The commercial and strategic opportunity offered by gas fermentation in the UK

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E4tech (UK) Ltd

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Executive Summary

Gas fermentation is the conversion of gaseous carbon containing molecules, such as carbon monoxide (CO), carbon dioxide (CO_2), and methane (CH_4), to chemical and fuel products via microbial processes. The technology has the potential to directly produce low carbon fuels for road transport, commodity chemicals, specialty chemicals, and single celled proteins. The direct products may be further processed to produce low carbon fuels for aviation, polymers such as nylon, and plastics.

The technology is highly feedstock flexible and may use a wide range of renewable and non-renewable feedstocks to provide carbon savings. It can use inputs as varied as industrial flue gas and gasified biomass wastes and residues (for example municipal solid waste). It allows capture and value creation from gases such as carbon dioxide (CO_2) and carbon monoxide (CO) that contribute to global warming.

The technology is operating with pre-commercial demonstration plants in China, Japan, Taiwan and the US. The technology is ready to scale up today in Europe and could make a contribution to reducing the UK's greenhouse gas emissions and dependency on fossil resources. It can also promote cross sector collaboration and market opportunities (steel, aviation, agricultural, chemicals) while enabling transition to a circular economy and bioeconomy.

There is a significant resource potential in the UK and whilst there are a limited number of companies developing commercial processes, the UK's scientific excellence in the field means that it is well positioned to benefit from this opportunity. Established research strengths in microbiology, synthetic biology and process engineering technologies associated with gas fermentation provide a solid foundation for the UK to take a technology leadership position in this strategically important field.

Environmental and social Benefits

Reduction of GHG emissions: E4tech's Life Cycle Assessment of LanzaTech ethanol derived from steel mill off gases, shows up to 70% GHG emissions reduction compared to petroleum gasoline on a well-to-wheel energy basis.

Promotion of Industrial Growth: Gas fermentation enables industries to add value to a waste stream while reducing their carbon footprint. This promotes regional industrial growth and employment in industrial zones.

Promotion of a Circular Economy and Bioeconomy: Gas fermentation enables industries to maximize resources and add value by being resource efficient, creating new products by recycling waste streams. It also provides a means of deriving a wide range of products from biomass.

Contents

1 Introduction

Under the 2008 Climate Change Act, the UK is committed to reducing greenhouse gas emissions by at least 80% by 2050. This will be achieved by moving to a more energy efficient and low carbon economy, reducing the use of fossil fuels. All sectors will have to contribute to achieving this target. In road transport, fuel suppliers are required to provide a growing proportion of renewable fuels under the Renewable Transport Fuel Obligation (RTFO), and in other energy intensive sectors the Government has committed to work with industry to develop long-term decarbonisation and energy efficiency roadmaps – including the chemicals, iron and steel, and oil refining sectors.

Gas fermentation is the conversion of gaseous carbon containing molecules, such as carbon monoxide (CO), carbon dioxide (CO_2), and methane (CH_4), to valuable chemical and fuel products via microbial processes, in the presence or absence of air. The technology is operating with commercial-scale demonstration plants in China and the US, and could make a contribution to reducing the UK's greenhouse gas emissions and dependency on fossil resources. This report discussed the potential for gas fermentation to decarbonise the transport sector and other energy intensive industries, and actions that could help the development and deployment of these technologies in the UK.

1.1 Process

The gas fermentation process requires a carbon source and an energy source. The carbon containing gases used by the process are carbon monoxide (CO), carbon dioxide (CO_2), and methane (CH_4), while the energy content is provided by the carbon monoxide (CO) or methane (CH_4) itself and/or hydrogen (H_2).

These gases can be derived from a range of sources: biomass, and municipal and industrial wastes, including industrial waste gases (for example steel mill waste gases) and biogas. Hydrogen can be derived from water electrolysis. Biomass and solid municipal and industrial wastes must first be gasified to produce syngas (a mixture of mostly carbon monoxide, carbon dioxide and hydrogen) for fermentation, while industrial waste gases, methane or hydrogen can be fermented directly. Depending on the level of impurities in the gas and the tolerance of the microbes, the gas may require clean-up prior to fermentation.

Microorganism cultures are used to ferment the gases to produce the desired fuel or chemical in a bioreactor. The product(s) are dependent upon the type of microorganism culture used, and also influenced by the composition of the gas, and the operating conditions (temperature, pressure). Figure 1 provides an overview of the gas fermentation process chain.

1.2 Products

This nascent technology has the potential to produce building blocks for a wide range of consumer goods, and provides an opportunity to transition towards more sustainable feedstocks.

Gas fermentation is not only feedstock flexible, but it also presents a variety of product offerings, from low carbon fuels to commodity chemicals, speciality chemicals, and single cell proteins. Current commercial-scale processes are focused on the production of ethanol. Ongoing research is targeting a range of products including higher alcohols, ketones, and diols, organic acids, alkenes, and amines.

These products have a broad range of uses including as fuels, solvents, and food additives, and they may be further processed to produce drop-in fuels (including jet fuel), biodegradable polymers for food packaging and biomedical applications, polymers for engineering applications, and high value chemicals.

Other target molecules include fatty acids, terpenoids, aromatic compounds, polyhydroxyalkanoates (PHAs), and medium to long chain alkanes (as illustrated in Figure 2).

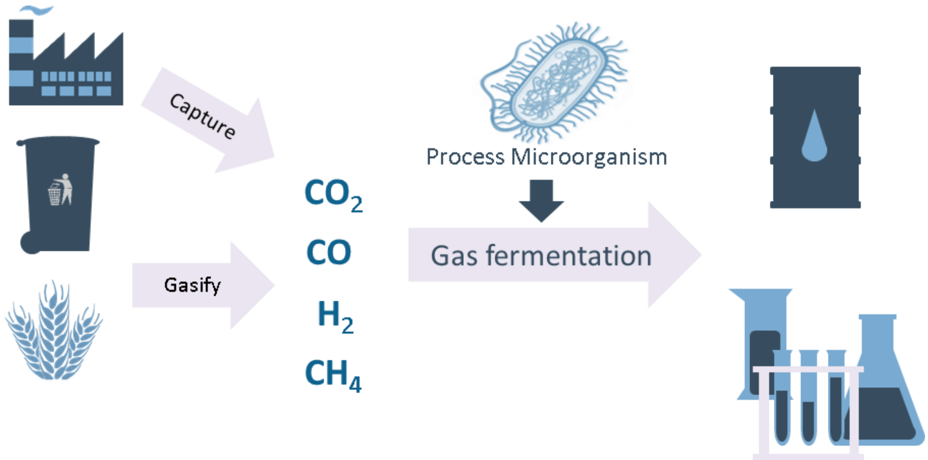

Figure 1: Description of the gas fermentation process.

1.3 Development status

Gas fermentation technologies are currently operating at a commercial scale to produce ethanol. Since 2012, LanzaTech have operated two pre-commercial plants in China. The first with Baosteel has capacity to produce 360 tonnes per year of ethanol, and the second with similar capacity is situated at Capital Steel near Beijing. LanzaTech are currently planning commercial-scale plants in Ghent, Belgium, with ArcelorMittal and Primetals Technologies, with capacity to produce 47,000 tonnes of ethanol per year, In China with Capital steel and in Taiwan with China Steel Corporation. These plants convert the waste gases produced during the steel making process, with each tonne of ethanol displacing 5.2 barrels of gasoline (ArcelorMittal, 2015). Additionally, through an agreement with Aemetis, an ethanol production company based in California, USA, LanzaTech will begin constructing a gas fermentation facility based on the use of gasified agricultural and construction waste resources.

INEOS Bio has operated an integrated pilot plant for 9 years at its Florida BioEnergy Centre, demonstrating and optimising the gasification of biomass and fermentation of the resulting syngas to ethanol. In 2013 INEOS Bio and NewPlanet Energy began production at the Indian River BioEnergy Centre at Vero Beach, a commercial demonstration centre with capacity to produce 24,000 tonnes of ethanol as well as 6MW of renewable electricity. The plant uses green waste and wood waste converted via gasification and syngas fermentation.

Calysta has partnered with Cargill, one of the world's largest agricultural firms, to secure funding for the establishment of a commercial scale single cell protein facility using methane as the sole carbon and energy source. The plant will be located in the US, and will produce up to 200,000 tonnes of single cell protein per year for use as an ingredient in aquaculture and livestock feeds. The product is comparable in composition and quality to super prime fishmeal, which is a limited resource produced by harvesting wild fish populations from the oceans. Whilst the first plant will use methane from natural gas, the opportunity exists to use renewable methane from biogas.

Across Europe, there are a number of open access facilities available to support the development of gas fermentation processes, enabling the scaling-up of processes developed in academic and industry laboratories. There are a range of reactor types available at different scales, including VTT in Finland, who have facilities to operate gas fermentation processes at up to 100 litre scale, suitable for a range of C1 gases. In Spain, facilities are installed at the biotech company Biopolis, and the National Renewable Energy Centre (CENER) enabling trials of up to 30 litres, and Wageningen University in The Netherlands provides both continuous and batch reactors at smaller scale. The BioBased Europe Pilot Plant in Ghent and the UK's Centre for Process Innovation (CPI) both have existing facilities to provide trials at up to 10 litres, and are collaborating with industry partners to install new reactors at larger scale. Academic facilities are also available in the UK at Loughborough University and the University of Nottingham, the University of Minho in Portugal, and the Technical University of Denmark.

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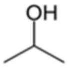
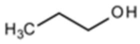
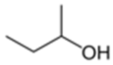
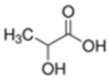
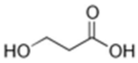
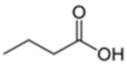
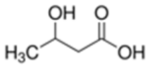
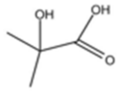
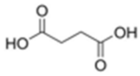
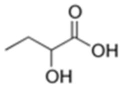
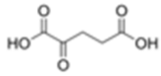
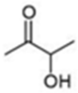
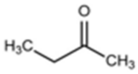
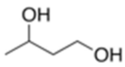
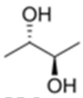
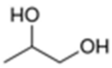
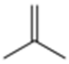
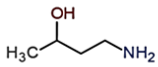
Alcohols	 Isopropanol  1-propanol	 1-Butanol  2-Butanol
Acids	 Lactic acid  3-Hydroxypropionic acid	 Butyric acid  3-Hydroxybutyric acid  2-Hydroxyisobutyric acid  Succinic acid  2-Hydroxybutyric acid  α-Ketoglutyric acid
Ketones	 Acetone	 Acetoin  MEK
Diols		 1,3-BDO  2,3-BDO  1,2-PDO
Alkenes		 Isobutylene
Amines		 3-Hydroxybutylamine

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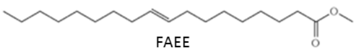
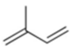
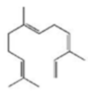
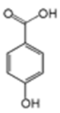
Fatty Acids	 FAEE
Terpenoids	 Isoprene  Farnesene
Aromatics	 pHBA

Figure 2: Target molecules for production via gas fermentation

2 Sustainability

Gas fermentation technologies can contribute to a lower carbon economy, with the potential to reduce emissions in both the chemical and fuel sectors. In the case of biomass feedstocks the carbon is fixed from the atmosphere, and in the case of waste carbon-containing gases the carbon that would otherwise be emitted is recycled. In both cases there is no net increase in carbon dioxide emissions as a result of combustion, and emissions savings are achieved as a result of displacing fossil resources for fuels and chemicals. However, the emissions associated with activities involved in supplying the feedstock to the gas fermentation process, and with input of energy and materials to the process need to be taken into account. The total greenhouse gas emissions associated with the production of fuel or chemicals from fermentation will vary depending on the specific supply chain, but could be very low. Two case studies are provided to illustrate the potential greenhouse gas emissions savings that may be achieved by technologies operating today.

Case Study: LanzaTech and ArcelorMittal, Ghent

LanzaTech and ArcelorMittal are currently planning a commercial-scale ethanol plant at the ArcelorMittal steel plant in Ghent. The plant intends to convert blast furnace gas and basic oxygen furnace gas, which are both unavoidably generated in the steel manufacturing process. The greenhouse gas emissions associated with ethanol produced are estimated at 10 gCO_{2eq}/MJ. This represents an 87% reduction in greenhouse gas emissions compared to fossil fuels (Ecofys, 2015).

No emissions are associated with the production of the waste gases, as they would be produced anyway in steel production, and no emissions are associated with the combustion of ethanol in an engine, as it is assumed that these emissions would have occurred anyway with the combustion of the blast furnace gas and basic oxygen furnace gas. The emissions accounted for are then a result of the conversion process, with a small amount also due to transport of the product.

Some steel mills generate electricity from basic oxygen furnace gas, and a comparison has been made of the greenhouse gas emissions savings of ethanol production via gas fermentation to electricity generation. The comparative assessment found that the greenhouse gas emission savings for electricity generation via a steam turbine where the steam is produced in a boiler fired with basic oxygen furnace gas, backing out European grid average electricity, is 38 $kgCO_2eq$ per tonne of steel, while for the production of ethanol via gas fermentation, with ethanol displacing fossil fuel, the emissions savings are 41 $kgCO_2eq$ per tonne of steel (E4tech, 2014c). The difference in savings is small, and sensitive to the assumptions regarding the carbon intensity of the electricity displaced. But, as the carbon intensity of the electricity grid reduces, then the gas fermentation process will compare more favourably.

Case Study: INEOS Bio, previously planned plant at Seal Sands

INEOS Bio and NewPlanet Energy operate a commercial-scale demonstration plant at Vero Beach, using vegetation and wood waste which is converted to ethanol via gasification and syngas fermentation. At the time of development of this plant, INEOS Bio was also developing a project at Seal Sands on Teesside which was since abandoned due to unfavourable market conditions.

However, the greenhouse gas emissions assessment of this plant was published (Eunomia, 2010). It estimated the emissions associated with ethanol production from several different biomass feedstocks, including residual municipal solid waste, separately collected garden and food waste, garden waste, and waste wood. The assessment estimates that the emissions associated with ethanol production range from -20.2 gCO_2eq/MJ to 13.6 gCO_2eq/MJ, representing a greenhouse gas emissions reduction of 84% to 124% compared to fossil fuel.

In the case of municipal solid waste, which is not 100% biological, there will be emissions associated with fossil-based material in the waste (unless the carbon is permanently stored), highlighting the importance of the carbon source and its fate in determining the greenhouse gas benefit.

With regard to chemicals, a high level greenhouse gas assessment carried out by LanzaTech on greenhouse gas savings offered by gas fermentation of waste carbon-containing gases for different products range from 25% for PET bottles (comprising around 30% ethylene by weight) to 210% for polypropylene (LanzaTech, 2016). Gas fermentation processes can potentially offer other environmental benefits. In the case of Calysta, producing single cell protein as a replacement of fishmeal produced by harvesting wild fish or produced on land, the fermentation based-process may reduce the demand for land and water.

3 Feedstocks

Gas fermentation provides an opportunity to utilise resources that do not compete with food or feed production, including waste carbon gas streams that can be captured and used directly at source, municipal and industrial wastes, waste wood, and forestry residues. Biomass crops too could provide a sustainable source of feedstock as long as careful consideration is given to land use impacts and competition with food and feed. This section explores the current and future availability of these feedstocks for gas fermentation.

Waste carbon gases

Waste carbon gases refer to waste gas streams rich in carbon monoxide, carbon dioxide and/or methane from a variety of sources. Not all waste streams are useful for gas fermentation, however. CO_2 streams cannot be used alone unless associated with an energy source in the form of H_2, while syngas (a mixture of CO, H_2 and CO_2), CO and reformed methane can be used directly. Steel manufacturing waste gases provide an interesting waste gas stream. Steel mill waste gases generation in the UK is estimated at 0.9M tonnes per year and global volumes at 101M tonnes per year (E4tech, 2014b). Waste gas streams can also contain contaminants that affect the viability of the fermentation process as they require expensive scrubbing technology to upgrade the gas to acceptable purity levels. However, recent advancements have made the microbes used for fermentation highly tolerant to gas contaminants. Steel mills typically combust waste gases, either losing this heat to the atmosphere ('flaring') or recovering some of the energy, for example in a CHP plant, typically at low efficiency. It is not always feasible to convert waste carbon streams to energy, however, as the contaminants found in the stream may be too expensive to clean before combusting on-site (E4tech, 2014a). Despite the option for energy recovery, it is estimated that about half of waste gases generated by steel mills in the EU is still flared (E4tech, 2014a).

Municipal solid waste (MSW)

MSW in the UK consists of all wastes collected by local authorities, from households, businesses, gardens, and municipal parks. Current volumes of MSW in the UK and globally are significant at 30M tonnes per year and 1280M tonnes per year, respectively (E4tech, 2014b). In the UK, around 46% of MSW is recycled; of the remaining waste, 27% is combusted with energy recovery (energy-from-waste incineration) and a small fraction is exported as solid recovered fuel or refuse derived fuel (Defra, 2014). The remaining 8M tonnes per year is sent to landfill or incineration without energy recovery. The European Commission targets a recycling rate of 50% for household waste – roughly 5% higher than current levels in the UK. All types of carbon-containing waste, such as paper, plastics and biomass, can undergo gasification to produce syngas, which can then be fermented to produce a range of products, effectively counting as recycling. The waste hierarchy should therefore consider the contribution the technology can make to recycling.

Also, in the EU Waste Framework Directive the definition of waste excludes gaseous effluents emitted into the atmosphere. The narrow scope of this definition does not allow for innovative gas fermentation solutions to benefit from the advantages of recycling mentioned in the Directive. CO and CO_2 is valuable waste for carbon recycling industries and by including it into the waste definition, these solutions will benefit from the waste hierarchy where prevention, reuse and recycling are top priority.

Wood residues and waste

Wood residues consist of forestry residues, such as treetops, small stem wood, small branches, stumps and leaves (see Figure 3), and sawmill residues such as saw dust and cutter shavings. These are produced as a by-product of the timber and pulp and paper industries. The total available volume of forest residues has been estimated at 5M tonnes per year in the UK and 421M tonnes per year globally (E4tech, 2014b). Wood waste is collected from a range of sectors such as construction and demolition, manufacturing, and households. A recent estimate from WRAP suggests that there are 4.1M tonnes year of wood waste generated in the UK (Wrap, 2011).

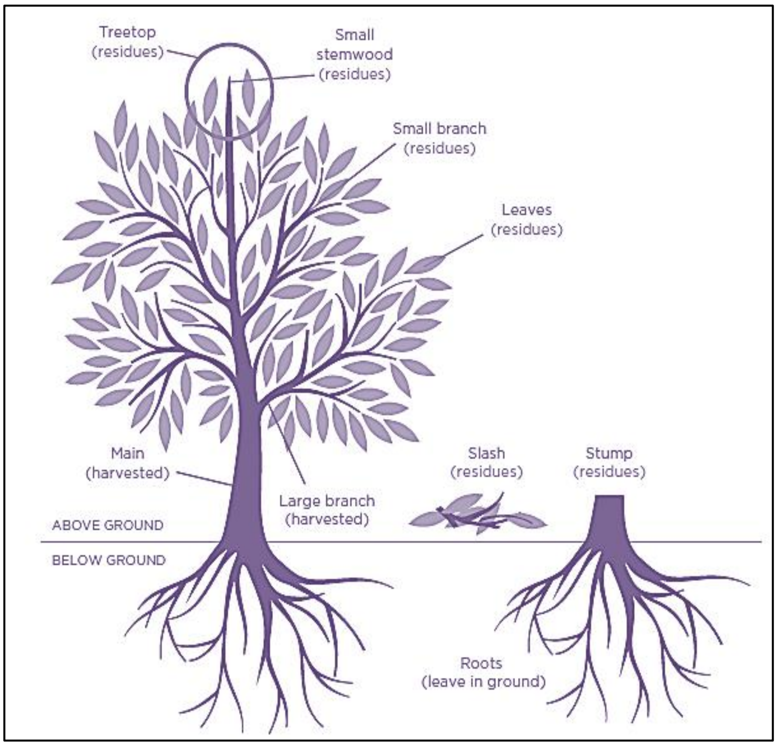


Figure 3 Diagram of forestry residues. Source: ICCT (2013)

Main competing industries for woody waste and residues include the panel board industry, animal bedding and the heat and power sector. The latter is now the largest consumer of UK wood residues and waste, followed by the panel board industry and animal bedding. In total, around 3M tonnes per year of woody residue or waste is consumed by other sectors in the UK or exported (Woodfuel Disclosure Survey, 2015; Wood Recyclers' Association, 2012). This leaves 6M tonnes per year of resource potentially available for gas fermentation in the UK. For large scale biomass power plants, future demand is likely to be met with imports from North America as these residues are generally cheaper and provide the bulk quantities needed (NNFCC, 2014). Demand for UK waste wood and residues in existing markets is expected to peak at current levels (Woodfuel Disclosure Survey, 2015).

Industrial and Energy crops

Industrial and energy crops are generally perennial crops, such as miscanthus and short rotation coppice (SRC). Only a very small amount of industrial and energy crops are currently planted in the UK, and annual production is estimated at 0.16M tonnes per year in the UK and 2.1M tonnes per year globally. Current uses of miscanthus include power generation, horse and livestock bedding, small-scale CHP and use directly for heating buildings. A very small amount of SRC is used for power generation (36,000 tonnes per year) (E4tech, 2014b). However production could increase significantly in the medium to long term if the necessary policy and infrastructure is developed.

Biogas

Biogas is produced from the degradation of organic matter in the absence of oxygen, and is a mixture of primarily methane (CH_4) and carbon dioxide (CO_2), and traces of contaminant gasses. It is produced by sewage treatment plants and Anaerobic Digestion (AD) plants across the UK, using animal manure, agricultural residues, food waste and crops. Biogas is currently used to produce heat and power in the UK, and some is upgraded to biomethane for injection into the gas grid or compressed or liquefied for use as a transport fuel. Biogas may also be a feedstock for gas fermentation processes.

4 Global and UK low carbon fuel potential

Figure 4 shows global ethanol potential produced from gas fermentation for the relevant feedstocks discussed above, it does not account for current competing uses. Current global potential from the feedstocks stand at 350 billion litres; or more than three times the present global ethanol consumption. This is expected to increase by 2020 to 445 billion litres mostly due to the increase in MSW arising, with other significant contributions from wood waste. Availability for all feedstocks is further expected to increase after 2020.

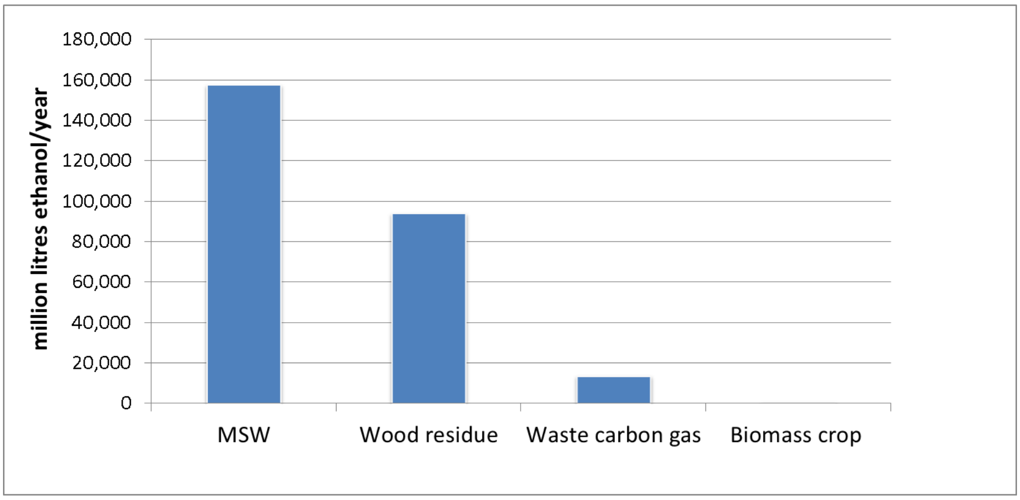


Figure 4: Global estimated theoretical low carbon fuel production without competing uses from each feedstock.[1]

Figure 5 shows the ethanol potential from gas fermentation for each feedstock for the UK before and after competing uses. Overall, even after factoring in competing uses from other sectors the low carbon fuel potential from gas fermentation is significant. If exploited it could provide 2.4 billion litres of ethanol per year – or 12 times current UK ethanol consumption of 190 million litres – the majority of which could be from MSW. This is a theoretical potential that does not take into account the economics or maturity of the different gas fermentation technologies, but shows that the potential for fuel production is significant.

[1] Data sources given in the text. 2020 potentials from E4tech (2014b), NEAA (2014), and global wood waste potential for 2020 derived from applying the same CAGR to wood waste between 2015 and 2020 as for MSW. low carbon fuel potential calculated by converting feedstock to dry tonne (for all feedstock except waste gases and MSW), multiplying by energy content and applying conversion route efficiency of 39%. This was then divided by the energy content of ethanol (GJ/tonne) and converted to litres.

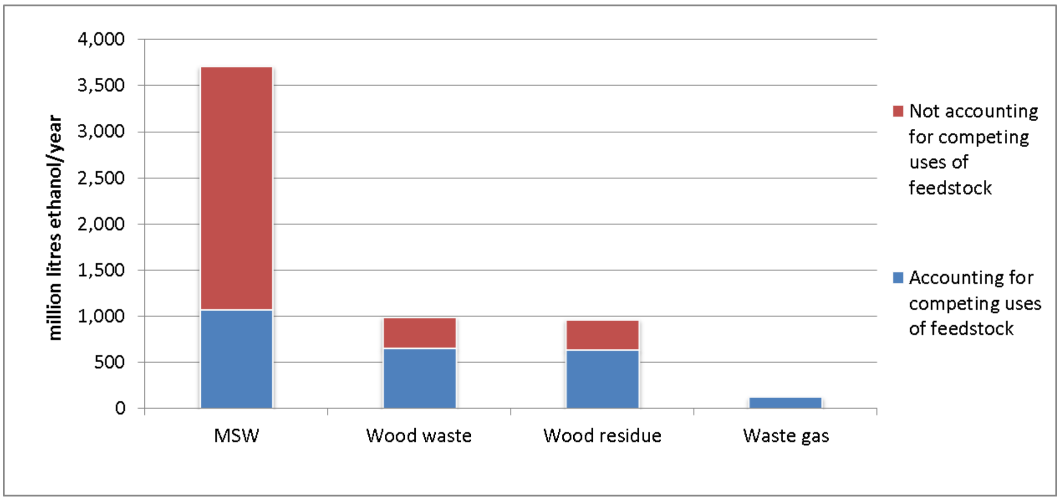


Figure 5: UK bioethanol potential from gas fermentation for available feedstocks before and after competing uses[2]

In order to illustrate the wider benefits of the gas fermentation industry to the UK we have outlined two hypothetical plants (Table 1) estimating the benefits associated with each plant, including the volume of low carbon fuel, number of jobs, and GHG emission savings.

Table 1: Estimation of jobs and emissions savings resulting from two different types of gas fermentation plants

	Waste gas fermentation plant[3]	Wood residue gasification & fermentation plant[4]
Feedstock use	300,000 odt / year	100,000 odt/year
Ethanol production	40 million litres / year	30 million litres / year
Number of jobs in feedstock supply chain	0	82 FTE
Number of jobs in plant operation	30 FTE	65 FTE
Number of jobs during plant construction	400 temporary	400 temporary
GHG saving	62,030 tonnes CO_{2eq}	66,390 tonnes CO_{2eq}

[2] We have not estimated the potential alternative uses of waste carbon gases due to poor data availability.
[3] The figures for a waste gas fermentation plant suggested here are based loosely on data from LanzaTech's operating gas fermentation plant, as a plant at a UK steel mill would be expected to be similar in size and employment. GHG savings are estimated from the LanzaTech ethanol LCA discussed in chapter 2, with a GHG saving of 72.8 gCO_{2eq}/MJ compared to fossil fuel.
[4] The wood residue gasification and fermentation plant is modelled on Ineos Bio's California waste gasification plant (Ineos Bio, 2013), with methodology from the ICCT used to estimate employment in feedstock cultivation / collection (ICCT, 2013). The GHG savings are estimated from the Ineos Bio LCA discussed in chapter 2, with a GHG saving of 103.9 $gCO_2eq.$/MJ compared to fossil fuel.

In the two examples given above, more jobs in plant operation are created by the wood residue plant, as it is an entirely new standalone plant, whereas the waste gas fermentation plant is an addition to an existing steel mill. In addition to direct jobs, the development of the gas fermentation industry would create or secure indirect employment for machinery suppliers and other ancillary industries. Furthermore, fermentation of waste industrial gases to produce fuel or chemicals could provide a valuable revenue stream for the steel industry.

Regional assessment

Figure 6 illustrates the distribution of feedstock availability across different regions of the UK[5], excluding existing competing uses, to give an indication of where the regional opportunities are. Scotland and the South East have the highest potential overall, with significant forestry residues and MSW, respectively. The South East also has the highest availability of waste wood.

Scotland is a key region for forestry residues, representing 60% of UK resource. Wales is another major region for forestry residues, and represents 12% of the UK resources. The remainder of low carbon fuel potential from forestry residues is relatively evenly distributed across the UK. For MSW, the highest potential is found in the South East which represents 14% of UK MSW resources. Another major source is London which represents 12%.

There are currently five steel mills operating in the UK located in Wales, Yorkshire and the South East. It is estimated that Wales and South East England each produce enough waste gases for 44 million litres of low carbon fuel; or 46% of total current UK ethanol consumption. The Yorkshire region may have sufficient waste carbon gases to produce 32 million litres of ethanol.[6]

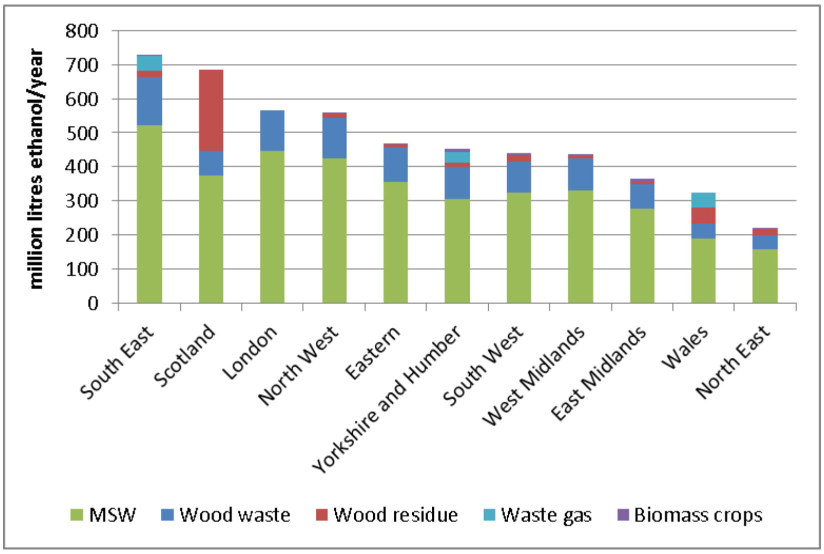


Figure 6: Regional breakdown of feedstock potential, as ethanol equivalents. Not accounting for competing uses (litres ethanol/year). Saw mill residues are not included in 'Wood residue' category due to lack of regional data

[5] 'Wood residue' category does not include saw mill residues as this information was not complete on the regional level. Regional breakdown does not consider competing uses.

[6] Regional breakdown of waste gas availability has been estimated based on regional steel production. Integrated steel mills have been derived from UK Steel map (http://www.eef.org.uk/uksteel/About-the-industry/Steel-facts/Steel-production-facilities---UK.htm) and taking into account recent closures e.g. Redcar in Yorkshire.

5 Building on UK scientific excellence

The most well-established gas fermentation process is the production of ethanol. LanzaTech produces ethanol from the fermentation of steel mill waste gases, with demonstration scale plants in China and Taiwan and ongoing projects to build commercial-scale plants in Ghent, China, Taiwan and the USA. Also INEOS Bio and NewPlanet Energy, in a joint venture, have a commercial-scale plant in Florida which produces ethanol by fermenting syngas derived from biological waste. In the UK, US biotech company Calysta is locating its £30 million pilot plant on Teesside, where they will further develop their proprietary gas fermentation technology, to produce single cell proteins from methane. Calysta are collaborating with the Centre for Process Innovation (CPI) and are therefore placing the new facility adjacent to the CPI's National industrial Biotechnology Facility 2 (Calysta, 2016). Zuvasyntha Limited is a UK company developing gas fermentation processes for the production of butadiene, an important chemical intermediate which is used worldwide for making car tyres. Routes to other chemical intermediates have been identified and their development will follow.

Other gas fermentation processes are under development in UK universities, targeting a range of platform and speciality chemicals. For example the BBSRC/EPSRC Synthetic Biology Research Centre (SBRC) at the University of Nottingham is developing methods of producing a range of platform chemicals from both aerobic and anaerobic process organisms. SBRC Nottingham are partners in an ERA-IB5 project (C02CHEM, 2015) which is developing a biological process for the conversion of CO_2 to the platform chemical 3-hydroxypropanoic acid and leads a BBSRC 'strategic longer and larger award' (sLoLa) **t**hat is focused on producing chemicals and fuels from Syngas using acetogenic bacteria (GASCHEM 2013). The Sustainable Environment Research Centre at the University of South Wales is developing both fermentation organisms and novel reactors. The University of Manchester is participating in the European Commission-funded project SYNPOL, which is developing gas fermentation techniques to produce bio-plastics and building block chemicals which could have a very wide range of applications (Synpol, 2016).

The development of gas fermentation links with several areas of UK expertise and excellence: industrial biotechnology and synthetic biology – providing the biological pathways for syngas fermentation; chemical and material sciences – the downstream users of chemical intermediates produced by syngas fermentation; and process engineering and other services providing the support required for process scale up.

Biotechnology research and development

The UK has many globally recognised research universities and particular strength in biotechnology, and is one of the top eight countries globally in terms of number of patents filed relating to biotechnology (OECD, 2014). The Biotechnology and Biological Sciences Research Council (BBSRC) has identified industrial biotechnology and bioenergy as a high-level priority and promotes collaboration between business and research, recognising the value in this to the UK (BBSRC, a). In Scotland, the Industrial Biotechnology Innovation Centre (IBioIC) was launched in 2014 with the aim to bring together industry, academia and the government and develop commercially viable industrial biotechnology solutions (IBioIC, 2016). A Synthetic Biology Research Centre (SBRC) has been recently established in the UK by the BBSRC and EPSRC at the University of Nottingham which is entirely focused on gas fermenting process organisms (SBRC Nottingham, 2015). This multi-disciplinary research centre will enable further research in the development of new fermentation organisms and gas fermentation processes (BBSRC, b; C1net, 2015). Strong research in biotechnology and process engineering provides a skilled workforce and an enabling environment in the UK, and the opportunity to profit from industrial collaborations.

Downstream users

There is potential for UK chemical companies to benefit from the development of low carbon chemical intermediates or building blocks. Global chemical technology company INVISTA, which has manufacturing and research centres in Wilton, Gloucester and Londonderry, has a joint development agreement with LanzaTech to develop processes to produce butadiene, which is used by INVISTA in its proprietary adiponitrile production technology, as an intermediate in the production of nylon (Invista, 2016). As other gas fermentation technologies near commercialisation, collaborations with UK chemicals companies utilising these products could become more commonplace.

Low carbon fuels have an important role in helping the UK aviation industry to achieve its goal of halving net greenhouse gas emissions by 2050 (Sustainable Aviation, 2014). This presents an opportunity to use gas fermentation to produce ethanol that can be converted into drop in jet fuel. UK airline Virgin Atlantic have partnered with LanzaTech and other technology partners to pioneer this process.

Other supporting expertise

The UK has strong engineering and biotechnology sectors, which could provide supporting services to the gas fermentation industry. The Centre for Process Innovation (CPI) is building up capabilities in this area through a number of industry collaborations, including collaborating with INVISTA to develop gas fermentation-based processes (CPI, 2013), and are building a new gas fermentation delivery laboratory (CPI, 2015). US biotech company Calysta have chosen to locate its market introduction facility alongside the CPI in Teesside, which will enable CPI to integrate Calysta’s novel loop reactor within the National Industrial Biotechnology Facilities, expand the capabilities of the facility and the skills of CPI staff (Calysta, 2016).

Fully developing C1 gas fermentation technology in the UK will rely on effective collaboration and communication between these groups, and this is facilitated by C1net through sandpit events, partnering meetings, workshops, outreach, training and the dissemination of BBSRC grant funding.

6 Legislation

As with many innovative technologies, gas fermentation requires significant investment in process scale-up, which is critical to reducing production costs. Investor confidence requires that any legislation is stable and while, scope for progressive amendments is necessary in an industry where innovation is key, policies should maintain stable supportive frameworks, to ensure the investor and consumer confidence in the market.

The main policy mechanism to support the decarbonisation of the road transport sector in the UK is the Renewable Transport Fuels Obligation (RTFO). The RTFO places an obligation on suppliers of fuel for road transport to supply a proportion of renewable fuels, or 'buy-out' of their obligation, paying 30 pence per litre of biofuel that would otherwise have to have been supplied. The RTFO is currently met with ethanol, produced from wheat, corn, sugar beet, and sugar cane; biodiesel, produced from used cooking oil, tallow, and vegetable oils; and biomethane. However, there is significant concern that the increased use of biofuels requires agricultural expansion at a global scale, leading to additional greenhouse gas emissions. These concerns have stifled the progression of the RTFO towards the Renewable Energy Directive target of 10% renewable energy in transport in 2020.

Gas fermentation pathways can produce low carbon fuels from a range of waste feedstocks that do not pose the risk of increasing demand for land. Fuels produced from renewable feedstocks are eligible under the RTFO as it is currently defined, but low carbon fuels produced from carbon-containing waste gases are today not eligible to contribute toward the obligation, despite the greenhouse gas emissions reductions they can provide. This acts as a significant barrier to the commercial deployment of the gas fermentation processes. A broader and more encompassing framework is needed to increase the production of low carbon fuels in the UK, this could be achieved by focusing on the ultimate goal of lowering the greenhouse gas emissions of transport fuels, and supporting all low carbon fuels.

Within the chemicals industry there is no policy or regulation to promote the use of low carbon alternatives, and this can influence research, development and demonstration (RD&D) activities to focus on the production of fuels rather than products for the chemical industry.

While gas fermentation processes can use a broad range of low cost feedstocks, and could provide cost competitive production pathways when fully commercial, support is needed in the short term to achieve scale and associated reduction in production costs, as well as supporting the development of strategically important products and processes at a time of low oil prices.

Without the support of policy frameworks that aim to minimise risks for investment in new processes and products and their development, it remains challenging to secure project finance for early commercial plants and fund innovation in the area. The priorities of finance institutions, such as the European Investment Bank, are influenced by policy e.g. Renewable Energy Directive, and therefore exclusion from such policies acts as a barrier to securing finance.

7 Recommendations

There is significant potential for the deployment of gas fermentation in the UK and a large opportunity globally. Which will depend on the commercial viability of the technology in different markets as it matures.

The use of biomass, wastes, and residues to produce chemicals, materials and fuels is in line with current drivers to make a more efficient use of available resources while reducing GHG emissions, in particular where possible by recycling carbon that would otherwise be emitted to the atmosphere.

Current opportunities range from processes that are operating at commercial scale outside of the UK, to new routes to chemical and material products being developed in UK universities and research organisations. The UK has high quality research and innovation capabilities in biotechnology and specifically gas fermentation, and there are cases of companies being attracted to the UK to leverage these skills.

A supportive framework is required to ensure the potential benefits are realised. This must promote a level playing field for the sustainable use of biomass and wastes for the production of chemicals, materials and fuels, and may include:

- Long term policy support for all low carbon fuels and products either through incentivising their use or disincentivising the use of fossil resources. This may be achieved, in part, through amendment of the RTFO, to include low carbon fuels made from non-biological waste feedstocks. Incentivising the use of all low carbon fuels according to the degree to which they reduce carbon emissions would provide an outcome-oriented approach, ensuring technology and feedstock neutrality.
- A framework whereby the production of chemicals and materials are not at a disadvantage to fuels where they lead to similar benefits. In the near term, there could be a role for public procurement in stimulating the market for products with renewable content or recycled carbon content. In the longer term this may be achieved with an appropriately defined carbon tax.
- Policy support aimed at increasing the availability of sustainable biomass resources, and/or further supporting the use of waste resources.
- Improved access to capital for all low carbon technologies, for example through the use of loan guarantees, or by including the technology platform in the priorities of publically-backed lenders.
- Targeted R&I support addressing specific technology challenges and scale-up.

Developers of new processes, both in academia and industry, must credibly assess the economic viability of these processes, ensuring that they understand the conditions in which the processes will be commercially viable. They must also take a proactive approach in communicating the benefits of new products and processes.

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