



From Shale Gas to Biomass: the Future of Chemical Feedstocks

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Executive Summary

The chemicals industry produces a diverse range of products — including pharmaceuticals, plastics, lubricants, paints, dyes, surfactants, cleaning fluids, advanced materials and composites — that are essential inputs to almost every other major sector of the economy. The most notable sectors include: automotive, aerospace, construction, energy, food and healthcare.

However, as the global population increases, so too does consumer demand for these chemicals. Given the world's finite natural resources, as well as issues of climate change and security of supply, the world will need to develop new, sustainable, chemical feedstocks in order to meet the growing demand.

This scoping study provides a summary of the innovation landscape and some of the key innovation challenges/opportunities associated with raw materials (or 'feedstocks') for the production of chemicals now and into the future. Raw materials covered within the study are:

- Unconventional oil and gas (particularly shale gas)
- Carbon dioxide
- Renewable feedstocks
- Scarce metals and minerals
- Renewable hydrogen

The study found that all of the raw materials outlined above are important parts of the future mix for the UK chemical and chemical-using industries. It also identified a number of recommendations (refer to *Summary of recommendations*) where follow-up action is required to better understand and take advantage of the opportunities identified. With regard to shale gas, it is clear that if production occurs in the UK, it will provide a secure supply of feedstock (and energy) for the chemicals sector now and into the future, helping to secure investment in existing UK infrastructure and providing opportunity for growth in the sector and its supply chains. A number of opportunities have been identified where chemistry-related innovation can help improve productivity and minimise environmental risks associated with shale gas extraction. The chemical innovators and shale gas producers should come together to explore and exploit these opportunities. A more focused investigation is also required to investigate innovation opportunities through the chemicals supply chain that result from having access to indigenous shale gas. This investigation should bring together the chemistry and industrial biotechnology communities that are investigating pathways to exploit methane and natural gas liquids as chemical feedstocks.

As the world continues to transition to a low carbon economy, it is vitally important that alternative chemical feedstocks, beyond petrochemicals, are developed. One such alternative feedstock is carbon dioxide. Produced as a by-product of many industrial processes, it can be turned into chemicals, fuels and other materials via a range of different chemical or bio-chemical pathways. The Technology Readiness Level (TRL) of these different pathways varies and certainly the current lack of economic incentive for industry to do anything with carbon dioxide is holding back commercial exploitation. Further support is required to help accelerate carbon dioxide utilisation (CDU). The UK's leading academic community, startups and SMEs working in this area should come together with carbon dioxide producers to find new niche market opportunities where its incorporation into chemicals/materials provides performance improvements at lower cost and where the benefits of utilising carbon as part of circular economy thinking are appreciated. Opportunities for CDU should be explored within carbon-intensive industry clusters, particularly where there is access to excess renewable energy that can help lower the energy demand (and cost) to utilising carbon dioxide.

Of all the feedstock categories that are covered in this study, renewable feedstocks have been the best supported by the UK government, Research Councils, academia, funders, RTOs and industry. They are recognised as having significant potential in the UK as it moves towards a sustainable bioeconomy of the future. This study focuses on renewable feedstocks that are derived from second and third generation biomass and carbon-containing wastes, although it still only manages to skim the surface of this broad area. It identifies a number of different sources of biomass and carbon-containing wastes that may provide routes to high value chemicals in the future. It also identifies a number of UK-based companies that are making significant progress in this area. Further, more detailed consultation is required to understand which combination of biomass/carbon-containingwaste feedstocks, conversion technologies and market opportunities will be the most commercially attractive for the UK in the future.

Scarce metals and materials are another very important area when considering the supply of inorganic chemical feedstocks for the future. Important research has already been undertaken through projects like the Critical Raw Materials Innovation Network (CRM_Innonet), which identified 14 critical raw materials (CRMs) for Europe's energy, transport, ICT and electronics industry supply chains. This study summarises some of the challenges and opportunities for the chemicals sector, particularly in substituting precious metals for catalysis, as well as opportunities for chemistry-related innovation to assist in minimising or substituting scarce metals and minerals in other sectors. There continues to be an important role for organisations like the Knowledge Transfer Network (KTN) in helping businesses and government understand the supply chain risks associated with CRMs and how these can be mitigated through innovation. Collaborative innovation that addresses the issue of CRM substitution in the chemicals sector (for catalysis) and in other sectors will continue to be important for the future.

An additional feedstock for the future that has been identified through this study is renewable hydrogen. This is hydrogen that has been produced via the electrolysis of water, utilising energy from a renewable energy source. The commercial interest in developing renewable hydrogen as a chemical feedstock will be strongly linked to the development of infrastructure to support a 'hydrogen economy'. Further exploratory work is also required to understand the range of chemicals that could be commercially viable based on a renewable hydrogen feedstock.

Summary of recommendations

The following recommendations are aimed at stimulating and supporting innovation and growth in the chemical and chemistry-using industries and throughout the wider supply chains. The Knowledge Transfer Network (KTN) will continue to work with industry and other key stakeholders to ensure the UK benefits from these opportunities.

Unconventional oil and gas

- Shale gas producers should come together with the chemistry community to exploit opportunities to further improve the productivity of shale gas extraction and minimise any associated environmental risks. Given that the challenges of conventional and unconventional extraction are often the same and the conventional extraction industry is facing mounting cost pressures, this activity could be broadened to cover innovations for conventional oil and gas extraction.
- A more detailed investigation should be undertaken to consider the innovation opportunities that might result through the supply chain as a result of having access to indigenous shale gas. This investigation should bring together the chemistry and industrial biotechnology communities that are investigating pathways to exploit methane and natural gas liquids as chemical feedstocks.

Carbon dioxide

 Further support is required to help accelerate carbon dioxide utilisation (CDU) innovation. The UK's leading academic community, start-ups, SMEs and industry clusters should come together to explore the near- and mid-term market opportunities for CDU.

Renewable feedstocks

 Further investigation is required to identify which combination of biomass/carbon-containing-waste feedstocks, conversion technologies and market opportunities will provide UK businesses and the UK with a competitive advantage in the years to come.

Scarce metals and minerals

- There continues to be an important role for industry support organisations such as KTN to work across sectors, helping businesses understand the risks posed to supply chains through scarce metals and minerals and how, through innovation, these risks can be mitigated.
- Collaborative R&D between industry and academia that is focused on helping to minimise or substitute the use of scarce metals in catalysis continues to be important.

Renewable hydrogen

 The potential challenges and opportunities of renewable hydrogen, including water splitting and beyond green ammonia as a product, should be investigated further. UK companies innovating in this area would benefit from continued support.

1.0 Introduction

Aim of scoping study

The aim of the scoping study was to conduct a sixmonth desktop review of 'raw materials of the 21st century', which is one of the key strategic topic areas of the 2013 report 'A strategy for Innovation in the UK chemistry-using industries' (referred to hereafter as the 'CGP Innovation Strategy').

Objective

The objectives of the study were to:

- Determine the relevance of the 'raw materials of the 21st century' area and whether it is aligned with current industry needs.
- Identify the innovation challenges and opportunities in this area and any strategic support required to help the UK exploit these opportunities.

Scope and approach

The raw materials that are the subject of this study include:

- Unconventional oil and gas (particularly shale gas)
- Renewable feedstocks
- Carbon dioxide
- Scarce metals and minerals
- Renewable hydrogen

This study has primarily focused on raw materials for producing chemical feedstocks, rather than feedstocks for energy (fuels). Note that the terms 'raw materials' and 'feedstock' will be used interchangeably throughout this report.

The following activities were conducted as part of this study:

- Stage 1 Internal consultation with KTN's Knowledge Transfer Managers, who have expertise in a broad range of areas. Also, a desktop review of reports and other media to assess the innovation landscape and identify innovation challenges/opportunities.
- Stage 2 Consultation with key external stakeholders.

In undertaking these activities, the following highlevel key questions were used to help guide the study:

- 1. What activity has there been in the past three years?
- 2. What has changed (politically, socially, environmentally) since the production of the CCP Innovation Strategy, published June 2013?
- 3. What are the key innovation challenges in each area?
- 4. How close is the technology to be being commercially ready (i.e. what is the technology readiness level (TRL))?

All key reference documents reviewed as part of this study are summarised in Appendix A.

2.0 Background

The UK chemicals industry (including pharmaceuticals) provides products and services for almost every other industry sector in the economy, employing more than 150,000 people directly in highly skilled jobs and contributing £60m of added value every single working day (over £15 billion per year) to the UK's gross domestic product. The industry is the UK's largest manufacturing export sector, with exports of nearly £50bn each year.

Similar to many other parts of the UK manufacturing sector, the UK chemicals industry has encountered many challenges in recent years, with parts of its domestic supply chain relocating to more economically attractive locations and overseas markets providing new competition from a lower cost base.

In 2013, the Chemistry Growth Strategy Group (CGSG) developed a *Strategy for Delivering Chemistry-Fuelled Growth of the UK Economy* (referred to hereafter as 'the CGSG Strategy'). This strategy set a vision for growing the chemicals industry, setting the target of the UK chemicals industry increasing its gross value added (GVA) contribution to the UK economy by 50% by 2030 — from £195bn to £300bn. Importantly, it also identified three critical priorities that are needed to achieve this vision:

- 1. Securing competitive UK energy and feedstock supplies.
- 2. Accelerating innovation.
- 3. Rebuilding UK chemistry supply chains.

At the same time, the former Chemistry Innovation Knowledge Transfer Network (CIKTN) — now part of KTN — together with the Centre for Process Innovation (CPI), developed the CGP Innovation Strategy. This strategy was adopted by the CGSG, and subsequently the Chemistry Growth Partnership (CGP), as the basis for its strategy for accelerating innovation. The CGP Innovation Strategy identified the following innovation opportunities across the UK's key manufacturing sectors:

- Aerospace lightweight materials and formulated products for lower cost and reduced environmental impact.
- 2. Automotive low carbon vehicles with improved driver experience.
- **3. Construction** sustainable, low carbon buildings delivered through the whole supply chain.
- **4.** Energy generation and supply delivering secure, economical, sustainable energy.
- 5. Life sciences personalised treatments requiring niche, high-value products with improved delivery.
- **6.** Food food for the world: nutritional, pleasurable and sustainable.
- **7.** Home and personal care delivering desired functionality to a demanding consumer base using natural ingredients and clever formulation.
- 8. Chemicals manufacturing manufacturing chemicals more competitively and sustainably from a variety of feedstocks.

The CGP Innovation Strategy also used this sector information to define three key areas where public intervention should help accelerate innovation:

- Raw materials for the 21st century the raw material used as input materials for the production of energy, chemicals, components and structures.
- Smart manufacturing processes the processes used in the manufacture of chemicals.
- **Design for functionality** the efficient design and manufacture of chemical entities, materials and systems that offer desired functionality.

This study focuses on the first of these areas: raw materials for the 21st century (referred to hereafter as '**raw materials**'). Within this area, the following innovation topics are identified:

TOPIC	SUB-TOPIC		
Renewable feedstocks	 Sources of renewable feedstocks to feed chemical production. All renewable materials including biobased raw materials, recycled materials and waste materials. Identifying, sourcing, converting and using these materials. 		
Unconventional oil and gas	 Oil and gas from shale deposits and from depleted and hard-to-access conventional fields. Enabling extraction operations of oil and gas in a safe and sustainable way. Use of these feedstocks in chemical manufacture. 		
Scarce metals and materials	 Materials that are economically important and at high risk of supply disruption: scarce metals and minerals, heavy rare-earth elements, platinum group metals. Materials used in chemical processing such as catalysis. Materials used in products with growing markets, for example in LCD displays and in energy-efficient lighting. Devising technologies and approaches to reduce usage and for recovery and recycling. Identifying technologies and approaches to reduce usage and for recovery and recycling. Identifying technologies and approaches for substitution with sustainable alternatives. Securing, extracting and refining additional supplies with minimal environmental impact. 		

Conventional chemical feedstocks

Before exploring chemical feedstocks of the future, it is worth taking some time to introduce the conventional feedstocks that have been used to make chemicals for centuries.

The vast majority (90%) of organic chemicals made around the world today are derived from petrochemicals (i.e. chemicals from petroleum or natural gas), while the rest are derived from coal (in the case of syngas) and, as will be explored in this report, other renewable feedstocks. The three major groups of chemicals that are derived from petrochemicals can be categorised as follows:

- Aromatics (unsaturated cyclic hydrocarbons containing one or more rings) — includes benzene, toluene, and xylene isomers.
- Olefins (unsaturated aliphatic hydrocarbons) — includes ethylene, propylene, butadiene, butylenes.
- Synthesis gas (or 'syngas') a mixture of carbon monoxide, hydrogen and often carbon dioxide.

Aromatics and olefins are produced from petroleum in oil refineries by a process known as catalytic cracking. Olefins can also be produced in gas processing plants via steam cracking of natural gas liquids (like ethane or propane), while aromatics can be produced via the catalytic cracking of naphtha.

In the UK, there are three major cracking plants (refer to Table 2-1) that play a vitally important role in the domestic chemicals supply chain and broader economy.

PLANT LOCATION	OPERATED BY	CAPACITY KT ETHYLENE/YEAR (2014)
Grangemouth	Ineos Olefins	700
Mossmorran	ExxonMobil / Shell	770
Wilton	Sabic UK	865

Table 2-1: Steam Crackers in the UK (source: Petrochemicals Europe website)

It is not surprising that there are clusters of downstream chemicals companies co-located in areas surrounding these crackers as they provide the feedstock for many of the other chemical manufacturing plants in the local area. Having these crackers in the UK provides the country with tremendous domestic capability to make a range of important basic chemicals that are critical feedstocks to many other processes and products in sectors such as automotive, health care, etc.

Figure 2-1 summarises the key chemical products from petroleum oil refineries and gas processing plants.



Figure 2-1: Chemical products from oil refineries and gas processing plants (Source: Int. J. Mol. Sci. 2015, 16 by James H Clark et al)

The primary products from petrochemicals will be used to produce speciality chemicals, fine chemicals and pharmaceuticals, which go on to be made into plastics (packaging, furniture, etc.), advanced materials and composites, paints, dyes, surfactants, cleaning fluids, medicines, etc. One of the most important 'platform molecules' is syngas. The products of syngas are very important, for instance, hydrogen can be used in other industrial processes (e.g. in ammonia production) or for storage as part of powering a hydrogen energy economy. Alternatively, coal-derived syngas can be converted into transportation fuels (e.g. gasoline and diesel) via the Fischer-Tropsch process or into methanol. All of these potential conversions are shown in Figure 2-2.



Figure 2-2: Products from syngas (Source: CleanCoalSyngas website)

Innovation opportunities/ challenges in conventional chemical feedstocks

As the global population increases so too does consumer need and demand for chemical products. Taking into consideration the world's finite natural resources — as well issues of security of supply and the impacts of climate change — new chemical feedstocks and novel chemical and bio-chemical pathways will need to be adopted to meet this growing demand.

Certainly with regard to climate change, it is worth pointing out that global leaders met in December 2015 for the annual climate change summit in Paris (COP21) with the outcome being a deal that agreed to attempt to limit the rise in global temperatures to less than 2°C. This monumental meeting also led to leaders agreeing to "peak greenhouse gas emissions as soon as possible and achieve a balance between sources and sinks of greenhouse gases in the second half of this century". What is not yet clear is how governments will respond to this task. Will it be through a direct carbon pricing mechanism or through indirect measures or new regulation? We don't know. Either way, it will be essential that the UK economy is decarbonised, and quickly. That will mean producing as little carbon as possible and, where it is produced, as much of it as possible must be kept in a closed-loop system or at least stored/ sequestered. On that basis, utilising carbon dioxide as well as renewable and waste feedstocks will be critical in helping to meet any future greenhouse gas abatement targets.

However, in the search for new chemicals feedstocks, it is important that the innovation challenges and opportunities of the current chemicals sector that utilise petrochemicals are not overlooked. Indeed the vast majority of investment in the chemicals sector is based on petrochemicals and without doubt the world will need to rely on this feedstock — at least in the foreseeable future.

With this in mind, there are three key points that should be considered when thinking about innovation challenges/opportunities associated with chemical feedstocks:

- New feedstocks should make full use of the existing infrastructure associated with conventional feedstocks where possible (including plant technology, storage and transport infrastructure) to minimise capital expenditure and reduce time-to-market.
- Two of the biggest challenges facing the UK chemicals sector that use conventional feedstocks are the security of supply of feedstock and the cost of energy. As such, innovations that can assist in meeting these challenges will be critically important for the survival and growth of this industry in the UK.
- 3. It is critically important for the on-going sustainability of the UK chemicals sector that it decarbonises its operations (including energy supply, feedstock utilisation and manufacturing processes) as far as possible. The rapid development and deployment of scaleable low carbon technologies (e.g. carbon capture and storage or industrial heat recovery) are therefore of great importance for the survival of the industry.

Hopefully this brief introduction to conventional chemical feedstocks, processes and products has been helpful in setting the scene for the challenges and opportunities associated with introducing 'new' feedstocks.

3.0 Unconventional oil and gas

'Conventional oil and gas' is a term used to describe crude oil, natural gas and its condensates. 'Unconventional oil and gas' is essentially the same the 'unconventional' part simply refers to the methods that are used to extract the resources, as well as the types of rock from which the oil and gas are produced.

This study will concentrate on the innovation challenges and opportunities associated with unconventional gas or, more specifically, shale gas as significant reserves of this have been discovered and are expected to be exploitable in the UK in the near future.

So what is shale gas? It is simply natural gas that is trapped within shale deposits. The gas is extracted by drilling a well down into the shale deposit, then using a well-stimulation technique called 'hydraulic fracturing' (often just referred to as 'fracking'), which involves the application of a high-pressure liquid (fracking fluid) to fracture the rock (shale) to release the trapped gas. A diagram showing the fracking process and well design is provided in Appendix B.

The shale deposits will include natural gas, which is used in the chemicals industry as a feedstock for hydrogen production, hydrocracking, hydrodesulphurisation, ammonia production, and to produce methanol and its derivatives, e.g. MTBE, formaldehyde, and acetic acid. Importantly, it is also hoped the shale gas deposits in the UK include a significant proportion of natural gas liquids (NGLs) such as ethane, propane and butane, which are valuable petrochemical feedstocks. A detailed map of the diverse range of products and value chain of just ethane is provided in Figure 3-1.

It should be noted that while the chemicals derived from shale gas are incredibly valuable, the world will continue to need aromatics that are not found in shale gas and are traditionally derived from oil refining (refer back to Figure 2-1).



Figure 3-1: Shale gas through the ethane value chain into manufactured products (Source: Shale gas reshaping the US chemicals industry, PWC, 2012)

There are two distinct areas of innovation related to shale gas that have been investigated in this study:

- 1. The chemistry-related innovation challenges and opportunities associated with the extraction and production of shale gas.
- 2. The innovation challenges and opportunities for the chemistry-using industries and its supply chains associated with having access to a new, indigenous supply of shale gas as a chemical feedstock.

Recent developments and market update

There is an abundance of shale at depth in the UK. For instance, a 2013 study of the Bowland deposit by the British Geological Survey (BGS) suggested there are 1300 trillion cubic feet of gas in place. This is equivalent to 40 years of current UK requirements. However, what is not totally clear is how much of this shale gas is economically recoverable.

Of course drilling companies, supported by industry, have been keen to explore the UK's shale gas deposits for a number of years but have been held back due to public concern and lack of strong policy support from government.

This shifted somewhat in 2015 with the Conservative government demonstrating support for the safe exploitation of shale gas by awarding (through the Oil and Gas Authority) a raft of licences to explore parts of mainland UK for deposits. Some of the companies that received licenses include **Cuadrilla** and **INEOS**. This shift in government policy has the potential to accelerate the timeline for shale gas exploitation in the UK, although many local authorities remain against development due to the high level of public concern that exists.

The UK is not the only country to look to exploit shale gas. For instance, Australia has significant unconventional gas deposits in Queensland that it has been developing for a number of years, with further deposits in Victoria and New South Wales to be explored. However, by far the best example of a country that has seen significant growth in its chemicals industry and broader economy through the exploitation of its shale gas reserves is the US. Price Water House Coopers (PwC) suggested that by 2025, shale gas could add more than one million workers to the US manufacturing industry and allow US manufacturers to lower their raw materials and energy costs by as much as \$11.6bn annually. For US chemical companies, the impact of shale gas has been to decrease the costs of both raw materials and energy, with the price of natural gas declining from \$12.50/MBTU in 2008 to approx. \$3.00/MBTU in 2012. This has led to an investment of \$15bn in ethylene production, increasing capacity by 33%.

Companies like **INEOS** in the UK have turned to the US in recent years for their feedstock supply in light of dwindling reserves from the North Sea. In 2014, it built a brand new tank and terminal at its Grangemouth site. This tank is designed to hold 60,000 cubic metres of ethane, making it the biggest ethane tank in Europe. With a displacement volume of 108,372 cubic metres, it is large enough for 560 double-decker buses to fit inside.

However, it is not all rosy for unconventional oil and gas producers in the US and elsewhere. The recent crash in world oil and gas prices makes the economic case for exploiting these harder and more expensiveto-reach unconventional gas deposits much weaker.

Nevertheless, if shale gas is economically recoverable in the UK it would certainly go a long way to helping to secure the supply of feedstock and energy, which is a key goal of the chemicals industry.

Current and historical innovation support

Innovate UK

In recent years, any UK company with a project that can demonstrate it is addressing the energy 'trilemma' (reducing emissions, improving security of supply, and reducing cost) has been able to access funding support through the Innovate UK Energy Catalyst programme. This programme, which continues to be supported by Innovate UK today, is very broad in that it supports early-stage concept R&D, through to pre-commercial validation.

More specific funding was also available in early 2015 from Innovate UK through their competition 'Developing technologies for the safe and responsible extraction of shale gas'. The £2m funding for this programme was awarded to 19 projects exploring a range of innovative approaches to the safe and responsible extraction of shale gas.

Examples of UK SMEs that were funded through this competition and that have a strong focus on chemistry include the following:

- Advanced Defence Materials Ltd (Warwickshire): new, wear-resistant titanium-based components for shale gas wells that are much less susceptible to corrosion.
- Aquaology Environment Ltd (Bristol): adapting electrochemical wastewater treatment to the shale gas industry.
- Cambridge Carbon Capture Ltd: gas-scrubbing technologies that lead to the removal of carbon dioxide and hydrogen sulphide from shale gas.
- Keronite Ltd (Haverhill): developing a new 'photocatalyst' technology for safe water treatment.

Oil and Gas Innovation Centre (OGIC)

In terms of other support for the exploitation of shale gas, there are specialist centres like the Oil and Gas Innovation Centre (OGIC). OGIC works together with universities and businesses in the oil and gas sector to accelerate innovation through collaborative R&D. It is one of eight different Innovation Centres launched by the Scottish Funding Council.

Industry Technology Facilitator (ITF)

The Industry Technology Facilitator (ITF) is a global not-for-profit organisation that works with its members in the oil and gas sector to identify technology needs, foster innovation and facilitate the development and implementation of new technologies. It has facilitated the launch of more than 200 projects from early-stage concepts through to field trials and commercialisation.

Current innovation challenges and opportunities associated with the extraction and production of shale gas

The key innovation challenges associated with production of shale gas where chemistry innovation can play a key role that have been identified through this study are summarised below.

Well integrity

Innovations that continue to improve the integrity of the well during operation and at the end of its lifetime (once 'plugged and abandoned') would be valuable. This is also relevant for conventional oil and gas extraction where there is a particular need for materials that can be used to plug and abandon deepsea wells.

Innovations could include new polymers, additives or other materials. Additives for cement are particularly important. The cement is used in well casings to help prevent leaks at the top of the well — but also between the well wall and pipe. It is also used as a cap to plug the well at the end of its lifetime. These cements and materials must be able to cope with the acidic subsurface conditions and be environmentally friendly. One particular area of innovation that is attracting interest is self-healing cement.

New fracking fluids

Figure 3-2 below shows the breakdown, by volume, of the components of fracking fluid. It is apparent that less than 1% of the fluid is a mixture of chemicals, with the rest being made up of water and sand.



Figure 3-2: Typical composition of a fracturing fluid by volume (Source: Shale gas extraction in the UK: a review of hydraulic fracturing, June 2012)

Despite the relatively small volume, the chemicals all play an important role in the process of stimulating the shale, keeping the drill lubricated, extracting the gas and carrying the rock to surface. A more detailed breakdown of the chemicals used in the extraction process, and why they are important, is provided in Appendix B.

Consequently the development of new,

environmentally benign fracking chemicals that can cope with the significant pressures and temperature involved in shale gas extraction will be valued by the industry.

The same is also true of drilling fluids (referred to as 'drilling mud'). These fluids are used whilst drilling the well to keep the drill bit cool, stop nearby water/fluids coming into the well and to transport debris to the surface. Proppants are another group of chemicals that play an important role in the extraction process and where there is opportunity for new, more environmentally benign alternatives to impact the market. Proppants are materials that are sent down with the fracking fluid to hold open the fractures that have been made. Proppants are used in conventional wells too.

Another area of opportunity is in designing systems to recover the fluids more easily. In the US approximately only 10% of these fluids are recovered.

Enhanced Oil Recovery (EOR)

There are three stages to conventional oil and gas production. Firstly, there is primary production where the gas exits the well under its own pressure so no support is required. Then there is secondary production, which occurs when gas/oil flow rates have dropped to a level where a water injector can be used to restore pressure and help drive out more gas from the well. A third option is to then employ EOR techniques to extract more product. Oil and gas companies do not always progress through all these stages because of the cost, so it depends on the economics of the process at each specific location.

The three main types of EOR process are summarised:

- **Thermal recovery** involves the introduction of heat such as the injection of steam to lower the viscosity or thin the heavy viscous oil and improve its ability to flow through the reservoir.
- Gas injection, which uses gases such as natural gas, nitrogen or supercritical carbon dioxide (scCO₂) that expand in a reservoir to push additional oil to a production wellbore, or other gases that dissolve in the oil to lower its viscosity and improve its flow rate. CO₂ as a gas for EOR is nascent but very interesting because if the CO₂ can be trapped underground in the reservoir then not only can it be used to increase well production, it can also be utilised as a means of storing CO₂ and therefore offsetting carbon emissions.
- Chemical injection involves the use of polymers to increase the effectiveness of waterfloods, or surfactants to help lower the surface tension, which often prevents oil droplets from moving through a reservoir.

The EOR process is more applicable to conventional oil and gas production but given there are opportunities for chemistry innovation to improve the productivity of EOR through better gas injection and chemical injection processes, it is worth including.

Produced water

Novel methods to separate water from the sand of the produced water will be beneficial. Separating low concentration contaminants (mercury, etc. on ppm scale) that are retrieved with the sand and water is another potential opportunity for innovation. The water produced is extremely saline, so if the minerals in this solution can be captured in an economically viable manner then this would be advantageous.

Depending on the local geology, some wells will have a particular problem of lots of loose and unconsolidated sand. In other local areas, there may be huge amounts of water in the reservoir. So another challenge for the chemistry community is to find a way to extract the gas and oil from the well, without removing the water and sand.

Another challenge for conventional oil and gas extraction is flow assurance. This is the process of maintaining the flow along the pipeline. The pipeline runs along the seabed so depending on the depth of water the temperature and pressure can cause problems. Asphaltene in particular is an issue for flow assurance. This is becoming a more pressing issue as the industry moves into deeper water or arctic regions of the world.

Current innovation challenges and opportunities associated with a new, indigenous supply of shale gas in the UK

Owing to the scope of this task and the relative short period of this study, it has not been possible to identify clear innovation opportunities through the supply chain from having access to an indigenous supply of shale gas.

Certainly having access to indigenous shale gas will go a long way to providing a secure feedstock for the chemicals industry now and into the future. It is likely to help secure investment in existing UK infrastructure (crackers and plants) and lead to growth in the sector to help meet growing global demand for their products. However, what is less clear is exactly where the innovation opportunities lie from having access to indigenous shale gas.

A further more detailed, cross-cutting review that involves the chemistry and industrial biotechnology communities who are working across the C1, C2 and C3 feedstock supply chain (including downstream users) would be helpful to further investigate potential opportunities.

Summary

A number of innovation challenges and opportunities where chemistry-related innovation can help play a key role in making the extraction and production of shale gas more productive and sustainable have been identified.

Support for innovation in this area within the UK comes from groups like OGIC, which offers a dedicated facility in the UK for companies looking to engage with this sector and innovate. Following conversations with them, it is clear that there are a number of interesting projects underway that are looking to address the challenges mentioned, showing evidence that the UK is already innovating in this space. Innovate UK has provided support in the past, running a competition in 2014 called *Developing technologies for safe and responsible exploitation of shale gas.*

RECOMMENDATION: The shale gas and UK-based chemistry sector should come together to explore and exploit innovation opportunities to improve the productivity and minimise the environmental risk of shale gas extraction. Given the challenges of conventional and unconventional extraction are often the same and the conventional extraction industry is facing mounting cost pressures, this activity could be broadened to cover innovations for conventional oil and gas extraction.

With regard to the innovation challenges and opportunities through the supply chain associated with having access to a new indigenous supply of shale gas, further work is needed to explore this. It is certainly clear that shale gas production in the UK would help keep and generate jobs, hopefully leading to investment in the chemicals sector and its supply chains. However, more detailed consultation with the research base and industry that is involved in the conversion of methane and NGLs is required to understand the challenges and opportunities in more detail.

RECOMMENDATION: More detailed investigation is required to explore the possible innovation opportunities through the supply chain if the UK has access to indigenous shale gas. This investigation should bring together the chemistry and industrial biotechnology communities that are investigating pathways to exploit methane and NGLs as chemical feedstocks.

4.0 Carbon dioxide utilisation

This study is interested in anthropogenic CO_2 . That is CO_2 that has been produced as a by-product ('waste') of industrial processes or as a consequence of burning fuels. This study is primarily focused on the capture and utilisation of CO_2 (referred to hereafter as 'carbon dioxide utilisation' (CDU) and sometimes referred to by others as 'carbon capture and utilisation' (CCU)) to produce higher value products, primarily chemical feedstocks but also synthetic fuels and building products.

The capture of CO_2 for the sole purpose of permanently storing it underground in geological formations — referred to as 'carbon capture and storage' (CCS) — is not a focus of this study, although as capturing CO_2 is a necessary step before it can be utilised, CCS and CDU are inextricably linked.

Once captured, there are a variety of pathways to use CO_2 'as-is' or alternatively convert it to a higher value chemical (refer to Figure 4-1). A more detailed diagram showing the chemical products from CO_2 is provided in Appendix C.



Figure 4-1: Different pathways for CDU

(Source: Carbon Dioxide Utilisation Electrochemical Conversion of CO2 – Opportunities and Challenges, 2011)

For instance, CO_2 can be used, without any further conversion, by the beverage industry to make carbonated drinks. Alternatively, if pressurised to a supercritical state, CO_2 becomes a tuneable solvent, which can be used for separations or extractions, reaction chemistry or (as mentioned in Section 3) to improve the productivity of oil and gas wells in the EOR process. However, given significant amounts of energy are required to capture and compress CO_2 , the CO_2 needs to be adding significant value in its current state before it is economical. Hence the attraction of utilising the CO_2 for higher value products such as chemicals, fuels or materials and the reason it is the focus of this study.

Recent developments and market update

As CO_2 is a greenhouse gas, one of the key drivers for its valorisation is to help reduce greenhouse gas emissions. For instance, if the CO_2 that has been utilised is taken from an industrial process where the CO_2 would otherwise have been vented to atmosphere but instead is permanently sequestered inside another product, then the emissions from that industrial process have been offset. Additionally, if CO_2 can be utilised in a chemical product where that chemical would otherwise have been produced via a virgin petrochemical feedstock, then (dependent on a full lifecycle assessment) further carbon emissions have been avoided.

It is therefore clear that CDU and CCS have an important role in helping to decarbonise industry. Indeed, the Department of Energy and Climate Change (DECC) recently recognised this, with CCS (and CDU to a lesser extent) featuring in their Industrial Decarbonisation and Energy Efficiency Roadmaps to 2050 covering the UK's eight most energy-intensive industries.

In their report, they suggest that CCS would be the single largest contributor to decarbonisation, with a total emission reduction potential of 23m tonnes of CO_2 per annum in 2050 (37% of the total combined reduction under their 'Max Tech' scenario). They also suggest it is a key decarbonisation technology in four sectors: cement (at 62% of the 'Max Tech' scenario), chemicals (43%), iron and steel (45%) and oil refining (56%).

Specifically with regard to CDU, DECC states that, "although CDU could offer the potential for more commercially viable decarbonisation, it is currently an area of academic research and that the current industry view is that CDU will not be possible at sufficient scale to make a significant contribution to sectors such as refining, chemicals, cement and iron and steel." However, it also states, "further research and development could, however, change this balance."

The view of DECC is countered by the EU Smart CO_2 Transformation (SCOT) project group (discussed later), which suggests in its *Vision for Smart CO₂ Transformation in Europe* that by 2030 CDU technologies will enable the world to:

- Buy a mattress from major European retailers, made with foam that uses recycled CO₂.
- Construct a truly carbon-negative house from mineralised wastes and CO₂ capturing cements.
- Fill a long-distance freight truck with CO₂-derived synthetic fuel.
- Travel on a plane powered by a percentage of CO₂-derived aviation fuel.
- Eat foods produced with fertilisers derived from CO₂.
- Live on an island that has a self-sufficient, sustainable agricultural industry powered by renewable energy, green urea and synthetic tractor fuels all made from CO₂.

It should be noted that there are already a number of commercial scale CDU processes that exist today. For instance, urea is made from ammonia and CO_2 on a scale of 80m tonnes per annum (Mt/a). Salicylic acid, which is used to make aspirin, is produced from phenol and CO_2 at a relatively small scale of 0.025 Mt/a. However, these examples are for lower value chemicals and/or small markets.

The SCOT project has been looking across the three major utilisation pathways to assess where the different CDU technologies stand in regard to their current TRL. From Figure 4-2 it is clear that the TRL of most technologies is very broad-ranging but with some mineralisation technologies reaching TRL 8–9. Certainly, Europe has seen significant commercial



Figure 4-2: TRLs for each different CDU technology across the three major CDU pathways: mineralisation (light blue), chemical products (dark blue) and synthetic fuels (red). (Source: SCOT — Vision for Smart CO2 Transformation in Europe, 2015)

interest in CDU, with a particular focus on polymers. As part of their Dream Production project, Covestro (part of the **Bayer group**) is investing €15m in the construction of a 5,000 ton capacity plant for producing CO₂-based polyols (which are intermediates in the production of polyurethanes) at its Dormagen site. The technology has been developed by Covestro in collaboration with the CAT Catalytic Center in Aachen, which helped develop a suitable catalyst for the process. Construction of the plant started in 2015. In the UK, Econic Technologies is a prime example of a start-up that is making progress towards commercial applications of CDU. In 2016, it announced an additional £5million investment to expand it's facilities and accelerate commercialisation of its catalyst technology for transforming CO₂ into polyurethanes and other polymers. This latest round of investment is complemented by a further £2M of funding recently awarded under the H2020 SME Instrument.

Mineralisation and accelerated carbonation using CO_2 is another route that has attracted interest and is currently the CDU technology that is the most advanced. This technology involves reacting the captured CO_2 with minerals (calcium or magnesium silicates) to form (Ca or Mg) carbonates. This is a high-volume sequestration process with relatively low value products but has the advantage over traditional CCS (i.e. sequestration in geological formations), in that mineralisation products can be utilised in the built environment as cement and aggregates rather than the CO_2 just being stored underground.

UK start-up **Carbon8** has been leading in this area, producing a high quality aggregate product using its Accelerated Carbonation Technology (ACT).

Elsewhere in the UK, **CCm Research** is developing a fertiliser product in a process which utilises CO₂. R&D is currently being undertaken at its pilot plant co-located at **Viridor**'s Energy Recovery Facility, in Ardley.

By combining ammonia-coated waste fibres from the Viridor site with CO_2 from Viridor's exhaust gas, CCm is able to produce a low-carbon fertiliser. Fertiliser produced via CCm's methods produces only 15% of the CO_2 compared with conventional fertiliser production methods.

CO₂ can be also be transformed into useful chemicals via biological processes such as microalgae technologies, bacterial fermentation, advanced biotechnological processes and bioelectrochemical systems. Microalgae technologies have received the most attention (refer to Figure 4-3, which shows the algae technology production process and postprocessing options).



Figure 4-3: Algae production system and potential products (Source: Carbon capture and utilisation in the green economy, 2011)

There are a number of organisations in the UK and overseas (particularly in the US where the aim has mainly been to make biofuels from algae) that have invested significantly in algal technologies. However, despite this significant investment, there are still no examples of using algae technologies to make fuels or chemicals on a commercial scale as yet. The utilisation of industrial gases like CO₂ was acknowledged as being important to the future of the UK economy in the government's report *Building a high value bioeconomy: opportunities from waste*. Indeed, as part of its vision for 2030, it stated that the UK shall "become a global leader in gaining economic value and environmental, and societal benefit from utilising carbon-containing wastes and residues as resources in a vibrant bioeconomy, where appropriate, producing high value resource efficient materials, chemicals, and energy."

Current and historical innovation support

Europe has seen significant investment and support in CDU R&D in recent years and it continues to be recognised as an important area that requires public funding and investment, as shown below.

EnCO₂re

 $EnCO_2$ re is an innovation and market development program focused on the reuse of CO_2 . Co-initiated by Climate-KIC and industry partner Covestro, it now consists of a consortium of 12 European partners from industry and research. Its ambition is large-scale CO_2 reuse through the establishment of a CO_2 value chain. Current research projects include catalysis for polymers from carbon dioxide and electrochemical conversation of CO_2 .

SusChem

The 2015 SusChem Strategic Innovation and Research Agenda is supportive of CDU, stating: "the utilisation of CO_2 as a feedstock by the European chemical industry could be a key solution to reduce use of fossil fuels, reduce the EU's dependence on imports of fossil resources and improve security of supply of carbon feedstock, while reducing pressure on biomass, land use and other environmental stressors. CO_2 from industrial flue gases could represent a new alternative feedstock to produce chemicals, materials (polymers and inorganic materials), fuels and store renewable energy through power to gas and power to liquid technologies."

SPIRE

The valorisation of process flue gases, and in particular CO_2 , is singled out in the 2013 Sustainable Process Industry through Resource Efficiency (SPIRE) Roadmap. Interestingly, in regard to CO_2 , they suggest that the short-term focus should be on overcoming technological hurdles for commercial introduction of high-value-added CO_2 -derived polymers and chemicals where a market already exists, as this will help generate the momentum to address other higher value utilisation opportunities such as CO_2 to fuels.

SCOT Project (FP7)

An important EU project is SCOT (which stands for Smart CO₂ Transformation). The objective of this collaborative FP7 EU project is to define a 'Strategic European Research and Innovation Agenda' for Europe in the field of CDU. Both the University of Sheffield and Yorkshire Chemical Focus (YCF) from the UK are part of the consortium.

Bio-TIC (FP7)

The Bio-TIC project aims to identify hurdles and develop solutions to the large-scale deployment of industrial biotechnology (IB) in Europe. The combination of IB and CO_2 as a feedstock is one of five product groups that have been identified as having significant potential for enhancing European economic competitiveness, and which have the potential to introduce cross-cutting technology ideas.

H2020

The following specific opportunities exist for European businesses involved in CDU under the H2O2O program:

- SPIRE-05-2016: Potential use of CO₂/CO and non-conventional natural resources in Europe as a feedstock for the process industry.
- **SPIRE-08-2017:** CDU to produce added value chemicals.
- SPIRE-10-2017: New electrochemical solutions for industrial processing, which contribute to a reduction of CO₂ emissions.
- LCE 25 2016: Utilisation of captured CO₂ as feedstock for the process industry.
- BIOTEC-05-2017: Microbial platforms for CO₂ reuse processes in the low carbon economy.

Support and activity in the field of CDU in the UK is summarised below.

Teesside Collective/DECC

A consortium consisting of Tees Valley Unlimited (the Local Enterprise Partnership) and the Teesside industrial cluster of BOC Linde, Lotte Chemical UK, CF Fertilisers, NEPIC, National Grid and TVU, was awarded £1m by DECC to develop a business case for deploying industrial CCS in the Teesside cluster and to make recommendations for a funding mechanism. SSI UK was also involved before its plant closed. The Teesside Collective has a shared vision of the Tees Valley being a leading hub of clean industrial production, assisting the UK to meet its greenhouse gas reduction targets. The main focus has been CCS, but CDU is being investigated as part of collaborative research programmes. The funding for this project ran out at the end of 2015 and the consortia are currently assessing interest from government in taking this project further.

CO₂Chem Network

Launched in 2010, CO_2Chem brings together academics, industrialists and policy makers over a wide range of disciplines to consider the utilisation of carbon dioxide as a single carbon chemical feedstock for the production of value added products. The CO_2Chem Network is gathered into eight research sub-themes around the areas perceived to be the most important. The network is funded by the Engineering and Physical Sciences Research Council (EPSRC) as a 'Grand Challenge Network' and is led by the University of Sheffield, a world-leading academic group in the field of CDU.

Algal Bioenergy Special Interest Group (AB-SIG)

The AB-SIG is a network managed by KTN and supported by Innovate UK, the Biotechnology and Biological Sciences Research Council (BBSRC) and the Natural Environment Research Council (NERC). It is looking at opportunities to develop algal technologies.

BBSRC Networks in IB and Bioenergy (NIBBs)

The BBSRC has established 13 unique cross-disciplinary collaborative NIBBs. The purpose of these networks is to boost interaction between the academic research base and industry, promoting the translation of research into benefits for the UK. Additionally, they help to drive new ideas to harness the potential of biological resources for producing and processing materials, biopharmaceuticals, chemicals and energy. The NIBB of most relevance to CDU is PHYCONET, which is looking to unlock the IB potential of microalgae for high value products.

Current innovation challenges and opportunities

Based on the desktop research and consultation undertaken during this study, the key innovation challenges and opportunities can be summarised as follows:

- Low energy processes to capture carbon Development of sustainable technologies to recover CO₂ from industrial streams, (including new membrane technologies) for CO₂ separation and purification from flue gases and advanced materials for CO₂ capture.
- New sustainable catalysts The conversion of CO₂ to chemicals and materials requires reduction either with renewable sources of energy (electricity or non-fossil H₂) or via reaction of CO₂ with high-energy molecules. Arguably the most important challenge in the CDU field is the development of catalysts that lower than energy barrier for the conversion of CO₂ into chemicals and polymers. Alternatives to traditional catalysis would be electro-catalytic and photo-catalytic processes. These technologies also need to be scaled up.
- Lifecycle assessments Better understanding of the lifecycle benefits of utilising CO₂ in products is required to claim the benefit of sequestering the CO₂.

- Direct photo-conversion of CO₂ (longer term)

 A further key breakthrough in the chemical utilisation of CO₂ will be the direct photo-conversion of CO₂. This is a longer-term option (i.e. beyond 2030).
- Algal technologies and other bacterial processes — The main challenge is growing algae efficiently and productively. Robust and largescale cultivation methods are required to make phototrophic algae an economic and attractive crop. Harvesting, disruption, fractionation and refining of the algae biomass must also become more efficient. It will also be important to identify ways to reduce the large amounts of water used in processing, as this adds to the cost and energy demand. In comparison to microalgae technologies the process of producing CO_2 via bacterial fermentation is much simpler as light is not required. However, the cultivation media is more expensive due to high hydrogen costs, which highlights the key challenge in this area.

Summary

Specific technical challenges associated with producing chemicals and fuels via CDU have been identified. Based on an assessment of the TRL of various CDU pathways, it is clear that while some mineralisation pathways are close to commercialisation, significant R&D and business development is required before chemicals and fuels will be produced on a large commercial scale through CDU. The only exception to this is Covestro, which is leading the way in Europe and investing in a commercial-scale plant to produce polyols via CDU technology.

A number of important market and policy-related challenges are holding back the commercialisation of CDU. One of these is the current lack of economic or policy incentive for business to do anything with their 'waste' carbon dioxide emissions.

In Europe, the price of carbon (and hence price of CO_2) is determined by the European Emissions Trading Scheme (ETS), with the current price on carbon around $\in 8$ per tonnes CO_2 equivalents (tCO_2e -). That price will not drive change. It would need to be upward of \in 50 t CO_2e - to impact the investment decisions of big business. A similar direct or indirect carbon price would also need to be in place across the globe, otherwise carbon leakage (i.e. the movement of industrial activity from one country with an ambitious climate change policy to one with less ambition) would occur.

Another major challenge for the UK is that it is lagging behind in business-led CDU innovation when compared with the rest of Europe. Certainly, the EPSRC-funded CO_2 Chem Network is valuable, helping to leverage the world-leading academic capability in the UK. In addition, a number of UK-based SMEs have been identified that are looking to commercialise CDU processes. However, further investment and support is needed to help accelerate CDU technology and identify new near- and mid-term market opportunities. With the need to move toward a low carbon economy becoming ever more urgent, sources of carbon, like waste CO_2 from industrial processes, must be viewed as a valuable commodity, not to be wasted and certainly not to be released in large volumes into the atmosphere. This move towards decarbonisation will help accelerate technologies like CCS and CDU.

The immediate focus for industry should therefore be on understanding and identifying:

- Niche industrial symbiotic opportunities where CO₂ is considered as part of a part of a circular carbon value chain.
- Technology options and market opportunities within existing industrial clusters of CO₂-intensive industries.
- Niche opportunities where the incorporation of CO₂ into a product can bring demonstrable performance improvement at a lower cost.

When considering which CDU pathway might be the most commercially attractive for the UK, it is worth noting that a techno-economic analysis performed by Element Energy and others in 2014 suggests that if carbon sequestration is the key goal for CDU, then the UK should focus on methanol, mineral carbonation, polymer production and existing commercial industrial uses of CO₂ (i.e. EOR, Urea, refrigerant gas, etc). This analysis should be considered and tested by any future work in this area.

RECOMMENDATION: In order to help speed up commercialisation of CDU technology, the UK's CDU innovation community (including leading academics, start-ups, SMEs and industry clusters) should come together to identify new near- and mid-term market opportunities for turning CO₂ into higher value products.

5.0 Renewable feedstocks

As discussed in Section 2, it is essential that new, sustainable feedstocks are developed in order to meet the growing demand for chemicals. One of the most promising areas is renewable feedstocks.

As this is such a large area, this study focuses specifically on biomass and carbon-containing waste as a source of renewable feedstock. Biomass is organic matter derived from living, or recently living organisms.

It is recognised that there are other renewable feedstock sources beyond biomass and carboncontaining wastes, however, due to time constraints these have not been covered here.

There are three key categories of biomass, referred to as first-, second- and third-generation feedstocks.

First-generation feedstocks are derived from food crops, such as starch-rich or oily plants. It is sometimes referred to as 'edible biomass'. First generation agricultural feedstocks used in the production of biobased chemicals include corn, soy, sugarcane and sugar beets.

Starch-rich crops such as corn, wheat, and cassava (manioc), store energy as starch and polysaccharide. Starch can be hydrolysed enzymatically to produce a sugar solution, which subsequently can be fermented and processed into biofuels and biobased chemicals.

Although commercial-scale processes that turn firstgeneration feedstocks into fuels and basic commodity chemicals already exist, these first-generation feedstocks are unlikely to be sustainable in the long term to meet growing demand. This is because these feedstocks are competing for resources (land, water, energy) with food crops, which are themselves absolutely crucial for a growing population. **Second-generation feedstocks** utilise the non-food parts of food crops (which is often referred to as lignocellulosic biomass, or simply biomass) or other non-food crops like perennial grasses (e.g. miscanthus, switchgrass).

By weight, lignocellulosic biomass is the largest component of plant matter. Until recently, it would have been considered as waste, however, significant attention is now focused on its valorisation.

It consists of a mixture of cellulose, hemicellulose and lignin. Cellulose and hemicellulose are both chained polymers made up of individual sugar molecules. When these polymer chains are hydrolysed, either by reaction with acid or enzymatic hydrolysis, they are converted to their constituent sugars. Lignin is a major component of plant cell walls made of aromatic heteropolymer units, which are very difficult to break down.

Third-generation feedstocks — Algae were until recently considered part of second-generation feedstocks. But owing to the unique challenges and opportunities of utilising algae as a feedstock for fuels and chemicals, it has been allocated its own category.

Figure 5-1 provides a summary of the types of products that can be produced from various renewable feedstocks. A detailed breakdown of the chemicals that can be obtained from first- and second-generation feedstocks is also provided in Appendix D.



Figure 5-1: Summary of renewable and waste feedstocks, processes and products (Source: House of Lords Enquiry, 2014)

Figure 5-1 also shows three different approaches to processing renewable feedstocks: thermochemical (e.g. pyrolysis), chemical (e.g. catalytic) and bioprocessing / industrial biotechnology (IB) (e.g. fermentation or anaerobic digestion). This study considers all processes, but in terms of products focuses on the conversion of renewable feedstocks for the purpose of producing chemicals (rather than fuel, fibres, etc.) that sit at the top of the value chain.

Recent developments and market update

Biomass feedstocks

The opportunities for the UK in this area are very significant. The CGSG Strategy Report suggests that utilising biomass or waste as a material could bring potential long-term benefits of £8bn to the UK.

Biobased chemical markets are already significant in the United States, representing more than 2.2% of GDP — or more than \$353bn in economic activity in 2012. Figure D-2 (Appendix D) shows an overview of

the commercial routes that exist today for biobased chemicals, as well as the targets that are not yet commercial but being developed.

The most common type of biorefining today utilises first-generation sugar or starch-rich crops. The starch is derived from grains such as corn. Sugar crops include sugarcane, sugar beets, and sweet sorghum and it is the simple sugars (mono- and di-saccharides) from these crops that can easily be extracted from the plant material for subsequent fermentation to ethanol and other biobased chemicals.

The UK is well positioned to take advantage of the potential of the biobased chemicals market derived from biomass based on its world-class academic expertise. This includes research groups at the University of York and the University of Bath that are looking at green chemistry. Also the University of Nottingham is well positioned through the new Centre for Sustainable Chemistry (construction due to be completed summer 2016) but also the Synthetic Biology Research Centre, led by Nigel Minton and his group. This adds to the existing capability across numerous other academic organisations, RTOs and other supporting networks, which are discussed later.

Fermentation is certainly one process route of considerable interest in the UK, not just for academia but also at a commercial level. The UK already has plants that produce bioethanol from renewable feedstocks via fermentation. For example, **British Sugar (part of AB Sugar Group)** developed the UK's first bioethanol plant in Wissington in 2007. It is capable of producing 55,000 tonnes of bioethanol from its sugar beet sources in the UK. AB Sugar is also involved in a Joint Venture with **DuPont** to operate a bioethanol facility in Hull that uses wheat as a feedstock. **Ensus** also operates a large biorefinery in Yarm. But what about other higher value chemicals via fermentation?

Zuvasyntha (formerly BioSyntha) is developing proprietary routes to key commodity platform chemicals based on renewable C1 feedstocks (e.g syngas) using engineered acetogenic bacteria. Its lead program has been targeting production of 1,3-butanediol.

Ingenza is applying its expertise in synthetic biology to the manufacture of industrial products including enhanced biofuels, sustainable manufacturing of chemicals and the production of protein therapeutics.

Calysta is using methane as a biological feedstock to create essential building blocks for high value industrial materials and consumer products, based on its gas fermentation technology. It is currently working with CPI to develop a pilot scale facility in Teesside to make a sustainable fish feed product (FeedKind[™] Aqua) based on its technology platform.

Elsewhere in Europe, **Clariant** (a global speciality chemicals business with over 17,000 employees worldwide) is developing a process to produce Sunliquid®, which is cellulosic ethanol produced from agricultural residues. The key residue they have been exploiting is wheat straw. The process involves integrated enzyme production and the simultaneous fermentation of C5 and C6 sugars into ethanol. They are looking to utilise cellulosic sugars and their Sunliquid® technology as a platform for a range of other chemicals.

Lanzatech (founded in New Zealand and now based in the US) is using gas fermentation technology based on a proprietary microbe to turn CO (a waste gas from industrial operations like steel production) into ethanol. It recently entered into a collaboration with ArcelorMittal (a steel and mining company) and Primetals Technologies (an engineering firm) to construct Europe's first ever commercial-scale bioethanol production facility utilising waste gases from the steelmaking process. This €87m flagship plant is currently being built, with €10.2m secured under the EU Horizon 2020 programme.

Another process that has received strong interest in the UK, and elsewhere, is anaerobic digestion (AD). This process involves the use of microorganisms to break down biodegradable materials in the absence of oxygen.

Much of the early commercial interest in AD was in energy-from-waste but the biogas produced via this process could potentially be utilised as a chemical feedstock.

NNFCC and Inspire Biotech were recently commissioned to undertake a study to assess whether there is a specific need for investment in pilot scale equipment in the UK and to develop the case for any investment in IB. One of the key findings was that there is a major investment opportunity to build UK excellence and leadership in C1 gas fermentation (and high-value products from microalgae). In addition, there is the opportunity in the UK to consolidate and grow fermentation from cellulosic feedstocks and high-value extractives. The report also recommends action be taken to promote industry interactions in the areas of biologics, anaerobic digestion and biocatalysis to help accelerate this. Regarding algae, there are a number of potentially attractive high-value target molecules. These include commodity chemicals (ethanol), speciality chemicals, nutraceuticals (e.g. Omega 3 oils, PUFAs, DHA and EPA) and pharmaceuticals (e.g. terpenoids). The AB-SIG's *UK Roadmap for Algal Technologies* identified the following areas as most promising commercially:

- In the short to medium term, high value products from both macro- (condiments and premium sea vegetables, high value uses of hydrocolloids) and micro-algae (increased production of established and emerging bioactives, e.g., DHA, EPA, pigments, antioxidants, sunscreens).
- In the medium to long term, integrated biorefining of micro- and macro-algae coupled to fractionation or thermochemical conversion for a suite of chemical and energy products. Also, novel bioactives through bioprospecting (microand to some extent macro-algae) and metabolic engineering (microalgae) for pharma, cosmetics, nutrition.

For details of which companies are involved in these areas, refer to the AB-SIG community website.

Specific opportunities for carbon-containing waste

In 2014 the House of Lords Science and Technology Select Committee held an enquiry, *Waste or resource? Stimulating a bioeconomy*, which has been critical in helping to build momentum in the UK for opportunities from carbon-containing waste and the bioeconomy. The enquiry is recognition of the importance of carbon-containing waste as a resource and the opportunities that exist for the UK to embrace circular economy thinking and the future bioeconomy.

The House of Lords enquiry report found that the UK produces almost 300 million tonnes of waste every year. This includes at least 100 million tonnes of carbon-containing waste and 14 million tonnes of biobased residues from crops and forestry sources. It is suggested that, with the right technology, at least 25 million tonnes of carbon-containing waste could be extracted and converted to 5 million tonnes of bioethanol with a value of £2.4bn.

In 2015, the government launched the report *Building a high value bioeconomy: opportunities from waste*. In it, the government agreed with the conclusion of the March 2014 report *Waste or resource? Stimulating a Bioeconomy*, that there is an enormous opportunity for growing the bioeconomy using a range of feedstocks, including waste. Importantly, it states that its vision is that by 2030 the UK will have a range of commercial-scale plants fed by wastes operating across the country.

Examples of UK-based companies and projects that are leading the way in the development of chemicals from carbon-containing waste are provided below:

- CelluComp Ltd Based in Scotland, this company is developing high performance products from residual food waste. Its principal product is Curran®, a material developed from the extraction of nanocellulose fibres of root vegetables. Curran® offers a range of properties, which make it attractive for numerous applications such as paints and coatings, personal care and composites. CelluComp has previously received funding through Innovate UK's IB Catalyst.
- Fiberight Ltd Fiberight has developed a Targeted Fuel Extraction (TFE) process based on enzymatic digestion and fermentation to cost-effectively and efficiently convert municipal solid waste (MSW) into cellulosic biofuel, plant energy and marketable electricity. It is currently engaged in a project with the Centre for Process Innovation (CPI), funded through Innovate UK's IB Catalyst program, to develop a demo-scale reactor for optimised enzymatic hydrolysis of Fiberight's high performance cellulose extracted from municipal solid waste.

- Solena Fuels and British Airways (Greensky project) – The Solena Green Sky project was a partnership between Solena Fuels and British Airways, committed to building the world's first facility to convert 575,000 tonnes of landfill waste into jet fuel. The facility, due to open in 2017 at an ex-oil-refinery in Thurrock, Essex, was planned to use Solena's patented high temperature plasma gasification technology to convert the waste efficiently into synthetic gas. The gas would then be converted into liquid hydrocarbons using third party technologies, which will include cleaning and conditioning of the gas, a Velocys Fischer-Tropsch conversion process, hydrocracking and electric power production. Unfortunately in January 2016, BA announced the project would be mothballed because of "low crude oil prices, jitters among investors, and a lack of policy engagement from 10 Downing Street". This is disappointing, as a plant of this scale would have been valuable to the UK.
- ReBio Technologies Ltd is specialising in the development of new biosynthetic pathways in a range of microbial hosts to produce high-value chemicals through fermentation. It is currently engaged in a lab-scale demo project with CPI and the University of Bath to produce modified strains of microorganisms to produce D-lactic acid for the manufacture of biobased products such as high performance bio-plastics. The bacterial host grows at high temperatures and has the ability to convert long chain sugars (C5-C6) from nonfood materials. This project has the potential to unlock an economic approach to transforming cellulosic sugars and the millions of tonnes of food and landfill waste derived sugars produced every year into sustainable, high value chemicals. ReBio Technologies has received funding from Innovate UK through mechanisms including the IB Catalyst.

Current and historical innovation support

A summary of some of the key areas of innovation support is provided below.

Innovate UK funding

The **IB Catalyst**, which closed in 2015, was a programme jointly funded by Innovate UK, EPSRC and BBSRC that supported R&D into the processing and production of materials, chemicals (including pharmaceutical precursors and biopharmaceuticals) and bioenergy, as well as the development and commercialisation of innovative IB processes to manufacture a wide range of existing and new products through collaborative and non-collaborative research grants. The program committed over £41m in projects spanning the five challenge areas below:

- Production of fine and speciality chemicals and natural products (e.g. fragrances, flavours, pharmaceutical intermediates).
- Production of commodity, platform and intermediate chemicals and materials (e.g. plastics, resins, silks).
- 3. Production of liquid and gaseous biofuels.
- 4. Production of peptides and proteins (e.g. enzymes, antibiotics, recombinant biologics).
- 5. Novel or improved upstream or downstream processes to reduce costs or improve efficiency in industrial biotechnology applications.

Several types of award were available to support research at different TRLs:

- Early-stage translation
- Early-stage technical feasibility studies
- Industrial research
- Late stage technical feasibility studies
- Experimental development

Some examples of projects funded through rounds 1-3 of the IB Catalyst that are most relevant to this study are provided in the table below.

FUNDING CALL STAGE	PROJECT TITLE	PROJECT PARTNERS (LEAD FIRST)
Early-stage translation	Integrated energy-efficient microwave and unique fermentation processes for pilot-scale production of high value chemicals from lignocellulosic waste	University of Bath, University of York, Croda, C- tech Innovation, and AB Agri
Early- stage feasibility	Fermentation of C1 feedstocks to 1,3-butanediol	BioSyntha
Industrial research	Bioplastic polymers based on aromatic dicarboxylic acids derived from lignin	Biome Technologies, University of Warwick, University of Leeds, CPI
Late-stage technical feasibility	Driving down the cost of waste derived sugar	Fiberight, CPI, ReBio Technologies, University of Leeds, Aston University, Knauf and Novozymes

Table 5-1: Selection of funded projects through Rounds 1-3 of the IB Catalyst (Source: Innovate UK)

In 2013, Innovate UK, with support from BBSRC and EPSRC, provided £2.5m for the call *High Value Chemicals through Industrial Biotechnology (HVC-IB)* to support innovation projects from feasibility to demonstration. This project again delivered some interesting collaborative R&D projects, which focused on the development of biobased products.

High Value Manufacturing Catapult

CPI is a UK-based technology innovation centre and the process arm of the High Value Manufacturing Catapult. Established to support the UK process manufacturing industry, CPI collaborates with universities, SMEs and large corporates to help overcome innovation challenges and develop next generation products and processes. It has specialist capability across four main technology areas, two of which are IB and biorefining (at Wilton) and biologics (through their new facility in Darlington). This centre has a fantastic range of capability for supporting UK businesses to scale up from laboratory to market.

Networks and intelligence

There a large number of support networks associated with the development of renewable feedstocks, which are summarised below:

- BBSRC NIBBS As mentioned earlier, there are
 13 NIBBS looking to accelerate specific areas of IB.
 The following NIBBS are of particular interest to
 biobased and waste feedstocks:
 - Anaerobic Digestion Network addresses scientific and technical challenges in the development of anaerobic biotechnology.
 - * A Network of Integrated Technologies: Plants to Products focuses on the conversion of plant material, including agricultural by-products and agro-industrial co-products to chemicals and materials.
 - * **C1NET: Chemicals from C1 Gas** is tasked with unravelling the biological, chemical and process engineering aspects of gas fermentation and to steer translational outputs towards commercial application.
 - * Food Processing Waste and By-Products Utilisation Network (FoodWasteNet) fosters interaction between researchers and industrialists in order to realise the potential of using food waste and by-products to

produce chemicals and biomaterials with market potential.

- * High Value Chemicals from Plants Network, working in partnership with industry, focused on identifying novel products and optimising and developing both feedstocks and processes in plants.
- * Network in Biocatalyst Discovery, Development and Scale-Up is seeking to discover, develop and make available a broader range of biocatalysts, which can be screened and applied by the end users.
- WRAP is a charitable organisation that works between governments, businesses, communities, thinkers and individuals forging partnerships and delivering initiatives to support more sustainable economies and society. It helps drive change in three key sectors where it has particular expertise: food and drink, clothing and textiles, and electricals and electronics.
- **NNFCC** is a leading consultancy based in York with world-class expertise on the conversion of biomass to bioenergy, biofuels and biobased products. It is well connected and informed on all activities in the UK and across Europe in these areas.
- BioVale is a not-for-profit, member-based organisation supported by regional industry in the Yorkshire and Humber region, research organisations, higher education and government. It provides support to build the region's capability and reputation as an innovation cluster for the bioeconomy and ensure that it fully exploits new business opportunities in this sector. It does this by providing business support and access to networks and information.
- BEACON is led by Aberystwyth University in collaboration with partners at Bangor and Swansea Universities. Its aim is to help Welsh businesses develop new ways of converting crops such as rye grass, oats and Miscanthus into products including pharmaceuticals, chemicals, fuels and cosmetics. It is funded using £10.6m from the European Regional Development Fund through the Welsh Government.

- IBLF The IBLF brings together those from industry (large and small), government, funding bodies, related associations and the skills councils providing strategic direction on how to fully exploit IB in the UK. It is also responsible for implementing the recommendations of the Biotechnology Innovation & Growth Team (IB-IGT) report to produce a capable and connected UK IB community of critical mass.
- **AB-SIG** Managed by KTN, the objectives of the AB-SIG are to:
 - * Connect academia and industry in developing the evidence base for the sustainable production of algal products.
 - * Help UK businesses operating in the fields of algal bioenergy or using algal-derived products, to profit and grow through new biosciences-inspired innovation.
 - * Ensure that project developers fully understand the environmental implications of any planned algal commercialisation activity in the fields of bioenergy and commodity chemicals.

Centres of excellence and translational research

- IBioIC One of the eight centres of excellence funded by the Scottish Funding Council, the Industrial Biotechnology Innovation Centre (IBioIC) was launched in 2014 to bridge the gap between education and industry in Scotland. It provides networking opportunities for its academic and industrial communities, technical expertise, access to new equipment and financial support for projects.
- BDC The Biorenewables Development Centre (BDC) is a not-for-profit company based at the University of York that assists businesses to develop ways to convert plants, microbes and biowastes into profitable biorenewable products. The centre has a range of expertise, capability and equipment that it can use to help companies in the development and scale up of new greener processes and products. It was established through collaboration between the Green Chemistry Centre of Excellence at York and the Centre for Novel Agricultural Products.

 Synthetic Biology Research Centre – In 2014, BBSRC and EPSRC established three new multidisciplinary synthetic biology research centres in Bristol, Nottingham and through a Cambridge/Norwich partnership. The £40m+ investments will receive funding over five years to boost national synthetic biology research capacity and ensure that there is diverse expertise to stimulate innovation in this area. The centres offer the opportunity for collaboration; provide essential state-of-the-art equipment, facilities, trained researchers and technical staff; drive advancement in modern synthetic biology research; and develop new technologies.

In Europe, the following support has been available.

H2020 funding

There has been — and continues to be — a huge number of funding opportunities available through the \in 3.7bn H2020 Biobased Industries (BBI) Joint Undertaking (JU) program. A summary of some of the recent calls are provided below:

- BBI.VC1.F1 From lignocellulosic feedstock to advanced biobased chemicals, materials or ethanol.
- **BBI VC2.F2** Valorisation of cellulose into new added value products.
- BBI VC4.F3 Innovative processes for sugar recovery and conversion from Municipal Solid Waste.

Outside of the BBI JU, there are other opportunities:

- BIOTEC-02-2016 Bioconversion of nonagricultural waste into biomolecules for industrial applications.
- SPIRE-03-2016 Industrial technologies for the valorisation of European bio-resources into high added value process streams.
- BIOTEC-06-2017 Optimisation of biocatalysis and downstream processing for the sustainable production of high value-added platform chemicals.

European projects and support

- BioBase NWE This project supports the development of North-West Europe as a leading European region in the biobased economy. Over 30 business vouchers with a value between €10,000 and €30,000 were given out to companies in the region to help them scale up novel processes. The project also had the aim of identifying and representing the needs and opportunities of SMEs in the implementation of the EU Bioeconomy Strategy. This analysis concluded with a report entitled *Bio Base NWE analysis report on the bottlenecks SMEs encounter in the bioeconomy*, which is soon to be published. The project concluded in September 2015.
- EnAlgae The objective of this project was to develop sustainable technologies for algal biomass production, bioenergy and greenhouse gas (GHG) mitigation, by developing and sharing data from nine pilot-scale facilities across North-West Europe. The main objective was to explore the potential for algal biomass to deliver sustainable energy and resources. With the barrel cost of oil almost halving compared to the beginning of this project (five years ago) and revised estimates for the realistic potential for algal biofuels, project partners concluded that is looks highly unlikely that algae can contribute significantly to Europe's need for sustainable energy. The study, however, highlighted the great potential for commercial exploitation of algae in other sectors, such as food and nutraceuticals. The need for food is just as important to Europe as energy, and algae contain valuable dietary components for humans.
- **Bio-TIC** CDU was already mentioned as one of the five key product groups in the Bio-TIC roadmap. But the other four product groups have been identified as being particularly promising based on their future market prospects.
 - Advanced biofuels (advanced bioethanol and biobased jet fuels), where the global markets could be worth €14.4bn and €1.4bn respectively by 2030. For both markets, the proportion fulfilled by industrial biotechnology-based processes is unclear given the range of technologies available and their early stage of development.

- Biochemical building blocks that can be transformed into a wide range of products which are either similar or offer additional functionality compared to fossil products, where the EU market could reach €3.2bn by 2030.
- **3. Biobased plastics** where the EU market could reach €5.2bn in 2030.
- 4. Biosurfactants derived from fermentation typically used in detergents, where the EU market could reach €3.1m in 2030.
- SusChem Biobased feedstocks are recognised in the 2015 SusChem Strategic Innovation and Research Agenda in a number of areas. Some of the specific biobased products they suggest should be targeted are as follows:
 - Bulk chemicals e.g. 3-hydroxypropionic acid, succinic acid, 1,3-propanediol, furfural and isoprene.
 - Building blocks for polymers e.g. longchain amino acids or diacids or di-amines for polyamides, diols or polyols for polyurethanes or polyesters.
 - * Specialty chemicals e.g. solvents, surfactants and lubricants.
 - * Fine chemicals, including intermediates for pharmaceutical active ingredients e.g. chiral molecules such as amino acids.
 - * Composites e.g. composites containing natural fibres as replacement for syntheticfibre-reinforced composites, and biocomposites where both fibres and resins are obtained from biomass. These will have applications in the building, automotive and packaging industries.

Chemical products from waste are not specifically covered, although lignocellulosic material is recognised a key feedstock to focus attention on.

- **SPIRE** In terms of industrial needs and the related research and innovation challenges, the SPIRE Roadmap identified six key components that target the four building blocks of a resource and energy efficient process industry. The first of these components is FEED, with the two relevant associated key actions being the following:
 - KA 1.2 Optimal valorisation of waste, residue streams and recycled end-of-life materials as feed.
 - KA 1.4 Advancing the role of sustainable biomass/ renewables as industrial raw material.

Another of those six key components is WASTE2RESOURCE, which has the following associated key actions:

- KA 4.1 Systems approach: understanding the value of waste streams.
- KA 4.2 Technologies for separation, extraction, sorting and harvesting of gaseous, liquids and solid waste streams.
- KA 4.3 Technologies for (pre)treatment of process and waste streams (gaseous, liquids, solids) for reuse and recycling.
- KA 4.4 Value chain collection and interaction, reuse and recycle schemes and business models.
- BIOOX (FP7) This project, coordinated by University of Manchester, is focused on the application of biocatalysis for aerobic oxidation. Its research areas include identifying new enzymes and enzyme optimisation and formulation, as well as reactor design and demonstration.
- KYROBIO (FP7) Led by C-Tech Innovation, the objective of the KYROBIO project is to broaden the toolbox of single enantiomer chiral chemicals that are produced by industry in Europe using biotechnological routes. The main target is applications of lyase enzymes to selectively synthesise molecules with multiple chiral centres, applying enzymatic carbon-carbon and carbonnitrogen bond formation as the key technical platforms.

Current innovation challenges and opportunities

With such a broad range of feedstocks, processes, and potential products it is not surprising that this study has been unable to provide detailed information on all of the innovation challenges and opportunities of each feedstock. Below is a snapshot of some of the key challenges and opportunities associated with biomass and carbon-containing waste feedstocks.

Which feedstock?

One of the key innovation challenges in creating a vibrant UK market for biobased feedstocks in the UK is finding a reliable and consistent feedstock. But which feedstock(s) provide the UK with a competitive advantage? How much of it is available? Is it produced consistently or restricted to certain seasons?

These are all important questions and further, more detailed research would be required to answer these questions fully. However, just taking lignocellulosic material, Figure 5-2 shows the volumes of different types of lignocellulosic material around the world.



Figure 5-2: Main sources of lignocellulosic material in the regions of the world (in million tons) (Source: Presentation by Martin Volmer, CTO, Clariant at RSC Chemicals from Waste event, 2015)

It clearly indicates that wheat straw is in plentiful supply in Europe (albeit also in Asia) and others like corn stover, bagass and rice straw are produced in relatively small volumes compared with other regions.

One expert consulted as part of this study suggested that straw would be a good feedstock for the UK to target, which correlates well with the data above. The UK certainly has a lot of it, more than some other countries.

There is also still a great deal of optimisation to be undertaken to identify the best strains of algae and enzymes for fermentation for certain target molecules.

How is the feedstock collected and separated?

This is a significant issue for feedstocks from mixed waste streams which require bioprocessing as these are often sensitive to contaminants and therefore require a high purity feedstock.

For instance, contaminants can be a significant issue when growing algae. Anaerobic digestion (AD) is another good example, with data showing that only a small fraction of the potential food waste feedstocks that are available are being sent to AD facilities. Food waste is therefore either going to recovery routes such as direct land spreading or animal feed or, in the case of the majority of food waste from households, is being sent to landfill or energy from waste options.

For this material to be captured and valued through AD or other processes that extract valuable compounds and chemicals there needs to be collection and supply mechanisms in place that ensure that the right quality materials are delivered to the processing facilities.

However, these can be expensive to introduce and run, so potential end users would need to contribute to collection costs for them to be viable for local authorities. This highlights one of the biggest challenges for using carbon-containing waste as a feedstock.

Other challenges in the collection and separation of waste streams, as identified in a recent Cross-NIBB workshop, can be: the concentration of feedstock of interest being too dilute, the heterogeneity of waste, and the quality and stability of the waste.

Which process route?

Perhaps the biggest challenge of producing biobased chemicals on a commercial scale is developing a robust and sustainable process. It is not possible (or appropriate) through this study to identify all of the challenges and opportunities associated with each process route. However, a snapshot of some of the key challenges and opportunities is provided.

For algae, large-scale land-based microalgal cultivation is possible in the UK if it is grown heterotrophically in fermenters that are scaled on volume rather than surface area. This is already established and has been highlighted in the AB-SIG as a near-term market opportunity for the UK. Some of the key innovation challenges associated with this are summarised below (taken from the 2012 NNFCC Report and the AB-SIG Roadmap 2015):

- Open access pilot plant/scale-up facilities are required.
- Ensure genetic stability in target strains.
- Develop model organisms.
- Improve the yield identify key environmental factors influencing yield and biochemical composition.
- Development of low-cost, effective techniques for cultivation, harvesting, extraction and downstream processing.
- Identify suitable sites for algal production.
- Develop lifecycle assessment capability, including carbon balance and sustainability information suitable for aquatic and marine systems.
- Assess the potential for algal diseases to affect both cultivated algae and wild stocks.
- Identify the biosecurity issues associated with using non-native or improved algal strains.
- Identify the best configuration for an algal farm to maximise yield and environmental benefits and minimise environmental impacts.
- Identify mechanisms to overcome nutrient limitation in offshore environments.

According to the 2012 report by NNFCC, the solution to a number of these challenges may be 15+ years away.

Another specific challenge for AD is that it requires very specific enzymes. However, these are very sensitive, so one challenge is the high lignin content that will kill the enzymes. An effective process for breaking down lignin is therefore required.

Which products, which markets?

There are many different markets for biobased chemicals including: fibres/materials (e.g. in construction or the auto industry); bioplastics and other biopolymers; surfactants, biosolvents, biolubricants (used in, for example, cosmetics, household and industrial detergents, paints, adhesives, inks, and papermaking); ethanol and other chemicals and chemical building blocks; biodiesel; pharmaceutical products including vaccines; enzymes (with industrial, healthcare and consumer applications); and cosmetics.

One of the markets that is showing real growth is biobased polymers. A recent report by the Nova-Institute has shown that the biobased polymer sector grew by 10% in production from 2012 to 2013, 11% from 2013 to 2014 and capacity is expected to triple from 5.7 million tonnes in 2014 to nearly 17 million tonnes in 2020.

Biobased drop-in PET (Polyethylene terephthalate) and the new polymer PHA (Polyhydroxyalkanoates) show the fastest rates of market growth, with the lion's share of capital investment expected to take place in Asia.

Strong demand is also seen in Europe. However, the Nova-Institute report suggests that an unfavourable political framework is holding Europe back.

One of the most well-known PET products is Coca-Cola's PlantBottle[™]. The bottle is produced using biobased mono ethylene glycol, which is itself derived from sugar and molasses.

In regard to products from algae, the AB-SIG believe that the UK is best suited to develop algae for high value products (like nutraceuticals and pharmaceuticals), where the UK's biotechnology and metabolic engineering expertise comes to the fore, and where medium-sized production capacity is appropriate. There are significant opportunities for developing distributed microalgal cultivation in the context of integrated biorefining and bioremediation for high value products.

Summary

The study shows that renewable feedstocks from biomass and carbon-containing wastes represent an area of enormous potential for the UK. With such a wide variety of different feedstocks, processing routes and routes to market, it is extremely difficult at this point to identify which specific renewable feedstock source represents the biggest commercialisation opportunity for UK businesses. Further, more detailed consultation is required to understand which combination of feedstock, process technology and product/market represents an area of competitive advantage for UK companies.

RECOMMENDATION: A more detailed, crosscutting investigation is required to identify which combination of biomass/carbon-containing waste feedstocks, conversion technologies and market opportunities will provide UK businesses with a competitive advantage in the years to come.

6.0 Scarce metals and minerals

This part of the study is looking at the innovation challenges and opportunities associated with metals and minerals that are economically important and at high risk of supply disruption, including scarce metals, heavy rare earth elements and platinum group metals. These can generally be referred to as critical raw materials (CRMs). The term CRM and scarce metal and minerals will be used interchangeably.

Scarce metals and minerals directly relevant to the chemicals industry will be considered, as well as challenges and opportunities in other sectors where chemistry innovation can play a key role in supporting innovation.

Recent developments and market update

Key industrial sectors for the EU (including construction, chemicals, automotive, aerospace and machinery) which provide a total added value of €1,324bn and 30 million jobs, all have one thing in common: they all depend on access to CRMs. The innovation options associated with CRMs can be summarised as follows:

- Replace (substitution)
- Reduce by:
 - * Dematerialisation
 - * Shared ownership
 - * Service
- Reuse by:
 - * Lifetime extension
 - * Simple reuse
 - * Repair
 - * Remanufacturing
 - * Recycling

Only small amounts of critical materials are used per functional unit but those materials perform a vital function. Substitution of critical materials is therefore generally not possible in the short-term without loss of performance. Development of substitute materials is also a lengthy and expensive process but technology substitution (developing an entirely new technology that performs the same function) can offer a promising alternative approach in some instances. Recycling is almost non-existent for many CRMs, generally due to the dispersed and diluted form of the material within the product. The Critical Raw Materials Innovation Network (CRM_Innonet) project (discussed later) identified 14 raw materials that are critical for the EU across three key sectors: energy, ICT, and electronics and transport (automotive and aerospace). It prioritised these materials according to economic factors, i.e. jobs involved in the EU, availability and strategic relevance to the EU. The 14 CRMs are:

- Antimony
- Beryllium
- Cobalt
- Fluorspar
- Gallium
- Germanium
- Graphite
- Indium
- Magnesium
- Niobium
- Platinum Group Metals (Platinum, Palladium, Rhodium, Iridium, Ruthenium, Osmium)
- Rare Earth Elements (Lanthanum*, Cerium*, Praseodymium*, Neodymium*, Gadolinium, Europium, Samarium, Scandium, Terbium, Dysprosium Erbium, Holmium, Thulium, Lutetium, Ytterbium, Yttrium)
- Tantalum
- Tungsten

* These are more abundant

The project also looked in detail at the substitution profile of all 14 CRMs, providing valuable information about where potential opportunities lie in substitution.

KTN has been a leading organisation in helping business and government understand the challenges and opportunities for the UK associated with CRMs. For instance, it has helped set up and manage the Materials Security SIG, Security of Supply of Mineral Resources Group and Critical Raw Material Recovery project (discussed later).

It has also developed, with support from industry stakeholders, the Methodology for the Risk Assessment in Materials Supply (RAIMS). The idea behind this being that the methodology can help overcome one of the biggest challenges associated with this area: making business aware of the supply chain risks. Trialling of this methodology is currently underway.

KTN is certainly not the only organisation that has been developing methodologies and tools to help businesses understand the supply chain risks associated with CRMs. Indeed, a number of commercial options are available to companies interested in understanding more about these risks.

For instance, UK SME **Granta Design** provides materials intelligence to companies through their bespoke software products. The information and intelligence embedded in this software can help businesses make informed decisions around which materials to incorporate into a new product at the design phase.

Another example is the Supply Chain Environmental Analysis Tool (SCEnAT). It is a modular supply chain modelling tool, which incorporates a very advanced lifecycle assessment (LCA) and inputoutput (I-O) methodology, supply chain mapping, intervention database and performance evaluation/ key performance indicator (KPI) facilities. Users can customise it in different ways, e.g. to calculate and identify carbon hotspots in the supply chain.

Specifically in regard to chemistry innovation, the

CRM_Innonet project identified a number of market opportunities where it can help to minimise, reduce, or replace the use of CRMs.

One of these issues is the need to find alternatives to indium used in the production of flat screen TVs — a product that has seen significant increase in demand over the past decade. The H2020 program has funded a specific project to help find a solution to address this issue. The project is called INFINITY.

INFINITY will develop an inorganic alternative to the scarce and high cost material, indium tin oxide (ITO), currently used as a transparent conductive coating (TCC) for display electrodes on glass and plastic substrates. The novel conductive materials to be developed in this project will be based on low cost sol-gel chemistry using more widely available metallic elements, and will leverage recent advances in nanostructured coatings. Furthermore, novel printing procedures will be developed to enable direct writing of multi and patterned nano-layers, removing the waste associated with etch patterning. This project aims to produce demonstrator PV and display devices using printed indium-free anodes, with performance characteristics equivalent to current devices. Partners involved in this project include UK SMEs **EpiValence** and Flex Enable, as well as the University of Hull and TWI.

Current and historical innovation support

European funding and support:

H2020

The following calls identify key challenges for Europe associated with CRMs that are relevant to the chemical-using industries:

- NMBP-03-2016: Innovative and sustainable materials solutions for the substitution of CRMs in the electric power system.
- **SC5-13-2016-2017:** New solutions for the sustainable production of raw materials. [This call is very much focused on the extraction/mining process.]
- **SC5-14-2016-2017:** Raw materials innovation actions that address one of the following issues:
 - * Intelligent mining.
 - * Processing of lower grade and/or complex primary and/or secondary raw materials in the most sustainable ways.
 - * Sustainable metallurgical processes.

SUSCHEM

The SUSCHEM Roadmap is supportive of this area, stating: "the chemical industry can provide innovative solutions to reduce dependency on CRM through more efficient and environmentally friendly technologies to enable processing, recycling or reducing the amounts of materials used. Substitution of CRM by new materials or technologies in specific applications while maintaining or improving performance is a complementary strategy to enable a competitive raw materials supply for Europe."

European Innovation Partnership (EIP) on Raw Materials

The European Innovation Partnership on Raw Materials is a stakeholder platform that brings together representatives from industry, public services, academia and NGOs. Its mission is to provide highlevel guidance to the European Commission, member states and private entities on innovative approaches to the challenges related to raw materials. The EIP on Raw Materials' aim is to help raise industry's contribution to the EU GDP to around 20% by 2020. The EIP targets non-energy, non-agricultural raw materials. Many of these are vital inputs for innovative technologies and offer environmentally friendly, clean-technology applications. They are essential for the manufacture of the new and innovative products required by modern society, such as batteries for electric cars, photovoltaic systems and devices for wind turbines.

European Institute of Innovation and Technology (EIT) RawMaterials

EIT RawMaterials was designated as an EIT Knowledge and Innovation Community (KIC) in December 2014. EIT RawMaterials has the ambitious vision of turning the challenge of raw materials dependence into a strategic strength for Europe. Its mission is to boost the competitiveness, growth and attractiveness of the European raw materials sector via radical innovation and entrepreneurship. EIT RawMaterials will focus on metal and mineral raw materials. Biobased and polymer materials will be covered in view of their substitution potential. Other materials will also be considered in the context of multi-material product recycling.

Critical Raw Materials Innovation Network (CRM_Innonet) (FP7)

Recognising the potential problems that resource scarcity poses, the European Commission funded CRM_InnoNet to drive progress in the field of substitution of CRMs. Substitution is one important strategy for reducing demand for raw materials but CRM_InnoNet considers substitution in the context of other approaches, such as recycling and increased extraction. KTN coordinated this project.

NOVACAM (FP7)

NOVACAM is a project supported by the EU and the Japan Science and Technology Agency that aims to harness the under-utilised resource of lignocelluloses by developing novel catalysts that incorporate non-critical metals to catalyse the conversion of lignocellulose into industrial chemical feedstocks and bio-fuels. From the UK, Cardiff University is involved and KTN is responsible for dissemination. UK funding and support:

Innovate UK funding

The most relevant funding call sponsored by Innovate UK in recent years is the *Recovering valuable materials from waste* call. Two interesting projects funded under this call are outlined below.

- **IMERYS** Lithium recovery through novel reprocessing of Cornish kaolin and granite waste.
- **PhosphonicS Ltd** Total Recovery of All Platinum group metals (TRAP).

Innovate UK has funded a significant number of projects through other calls that are to some extent looking at minimising or substituting CRMs. One example of such a project is LOCATE: LOw Cost cATalysts for water Electrolysers. This project was funded through the 2014 *Fuel Cell Manufacturing and the Supply Chain* call and is led by UK SME, **Amalyst**, in collaboration with **ITM Power**, **PV3 Technologies** and University College London. The project involves the development of low-cost, high-performance catalysts for fuel cell anodes and water electrolyser cathodes that are designed as 'drop-in' replacements for platinum.

Critical Raw Material Recovery Project

The Critical Raw Material Recovery project is working to ensure that a wider range of minerals and metals are recovered during the recycling of waste electronic and electrical equipment (WEEE). It is a collaborative project coordinated by WRAP, with a number of partners — including KTN — and is supported by the European Commission's LIFE funding instrument.

The project will demonstrate viable approaches to increasing the recovery of target CRMs from WEEE by 5% by 2020. It will run a series of collection trials (via competitive tender) to maximise recovery of target WEEE. Approaches to be tested may include incentivised return, take-back, collection events and via specific collection facilities. Recovery trials (via competitive tender) will evaluate processes to extract CRMs such as graphite, cobalt, tantalum, antimony, rare earths, silver, gold and platinum group metals from the WEEE collected. Finally the project will develop policy recommendations and an infrastructure map to pave the way for implementing the recovery of these valuable materials across all European systems. This project commenced in February 2016.

Materials Security SIG

Funded by Innovate UK and managed by KTN, the Materials Security Special Interest Group (SIG) helps to stimulate progress towards a circular economy for high value materials.

The Materials Security SIG brings together designers, chemists, materials scientists, engineers, product developers and recycling and waste experts to facilitate the adoption of new business models and the rapid formation of new supply chains capable of delivering high impact, innovative solutions to materials security challenges. It has a role in helping businesses to understand potential constraints on the availability of material resources, the risks and opportunities these present, and to develop lifecyclebased approaches for the better management of material resources throughout the supply chain. Funding for the Materials Security SIG ceased in 2014.

Security of Supply of Mineral Resources (SoS-MR) Group

The Security of Supply of Mineral Resources (SoS-MR) Group has been established to provide networking support for all elements of the mineral supply chain. The primary purpose is to support the delivery of a research programme funded by NERC and EPSRC with significant contributions from the Brazilian funding agency, FAPESP and the project research partners. Four research projects, with a duration period of four years, have been authorised, with total input of nearly £15m.

KTN hosts SoS-MR and will provide ongoing support during the formation of research partnerships, the development of research proposals and the project delivery.

British Geological Survey (BGS)

The BGS, Camborne School of Mines and the University of Exeter have formed a Critical Metals Alliance, which will address the growing concerns over security of supply and aims to improve research capability. At the heart of the Critical Metals Alliance is the BGS-sponsored Lecturer in Critical and Green Technology Metals ,who will develop research on the lifecycle of CRMs.

The BGS publishes production information for selected critical metals in its annual publications World Mineral Production and European Mineral Statistics. The BGS also produces the Risk List, a supply risk index for chemical elements of economic value, first launched at the British Science Festival's Metals, Mines and Mobiles event in 2011. The BGS Mineral Profile Series presents essential background information on rare earth elements, cobalt, fluorspar, niobium-tantalum, platinum group elements and tungsten.

The BGS has been awarded a knowledge exchange grant by the NERC titled Critical Metals – Science for a Secure Supply, which aims to disseminate authoritative and accessible information on all aspects of the critical metals lifecycle.

Current innovation challenges and opportunities

The biggest challenge for the chemicals sector is the development of novel catalysts that minimise the use of scarce metals and minerals.

Projects like NOVACAM are looking to address this. Companies like **Amalyst** are also looking to tackle this through the development of catalysts that are less reliant on platinum group metals. Of course, leading UK catalyst manufacturer **Johnson Matthey** is heavily invested in pushing the boundaries of existing and new catalyst technologies. For instance, together with Cardiff University, **Johnson Matthey** recently received acclaim for development of a mercury-free catalyst to support a more environmentally friendly method of producing PVC.

The continued advancements of biocatalysis will be important.

Table 6-1 summaries the opportunities/challenges in substituting the 14 CRMs that are traditionally used in catalysts.

For many catalytic applications, the truth is that despite the high materials cost, there is little drive to substitute given the small amount of catalyst required relative to total production costs. However, recycling of the catalyst is often economically favourable.

CRM USED IN CATALYST	APPLICATION	SUBSTITUTION OPPORTUNITY
Antimony	 Polymerisation of polyester fibres (as Antimony Trioxide) 	 Difficult to replace. Titanium catalysts may offer some hope but without regulatory pressure to replace Antimony it will be difficult.
Cobalt	 Used in the oil and gas sector for hydrodesulfurisation Production of bulk chemicals in hydroformylation reactions Gas to liquid processes Hydrogen fuel cells 	 Hydrodesulfurisation: ruthenium, molybdenum, nickel and tungsten can be used depending on nature of the feed instead. Also, alternative ultrasonic process can dispense with the use of cobalt. Hydroformylation: rhodium can serve as a substitute.
Germanium	 Polymerisation of polyesters (as GeO2) 	 Sb2O3 is possible. However, its potential health effects are a cause for concern. Other potentials are aluminium and titanium-based catalysts.
Platinum Group Metals	 Autocatalysts Multiple chemical processes (production of silicone, nitric acid, paraxylene, acetic acid, pharma. processes) Petrochemicals sector (cracking and hydrogenation) Conversion of biomass Fuel cells 	 Autocatalysts: transition metal carbides, oxycarbide nanoparticles have been developed but do not show the same activity. Chemical and petrochemical processes: options limited. Conversion of biomass: nickel is showing promise. Fuel cells research: efforts focused on metal-free electrocatalysts and include the use of graphene and biobased materials combined with nanoparticles.
Rare earth metals	 Lanthanum, cerium, praseodymium and neodymium used by the petroleum industry (catalytic cracking) Cerium, lanthanum, praseodymium and neodymium used in catalytic converters 	• Focus has been more on recovery and regeneration.

 Table 6-1: Substitution Opportunities for CRMs used in Catalysts (Source: CRM Substitution Profiles, CRM_Innonet)

Outside of the chemicals sector there are significant opportunities for chemistry innovation to help address the challenges and opportunities associated with scarce metals and minerals in other sectors.

The Innovation Opportunities and Material Security Report, issued by the Materials Security SIG in 2012, identified almost 90 potential areas for action, which are still relevant today. The more recent CRM_Innonet report *Critical Raw Materials Substitution Profiles* also provides insight into where there may be opportunities to substitute the 14 CRMs in certain applications. The four main substitution strategies they explore are outlined in Figure 6-1.



Figure 6-1: Four substitution strategies for CRMs (Source: CRM Substitution Profiles, CRM_Innonet)

In general terms, the main challenges for scarce materials and minerals where chemistry innovation can play a role can be summarised as follows:

- Develop separation and purification processes: the performance of primary extraction and recycling of CRMs like platinum group metals or rare earth elements can be improved through more efficient hydrometallurgical processes, for example.
- Develop substitutes for CRM that are compatible with the expected level of performance in targeted applications.

However, there are a huge number of specific areas of opportunity across various sectors. For instance, as identified in the Critical Raw Material Recovery project, each year nearly ten million tonnes of waste electronic and electrical equipment (WEEE) is generated in the EU. It is a rich potential source of recovered materials that is presently not well exploited. Collection and recycling rates are low (around 30%) but even for waste that is recycled, only a small fraction of the complex mixture of materials is actually recovered. Current processes can only recover a small number of materials, so many critical and valuable materials are lost from the system. The Critical Raw Material Recovery project will hope to make progress in this area. A number of UK companies are actively engaged in commercially focused R&D looking at developing new products to substitute CRMs. An example of this is the INFINITY project, discussed earlier, which is looking to develop indium-free transparent conductive oxides for glass and plastic substrates.

There are also a number of challenges associated with radioactive materials used in the nuclear and medical sectors which are highlighted by the Nuclear Industry Research Advisory Board (NIRAB) in their 2014 Annual Report. For instance, one of the major challenges associated with the use of radioactive isotopes in the nuclear industry — and where chemistry innovation can play a key role — is in understanding and being able to control the coolant chemistry in both primary and secondary coolant circuits of the Generation III+ and Generation IV reactor systems. This is vital in managing the lifetime of reactor components and inhibiting life-limiting mechanisms such as corrosion.

Another key challenge for the medical sector is associated with the use of medical isotopes. The principle radioisotope used for medical diagnostic imaging is Technetium-99m (99mTc), produced via separation from Molybdenum-99 (99Mo). The worldwide production of 99mTc/99Mo is dependent on a small number of research reactors and a similarly small number of organisations producing the irradiated targets and associated processing facilities. Between 2016 and 2020 there is expected to be a global shortage of 99Mo as several of main research reactors producing 99Mo shut down.

This is only a brief snapshot of some of the areas where chemistry innovation can play a role in minimising, substituting or recycling scarce metals and minerals.

Summary

Scarce metals and minerals that are critical to some of the most important sectors in the economy have been identified and substitution options reviewed. There are a huge number of challenges identified where chemistry-related innovation can play a key role in the solution.

From speaking to experts in the field, one of the biggest challenges that remains is that companies still do not understand their supply chains well enough to grasp the critical raw material risks. This is something that needs to be addressed. Projects like the Critical Raw Material Recovery will help to raise the profile of this area and to address some of the challenges.

RECOMMENDATION: There continues to be an important role for industry support organisations like KTN to work across sectors to help businesses understand the risks posed to their supply chains through scarce metals and minerals and how, through innovation, these supply chain risks can be mitigated.

In regard to priorities for the chemicals industry, the most critical issue is to ensure the continued development of chemical processes that can utilise catalysis as a means of improving efficiency but where those catalysts contain no, or minimal, scarce metals.

RECOMMENDATION: Collaborative R&D that is focused on helping to minimise or substitute the use of scarce metals in catalysis should continue to be supported.

7.0 Renewable hydrogen

Although this study has primarily focused on the feedstocks outlined in the 2013 CGP Innovation Strategy report, an additional feedstock that has been identified through this study is renewable hydrogen.

This has not been highlighted in any of the previous strategy documents but is certainly a feedstock that could have a niche role in the future, particularly if the hydrogen economy comes to fruition and as renewable energy becomes more abundant.

Renewable hydrogen is hydrogen that has been generated through the electrolysis of water where the energy for that process is derived from a renewable energy source.

The major reason for producing hydrogen is often for energy storage. However, there is significant interest in utilising the hydrogen for higher value purposes (e.g. converting it to synthetic gas, ammonia or methanol).

UK SME **ITM Power** is currently leading a project to build a demonstration-scale plant capable of producing urea fertiliser. The urea is made from ammonia and CO₂. The ammonia is produced via haber-bosch using the renewable hydrogen, which is produced in **ITM**'s PEM electrolyser system. This project, funded by the Innovate UK Agri-Tech Catalyst, is in collaboration with the University of Sheffield, FERA Ltd, **BPE Design and Support Ltd** and **Waitrose**, which is providing a farm to test the urea.

Other companies in the UK and Europe are also known to be looking at opportunities for green chemicals that utilise renewable hydrogen. **RECOMMENDATION:** The innovation challenges and opportunities of renewable hydrogen (including water splitting and going beyond green ammonia as a product) should be further explored. Innovative UK companies working in this area should continue to be supported.

8.0 Conclusions

It is clear from this study that all of the feedstocks identified in the 2013 CGP Innovation Strategy report are still important and relevant today when considering "what are the important raw materials now and into the future?" Indeed, the list of feedstocks that will play an important role in the future should be expanded to include others like renewable hydrogen. The conclusions for each feedstock are provided below.

Unconventional oil and gas (shale gas)

- A number of innovation challenges and opportunities have been identified where chemistry-led innovation can help to further improve the productivity of unconventional oil and gas production and minimise potential environmental risks. The shale gas community should be brought together with innovators to explore these opportunities further.
- Shale gas production in the UK would help generate jobs and investment in the chemicals sector and its supply chains. However, a more detailed investigation that brings together the chemistry and industrial technology disciplines needs to be undertaken to understand the innovation opportunities throughout the supply chain that might be expected if the UK has access to indigenous shale gas.

Carbon dioxide utilisation (CDU)

- CDU has been well supported and is recognised as an important area of innovation in Europe. Companies like Covestro (Germany) are leading in this and have invested in a plant to produce polyurethane intermediates utilising CO₂. In the UK, the EPSRC has supported CDU through the CO₂Chem Network. The UK is also home to a number of innovative start-ups and SMEs that are looking to innovate in this space, however, further support is required.
- The TRL of the various CDU pathways to producing chemicals, fuels and mineralisation products is very broad. A number of specific technical challenges have been identified, which, if solved, will help to accelerate many of these pathways.
- The current lack of economic or policy incentive to do anything with CO₂ is holding back innovation in CDU. However, as the world moves towards a low carbon future, this will need to change, which will help accelerate technologies like CCS and CDU.
- The cross-discipline research community should be brought together with industry to help identify niche market opportunities to valorise carbon dioxide and to help accelerate CDU up the TRL scale.

Renewable feedstocks

- This study has focused on biomass and carboncontaining wastes as renewable feedstocks, in particular second generation and third generation biomass feedstocks.
- It is clear that there is enormous potential for renewable feedstocks in producing biobased chemicals, a rapidly growing market. Certainly there has also been a great deal of support in the UK and elsewhere in Europe to support innovation in this area. This is largely based on the desire to move towards a sustainable bioeconomy.
- The UK has a fantastic array of research capability in this area through leading academic groups and research centres like CPI, BDC and BEACON. It also has a number of SMEs and larger chemical companies engaged in innovation in this area.
- One of the biggest challenges is that with such a wide variety of different feedstock sources, process technologies and markets/products to choose from, it is difficult to identify where are the real commercial opportunities in the UK. The knowledge and expertise across academia (IB, chemistry, engineering) and industry sectors (chemicals, agri-tech) should be pooled to help identify where there is competitive advantage for the UK.

Scarce metals and minerals

- Scarce metals and minerals that are critical to many sectors of the economy have been identified and substitution options reviewed. There are a huge number of challenges identified where chemistry-related innovation can help to minimise or overcome risks in these supply chains.
- One of the biggest challenges in this area is helping businesses and government understand these supply chain risks.
- A priority for the chemicals industry in this area is to find new catalytic processes that do not rely so heavily on critical raw materials.

Renewable hydrogen

- The production of hydrogen via the electrolysis of water, where the energy for that process comes from excess renewable energy, opens up the potential to produce renewable hydrogen.
- There are already interesting business-led innovation projects in the UK and Europe where companies are looking to utilise this hydrogen to produce other platform chemicals and intermediates.
- Innovation in this area should continue to be supported. This includes helping to identify innovative routes and commercial applications for other chemical products based on renewable hydrogen.

Appendix A Key reference documents

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Appendix B Unconventional oil and gas – further information



Figure B-1: The fracking process (Source: Shale gas extraction in the UK: a review of hydraulic fracturing, June 2012)



Figure B-2: Example of shale gas well design (Source: Shale gas extraction in the UK: a review of hydraulic fracturing, June 2012)

Chemicals used in the fracking process

ADDITIVE	PURPOSE	DOWNHOLE RESULT
Acid	Helps dissolve minerals and initiate cracks in the rock	Reacts with minerals present in the formation to create salts, water and $\mbox{CO}_{\mbox{\scriptsize 2.}}$
Acid/ Corrosion inhibitor	Protects casing from corrosion	Bonds to metal surfaces (pipes) downhole. Any remaining product not bonded is broken down by micro-organisms and consumed or returned in produced water.
Biocide	Eliminates bacteria in the water that can cause corrosive by-products	Reacts with micro-organisms that may be present in the treatment fluid and formation. These micro-organisms break down the product with a small amount of the product returning in produced water.
Base Carrier Fluid (water)	Create fracture geometry and suspend Proppant	Some stays in formation while remainder returns with natural formation water as "produced water" (actual amounts returned vary from well to well)
Breaker	Allows a delayed breakdown of gels when required	Reacts with "crosslinker" and "gel" once in the formation making it easier for the fluid to flow to the borehole. Reaction produces ammonia and sulphate salts which are returned to the surface in produced water.
Clay and Shale Stabilisation	Temporary or permanent clay stabiliser to lock down clays in the shale structure	Reacts with clays in the formation through a sodium-potassium ion exchange. Reaction results in sodium chloride which is returned in produced water. Also replaces binder salts like Calcium Chloride helping to keep the formation intact as the Calcium Chloride dissolves.
Crosslinker	Maintains viscosity as temperature increases	Combines with the "breaker" in the formation to create salts that returned in produced water.
Friction reducer	Reduces friction effects over base water in pipe	Remains in the formation where temperature and exposure to the "breaker" allows it to be broken down and consumed by naturally occurring micro-organisms. A small amount returns with produced water.
Gel	Thickens the water in order to suspend the proppant	Combines with the "breaker" in the formation thus making it much easier for the fluid to flow to the borehole and return in produced water.
Iron control	Iron chelating agent that helps prevent precipitation of metal oxides	Reacts with minerals in the formation to create simple salts, $\rm CO_2$ and water all of which are returned in produced water.
Non-emulsifier	Used to break or separate oil/ water mixtures	Generally returned with produced water, but in some formations may enter the gas stream and return in the produced natural gas.
pH Adjusting Agent/ Buffer	Maintains the effectiveness of other additives such as crosslinkers	Reacts with acidic agents in the treatment fluid to maintain a neutral pH. Reaction results in mineral salts, water and CO_2 which is returned in the produced water.
Propping Agent	Keeps fractures open allowing for hydrocarbon production	Stays in formation, embedded in fractures and used to "prop" fractures open.
Scale inhibitor	Prevent scale in pipe and formation	Product attaches to the formation downhole. The majority of product returns with produced water while remaining product reacts with micro-organisms that break down and consume the product.
Surfactant	Reduce surface tension of the treatment fluid in the formation and helps improve fluid recovery from the well after the frac is completed	Some surfactants are made to react with the formation, some are designed to be returned with produced water, or, in some formations they may enter the gas stream and return in the produced natural gas.

Table B-1: Typical types of chemical additive used in the fracking purpose (Source: https://fracfocus.org/chemical-use/what-chemicals-are-used)

Appendix C Carbon dioxide utilisation – further information



Figure C-1: Chemicals from Carbon Dioxide (Source: CCU in the green economy, 2011)

Appendix D Renewable feedstocks – further information



Figure D-1: Chemicals from biobased feedstocks (Source: Economic Impact Analysis of US Biobased Products Industry, 2015)



Figure D-2: Commercial and not-yet-commercial biobased chemicals (Source: A Roadmap to Accelerate the Advanced Manufacturing of Chemicals, 2015)



