio-based products and currently has 18 members. **Biobags** in Lancashire, for example, produces bio-degradable products such as compostable bags and films based on bio-polymers using technology from Novamont. Further north, **Innovia Films** is a UK company producing specialty products for the global packaging and labelling markets. The existence of several companies downstream in the value chain suggests that overall Humber has a well-developed route to market and chemical cluster to support a commercial biorefinery in the region.

4.1.4 UK capabilities and competitive position

The attractiveness of a biorefinery will also depend on the degree to which it can build on existing UK capabilities. While the UK has a strong presence downstream in the value chain, and in particular in the Humber region, the co-location scenario does not play on many UK strengths further upstream.

On the technology side, pre-treatment and fermentation technologies exist on a wide range of TRL levels (2-8). However, **most demonstration and commercial scale biorefineries operating on woody feedstock currently utilise thermo-chemical conversion routes** such as gasification and catalysis and there are no actors on the bio-chemical route utilising wood pellets that we are aware of. Steam explosion (TRL 8) offers the most advanced type of pre-treatment and is operating at a first-of-a-kind commercial scale based on agricultural residues (e.g. **Beta Renewables** and **Abengoa**). The UK has no commercial capability in steam explosion plants although the UK Biorefinery Centre in Norwich operates a pilot plant for R&D with the ultimate purpose of producing commercial biofuels and fibrous material. The Biorenewables Development Centre at York also has steam explosion facilities at pilot scale and is building demonstration scale pre-treatment and hydrolysis facilities with Wilson Biochemicals at Dunnington just outside of York. As for lower TRL alternatives, a Norwegian company, **Weyland**, operates a small-scale pilot plant producing sugars and lignin from woody biomass via concentrated acid hydrolysis (TRL 4-5). The type of pre-treatment needed for wood pellets needs more careful consideration, as well as whether there is opportunity for to build on existing UK pre-treatment activities e.g. CPI. However, pre-treatment technology is a well-developed area internationally, so existing technology could very well be adapted for use on wood pellets.

A possible UK provider of the fermentation process could be Oxford-based **Green Biologics**. Green Biologics is one of the key global players fermenting sugar streams into butanol and is experimenting with lignocellulosic feedstocks, including woody biomass. Using their clostridium microbial fermentation process, Green Biologics is fermenting C5 and C6 sugars to acetone, n-butanol and ethanol (ABE) and aiming through further work to produce butanol as the sole product at high yields (ButaNexT, 2015). They currently only use corn for their plants in the US but aim to move towards lignocellulosic feedstock on a pilot scale including woody feedstocks. Another UK company testing bio-chemical conversion routes from woody feedstocks is Buckinghamshire-based Bio-Sep Ltd. which is currently developing a pilot scale fractionation technology.

4.1.5 Role of Drax

To summarise, co-location could provide benefits to the biorefinery in terms of lower feedstock costs compared to stand-alone infrastructure elsewhere in the UK. Another important benefit of the co-location scenario is that the biorefinery could save ~25% on capex by avoiding the need for building a dedicated CHP plant (E4tech internal, 2015). This is clearly a significant part of the value of co-location as the economies of scale envisioned in Figure 4-3 would need large amounts of energy, which Drax's boilers would likely be able to supply. Realising these benefits, however, would depend on a player like Drax's willingness to convert to CHP and we have identified the following issues to consider from its perspective:

Timing

Drax's market support under the Renewable Obligation (RO) scheme is due to expire in 2027, after which time Drax has announced it intends to shut operations. If the biorefinery were to be built prior to the expiration of Drax's subsidies, Drax will need to be convinced there is an economic case for substituting power market revenues with energy supply to a biorefinery. If a biorefinery were to be built after the closure of the subsidy scheme, Drax may be more inclined to focus its business model on energy provision to the biorefinery and biorefining.

Scale

The scale of the biorefinery directly affects its energy demand and the amount of residual lignin available for Drax. A large scale biorefinery would demand a significant amount of energy from Drax and could also provide a meaningful amount of lignin to the CHP.[18] In order for Drax to substitute pellets with lignin, it would have to invest additional capital in lignin drying and pulverisation facilities, lignin feed-in line to the boilers and conduct feasibility tests on the viability of combusting lignin in their boilers. This additional capital layout is more likely justified if it could provide energy to

[18] Assuming 30% of biomass input, on a mass basis, left as lignin.

the biorefinery and accept lignin on a large scale. For example, assuming Drax converts one of its boilers to supply energy to a biorefinery, it would still need a supply of 2.7 Mtpa of pellets to run efficiently and close to current load factors. A biorefinery the size of Beta Renewables (240 ktpa) would only provide 72 ktpa of lignin- or 3% of Drax's current annual consumption at one of its units.

By way of example, after subsidy closure Drax could continue operation on the power market but only with access to abundant cheap feedstock. Assuming natural gas is the marginal fuel on the electricity market in 2030 we can use natural gas as a benchmark for Drax's competitiveness under various pellet and lignin mix feedstock scenarios. Using DECC's Updated Energy and Emissions projections (2015) we can establish an electricity price from natural gas in 2030 of £45/MWh. Table 4-2 summarises the weighted average cost of electricity under different lignin and pellet blends. These calculations suggest that Drax's unit must run on at least 30% lignin (70% pellets), or 820 ktpa, to be competitive with natural gas in 2030.[19] This is mainly due to a lower lignin than pellet price and to a lesser extent due to the slightly higher energy content of lignin compared to pellets. Assuming 30% of biomass input to the biorefinery is left as lignin this suggests a biorefinery capacity of 2.7 Mtpa – in line with the economies of scale envisioned in Figure 4-3. Building at this scale would bring significant savings, through the economies of scale, and would be potentially feasible using Drax's biomass supply chain. These are indicative numbers for the power market only and do not take into account capital cost of the CHP engines or potential revenue from supplying heat and steam to the biorefinery. They do, however, indicate that the biorefinery should operate at a sufficiently large scale to incentivise Drax to continue operations on lignin after the closure of government subsidies.

Table 4-2 Electricity cost at Drax under various pellet and lignin blends

% of lignin	100	70	50	30	0
Electricity price (£/MWh)	8	23	34	46	67

Age

The average life of coal plants is 40 years. After 30 years of operation, even Drax's newest boilers are now nearing the end of their operational life (Drax, 2016). Although the high and low pressure turbines at Drax were replaced between 2007 and 2012, there are engineering concerns regarding the viability of retrofitting old power plants with CHP, originally fitted with supercritical steam generators, as it may reduce the efficiency of the turbine for the power market and add costs to an asset nearing its operational lifetime.

4.1.6 Summary

Two central observations can be drawn from the preceding discussion. Firstly, the co-location of a lignocellulosic biorefinery with a power station can offer several benefits to the biorefinery not least in the form of a steady supply of large quantities of wood pellets. In the event that biorefineries grow

[19] Calculated using a lignin price of £20/tonne from E4tech internal (2015) and £121/tonne for pellets. Lignin LHV = 21.8 MJ/kg from E4tech internal (2015). CCGT efficiency = 50%. Biomass boiler electrical efficiency = 38%. It may well be that other factors such as emission performance standards or carbon taxes reduce the competitiveness of natural gas in 2030. This comparison only accounts for competitiveness based on fuel cost.

to the scales needed to achieve the envisioned cost improvements, the availability of feedstock in the Humber region will not be a constraining factor based on Drax's current pellet imports of 7.5 Mtpa. In addition, the UK has a strong cluster in the Humber area providing a route to market for potential sugars and platform chemicals, and Drax is also situated close to two of the main UK refineries for ethanol blending. There are also several companies in the area producing products for end-use markets who could be interested in bio-polymers and chemicals. The UK does not have domestic commercial capabilities in the most advanced forms of pre-treatment, hydrolysis and fermentation technology, but existing and innovative lab and pilot facilities such as Bio-Sep. In fact, the few demo-scale or planned commercial biorefineries operating on woody feedstock utilise the thermo-chemical route via gasification. These include the GoBiGas project in Gothenburg, Sweden operating at demonstration scale to produce bioSNG via gasification and catalytic upgrading (TRL 6-7) and the planned first-of-a-kind commercial plant by Red Rock Biofuels in the US to produce FT-Diesel (see section 2.7 on gasification). This could however also be seen as an opportunity for innovation for biochemical routes based on wood pellets.

Secondly, the co-location scenario can also offer significant savings on capex in the form of avoided costs from building a dedicated CHP and other infrastructure. However, a major question regarding the viability of this benefit is the degree to which the power plant, in this scenario Drax, would realistically be willing to convert one of its units to CHP and integrate its business model with that of a biorefinery. We have suggested that this decision will be strongly influenced by levels of subsidies in the power market, the scale of the co-located biorefinery, and the age of the boilers. On one hand, the power station will need to be compensated sufficiently to incentivise operation with a CHP unit. On the other hand, this compensation should not undo the benefit the biorefinery achieves from co-locating and avoided capex cost. Beyond that the viability of integrating a power plant with a biorefining model could be considered. Table 4-3 provides an overall assessment of the co-location scenario.

Table 4-3 Overall assessment of co-location scenario
Green = strong | Amber = medium | Red = weak[20]

Criteria	Rationale	Score
Feedstock	+ Infrastructure currently supporting ~7.5 Mtpa of pellets– sufficient to support large scale biorefineries + Optimised shipping and port facilities for pellets + High £/t cost of pellets potentially offset by economies of scale from surrounding infrastructure	Green
Regional cluster	+ The North East and Humber regions have a strong presence of chemical companies in need of bulk quantities of sugars or platform chemicals such as BASF, Croda and Airedale Chemicals. + Largest oil and biorefineries in the UK already located in Humber including Vivergo, Total and ConocoPhillips.	Green

[20] None of the criteria are evaluated as weak.

Criteria	Rationale	Score
UK capabilities and industrial competitive position	+ Strong downstream presence of UK-based or UK-owned chemical and end-use product companies + The UK is uniquely placed in having fully developed supply chains and contracts for import of wood pellets at a scale to allow the development of large-scale capex-efficient processing with round the year operations. The production of sustainable lignocellulosic sugars at this scale would prove attractive to the establishment of new bio-based chemicals and plastics companies. + Strong UK R&D and demonstration scale activity in pre-treatment and hydrolysis at BDC and CPI. In addition, Green Biologics are venturing into a pilot scale lignocellulosic biorefinery and Bio-Sep Ltd. are piloting a fractionation technology – both capable of handling woody feedstock. - Limited global and no UK commercial capability in pre-treatment or conversion of wood-based feedstocks. However, the UK has full scale commercial bioethanol fermentation plants using first generation sugars - Limited UK feedstock supply, dependence on imported feedstock	
Viability	Co-locating a biorefinery with a biomass power station brings strong advantages in terms of security of feedstock supply and logistics, but the higher costs of pellets would need to be offset by the integration with the biomass power plant and the economies of scale of the infrastructure in the Humber area. In comparison to the straw scenario, there is limited experience in pre-treatment of wood-based feedstocks and no commercial pre-treatment and fermentation plant operating globally using pellets as feedstock. However, the UK has some capabilities on pre-treatment and hydrolysis at pilot scale capable to use woody feedstocks that could be harnessed for a biorefinery using pellets. Similar to the straw-based biorefinery scenario, the Humber provides potential for integration with existing biofuel players and downstream chemical and refining industries. The added value of a co-located pellet-based biorefinery would depend on the business case for the power plant which would need to be ascertained for different levels of integration and business models as well as demonstrating commercial potential for UK innovation in fractionation and pre-treatment of pellets.	

4.2 Scenario 2: Straw biorefinery in Eastern England

4.2.1 Scenario introduction

Straw is an attractive biorefinery feedstock as it is a non-food agricultural residue, potentially interesting from an availability, cost and sustainability perspective, and could be used to complement existing cereal based biofuel production or used in a standalone plant. It is also a **relatively easier feedstock to process compared to wood or MSW**. There are however also overlaps with the other biorefinery scenarios, especially with regard to the conversion of sugars, but possibly also with pre-treatment.

The regions of **Eastern England**, considered for this biorefinery scenario are the East of England, the East Midlands and Yorkshire and the Humber (see Figure 4-4). They have the **largest straw availability in the UK**, and are home to the large first generation ethanol Vivergo plant on the Humber, which uses 1.1 Mtpa of locally sourced wheat grain. The existing infrastructure related to the wheat-to-ethanol plant could support the development of a straw-based biorefinery. **Straw sales could represent an additional income stream for farmers** in Eastern England who see a higher benefit in this than incorporating it back into the soil, though precautions need to be taken so that straw extraction does not negatively affect soil quality.

Besides the straw availability, the Humber area is attractive in terms of logistics associated with the port complex for selling higher value chemical products outside the UK, other chemical companies located in the Humber area for upgrading of sugars or sales of higher value chemical products, and refineries and blending facilities for fuel products such as ethanol or butanol.

The environmental benefits that could derive from this biorefinery scenario depend mainly on the sustainability of straw use and avoided environmental impacts of the products substituted in the market.

4.2.2 Feedstock assessment

Competing uses and net availability

Eastern England is the region with the highest straw availability in the UK and thus ideally suited for a biorefinery using straw as feedstock. Straw in Eastern England is derived mainly from wheat and to a small extent from barley, oil seed rape and oats. In this **scenario only straw that is currently uncollected is considered available,** as baled and collected straw is considered to serve an existing market (NNFCC, 2014) mainly for animal bedding and fodder (E4tech, 2014). However, currently uncollected straw is chopped and incorporated into the soil improving soil quality, so **only a fraction of uncollected straw will be available and the willingness of farmers to provide it may vary.** Uncollected straw in the three regions of Eastern England amounts to 2.7 Mtpa (NNFCC, 2014). Locating a biorefinery using straw close to Hull on the Humber delta, co-located with the Vivergo plant for example, would render a large amount of this feedstock unavailable due to transport cost. As an indication, the Vivergo plant in Hull receives its wheat from within a 50 mile radius and the DuPont corn stover ethanol plant in the US from within a 30mile radius (Vivergofuels, 2016; Dupont, 2016). Assuming 50 miles as an upper limit would exclude the 1.1Mt of straw available in the East of England. And, if we assume that around 50% of Yorkshire and the Humber as well as of the East Midlands would be within a 50mile radius, see Figure 4-4, this would limit the theoretically available uncollected straw to 0.8 Mt, and **assuming 50% would be left in the field for soil quality purposes, then approximately 0.4Mt could be available to a biorefinery** (based on NNFCC, 2014).

Figure 4-4 Regions in Eastern England, possible biorefinery location and feedstock sourcing area

This is in line with work by Glithero *et al*. (2013a) who suggest that within a maximal radius of 50miles farmers in Yorkshire & the Humber would be willing to sell around 0.42 Mtpa of uncollected straw and 0.8 Mtpa in the East Midlands.

The Sleaford **biomass CHP plant in the East Midlands manages to source 240,000 tpa of straw within a 30 miles radius** (Sleaford, 2014). This corresponds well to the feedstock requirements for a commercial scale lignocellulosic ethanol plant for example and indicates that it **could be feasible to source sufficient feedstock for a straw biorefinery plant close to Hull**, though Hull's position close to the coast may be a disadvantage in terms of radial sourcing. Clearly, a more detailed feedstock sourcing study is required to estimate the amount of uncollected straw available that could be available within a feasible radius, and the willingness of farmers to sell it rather than incorporate it back into the soil.

Seasonality and storage to allow a year round operation

The seasonality of cereal straw production requires storage as well on the farms and at the location of the biorefinery. The former can be a problem and makes the incorporating of the straw an attractive option for the farmer (IEEP, 2012). However, the two existing biomass straw plants in the UK in Sleaford and Ely have overcome the storage challenge. Given the similar size for a biorefinery close to Hull, valuable lessons could be learned through direct interactions with the operators and feedstock providers of both plants in a possibly more detailed feasibility study.

Feedstock cost

Cereal straw in the UK is traded in a range of 48 to 75 £/t depending on the location and season (E4tech, 2014). Competition for the resource to maintain soil quality and for other uses (animal bedding, fodder, energy) means that careful consideration needs to be given to securing the feedstock and its price.

4.2.3 Regional cluster assessment

A straw biorefinery in Eastern England is potentially **attractive as a result of feedstock availability, potential to co-locate with existing biofuel production, and presence of an industrial hub comprising chemical plants, refineries and blending facilities in the Humber** as explained in section 4.1.3 in the first scenario study. Conversion technologies and products are assumed to be very similar to the co-located scenario study using pellets, but current commercial technologies are more tailored to the use of straw The industrial hub is potentially attractive in terms of demand for bio-based products, as discussed in *Chapter* 3 *Market Assessment*. The Humber area has as well the largest UK port handling 17% of UK's port trade (CIA, 2009). Academic capabilities and collaborations with industrial partners by the University of York, the Biorenewables Development Centre and the University of Huddersfield add to the cluster.

The recent agreement between Vireol, a UK based biorefinery project developer, and Inbicon to develop a lignocellulosic ethanol plant using straw in Grimsby in the Humber delta is an indication of the attractiveness of this cluster in Eastern England.

4.2.4 UK capabilities and competitive position

The attractiveness of a biorefinery to the UK will strongly depend on the degree to which it can build on existing UK capabilities, either technical capabilities or project development ones.

Straw is a feedstock that has been a focus of attention for biological conversion. First-of-kind commercial scale bioethanol plants such as Beta Renewables use straw or similar feedstocks. Therefore, **from a technical maturity point of view a straw based biorefinery could be more easily implemented**, for example compared to a pellet based biorefinery, discussed as another possible biorefinery scenario in this report (section 4.1.4). Vireol is looking to use Inbicon technology in a lignocellulosic bioethanol plant in Eastern England.

Apart from the activities on pre-treatment and fermentation at commercial scale which are situated outside the UK, the **UK does have some capabilities on pre-treatment as well as on sugar catalysis which are currently at pilot and lab scale**. Bio-Sep Ltd. has piloted a fractionation technology separating among other feedstocks agricultural residues into cellulose, hemicellulose in the form of sugars and lignin (Bio-Sep, 2016). SERE-Tech Innovation Ltd, a company specialised in using ultrasonics in the food and drinks industry, has tested, together with the University of York and the Biorenewables Development Centre, their equipment to improve the deconstruction methods for straw pre-treatment (LBNet, 2016). For a more detailed assessment on UK capabilities, please see the UK capabilities sections in the Technology Assessment. Overall, the capabilities in the UK on pre-treatment are limited to lab and pilot scale, whereas global straw pre-treatment and fermentation technologies have reached first-of-a-kind commercial scale.

Lignin fractionation represents another option in a straw based biorefinery (depending on the pre-treatment method lignin from pellets in scenario 1 or perennial energy crops in scenario 4 could also be suitable for valorisation). The UK has some industrial capabilities with Biome Bioplastics, and a wide range of academic activities, but all are at lab scale (see chapter 2.5.5 on lignin valorisation). However, as **lignin valorisation**, with the exception of Borregard in Norway, **is less advanced than pre-treatment technologies this could represent an opportunity for the UK** given the strong academic base.

4.2.5 Summary

Three main observations can be drawn from the above discussion. Firstly, the uncollected straw availability would need to be assessed in a more detailed feasibility study within a 50 mile radius of a possible biorefinery. According to one study, farmers in the Humber area have indicated an interest in selling straw to a possible biorefinery in sufficient amounts, but this willingness would need to be carefully evaluated due to the benefits of incorporating straw for soil quality. However, the two existing biomass power plants using straw in Eastern England show that it is possible to source around 200,000 tpa within a geographical radius making it economically feasible to set up the required supply chain. Necessary lessons on straw sourcing could be learnt from both projects.

Secondly, first-of-a-kind commercial ethanol plants globally use straw or other agricultural residues as feedstock. There is more experience on pre-treatment of straw to fractionate lignin and then extract sugars from the cellulose and hemicellulose than from woody feedstocks such as pellets which could have implications in terms of experienced actors across the supply chain and possible short term scale of operations. However, as stated in scenario 1, the UK does not have domestic commercial capabilities in the most mature forms of pre-treatment, hydrolysis and fermentation technology, but does have innovative and complementary activities at lab and pilot scale on pre-treatment such as Bio-Sep or SERE Tech Innovation, see section 2.2.5.

Thirdly, the UK has a strong downstream cluster in the Humber area that could provide a route to market for potential sugars and bio-chemicals. Realising this potential would require careful selection of the biorefinery technology and products depending on the possible integration with companies in the cluster. In addition the port infrastructure could allow for the export of intermediary or final products. There is also an existing biofuel industry in the area with which there could be potential synergies and opportunities for co-location. See Figure 4-3 for an overall assessment of Scenario 2.

Table 4-4 Overall assessment of straw based scenario
Green = strong | Amber = medium | Red = weak[21]

Criteria	Rationale	Score
Feedstock	+ Feedstock is an agricultural residue potentially attractive from an economic and sustainability perspective. + Two existing biomass power plants using straw as feedstock in Eastern England at a similar scale of around ~200,000 tpa managed to build up a viable supply in a 30-50mile radius - Feedstock availability limitations due to transport costs - Potential uncollected straw availability depending on amount incorporated into the soil to improve soil quality.	
Regional clustering	+ The North East and Humber regions have a strong presence of chemical companies in need of bulk quantities of sugars or platform chemicals such as BASF, Croda and Airedale Chemicals + Largest oil and biorefineries in the UK already located in Humber including Vivergo, Total and ConocoPhillips. + Vireol is developing a lignocellulosic bioethanol plant in Humber using Inbicon technology + Large port complex for the export of possible chemical end products	
UK capabilities and industrial competitive position	+ Strong downstream presence by UK-based or UK-owned chemical and end-use product companies with some interest in bio-based products + UK activity in steam explosion in Norwich using various straws as feedstock input and some further UK pre-treatment capability at pilot and lab scale such as Bio-Sep Ltd. who are piloting a fractionation technology using a variety of feedstocks including straw and at BDC in York and CPI + Vireol is an active lignocellulosic UK biorefinery project developer - No UK (quasi-)commercial capability in pre-treatment or conversion of straw-based sugars	

[21] None of the criteria are evaluated as weak.

Criteria	Rationale	Score
Viability	Straw is an economically and environmentally attractive feedstock with some but limited availability in the UK, but much additional potential elsewhere. Technologies for pre-treatment of straw are relatively mature, but there is scope for complementary innovation based on UK research (e.g. Bio-Sep). The relative maturity of the straw based biorefinery relative to other feedstocks means that there are experienced actors, especially outside the UK, that could participate in a demonstration or in a commercial scale plant as in the case of Vireol and Inbicon. The Humber provides potential for integration with existing biofuel players and downstream chemical and refining industries. The added value of a straw-based biorefinery would rest on demonstrating commercial potential for UK innovation in fractionation and pre-treatment and in sugar fermentation to high value products, and potentially in integration of straw with cereal-based biorefining.	

4.3 Scenario 3: MSW-based lignocellulosic biorefinery

4.3.1 Scenario introduction

The attractiveness of municipal solid waste (MSW) as a lignocellulosic biorefinery feedstock has a number of motivations, including local availability all year round, regulatory and fiscal drivers such as reduction in landfill volumes and high landfill tax, and attractive sustainability credentials. Current alternative use of MSW as a feedstock for electricity and heat production may be a lower value option compared to the production of fuel and chemicals, providing an opportunity to create additional value from waste. There is also an established waste collection and management infrastructure which could be leveraged to create a viable feedstock supply chain. The ability to successfully process MSW into higher value products and fuels will also place the UK in a globally competitive position.

The sustainability credentials of using MSW as a biorefinery feedstock are borne out of its status as a waste product and the avoided land use which is seen for other feedstocks such as corn. Using MSW as a feedstock also diverts the waste from going to landfill. As an example of these sustainable benefits, an LCA study of the conversion of MSW to bioethanol estimated that the use of MSW-ethanol in vehicles reduces net GHG emissions by 65% compared to petrol and 58% when compared to corn-ethanol (Kalogo *et al*., 2007).

However, there are challenges. MSW is a diverse feedstock, and the different waste streams which arise from it are suitable for different conversion technologies. For thermochemical platforms a more heterogeneous mixture may be possible (for example raw waste in plasma gasification). For biochemical platforms however, the separation of biological waste is required, and it may be challenging to produce a stream of pure sugars – the composition of which is important for downstream processing. Process flexibility to accommodate different waste composition is vital for a biochemical waste-based biorefinery.

4.3.2 Feedstock assessment

Municipal waste in the UK comprises a number of waste streams – including household waste (household collections, kerbside recycling, garden waste, litter etc.), commercial waste (wholesalers, businesses, shops etc.), industrial waste (factories, industry etc.), and construction and demolition waste. Broadly speaking municipal solid waste (MSW) includes household waste as well as commercial and industrial waste which is similar in nature. MSW is composed of various different inorganic and organic fractions, and the separation and treatment of these differs according to government regulation. It is the biodegradable fraction (referred to as biodegradable municipal waste[22] - BMW) that is of primary interest in this scenario study.

Policy and regulation drivers

The European Commission places a high priority on environmental initiatives, including the reduction and management of waste. As a result, much of the UK's current waste policy and legislation has been driven by EU strategy and regulation, notably the revised Waste Framework Directive and the Landfill Directive – which set binding targets for recycling municipal waste and diverting BMW from landfill. The UK's waste policy is governed by the waste hierarchy (Figure 4-5), which prioritises waste prevention, reuse and recycling.

Current legislation aims to:

- Increase recycling and reuse to 50% by 2020 (England, Northern Ireland) or 70% by 2025 (Scotland, Wales)
- Reduce the amount of BMW going to landfill to less than 35% of 1995 levels by 2020 (England, Northern Ireland), or maximum of 5% by 2025 (Scotland, Wales). Across the UK, this means that the maximum allowable landfill of BMW in 2020 will be 6.39 Mtpa (IEA 2013). This decrease in allowable BMW landfill may increase the ease of access to BMW for a biorefinery.

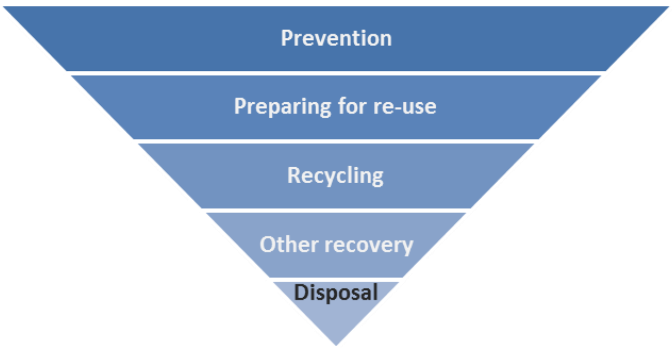


Figure 4-5 EU waste hierarchy from the EU Waste Framework Directive

Other Government regulations and initiatives include the Packaging Directive, Landfill Tax, England's waste prevention programme, and Zero Waste plans for Scotland and Wales.

In December 2015, the European Commission published a revised 'Circular Economy' package, which proposed a recycling target for municipal waste to 65% by 2030 (reduced from a 70% target proposed in 2014). While Scotland and Wales have adopted higher targets, Defra is maintaining the 50% target for 2020 in England (which produces the majority of waste), which will likely place

[22] Biodegradable waste refers to the volume of waste collected that is able to biologically decompose (e.g. food waste, garden waste, etc.)

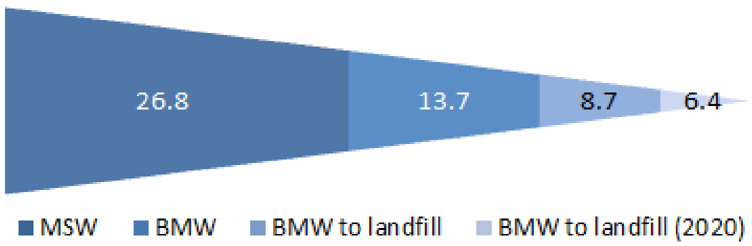
additional pressure on recycling from 2021 onwards – depending on the UK's stance on EU targets following Brexit.

In this scenario study, the role of lignocellulosic biorefinery is considered in the waste hierarchy to be a recovery mechanism. This increased recycling target, together with other competing recovery options (such as anaerobic digestion, incineration with energy recovery, gasification and pyrolysis), may reduce the amount of MSW feedstock available in future. There may be some room for manoeuvre in considering the potential for a biorefinery to 'recycle' the waste feedstock, especially if additional environmental benefits to recovery are recognised in the future. This is an area that would benefit from further consideration and clarification by the UK Government and policy makers.

Feedstock availability

In 2014 the UK produced 26.8 Mt of household waste (which includes household waste and C&I waste similar in nature) (Defra, 2016), or approximately 482 kg of MSW per capita - a 3% reduction from 1995 (Eurostat, 2016). Of this 482 kg per capita total, 473 kg was treated - 79kg composted/digested, 132kg recycled, 128kg incinerated (including energy recovery) and 134kg landfilled/disposed (Eurostat, 2016).

It is assumed that around 51% of household waste is biodegradable (Resource Futures, 2012) – approximately 13.7 Mtpa. In 2014 the UK sent **8.7 Mt of BMW to landfill**. This is a 24% reduction



from 1995 (Defra, 2016), but as noted previously the maximum allowable landfill of BMW will need to decrease to **6.39 Mtpa in 2020** (Figure 4-6).

Figure 4-6 Feedstock availability progression (Mtpa)

Thus, it is estimated that around 5 million tonnes of BMW is currently treated in existing facilities (such as incinerators, MBT, AD plants etc.), but that a further **2.3 Mtpa will require treatment by 2020** – and forms a potential feedstock for a biorefinery. If the landfill target is exceeded, additional BMW feedstock will be available.

This anticipated feedstock availability assumes that the amount of MSW, and the biodegradable proportion which is landfilled, will remain constant to 2020. However, the future availability of MSW is difficult to predict, depending largely on factors such as economic development (though this is likely to be a minor factor in the UK), increased waste prevention due to the landfill tax, and focus on better resource efficiency in sectors such as manufacturing (Eunomia, 2015).

A key challenge to the use of waste in a biorefinery is the **heterogeneity of waste streams**. The composition of biodegradable waste varies seasonally (for example, green waste might increase over summer), as well as regionally. Thus, a key to a successful biorefinery is a flexible process developed to adapt to consumer habit and suit the requirements of the region.

Around 83% of the UKs household waste is generated and managed in England, and is relatively evenly distributed (depending on population density) across the country. Around 79% of landfilled BMW is in England, and landfilled municipal waste follows a similar distribution, but is notably higher in the North West and South West regions.

Competing feedstock uses

While there are logistical costs associated to waste disposal, it is likely that MSW will constitute a revenue rather than cost for a waste user, due to the negative opportunity cost of disposal (i.e. landfill). Within the UK a waste disposal authority or council will contract the disposal and treatment of the household waste they receive from collectors. This is done via a gate fee - which is a weight-based payment made by the local council authority to a service provider for waste disposal or treatment. Shown in Figure 4-7 are the rates (in £/tonne) for various process options. A biorefinery treating the organic waste fraction is assumed to **attract a median gate fee similar to that for open-air windrow composting (£24/tonne), aerobic digestion (£41/tonne) or in-vessel composting (£46/tonne)**. It is unknown whether these gate fees will fall in coming years, but drivers behind a potential decrease include economic pressures and increasing competition for feedstocks (Wrap, 2013).

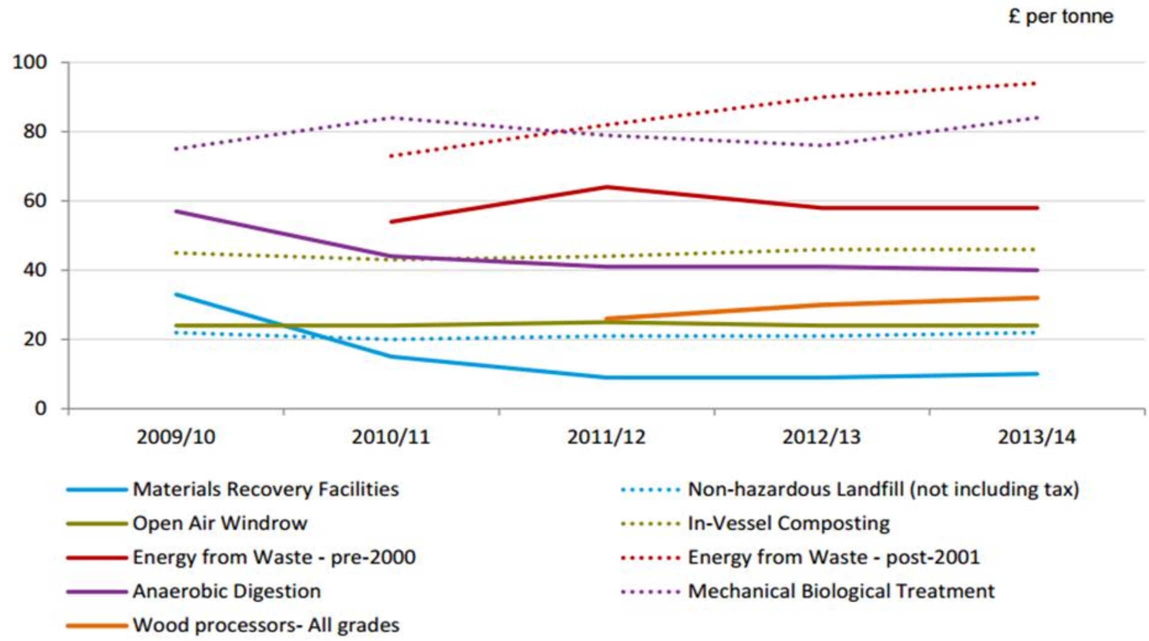


Figure 4-7 Median gate fees comparison for various waste streams (£/t)
(Defra, 2015)

In order to limit the amount of biodegradable municipal waste going to landfill there is a landfill tax in place (which is additional to landfill fees) for site operators – which is typically passed on to the local council or other users of the landfill site. This weight-based tax increases annually, and is currently £84.40 per tonne for active[23] waste. This will increase to £86.10 in 2017 and £88.95 in 2018. The higher cost of landfill is intended to make other advanced waste treatment options, which command a higher gate fee, more economically attractive.

[23] Everything excluding inactive waste (for example rocks or soil)

The competing demands for MSW are based on recycling and waste treatment capacities. Those most relevant to the bio-based fraction of MSW are composting, anaerobic digestion, incineration and other energy recovery such as advanced conversion technologies (including thermal technologies – gasification, pyrolysis and biological technologies –autoclave/fermentation) .

In 2014 the recycling and composting rate for household waste in the UK was 44.9% (targeting 50% by 2020, and varying targets depending on country out to 2030) (Defra, 2016). The UK has in-vessel composting capacity for 5.85 Mtpa of mixed food and garden waste, and AD capacity for 3.2 Mtpa of mixed food waste (household, farming, commercial and industrial) (Wrap, 2013; Wrap, 2012). Incentives including the Renewable Heat Incentive (RHI) and Feed-in Tariff (FiTs) have promoted additional AD capacity.

In addition, the UK has around 24.5 Mtpa of residual waste treatment capacity currently operating, under construction or committed. This includes 47 incineration and 14 gasification facilities, as well as 36 pre-treatment facilities (either MBT[24] or autoclave). A further 14.9 Mtpa of capacity has received planning consent, with 1.9 Mt seeking planning consent or seeking appeal following refusal, although there is uncertainty over how much of this capacity will be realised (Eunomia, 2015).

It is estimated that there is currently a capacity gap[25] of around 13.8 Mtpa (Eunomia, 2015). There is much debate as to whether the UK will experience a waste treatment capacity gap[26] in future, and what this gap might be. Defra (2013) anticipate overcapacity of around 3.8 Mt in 2020, similarly Eunomia (2015) estimates a capacity match by 2020 and overcapacity of around 2.4-6.9 Mt in 2030. However, other sources estimate undercapacity of between 5 and 11 Mt (Imperial College London, 2014; Ricardo-AEA, 2013) in 2020. Based on these sources, and the various ways in which waste amounts are publicly reported, it is difficult to estimate what the capacity gap specifically for the biodegradable fraction of municipal solid waste might be – which is directly applicable to the potential for a waste biorefinery. However, given the distribution and heterogeneity of waste across the UK, together with the different treatment facilities (Figure 4-8), it is proposed that **the issue of capacity gaps is best addressed at a regional level, and the potential location for a biorefinery better assessed on this basis too.**

[24] Mechanical-Biological Treatment
[25] The difference between residual waste arisings and available treatment capacity
[26] The difference between residual waste arisings and available treatment capacity

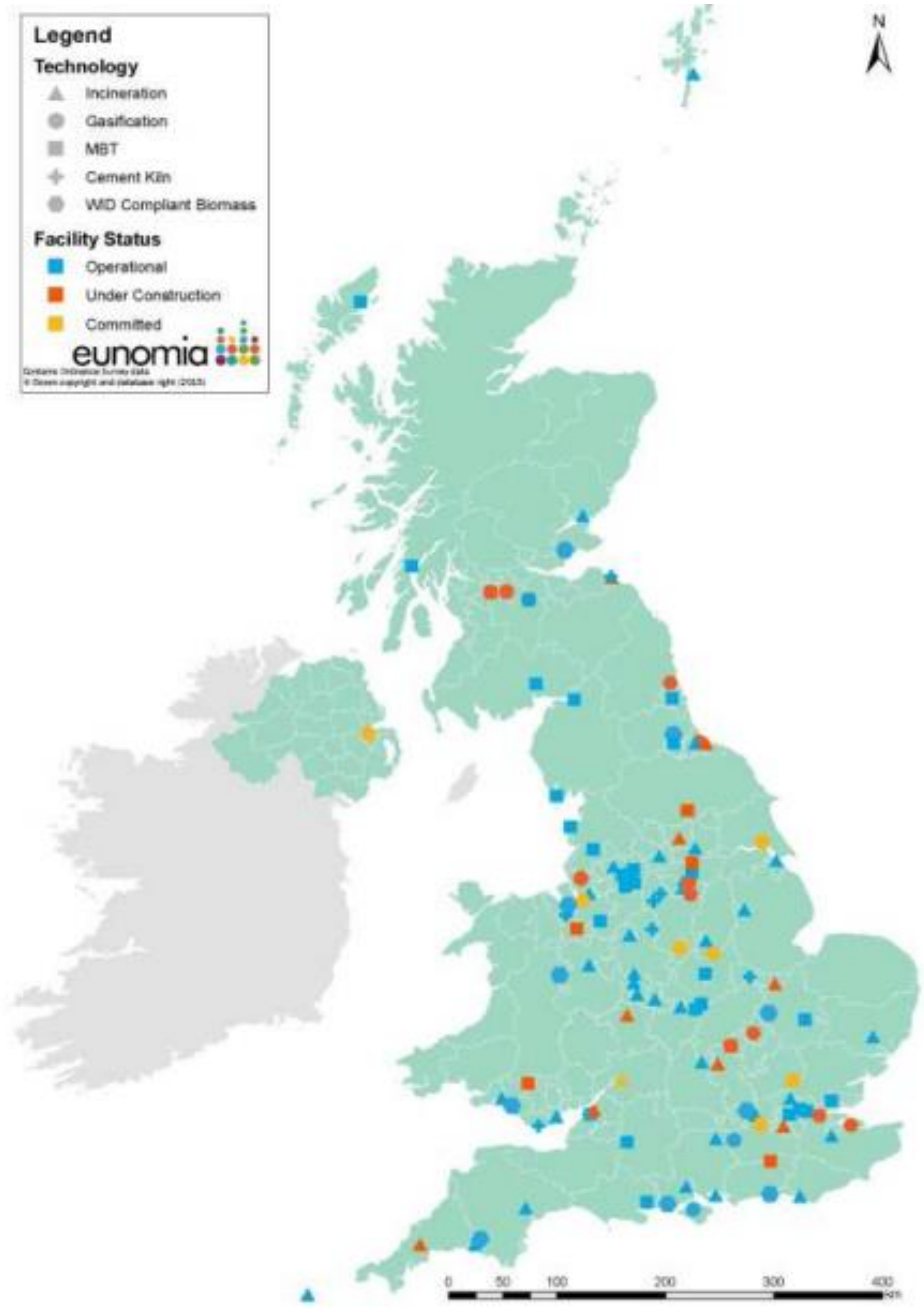


Figure 4-8 Location of residual waste facilities across the UK
(Eunomia, 2015)

4.3.3 Regional cluster assessment

Biorefinery location from a supply perspective

The existing infrastructure for waste collection and the policy framework, including the landfill tax and recycling targets, provides support and drive for the use of municipal waste in biorefining activities, but this is likely to require partnership with waste management companies, who effectively own this resource and have the responsibility to treat and/or dispose of the waste in line with the legal and contractual obligations. There is an increasing trend for the co-location or co-operation of pre-treatment and thermal treatment facilities, which are contractually linked together over the long-term (Eunomia, 2015). The appetite for waste management companies and specific waste treatment sites to engage with biorefining opportunities will be dependent on a number of factors including existing assets and investment profiles.

Waste is treated at various facilities across the UK (**Error! Reference source not found.**), and these **existing facilities could represent an opportunity for location of biorefinery plants, as a point of aggregation, fractionation and pre-treatment**. Each facility is individual in terms of the characteristic and quantities of waste collected and the treatment and processing capabilities, however MBT and landfill sites could provide a relevant opportunity for biorefining in the UK. The following big MBT sites, which are not currently co-located with other treatment plants, could be of potential interest:

- 417 ktpa MBT plant being commissioned in Essex. The plant will be operated by Urbaser (Urbaser, 2012)
- 440 ktpa MBT plant in North Lanarkshire, Scotland has been granted a planning permit by SEPA in consultation with the local council (SEPA, 2011). The plant would be operated by FCC Environment.

Other sites like the Air Products Teesside energy-from-waste project, now discontinued due to technical challenges and increasing costs (BBC, 2016), for which around 350 ktpa MSW from Impetus Waste Management was to be sourced could be worth considering as a biorefinery site (although Impetus now ships the waste to Europe) (Air Products, 2016; Goulding, 2016). Another project, led by consortium SITA SEMBCORP, is planning to freight 430ktpa from Liverpool to Teesside, highlighting that it is not necessary to co-locate with a waste treatment facility so long as BMW is made available to the plant.

When considering what a potential waste-based biorefinery might look like, it is estimated that an average biorefinery plant capacity could be around 200 ktpa. Taking into account that only ~50% of this is biodegradable, this doubles to around 400 ktpa MSW, equivalent to a city or region of roughly 800,000 people. Around 15 of the UK's 55 metropolitan areas have a population above 800,000. This crude calculation highlights the **potential challenge to accessing sufficient waste locally** (or the need to transport waste) **or with matching attractive technology scale with waste availability**. This may not be compatible with the economies of scale required by high capex costs associated with lignocellulosic biorefineries. However, if the process can be developed to be flexible and process MSW blended with other waste (such as agricultural residues) this will go a long way to overcoming this potential barrier.

Biorefinery location from a demand perspective

There are several routes to market that are possible for a waste-based biorefinery. The first is to sell the cellulosic sugars to material or chemical companies who require a sugar feedstock. For example upon commercialisation in the UK Fiberight will sell their sugar stream to a sugar offtake partner who will utilise it in resin production (Thomson & Puri, 2016, pers. comm., 9 August). Another route to market is the production of biofuels, such as cellulosic ethanol and n-butanol. A further route to market in the future could be the use of ethanol as a building block for bio-based chemicals, as well as the production of other high value chemicals. The market potential is further discussed in *Chapter 3: Market assessment*. Other routes, based on gasification technology, include the production of syngas - which can be used to catalytically produce fuels such as ethanol, methanol and hydrogen, or undergo syngas fermentation to fuels such as ethanol, and other high value chemicals. Perhaps the most well-established example of this route is Canadian-based Enerkem's first-of-a-kind commercial methanol plant (TRL 8).

Considering the above routes to market, it is important to consider the location of a waste-based biorefinery from a demand perspective and depending on the products produced it may be useful to site within an already-established industrial cluster (for example fuel refineries or chemical producers).

The UK has a well-established chemicals industry, with more than 3,125 chemical companies which including large multinational chemical and pharmaceutical companies, and a large number of small and medium size enterprises (CIA, 2009). These are concentrated in four main clusters: the North West, the North East, Yorkshire and Humber, and Scotland.

Many of the UK actors concentrating on municipal waste feedstocks are based in the Teesside region of North East England, which presents an opportunity for integration into the region's already existing chemical cluster. This cluster is comprised predominantly of well-established activity in the chemical sector (including big multinationals such as Ineos, BOC, DuPont, Huntsman Polyurethanes, Dow, Croda, GrowHow (now CF Fertilisers) and SABIC), some of whom may already be making use of renewable chemicals in their products. The cluster also supports growing research and innovation activity, such as the Centre for Process Innovation (CPI). The CPI, based in Wilton, is the process arm of the High Value Manufacturing Catapult and is supporting a number of SMEs across industrial biotechnology and biorefining. Bioethanol producer CropEnergies (previously Ensus) is operating one of the largest bioethanol production plants in Europe (315 ktpa) in the North East (Argus, 2016; Ensus, 2016), and the region provides good access to supply bio-based chemical and fuel s to Europe.

4.3.4 UK capabilities

A small number of existing UK actors are working towards commercialisation of their technologies, using waste feedstocks, including Fiberight, Wilson Bio-Chemical, ReBio Technologies, and Vireol.

The first, **Fiberight**, has developed a process to thermo-mechanically fractionate municipal waste to recyclables and biomass, followed by a hydrolysis process to produce simple sugars. Fiberight have tested this technology, including 3,500 hours of continuous operation, at their 8 ktpa demonstration plant in Lawrenceville, Virginia (Lane, 2015). In 2009 they procured a mothballed first generation corn ethanol plant in Blairstown, Iowa, which they had planned to retrofit for cellulosic ethanol production with production capability of ~10.5 ktpa. These plans are currently on hold as Fiberight is focusing on production of biogas for CNG instead. This switch is as a result of federal credits for biogas (Sapp, 2015).

In the UK, Fiberight is currently involved in two Innovate UK/BBSRC/EPSRC Industrial Biotechnology (IB) catalyst projects, both of which are at pilot scale. They have a demonstration plant in the USA and are currently testing the new technology developed, at pilot scale, within their demonstration facility in Virginia, USA. Fiberight are looking at a commercial-scale facility for 2018/19 in Wales, with the eventual aim of rolling out multiple plants around the UK, including Teesside, each with the capacity to process around 400,000 peoples' household waste per year (Fiberight, 2015). Fiberight is capable of processing kerbside non-sorted waste, which not only negates the need for waste sorting typically being contracted for by local councils, but also improves the economics of their process and the available feedstock.

Another UK player is **Wilson Bio-Chemical**, previously Wilson Steam Storage, who specialise in steam-treatment to breakdown biogenic materials through their autoclave technology. Wilson have worked closely with the University of York and the Biorenewables Development Centre (BDC) to develop a 50kg pilot-scale autoclave to demonstrate production of biobutanol, ethanol, acetone and hydrogen, as well as various lab-based process engineering and systems biology projects to hone the initial autoclaving process and optimise enzymes for use in the fermentation stage (BDC, n.d; Wilson, 2016). In 2013, as part of call for bioenergy demonstrator projects - BioEnergy Sustaining the Future 2 (BESTF2), Wilson won a 36 month grant to prove the technology, producing n-butanol and hydrogen from MSW, on an industrial scale at a competitive price (ERA-NET, n.d.).

There is also potential for the production of other high value products which may be integrated into the above processes, or act as a standalone additions. For example **ReBio Technologies**, who specialises in the development of proprietary routes to key commodity platform biochemicals, including the design and development of biosynthetic pathways in a range of microbial hosts. They have experience developing industrial strains, based on Geobacillus host bacteria, for the production of bioethanol, and operate a demonstration plant in Guildford. There is an opportunity for development of a supply chain containing Fiberight and ReBio, and they are already working together as part of the IB Catalyst Late Stage feasibility project (CPI, 2015). ReBio are also engaged with the CPI and University of Bath in a lab-scale demonstration project to produce modified strains of Geobacillus for D-lactic acid production from waste-based feedstocks. Once proven, it is foreseen that this could be developed further into a scalable manufacturing process (ReBio, 2016; Clark, 2016). The current status of ReBio is uncertain, but it is nevertheless included here to acknowledge that technology and expertise that has already been developed could be exploited elsewhere.

There are also actors focusing on thermochemical platforms. UK-based **Advanced Plasma Power** (APP) has developed a proprietary gasification technology (Gasplama®) to process waste to syngas. They were recently awarded £11 million in the DfT Advanced Biofuels Demonstration Competition to develop and build a plant to turn municipal waste into biomethane for transport (APP, 2015).

4.3.5 Summary

Municipal solid waste provides a biorefinery feedstock with several attractive features, including availability (at national level), a low (or negative) cost, and an established waste collection supply chain. Looking at the biodegradable fraction of waste, it is plausible that at least up to 2.3 million tonnes of waste across the UK can be diverted from landfill towards a biorefinery. The low feedstock cost could provide an advantage over other higher cost feedstock options, and rewarding gate fees in the UK may be attractive to investors and overseas actors looking to site a biorefinery. However, there are also feedstock challenges. These include competing uses from existing waste treatment facilities and the growing capacity of these facilities – which is difficult to quantify and very regionally specific. Also, a biochemical biorefinery could face growing competition from thermochemical plants (gasification and pyrolysis). Further, the heterogeneity of MSW feedstocks requires a process that can be flexible to variations according to season and region; which in the future will provide a useful means to consider organic fractions from other waste (for example agricultural residues).

Locating a biorefinery according to feedstock availability requires a detailed analysis of the biggest feedstock potential – taking into account both availability (which is greatest around big metropolitan areas with a dense population) and competing uses. Areas with high rates of landfill, particularly biodegradable waste, are also attractive locations. Co-location with an existing facility, such an MBT, could represent an opportunity for location of biorefinery plants, as a point of aggregation, fractionation and pre-treatment. From a demand perspective, it makes sense to cluster with potential end users, such as refineries for fuel blending and chemical producers. Given the UK's strong chemical clusters, an area like the North East could be attractive and already hosts some key UK biorefinery actors around Wilton. The recent closure of the Air Products municipal project in Teesside may also be an opportunity for a biorefinery, however this requires further investigation.

The UK has local actors who are working towards commercialisation (currently pilot or demonstration scale), including Fiberight, Wilson Bio-Chemical and more recently Vireol. The focus of these actors is on cellulosic ethanol and n-butanol, which are anticipated to be high growth markets, but in future there may be opportunity for bio-based chemical production to supply locally based chemical companies or for export. Given the global availability of municipal waste, the opportunity for wider technology rollout also presents an attractive market proposition.

There is however competition, in particular from thermochemical actors both locally and overseas, both to access available feedstocks and to commercialise technology as quickly as possible to build a strong market position. Locally APP is building a plant to convert MSW to biomethane for transport application. Further afield, biochemical actor Abengoa has filed for bankruptcy and their demonstration plant is currently idle, however Canadian thermochemical actor Enerkem is operating their first commercial plant producing methanol and in the future ethanol, and is exploring opportunities in the UK. US-based Fulcrum Bioenergy is currently developing a plant to produce jet fuel via FT using MSW feedstocks. Other actors using MSW feedstocks are INEOS bio working on syngas fermentation and Advanced Plasma Power using plasma syngas clean-up technology to produce methane in Swindon, UK and AlterNRG producing syngas through plasma gasification of MSW (see section 2.7 Gasification).

The advantages and disadvantages of an MSW biorefinery, considering elements such as feedstock potential and attractiveness, ability to leverage a regional cluster, the presence of UK capabilities, and the UK's competitive position are summarised in Table 4-5.

Table 4-5 Overall assessment of MSW-based scenario
Green = strong | Amber = medium | Red = weak[27]

Criteria	Rationale	Score
Feedstock	+ >2.3 Mtpa BMW to be diverted from landfill + Gate fee of ~ £24 – 46 per tonne + Attractive sustainability credentials + Key competing uses: heat & power; compost; AD + Accessing feedstock may be challenging and require negotiations with waste management companies (especially for co-location with MBT)	Green
Regional clustering	*Supply* + Waste is distributed nationally, with mature waste collection infrastructure + Potential for co-location with an MBT plant - May need to transport waste to achieve required feedstock volumes - Feedstock supply cluster may not match demand cluster *Demand* + Potential to cluster close to existing refineries and chemical sectors	Amber
UK capabilities and industrial competitive position	+ Existing biochemical actors working towards commercialisation (e.g. Fiberight, Wilson Bio-Chemical, Vireol) + Thermochemical technology players (e.g. APP) + Well placed globally because of existing UK actors (but not yet commercial scale) + MSW is a global problem, scope for technology rollout if successful + High gate fees to encourage investment in UK waste - Competition from established overseas players – mainly thermochemical (e.g. Enerkem, Fulcrum Bioenergy, AlterNRG)	Green
Viability	MSW is a low cost and sustainable feedstock, with attractive gate fees, local availability spread across the UK and an established waste collection supply chain. Regulatory restrictions on the landfill of BMW create an opportunity to divert this to biorefineries, however more generally waste policy and regulation may also favour options other than a lignocellulosic biorefinery – such as advanced thermal treatment or anaerobic digestion. The competing use for this feedstock from existing or planned facilities also presents a challenge, particularly at a regional level. The UK has players operating at pilot scale, but they face competition from thermochemical players – both locally and overseas. While there is an opportunity for a waste-based biorefinery in the UK, it is vital that the existing fermentation-based technologies are supported to move to demonstration scale as quickly as possible.	Amber

[27] None of the criteria are evaluated as weak

4.4 Scenario 4: Dedicated biomass crop biorefinery in the West of the UK

4.4.1 Scenario introduction

Perennial energy crops such as Short Rotation Coppice (SRC) willow and Miscanthus are a domestic feedstock that is well suited to parts of the West of the UK[28]. SRC is better suited to Wales and the Northwest, while Miscanthus is better suited to the Southwest and a small area around Merseyside in the Northwest (ETI, 2015a; Hastings et al., 2014). SRC and Miscanthus has been successful in small areas in the UK and could be produced at higher regional densities by farmers with dedicated production. Other crops suited to the UK climate would be SRC poplar and forage grasses such as rye grass. Should high yields be achieved and the transport distances to biorefineries be short, then perennial energy crops could be a potentially attractive domestic feedstock for a biorefinery in the west of the UK. However, despite sporadic support from Government Energy Crop Schemes, the uptake of perennial energy crops has been limited due to lack of specialist planting and harvesting equipment, previously poor establishment and management practises, limited local supply infrastructure, high upfront establishment costs and low economic viability for farmers (NNFCC, 2012). A perennial energy crop biorefinery would need to offer a very compelling case for these barriers to be overcome.

Besides the perennial energy crop potential in the west of the UK, the area in the Northwest around the Mersey River has a considerable chemical cluster which could represent important opportunities downstream of the biorefinery.

4.4.2 Feedstock assessment

Dedicated perennial energy crops, primarily Miscanthus and Short Rotation Coppice (e.g. willow and poplar), have been grown in the UK since the 1970s (Lawson et al., 1989). Two rounds of Energy Crop Schemes between 2000-2006 and 2008-2013 provided establishment grants for perennial energy crops, which led to the planting of around 11,300 ha (NNFCC, 2012), of which roughly two-thirds was Miscanthus and one-third Short Rotation Coppice (mostly willow and some poplar). The currently planted area is just below 10,000 ha (Defra, 2015). Assuming an average yield of 10 dry tpa/ha, the energy crop annual production from this land area equated to about 100,000 dry tpa (Defra, 2015). Overall, in 2014 around 122,000 ha of UK agricultural land were used for bioenergy (Defra, 2015).

The Food and Environment Research Agency and the agricultural consultants ADAS identified over 0.85 Mha of ‘idle’ non-agricultural land, along with up to 2.9 Mha of agricultural land where perennial energy crops could be competitive. Similarly the CCC reviewed estimates in its 2011 bioenergy review and suggested a top range of 0.8 Mha in its assessment. A more recent suggestion of the Energy Technology Institute (ETI) of 0.5 to 1.2 Mha for 2030 is in line with the estimates by the CCC (ETI, 2015).

Other perennial energy crops besides SRC and Miscanthus could be grown in the UK, such as high sugar grasses, like rye grass, and Eucalyptus. The species of energy crops grown so far are well-suited for heat and power generation, other energy crops, like rye grass, may be better suited for

[28] The west of the UK is here defined as Cornwall, Devon, Somerset, Wales, west Midlands, wider Manchester and Liverpool area and Cumbria.

biorefineries depending on the type of biorefinery technology and products. Researchers in Wales have been exploring the establishment of a biorefinery based on rye grass which could be competitive with East Anglican sugar beet (Chemistry Innovation KTN *et al*. 2009)

While there is potentially land that could be designated for energy crops, experience so far indicates that scaling the energy crop industry is challenging, especially in providing a compelling case to farmers for planting a perennial crop. Ramping up a large scale industry will take considerable time (in developing skills, personnel, specialist machinery and propagation material), as well as the time lag between planting and first harvests (which for SRC are typically every 3 years). In addition sustainability concerns over land use change have hampered policy enthusiasm on energy crops (currently there is no planting grant support for energy crops). Finally, for energy crops to be viable would require yields higher that the 10 dry tpa/ha mentioned above, and effective localised logistics. Planting densities around a particular location, yields and allowable transport distances will constrain the capacity of a biorefinery. It could however be possible to combine energy crops with other biomass feedstocks (e.g. straw) in regions where these other feedstocks are generated.

4.4.3 Regional cluster assessment

There are favourable growing conditions for energy crops in the West of England see Figure 4-9, in particular for SRC willow in the wetter areas in the North West from Manchester to Cumbria as well as Wales, and Miscanthus in the South-West and to a smaller extend in the Northwest around Merseyside (ETI, 2015a; Hastings *et al*., 2014). However, much of the best yielding areas are either under existing forestry (as in Wales), or on steeply slopping land, or protected areas such as National Parks – various constraint masks can be applied that significantly reduce the likely available area in the West of the UK in particular. However, some smaller areas with high yields still remain, for example around Merseyside in the Northwest for Miscanthus and areas between Manchester and Lancaster in the Northwest for SRC (see Figure 4-9).

The Northwest has a strong concentration of chemical manufacturing and is the largest chemical cluster in the UK with a turnover of £10 billion (Chemicals Northwest, 2016). Around 60% of the world's largest 50 chemical companies are active in the region (CIA, 2009). These include among others BASF, Glaxo Smith Kline (GSK), INEOS, Croda and Lucite International.

Fuel products could be sold to the Stanlow refinery in Cheshire supplying 16% of UK transport fuel, close to the Runcorn chemical complex (Essar Oil, 2016). The cluster also contains one of the largest ports in the UK, Liverpool port on the Mersey River. Other companies such as Biobags and Innovia Films (mentioned in section 4.2.3) could form part of this cluster as well.

Conversion technologies and products are assumed to be very similar to the co-located scenario using pellets (see section 4.1), but would have to be designed and tested with each specific energy crop. The existence of several companies downstream in the value chain suggests that overall the Northwest of the UK could have a well-developed route to market and chemical cluster to support a commercial biorefinery in the region. However, this would need to be analysed in more detail depending on the exact products and demand in the cluster.

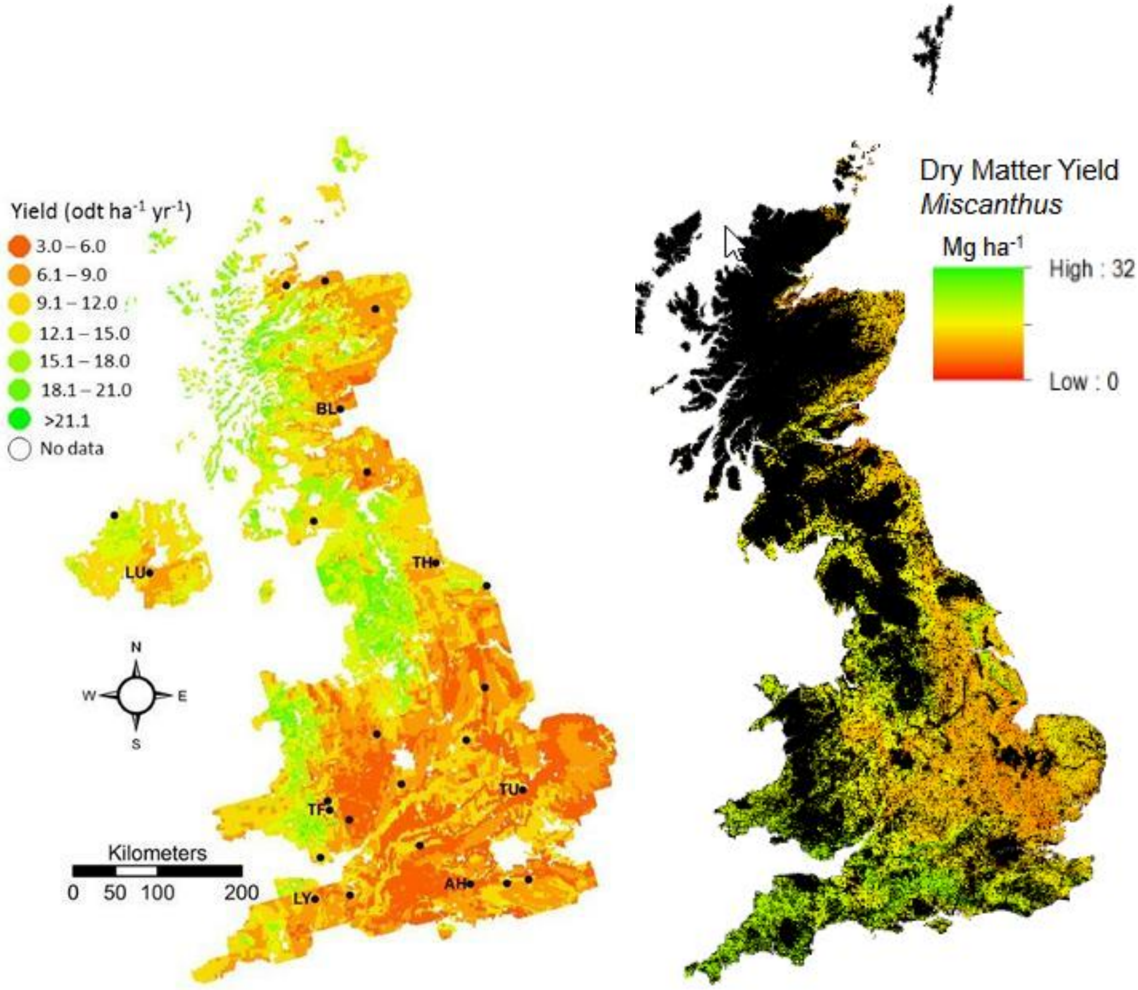


Figure 4-9 UK map of SRC willow and Miscanthus yield potential (unconstrained areas)
(University of Southampton, 2012; UKERC, 2012)

4.4.4 UK capabilities and competitive position

The UK has experience with energy crops, and commercial players in the area (i.e. growers, grower cooperatives and intermediaries). However, production costs for energy crops remain relatively high in the UK (of the order of £90/dry tonne for chipped material and £140/dry tonne for pelletised material), which has implications in terms of the value biorefinery products would have to achieve and the level of support required.

There has not been much interest and research on energy crop based biorefineries in the UK, as the primary focus for energy crops has been in heat and power applications, with other minor uses in e.g. animal bedding. A few years ago the opportunity of a rye grass biorefinery was explored in Wales (Chemistry Innovation KTN et al. 2009). Rye grass was found to be theoretically competitive with East Anglian sugar beet as a feedstock. This study found that high-sugar grasses grown on 50,000 ha of recovered temporary grassland as a feedstock could reverse the decline in Welsh farming and diversify production without changing the landscape, affecting food production or utilising GM technology, and that a biorefinery in Wales could be well-placed to serve large clusters in the Mersey basin/M62 corridor, Birmingham area or Bristol/M4 corridor depending on its location.

4.4.5 Summary

Growing dedicated energy crops in the West of the UK for a biorefinery represents an interesting opportunity as SRC willow has been planted successfully in the Northwest and Miscanthus in the Southwest of the UK before as further detailed in Table 4-6. It would require selecting crops with suitable characteristics for conversion processes and could only be attractive from a cost perspective if high yields and efficient logistics could be achieved and high yield areas would be selected. However, the main barrier lies in convincing farmers (or other land owners) to plant energy crops, especially given there is currently no policy support for what amounts to a very different style of farming. The allowable scale of a biorefinery from dedicated energy crops would strongly depend on the possible supply of energy crops. Besides the upstream opportunities and barriers, there is currently limited global expertise, and no UK capabilities, in using perennial energy crops in a conversion process to generate higher value biofuel or biochemical products at commercial scale. Establishing a biorefinery in the Northwest has the advantage of a large local downstream chemical cluster that could bulk chemicals, with an existing oil refinery potentially able to integrate bio-based fuel products. This would however require exploring the exact downstream opportunities further. The Northwest has high yield potential for Miscanthus, but areas are likely a limiting factor, and further North towards Cumbria a good high yield potential for SRC willow.

Table 4-6 Overall assessment of dedicated biomass crop scenario

Green = strong | Amber = medium | Red = weak[29]

Criteria	Rationale	Score
Feedstock	+ Domestic feedstock with potentially high volumes available depending on location, yield and logistics + Potential to select crops with suitable characteristics + Some local feedstock sourcing activities already in the North West with Iggesund paper mill contracting directly with SRC growers in Cumbria, and with local Miscanthus growers for heating applications in South-West - Significant challenges in establishing a supply chain - Will take decades with current policy and prices to scale up to very large supply volumes, and limits to growth imposed by the crop itself - No current policy support for energy crops - Feedstock cost higher than other biomass options	(Amber)

[29] None of the criteria are evaluated as weak

Criteria	Rationale	Score
Regional clustering	+ Existing SRC growers in Cumbria + The Northwest of the UK has the largest chemical cluster in the UK with companies that could require bulk quantities of sugars or platform chemicals + Large oil refinery located on Merseyside for integration of fuel products + Large port complex for the export of possible chemical end products - Currently few energy crop growers in West of England, very few in Wales - South West England has very limited port infrastructure, and no major chemicals cluster	
UK capabilities and industrial competitive position	+ Commercial experience in growing and supplying energy crops. Other relevant capabilities will depend on the energy crop type and end-products - Limited global and no UK (quasi-)commercial capability in pre-treatment or conversion of wood-based feedstocks + Pilot scale activities in the UK: Green Biologics who are venturing into a pilot scale lignocellulosic biorefinery, Bio-Sep Ltd. who are piloting a fractionation technology and Nova Pangea who are working on a thermo-chemical wood to sugars route + Strong downstream chemical sector in the Northwest, with some interest in bio-based products	
Viability	Dependent on energy crop type (compatibility with UK technical capabilities), allowable scale based on energy crop availability, cost of crop vs value of products, and timely establishment of energy crop infrastructure (unless “stranded” energy crops are available). The regional cluster for downstream products represents a potential opportunity, but the UK has no commercial capabilities in converting energy crops to higher value chemical products except some companies working on pilot scale facilities.	

5 Synthesis and conclusions

The market for biorefinery products was estimated at £262 billion in 2014, and **estimated to grow at 14% p.a.** in the period to 2020. Biological routes dominate the biorefining sector, contributing around half of the total market value, while thermo-chemical and physico-chemical routes make up the other half. The biorefining sector is driven by climate change targets, the opportunity to provide more sustainable products, alternatives to fossil fuel derived products, better performing and cheaper products in some cases, and the opportunity to build an internationally competitive sector.

Biorefining of lignocellulosic biomass is still a **nascent industry** characterised by a variety of feedstocks, conversion technologies and products. Only a few conversion routes such as ethanol production from agricultural residues or methanol production from MSW are currently at commercial scale, and there is still a very **large potential for innovation** within these routes and in many other feedstocks, routes and products.

In biological routes there is potential for innovation in pre-treatment, sugar conversion as well as lignin valorisation. Pre-treatment is an important area for innovation as energy use is typically high, enzyme costs can be reduced, quality of products (lignin and sugars) can be improved and inhibitors that impact the downstream fermentation process can be prevented. Fermentation has significant innovation potential as many interesting products are at an early TRL stage, new products could be developed, and those products at later TRL stages have been produced from starch or sugar derived products, with innovation needed to produce them from lignocellulosic sugars. Lignin valorisation has a significant innovation potential as the heterogeneous structure of lignin makes processing challenging and only a few global actors have successfully addressed some of these challenges.

Even though the UK does not have any commercial scale biorefinery at the moment[30], the UK has both **strong academic and commercial capabilities** and interest across the biorefining chain (Table 5-1).

Table 5-1 Examples of UK academic and industry players in biorefining

	Academic Players	Industry players
Pre-treatment	Imperial College London University of Bath University of Edinburgh University of Southampton University of York	Advanced Extraction Technology Advanced Microwave Technologies Biome Technologies Bio-Sep Fiberight Plaxica SERE-Tech Innovation Wilson Bio-Chemical

[30] Excludes production of ethanol from sugar and starch crops and biodiesel from oils and fats

	Academic Players	Industry players
Fermentation (including biocatalysis & synthetic biology)	Durham University Heriot-Watt University University of Bath University of Cambridge University of Edinburgh University of Manchester University of Nottingham University of Strathclyde University of York University College London	Butamax Celtic Renewables CHAIN Biotechnology Croda C-Tech Innovation Fiberight Green Biologics GSK Ingenza Itanconix Marlow Foods ReBio Technologies Vireol Wilson Bio-Chemical
Catalytic conversion of sugars	Aston University University of Huddersfield University of Liverpool University of York	BASF Biome Bioplastics / Biome Technologies Johnson Matthey Plaxica
Lignin valorisation	Imperial College London University of Dundee University of Warwick University of York	Biome Bioplastics

Academic and industrial strengths in the UK cover pre-treatment and fermentation (including biocatalysis and synthetic biology), and to a lesser extent catalytic conversion of sugars and lignin valorisation. There is however only a limited number of examples of technologies that have been demonstrated past the lab scale, so there is opportunity and **need to support technology development** through pilot and demonstration stages.

The broad range of products from **fermentation** technology provides a significant opportunity for UK industry. Companies such as Butamax, Green Biologics and Fiberight and Wilson Bio-Chemical are already operating at pilot scale, and Fiberight is operating at demonstration scale in the US using their pilot technology. Actors such as CHAIN Biotechnology, Ingenza and C-Tech Innovation are active in microbial development and can support increased commercial activity and demonstration. Organisations such as the CPI, the process arm of the High Value Manufacturing Catapult, the BDC, and the IBIoC are instrumental in moving technologies into pilot scale, and supporting their development activities. And there is research excellence in institutions like the Centre of Excellence for Biocatalysis, Biotransformations and Biocatalytic Manufacture (CoEBio3) based at the University of Manchester, The Centre for Bioactive Chemistry at Durham University, the Green Chemistry Centre of Excellence at York University, and other universities like Nottingham, Cambridge, Bath, Strathclyde,Edinburgh, and several others. Green Biologics, Celtic Renewables and CHAIN Biotechnology are examples of commercial spin-outs from academic research. Academic-industry collaboration to develop process routes is active, much of it funded through the IB Catalyst Programme. There is also an interest from product end users, and companies such as GSK and Marlow Foods are active in projects with SMEs and researchers.

The UK has around ten technology developers (see Table 5-1), especially SMEs, working on **pre-treatment and hydrolysis** technologies, with Fiberight, Bio-Sep, Plaxica and Wilson Bio-Chemical engaged in pilot activities. There is also a strong focus on collaboration between industry and academia, to further test technologies at lab scale and overcome key technical challenges. Much of this activity is also supported by the CPI, BDC and IBioIC.

Technologies for the **catalytic conversion of sugars** are being developed globally, driven by interest in bio-based chemicals such as HMF and FDCA. UK-based activity is limited, but technology developers, such as Plaxica and Biome Bioplastics, are working at pilot and lab scale. Johnson Matthey is also potentially a strong player in UK biorefining, and it's recently announced collaboration agreement with US-based Virent highlights the potential to actively partner with locally based technology developers.

Lignin valorisation as part of biorefining is still in the early stages of development, and a potential area of opportunity for UK innovation. There is strong academic research in the area at institutes such as Imperial College London, and the Universities of Dundee and Warwick. Biome Bioplastics, a UK-based SME, is working with Warwick's Centre for Biotechnology and Biorefining. This lab scale activity provides a base for pilot activity, supported by actors such as the CPI and BDC.

The launch of the IB Catalyst Programme, supported by InnovateUK, BBSRC and EPSRC has been instrumental in supporting much of this research and collaboration activity – and it is vital that it continue to do so, in order to create a strong base for future demonstration activity. However, additional support is needed to create demonstration activity.

Given the sizeable and growing biorefining sector and the existing academic and commercial UK capabilities across the biorefining chain, there could be **opportunity to and value in developing biorefining demonstration activities** in the UK. A scenario based approach was used to explore the attractiveness of different demonstration possibilities based on different feedstocks and locations. Four scenarios that have been identified at an LBNet workshop in April 2016 were assessed in the frame of this report. These included the co-location of a lignocellulosic biorefinery with a biomass power station, a straw biorefinery in Eastern England, a MSW-based lignocellulosic biorefinery and a dedicated biomass crop biorefinery in the west of the UK. Each scenario is characterised by opportunities and barriers as summarised in Table 5-2.

Table 5-2 Opportunities and barriers of four biorefinery scenarios

Scenario 1: Co-location of a lignocellulosic biorefinery with a biomass power station	Scenario 2: Straw biorefinery in Eastern England
+ Established large scale feedstock import and distribution infrastructure - Very limited UK resource, dependent on sustainable imports + Potential for large scale and integration with	+ Potentially low cost and sustainable feedstock ± Some, but limited UK feedstock potential, but potential globally (UK technology export) + UK experience with straw logistics for power plants

Scenario 1: Co-location of a lignocellulosic biorefinery with a biomass power station	Scenario 2: Straw biorefinery in Eastern England
power plant possibly offsetting relatively high feedstock cost - Limited global and no UK commercial capability in pre-treatment or conversion of wood-based feedstocks + Existing UK R&D capability in pre-treatment (e.g. BDC, CPI, pilot plant by Bio-Sep) and fermentation (e.g. planned pilot by Green Biologics) – all capable of using woody biomass + Large chemical and petro-chemical pole in the Northeast with end-users potentially interested in biochemical building blocks and biofuels (e.g. Croda, BASF or the Total and ConocoPhillips refineries) ± The viability of the integration with the biomass power plant depends on the level of integration and the business model	+ Commercial straw biorefineries are being built globally, so there is a potential to attract international players to complement UK ones + Vireol together with Inbicon is developing a lignocellulosic ethanol plant using straw in Humberside + Existing UK R&D capability in pre-treatment (e.g. BDC, CPI, pilot plant by Bio-Sep) and fermentation (e.g. planned pilot by Green Biologics) – all capable of using straw + Large chemical and petro-chemical pole in the Northeast with end-users potentially interested in biochemical building blocks and biofuels (e.g. Croda, BASF or the Total and ConocoPhillips refineries) + Potential co-location benefits with existing 1st generation ethanol plant
Scenario 3: MSW-based lignocellulosic biorefinery	**Scenario 4: Dedicated biomass crop biorefinery in the west of the UK**
+ BMW is a low cost, sustainable feedstock that is available widely in the UK - Feedstock accessibility and competition might be an issue ± UK regulation favours the use of BMW rather than landfilling and encourages investment into alternative uses, but current waste policies do not clearly define biorefining as a recycling option. + Existing UK actors such as Fiberight, Wilson Bio-Chemical or APP currently operating at pilot and demonstration scale + Wide global market potential for UK technology - Competition from players outside the UK already operating at commercial scale using MSW (e.g. Enerkem)	+ Perennial energy crop experience in parts of the West of the UK, and potential high domestic volumes available depending on yields and location - No existing policy support and establishing a supply chain would be very challenging ± High SRC potential in the Northwest, existing SRC growers, but SRC more challenging feedstock for biological routes and Miscanthus has limited potential in the Northwest + Largest chemical cluster in the UK is situated in the Northwest with a potential demand for bio-based chemical inputs - The Southwest, the most suitable area for Miscanthus, has limited chemical clusters or port facilities + Existing UK R&D capability in pre-treatment (e.g. Bio-Sep could use Miscanthus)

Table 5-2 shows that each scenario is only viable under certain conditions and if certain barriers could overcome, and UK chemical clusters in the Northeast or Northwest could provide an outlet for bio-based chemical building blocks.

A set of high-level conclusions can be drawn from the assessment of the four scenarios:

- Co-location of a biorefinery next to a biomass power station is appealing due to the existing feedstock and power plant infrastructure. But, pellets are a relatively expensive feedstock and there is limited global or UK experience using pellets in a biological conversion process. Also, matching the scales and interests of biomass power and biorefining activities is non-trivial. Nonetheless, the level of maturity and co-location potential of wood-based biorefineries could represent an opportunity for UK innovation and existing UK activities, for example pre-treatment activities currently at pilot scale.
- Straw is an attractive feedstock because of experience and cost, though the potential is limited. Straw is the only feedstock, among the four scenarios, that has been used in commercial scale facilities globally and for which there is a UK lignocellulosic ethanol plant in the design phase. The UK could benefit from lignocellulosic biorefinery developers with commercial experience and potentially combine this with UK pre-treatment, fermentation or catalytic upgrading of sugars capabilities. Existing supply chain experience with straw for power generation in the UK could also be useful.
- Producing bio-based products from UK MSW is a favourable scenario with respect to sustainability, feedstock costs and waste policy objectives. A MSW-based biorefinery demo plant could support existing UK actors in their path to commercialisation and give the UK a potential competitive advantage in biological MSW-based biorefinery technologies. However, it would require identifying a site with available and accessible feedstock that is not already contracted to competing uses.
- A biorefinery based on dedicated perennial crops in the West of the UK is attractive from the perspective of having a dedicated feedstock, but poses significant challenges in terms of engaging farmers to grow the crops, establishing dedicated supply chains, and potentially dealing with land use change issues. Overcoming these issues would require careful planning, including finding sufficient land with high yield potential in proximity of the plant, and significant public sector support in establishing the feedstock supply chain.

There are a **wide range of biorefinery activities in the UK at lab or pilot scale**. While broad basic and applied research relevant to the area remains important, the sector could benefit from **greater emphasis on the commercialisation and scale up of activities**. The establishment of a “UK Biorefinery Forum”, facilitated by BEIS initially for example, and focused on activities aimed at commercialisation and deployment of biorefining activities, could provide a vehicle for biorefinery actors to elaborate activities and actions in support of the sector and develop a “roadmap” / “action plan”. Research could then also be tailored to help meet the commercialisation and deployment challenges. A “UK Biorefinery Forum” would complement the existing “Industrial Biotechnology Leadership Forum (IBLF)”. There also appears to be scope, given the range of activities and players, to set up a “UK Biorefinery Demonstration Competition”, somewhat along the lines of the DfT Advanced Biofuels Demonstration Competition. This would stimulate the UK biorefinery community to address the scale up challenge, potentially in collaboration with international players. LBNet’s activities would be an important element in establishing the case for such a competition, especially in relation to the readiness of the UK sector and the scale and objectives the competition could target. In addition, a target for advanced biofuels in the UK would send positive market signals to the biorefining community, and there could also be a role for government in creating additional market pull to stimulate the sector early on, through for example procurement programs like the US BioPreferred Program.

6 List of references

6.1 Introduction

House of Lords (2014) “Waste or resource? Stimulating a bioeconomy”, Science and Technology Select Committee. Available www.publications.parliament.uk/pa/ld201314/ldselect/ldsctech/141/141.pdf

PRNewswire (2016), “Global Biorefinery Market Size, Share, Development, Growth and Demand Forecast to 2020 - Industry Insights by Technology (Industrial Biotechnology, Physico-Chemical and Thermochemical)“. Available www.prnewswire.com/news-releases/global-biorefinery-market-size-share-development-growth-and-demand-forecast-to-2020--industry-insights-by-technology-industrial-biotechnology-physico-chemical-and-thermochemical-300214777.html

Scottish Enterprise (2015), “The Biorefinery roadmap for Scotland”. Available www.scottish-enterprise.com/knowledge-hub/articles/comment/biorefinery-roadmap

6.2 Technology assessment

Pre-treatment, hydrolysis and lignin recovery

Advanced Microwave Technologies (2016) “When the oil runs out – head for the woods”. Available www.advancedmicrowavetechnologies.com/2016/08/02/when-the-oil-runs-out-head-for-the-woods/

AET (2016) “Biofuels & green chemistry”. Available www.advancedextractiontechnology.co.uk/biofuels-green-chemistry

Altenergymag (2016) “Commercialising the biorefinery scenario”. Available www.altenergymag.com/news/2016/05/04/commercialising-the-biorefinery-scenario/23556/

Bio-Sep (2016) “Technology”. Available http://bio-sepltd.com/technology/

Chiaramonti, D., Prussi, M., Ferrero, S., Oriani, L., Ottonello, P., Torre, P., Cherchi, F., 2012. “Review of pretreatment processes for lignocellulosic ethanol production, and development of an innovative method”, *Biomass and Bioenergy*, vol. 42, no. 1, pp. 25-35

E4tech, RE-CORD and WUR, 2015. *“From the Sugar Platform to biofuels and biochemicals”.* Final report for the European Commission, contract No. ENER/C2/423-2012/SI2.673791

Harmsen, P.F.H. , Huijgen, W. J.J., Bermudez, L. M., Bakker, R.R.C., 2010. Literature review of physical and chemical pretreatment processes for lignocellulosic biomass, Wageningen Univeristy, Netherlands

Garcia, A., Alriols, M.G. and J. Labidi, 2014. “Evaluation of different lignocellulosic raw materials as potential alternative feedstocks in biorefinery processes”, *Industrial Crops and Products*, vol. 53, no. 1, pp. 102– 110

Lin, Y. and Tanaka, S., 2006. “Ethanol fermentation from biomass resources: current state and prospects”, *Applied Microbiology & Biotechnology*, vol. 69, no. 1, pp. 627–642

LBNet, 2016a. "Business Interaction Vouchers – Projects funded by LBNet" Available https://lb-net.net/wp-content/uploads/2016/05/BIV-funded-by-LBNet-May2016.pdf

LBNet, 2016b. "Proof of Scenario Funds – Projects funded by LBNet" Available https://lb-net.net/wp-content/uploads/2016/05/PoC-funded-by-LBNet-May-2016.pdf

Plaxica, 2016. "Pre-Treatment". Available www.plaxica.com/technology/pre-treatment/

Ragauskas, A.J. et al., 2014. "Lignin valorization: Improving lignin processing in the biorefinery", *Science*, vol. 344, no. 1, pp. 709-719

Fermentation

Beta Renewables (2013) "Proesa™ / Biorefinery". Available www.betarenewables.com/proesa/biorefinery

Centre for Process Innovation (2015) "Fiberight Ltd and CPI launch project to produce sugar from landfill waste from Industrial Biotechnology". Available www.uk-cpi.com/news/fiberight-ltd-and-cpi-launch-project-to-produce-sugar-from-landfill-waste-from-industrial-biotechnology/

CHAIN Biotechnology (2016) "Technology Platform". Available http://chainbiotech.com/technology/

E4tech, RE-CORD and WUR (2015) *"From the Sugar Platform to biofuels and biochemicals".* Final report for the European Commission, contract No. ENER/C2/423-2012/SI2.673791

Liu, Z.L. and Blaschek, H.P. (2010) "Biomass conversion inhibitors and in situ detoxification", *Biomass to biofuels: Strategies for global industries*, eds O.A. Vertès, H.P. Blaschek and H. Yukawa, John Wiley and Sons, West Sussex, pp. 233-259

Green Biologics (2016) *Green Biologics Named in the 2015 Global Cleantech 100* [Press release]. Available www.greenbiologics.com/pdfs/pr-01292016.pdf

Lokare, K. (2016) 50 Hot Bio-Based Companies, 50 Quick Takes, *Renewable Energy World*, 29 July. Available www.renewableenergyworld.com/articles/2016/07/50-hot-bio-based-companies-5-quick-takes.html

Pacific Northwest National Laboratory & National Renewable Energy Laboratory (2004), Top Value Added Chemicals from Biomass, *U.S. Department of Energy*, http://ascension-publishing.com/BIZ/HD49.pdf

Unrean, P. (2016) "Bioprocess modelling for the design and optimization of lignocellulosic biomass fermentation", *Bioresources and Bioprocessing*, vol. 3, no. 1, pp. 1-9

Catalytic conversion of sugars

BCC Research (2016) "Global Furfural Market on the Move with Double Digit Growth". Available www.bccresearch.com/pressroom/avm/global-furfural-market-on-the-move-with-double-digit-growth

Biomass Conversion Interagency Working Group (2011) "Biomass conversion: Challenges for federal research and commercialization". Available http://biomassboard.gov/pdfs/biomass_conversion_report.pdf

Centi G., Lanzafame P. and Perathoner S. (2011) “Analysis of the alternative routes in the catalytic transformation of lignocellulosic materials”, *Catalysis Today*, vol. 167, no. 1, pp. 14-30

Centre for Process Innovation (2015) “Fiberight Ltd and CPI launch project to produce sugar from landfill waste from Industrial Biotechnology”. Available www.uk-cpi.com/news/fiberight-ltd-and-cpi-launch-project-to-produce-sugar-from-landfill-waste-from-industrial-biotechnology/

Dashtban, M., Gilbert, A. and Fatehi, P. (2012) “Production of furfural: Overview and challenges”, *Journal of Science & Technology for Forest Products and Processes*, vol. 2, no. 4, pp. 44-53

Davda, R.R. et al. (2005) “A review of catalytic issues and process conditions for renewable hydrogen and alkanes by aqueous-phase reforming of oxygenated hydrocarbons over supported metal catalysts”, *Applied Catalysis B: Environmental*, vol. 56, no. 1, pp. 171-186

E4tech and TUHH (2016) “Advanced Liquid Biofuels for Transport Innovation Outlook”*, International Renewable Energy Agency* (awaiting publication)

E4tech, RE-CORD and WUR (2015) *“From the Sugar Platform to biofuels and biochemicals”.* Final report for the European Commission, contract No. ENER/C2/423-2012/SI2.673791

Fernanda Neira D’Angelo, M. (2014) “Aqueous Phase Reforming of bio-carbohydrates: Reactor engineering and catalysis”, Technische Universiteit Eindhoven. Available https://pure.tue.nl/ws/files/3781775/780924.pdf

Future Market Insights (FMI) (2016), “Bio-based levulinic acid market: global industry analysis and opportunity assessment 2014-2020”. Available www.futuremarketinsights.com/reports/bio-based-levulinic-acid-market

IBioIC (2016b), “Case Study GSK”. Available www.ibioic.com/Case%20Study_GSK.htm

ICIS (2012), “Plasticizers”. Available https://s3-eu-west-1.amazonaws.com/cjp-rbi-icis-compliance/wp-content/uploads/2013/08/Plasticizers-Methodology.pdf

Kovacs-Schreiner, k. (2015) “Lignocellulose to Polyesters”. Available https://connect.innovateuk.org/documents/3285671/27485925/12.+KTN_IB_Catalyst_Workshop_June_2015_Presentation_Biome.pdf/b10ca8ad-e829-4205-8311-b9ed59df1b81

Lerner, R. (2015) “Bioplastic Market Overview and the Road to Hundred Percent bio-PET”, Virent. Available www.bio.org/sites/default/files/WorldCongress/Ralph%20Lerner.pdf

Machado et al. (2016) “Literature review on furfural production from lignocellulosic biomass”, *Natural Resources*, vol. 7, no. 1, pp. 115-129

Matson et al. (2011) “One-Pot Catalytic Conversion of Cellulose and of Woody Biomass Solids to Liquid Fuels”, *Journal of the American Chemical Society*, vol. 133, no. 35, pp. 14090-14097

National Advanced Biofuels Consortium (2011) “Catalysis of Lignocellulosic Sugars Process Strategy”. Available www.nabcprojects.org/catalytic_sugar.html

Pang, J. et al. (2012) “Catalytic conversion of cellulose to hexitols with mesoporous carbon supported Ni-based bimetallic catalysts”, *Green Chemistry*, vol. 14, no. 1, pp. 614-617

Song, Z. et al. (2015) “Selective conversion of cellulose to hexitols over bi-functional Ru-supported sulfated zirconia and silica-zirconia catalysts”, *Frontiers of Chemical Science and Engineering*, vol. 9, no. 4, pp. 461-466

SusFuelCat (2016) “Johnson Matthey PLC”. Available http://susfuelcat.eu/consortium/johnson-matthey-plc-jm-,-united-kingdom

Virent (2010) “Virent and Shell start world’s first biogasoline production plant”. Available www.virent.com/news/virent-and-shell-start-world%E2%80%99s-first-biogasoline-production-plant/

Wang, A., Li, C., Zheng, M. and Zhang, T. (2012) “Heterogeneous Catalysts for Biomass Conversion”, *The Role of Green Chemistry in Biomass Processing and Conversion* (eds H. Xie and N. Gathergood), John Wiley & Sons, Inc., Hoboken, NJ, USA

Wang, G. et al. (2016), “Highly selective conversion of cellobiose and cellulose to hexitols by Ru-based homogeneous catalyst under acidic conditions”, *Industrial & Engineering Chemistry Research*, vol. 55, no. 18, pp. 5263-5270

Wei et al. (2014) “Renewable hydrogen produced from different renewable feedstock by aqueous-phase reforming process”, *Journal of Sustainable Bioenergy Systems*, vol. 4, no. 1, pp. 113-127

Xia, Q. et al. (2016) “Direct hydrodeoxygenation of raw woody biomass into liquid alkanes”, *Nature Communications*, vol. 7, no. 1.

Wang et al. (2012) “Heterogeneous catalysts for biomass conversion“, The Role of Green Chemistry in Biomass Processing and Conversion, eds H. Xie and N. Gathergood, John Wiley and Sons, West Sussex, pp. 114-116

Valorisation of lignin

Biome Plastics, n.d. “Biome Bioplastics An Exploration of Lignin”. Available www.biometechnologiesplc.com/uploads/files/Biome_Lignin_Handout_WEB.pdf

Crestini, C. (n.d.) “Analytical techniques in lignin characterization: advances and challenges”, Tor Vegata University, Rome. Available http://bit.ly/2b2Fu0s

LBNet (2016a), “Business Interaction Vouchers – Projects funded by LBNet” Available https://lb-net.net/wp-content/uploads/2016/05/BIV-funded-by-LBNet-May2016.pdf

LBNet (2016b), “Proof of Scenario Funds – Projects funded by LBNet”. Available https://lb-net.net/wp-content/uploads/2016/05/PoC-funded-by-LBNet-May-2016.pdf

Linger, G. et al. (2014) “Lignin valorization through integrated biological funneling and chemical catalysis”, *Proceedings of the National Academy of Sciences of the United States of America*, vol. 111, no. 33, pp. 12013-12018

Ragauskas, A.J. et al. (2014) “Lignin valorization: Improving lignin processing in the biorefinery”, *Science*, vol. 344, no. 1, pp. 709-719

Rinaldi, R. et al. (2016) “Paving the way for lignin valorisation: Recent advances in bioengineering, biorefining and catalysis”, *Angewandte Chemie*, vol. 55, no. 29, pp. 8164-8215

Strassberger, Z., Tanase, S. & Rothenberg, G. (2014) “The pros and cons of lignin valorisation in an integrated biorefinery”, *Royal Society of Chemistry Advances*, vol. 4, no. 1, pp. 25310-25318

Valmet (2016) “Valmet and Biochemtex to collaborate in developing technology for lignin derived biochemicals”. Available www.valmet.com/media/news/press-releases/2016/valmet-and-biochemtex-to-collaborate-in-developing-technology-for-lignin-derived-biochemicals/

Vishtal, A. and Kraslawski, A. (2011) “Challenges in industrial applications of technical lignins”, *BioResources*, vol. 6, no. 3, pp. 3547-3568

VTT (2016) “Value from lignin – Promises, challenges and breakthroughs” (webinar). Available www.vttresearch.com/services/bioeconomy/biobased-platform-chemicals/extracting-value-from-lignin/lignin-separation-and-characterisation

Werhan, H. (2013) “A Process for the Complete Valorization of Lignin into Aromatic Chemicals based on Acidic Oxidation”. Available http://e-collection.library.ethz.ch/eserv/eth:7017/eth-7017-02.pdf

Pyrolysis

IEA Bioenergy Task 34 (2012). Available www.pyne.co.uk/?_id=76

Bridgwater A.V. (2009), “ Life Cycle and Techno-Economic Assessment of the North East BtL Project: Thermal Processes for Biofuels”, NNFCC 08-018

Bridgwater A.V. (2011),” Review of fast pyrolysis of biomass and product upgrading”, *Biomass and Bioenergy*, vol. 38, no. 1, pp. 68-94

BTG (2016), “Bio-materials & chemicals”. Available www.btgworld.com/en/rtd/technologies/bio-materials-chemicals

Carbon Trust (2016), “Technology Innovation Needs Assessment: Bioenergy”. Awaiting Publication.

E4tech (2016), Carbon Trust TINA – Bioenergy refresh.

EMPYRO (2015). Available www.empyroproject.eu/index.php

Envergent (2016), “RTP for Transportation”. Available www.envergenttech.com/technology/transporation-fuels/

Fortum (2016), “Bio-oil to replace fossil fuels”. Available www.fortum.com/en/products-and-services/biooil/pages/default.aspx

IRENA (2016), “Technology Innovation Outlook for Advanced Liquid Biofuels”. Awaiting publication.

Karatzos, S., McMillan, J.D. and J.N. Saddler (2014), “The Potential and Challenges of Drop-in Biofuels”, IEA Bioenergy Task 39, available http://task39.sites.olt.ubc.ca/files/2014/01/Task-39-Drop-in-Biofuels-Report-FINAL-2-Oct-2014-ecopy.pdf.

Lehto, J. *et al.* (2014), “Review of Fuel Oil Quality and Combustion of Fast Pyrolysis Bio-Oils from Lignocellulosic Biomass,” *Applied Energy,* vol. 116, no. 1, pp. 178-190.

Mufson, A. (2014), “Billionaire Vinod Khosla’s Big Dreams for Biofuels Fail to Catch Fire,” *Washington Post.* Available http://wapo.st/1CuVIX2.

NER300.com (2013), "Pyrogrot Abandoned". Available www.ner300.com/?p=328.

NovaPangaea (2016), "Converting Biomass Waste into Fuel and Chemical Precursors at Oil Industry Scale and Profitability". Available www.novapangaea.com/

PYNE (2015), "Biomass and Waste Pyrolysis. A Guide to UK Capabilities".

Stevens D.J. (2009), "Testimony Regarding The Role of Biomass Pyrolysis in Bioenergy" 21 October 2009, Available http://science.house.gov/sites/republicans.science.house.gov/files/documents/hearings/102109_Stevens.pdf, (accessed on 16 August 2016)

SUPERGEN Bioenergy Hub (2016). Available www.supergen-bioenergy.net/

Gasification

Advanced Plasma Power (APP) (2015), "References and partners". Available http://advancedplasmapower.com/references-and-partners/towards-sustainable-future/

Air Products (2016). Available www.airproducts.co.uk/microsite/uk/teesvalley/

Advanced Plasma Power (APP) (2016). Available http://advancedplasmapower.com/references-and-partners/

C1Net (2016), "The commercial and strategic opportunity offered by gas fermentation in the UK". Awaiting publication.

Calysta (2016), "Gaseous fermentation". Available http://calysta.com/technology/gaseous-fermentation/

Flagship ventures (2015), "Investment from Flagship ventures brings Red Rock Biofuels closer to construction of its first commercial biofuel refinery". Available www.flagshipventures.com/about/news/investment-flagship-ventures-brings-red-rock-biofuels-closer-construction-its-first-comme

Fletcher (2015), "Fulcrum awards Abengoa EPC contract for 10 MMgy biofuel plant". Available http://biomassmagazine.com/articles/11898/fulcrum-awards-abengoa-epc-contract-for-10-mmgy-biofuel-plant

Goeteborg Energi (2015). Available http://gobigas.goteborgenergi.se/Svensk_version/Anlaggningen/Folj_projektet

Ineos Bio (2016), Available www.ineos.com/businesses/ineos-bio/news/ineos-bio-begins-advanced-bio-ethanol-plant-feasibility-study

IRENA (2016), "Technology Innovation Outlook for Advanced Liquid Biofuels". Awaiting publication.

Lane, J. (2014), "Enerkem: Alberta's municipal waste to fuels juggernaut, in pictures". Available www.biofuelsdigest.com/bdigest/2014/10/22/enerkem-albertas-municipal-waste-to-fuels-juggernaut-in-pictures/

National Grid (2015). Available www2.nationalgrid.com/UK/Our-company/Innovation/Gas-distribution-innovation/NIC-Projects/BioSNG/

Synthetic Biology Research Centre (SBRC) (2016), "Mission statement". Available http://sbrc-nottingham.ac.uk/about.php#sbrc

Waste Management World (2015", "£6m for Waste Gasification Biomethane to Grid Project in Swindon". Available https://waste-management-world.com/a/6m-for-waste-gasification-biomethane-to-grid-project-in-swindon

Zuvasyntha (2016). Available http://www.biosyntha.com/

6.3 Market assessment

E4tech, RE-CORD and WUR, 2015. "From the Sugar Platform to biofuels and biochemicals". Final report for the European Commission, contract No. ENER/C2/423-2012/SI2.673791

International Energy Agency (2013), "Bio-based Chemicals: Value Added Products from Biorefineries". Available www.ieabioenergy.com/wp-content/uploads/2013/10/Task-42-Biobased-Chemicals-value-added-products-from-biorefineries.pdf

U.S. Department of Energy (US DoE) (2004), "Top Value Added Chemicals from Biomass". Available www.nrel.gov/docs/fy04osti/35523.pdf

6.4 Scenario studies

Scenario 1: Co-location of a lignocellulosic biorefinery with a biomass power station

Argus Media (2016) "Argus Biomass Markets". Available www.argusmedia.com/~/media/files/pdfs/samples/argus-biomass.pdf/?la=en

Biobased Delta (2016) "Redefinery: Biorefinery Cluster Initiative".

ButaNexT (2015)

ChronicleLive (2016). Biomass power could bring thousands of jobs to the North East – but is beset by uncertainty. Available www.chroniclelive.co.uk/business/business-news/biomass-power-could-bring-thousands-10726768

DECC (2015) "Updated energy and emissions projections: 2015 - Annex M". Available www.gov.uk/government/publications/updated-energy-and-emissions-projections-2015

Drax (2013) "Biomass sourcing: capital markets day". Available www.drax.com/media/13853/2_cmd_biomass_markets_final.pdf

Drax (2016) "Our history". Available www.drax.com/about-us/our-history/

E4tech estimation (2016)

E4tech (2016) Advanced Biofuel Database

E4tech internal (2015) (EBRD)

E4tech, RE-CORD and WUR, 2015. "From the Sugar Platform to biofuels and biochemicals". Final report for the European Commission, contract No. ENER/C2/423-2012/SI2.673791

Grimsby Telegraph (2016) "Multi-million pound bio-refinery plan back on for Grimsby". Available www.grimsbytelegraph.co.uk/multi-million-pound-bio-refinery-plan-grimsby/story-28778870-detail/story.html

UK Trade and Investment (2015) "Chemicals – the UK advantage". Available www.cia.org.uk/Portals/0/downloads_pdf_1_Chemicals-Brochure-FINAL-JAN-09.pdf

Scenario 2: Cereal straw biorefinery in Eastern England

Agriculture and Horticulture Development Board (2011), "Straw – what is it good for?" Available www.ahdb.org.uk/projects/straw.aspx

Bio-Sep (2016), "About us". Available http://bio-sepltd.com/

Chemicals Industry Association (CIA) (2009), "Chemicals – the UK advantage". Available www.cia.org.uk/Portals/0/downloads_pdf_1_Chemicals-Brochure-FINAL-JAN-09.pdf

DuPont (2016), "The DuPont Cellulosic Ethanol Facility in Nevada, Iowa: Leading the Way for Commercialization". Available www.dupont.com/products-and-services/industrial-biotechnology/advanced-biofuels/cellulosic-ethanol/nevada-iowa-cellulosic-ethanol-plant.html

E4tech et al. (2014), "Advanced Biofuel Feedstocks – An Assessment of Sustainability", Department for Transport. Available www.gov.uk/government/uploads/system/uploads/attachment_data/file/277436/feedstock-sustainability.pdf

Glithero et al. (2013), "Straw use and availability for second generation biofuels in England", *Biomass and Bioenergy*, vol. 55, no. 1, pp. 311-321

Glithero et al., (2013a), "Barriers and incentives to the production of bioethanol from cereal straw: A farm business perspective", *Energy Policy*, vol. 59, no. 1, pp. 161-171

Institute for European Environmental Policy (IEEP) (2012), "Mobilising cereal straw in the EU to feed advanced biofuel production". Available www.ieep.eu/assets/938/IEEP_Agricultural_residues_for_advanced_biofuels_May_2012.pdf

LBNet (2016), "Business Interaction Vouchers – Projects funded by LBNet". Available https://lb-net.net/wp-content/uploads/2016/05/BIV-funded-by-LBNet-May2016.pdf

NNFCC, (2014), "Lignocellulosic feedstock in the UK. A report for the Lignocellulosic Biorefinery Network".

Sleaford (2014), "Environment". Available www.sleafordrep.co.uk/?page_id=823

Vivergofuels (2016), "Our Process, How do we do it?" Available https://vivergofuels.com/process/

Scenario 3: A waste-based lignocellulosic biorefinery

Advanced Plasma Power (2015) "Government grant awarded to fuel UK towards sustainable future". Available http://advancedplasmapower.com/tag/dft/

Air Products (2016) "Air Products will exit energy-from-waste business". Available at www.airproducts.co.uk/microsite/uk/teesvalley/index.htm

BBC (2016) "Air Products scraps plans for Teesside renewable energy plant". Available www.bbc.co.uk/news/uk-england-tees-35962958

BBSRC (n.d.) "Industrial Biotechnology Catalyst: Funded Grants Rounds 1-4". Available www.bbsrc.ac.uk/documents/ib-catalysts-funded-grants-pdf/

Clark, P. (2016) "From Shale Gas to Biomass: the Future of Chemical Feedstocks", The Knowledge Transfer Network. Available https://connect.innovateuk.org/documents/15494238/0/Shale+Gas+to+Biomass+2016+Web+020816.pdf/e4211721-5da2-4743-ae28-666409706c40?_ga=1.132283273.687503737.1471886873

Centre for Environmental Policy (2014) "Waste infrastructure requirements for England", Imperial College London. Available https://workspace.imperial.ac.uk/environmentalpolicy/Public/NV%20Veolia/IC2014_waste%20report.pdf

Centre for Process Innovation (2015) "Fiberight Ltd and CPI launch project to produce sugar from landfill waste from Industrial Biotechnology". Available at www.uk-cpi.com/news/fiberight-ltd-and-cpi-launch-project-to-produce-sugar-from-landfill-aste-from-industrial-biotechnology/

Chemical Industry Association (CIA) (2009), "Chemicals – the UK advantage". Available www.cia.org.uk/Portals/0/downloads_pdf_1_Chemicals-Brochure-FINAL-JAN-09.pdf

Department for Environment, Food & Rural Affairs (2016) "UK Statistics on Waste". Available www.gov.uk/government/uploads/system/uploads/attachment_data/file/547427/UK_Statistics_on_Waste_statistical_notice_25_08_16_update__2_.pdf

Department for Environment, Food & Rural Affairs (2015) "Digest of Waste and Resource Statistics". Available www.gov.uk/government/uploads/system/uploads/attachment_data/file/482255/Digest_of_waste_England_-_finalv3.pdf

Department for Transport (2016) "Renewable Transport Fuel Obligation statistics: period 8 2014/2015, report 4". Available www.gov.uk/government/uploads/system/uploads/attachment_data/file/543693/rtfo-year_8-report-4.pdf

Ensus (2016) "Welcome to Ensus". Available www.ensus.co.uk/Home/

ERA-NET (n.d.) "BESTF2-Projects ". Available http://eranetbestf.net/two/wp-content/uploads/sites/2/2012/11/BESTF2-Projects.pdf

Eunomia (2015) "Residual Waste Infrastructure Review, Issue 9", December 2015

European Commission (2015) "Workshop Report: Integrated biorefineries and innovations in the optimal use of biomass", December 2015. Available https://ec.europa.eu/research/bioeconomy/pdf/workshop_on_optimal_use_of_biomass-integrated_biorefineries_10Dec2015.pdf

Eurostat (2016a) "Waste main tables". Available at http://ec.europa.eu/eurostat/web/waste/data/main-tables (accessed 24 August 2016)

Eurostat (2016b) "Municipal waste generation and treatment, by type of treatment method". Available http://ec.europa.eu/eurostat/tgm/table.do?tab=table&init=1&language=en&pcode=tsdpc240&plugin=1

Fiberight (2015) "US firm developing plans to turn household waste into sugar on Teesside" Available http://fiberight.com/us-firm-developing-plans-to-turn-household-waste-into-sugar-on-teesside/

Goulding, T. (2016) "Impetus 'anticipated' Air Products Teesside exit". Available www.letsrecycle.com/news/latest-news/impetus-anticipated-air-products-teesside-exit/

IEA Bioenergy Task 36 (2013) "The Municipal Solid Waste Resource in England". Available http://bit.ly/2coQALg

Kalogo, Y. et al. (2007) "Environmental implications of municipal solid waste-derived ethanol", Environmental Science & Technology, vol. 41, no. 1, pp. 35-41

Lane, J. (2015) "Fiberight: Biofuels Digest's 2015 5-Minute Guide", Biofuels Digest. Available www.biofuelsdigest.com/bdigest/2015/05/06/fiberight-biofuels-digests-2015-5-minute-guide/

Nepic (2016) "North East England Chemical-processing Sector and Supply Chain". Available www.nepic.co.uk/

ReBio (2016) "ReBio Technologies Limited". Available www.linkedin.com/company/rebio-technologies-limited

Resource Futures (2012) "Biodegradability of municipal solid waste", Defra. Available http://bit.ly/2chF3io

Ricardo-AEA (2013) "Waste on the front line – Challenges and innovations", Chartered Institute of Waste Management. Available http://bit.ly/2bTf3Wf

Sapp, M. (2015) "Fiberight puts MSW-to-ethanol on hold in Iowa and opts for bio-CNG instead", Biofuels Digest. Available www.biofuelsdigest.com/bdigest/2015/04/20/fiberight-puts-msw-to-ethanol-on-hold-in-iowa-and-opts-for-bio-cng-instead/

SITA (2013) "SITA UK selected as preferred bidder for 30-year £1.18 billion / €1.4 billion resource recovery contract with Merseyside Recycling and Waste Authority" [Press release]. Available www.sita.co.uk/news-and-views/press-releases/sita-uk-selected-as-preferred-bidder-for-30-year

Urbaser (2012) "Urbaser wins Essex county council waste treatment pfi contract". Available http://urbaser.co.uk/urbaser-wins-essex-county-council-waste-treatment-pfi-contract

Wilson Bio-Chemical (2016) “The autoclave system”. Available at http://wilsonbio-chemical.co.uk/the-wilson-system/

Wrap (2013) “A survey of the UK Anaerobic Digestion industry in 2013”. Available www.wrap.org.uk/sites/files/wrap/A_survey_of_the_UK_Anaerobic_Digestion_industry_in_2013.pdf

Wrap (2012) “A survey of the UK organics recycling industry in 2012”. Available www.wrap.org.uk/sites/files/wrap/ASORI%202012.pdf

Scenario 4: Dedicated biomass crop biorefinery in the West of the UK

Chemistry Innovation KTN, NNFCC and TBR (2009), “The Biorefining Opportunities in Wales: From Plants to Products”. Available http://beaconwales.org/uploads/resources/biorefining-opportunities-in-wales.pdf

Chemical Industry Association (CIA) (2009), “Chemicals – the UK advantage”. Available www.cia.org.uk/Portals/0/downloads_pdf_1_Chemicals-Brochure-FINAL-JAN-09.pdf

Chemicals Northwest (2016). Available www.chemicalsnorthwest.org.uk/

Defra (2015), “Area of Crops Grown for Bioenergy in England and the UK: 2008-2014”. Available www.gov.uk/government/uploads/system/uploads/attachment_data/file/483812/nonfood-statsnotice2014-10dec15.pdf

Essar Oil (2016), “Stanlow”. Available www.essaroil.co.uk/our-work/stanlow/

Energy Technology Institute (ETI) (2015), “Bioenergy. Enabling UK biomass”. Available http://www.eti.co.uk/wp-content/uploads/2015/09/3504-Biomass-Insights-Lores-AW.pdf?dl=1

Energy Technology Institute (ETI) (2015a), “Bioenergy. Overview of the ETI’s Bioenergy Value Chain Model (BVCM) capabilities.” Available www.eti.co.uk/wp-content/uploads/2015/03/BVCM-Guide-FINAL1.pdf

Hastings et al. (2014), “The technical potential of Great Britain to produce lingo-cellulosic biomass for bioenergy in current and future climates”, *GCB Bioenergy*, vol. 6, no. 1, pp. 108-122

Lawson, G.J., Callaghan, T.V. (1989). “Agroforestry” In: Adamson, J.K. (ed.) Cumbrian woodlands – past, present and future. London, HMSO, 73-86.

NNFCC (2012). “Domestic Energy Crops; Potential and Constraints Review”. Available www.gov.uk/government/uploads/system/uploads/attachment_data/file/48342/5138-domestic-energy-crops-potential-and-constraints-r.PDF
Chemistry Innovation KTN, NNFCC and tbr (2009), The Biorefining Opportunities in Wales: From Plants to Products

UKERC (2012), “Spatial Mapping and Evaluation of Miscanthus Crop Distribution in Great Britain in 2050.” Available www.carbo-biocrop.ac.uk/uploads/Hastings_miscanthus%20yields_UKERC.pdf

University of Southamption (2012), “Research project: Mapping the supply and demand of bioenergy in Great Britain to 2050.” Available www.southampton.ac.uk/biosci/research/projects/mapping_the_supply_and_demand_of_bioenergy_in_great_britain_to_2050.page#project_overview