Innovation Needs Assessment for Biomass Heat

Final report

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Executive summary

Heat from biomass is an important option for the decarbonisation of heating, via a range of feedstocks, conversion technologies and energy vectors at different stages of development

BEIS has commissioned a series of projects to better understand the contribution that bioenergy can make to decarbonising heat. This project focuses on assessing the impact that innovation could have on the development of technologies and feedstocks for biomass heating. It is linked with a parallel project which reviews the evidence on biomass heating to assess the costs, supply and greenhouse gas emissions of routes from biomass to heat.

This project identifies actions needed to drive five technology and feedstock options where innovation could make the biggest difference to their potential to decarbonise heat to 2050

Five technologies or feedstocks were selected on the basis of their potential contribution to decarbonisation of heat, and the potential for innovation to have a significant impact on their costs, supply potential or sustainability characteristics. Biomass can be gasified to produce methane (termed bio synthetic natural gas, or **bioSNG**), or **hydrogen**, either of which could be injected into the gas grid. These routes are at an early stage of commercialisation, and have high potential, given the wide range of biomass and waste sources that could be gasified. Innovative **pretreatment technologies for thermochemical routes** could improve the economics of these routes. **Woody and grassy energy crops** are projected to be one of the primary sources of biomass globally and in the UK, but have very limited planting in the UK, and there is potential for significant yield increases. They could be used to produce bioSNG and hydrogen, but also in other biomass heat, power, transport fuel and chemicals applications. Lastly, **pretreatment technologies for anaerobic digestion** (AD) could greatly increase the resource available to the UK's AD plants.

BioSNG costs are expected to fall substantially if commercial scale plants are supported and deployed, which will provide a route to market for research stage innovations that could reduce costs further

BioSNG is in the early commercial stage globally, with the UK having one of the main developers of this technology. Deployment of multiple plants, plus scale up of these plants from 38MW_{SNG} to 77MW_{SNG}, is expected to bring down plant capex by 30% and opex by 19%[1]. These reductions arise primarily from economies of scale in the major capital cost components (gasifier, methanation) and labour, and reduction of real and perceived risk leading to reduction in Engineering, Procurement and Construction (EPC) and construction management costs. However, high capital costs and technology risk limit developers' access to capital, and the costs of methane produced will be higher than natural gas for the first plants. In addition, the value of negative emissions if bioSNG were combined with carbon capture and storage (CCS) cannot currently be monetised. Providing support for first commercial scale

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[1] Overall capex and opex reductions anticipated for construction of multiple plants (capex reduction 15%, opex reduction 6.1%) and plant scale up (capex reduction 18%, opex reduction 14%). Gogreengas (2016) First project progress report, http://gogreengas.com/wp-content/uploads/2015/11/BioSNG-Demonstration-Plant-June-2016-Project-Progress-Report.pdf

plants could reduce project risk, coupled with improved market-based support for bioSNG, reflecting its greenhouse gas (GHG) benefits and potential contribution.

A range of potential improvements to today's bioSNG technologies could reduce costs, improve efficiency and reduce GHG emissions. These include high pressure gasification, sorption enhanced gasification, more efficient hot gas clean up, more robust methanation catalysts, alternative air separation technologies and coupling bioSNG with renewable hydrogen inputs. However, the impact of each improvement will vary considerably between bioSNG technologies: for example, air separation technologies only benefit oxygen-blown gasifiers. Those that are of most benefit to the UK will depend on which technologies are deployed in the UK, which in the near term depends on the priorities of technology developers and in the longer term depends on which are shown to have reliable and lowest cost operation at scale. In addition, the potential impact of many of these activities has not been fully quantified by those developing the technologies. As a result, it is not possible or desirable to prioritise between them at this time. Further research and demonstration at scale is needed to identify which will be most valuable for the UK. As a result, this report highlights actions which could be taken which take account of these uncertainties.

Interest in pursuing these innovation opportunities is likely to be dependent on the existence of a route to market. Support for innovation in bioSNG in the UK could focus on boosting UK capabilities through access to larger scale research and testing facilities, to allow these innovation options to be investigated further and their benefits to be quantified, in close collaboration with industry partners to ensure their relevance. Continued collaboration between work on gasification for heat, power and transport fuels is key. Importantly, interest in bioSNG R&D will only be maintained with a clear route to market, which relies on continued progress in bioSNG deployment.

For bioSNG to be widely successful, development of reliable and sustainable biomass supply chains will be required, coupled with CCS infrastructure to maximise decarbonisation. There is a low risk of stranded assets if the gas grid is converted to hydrogen, given that bioSNG and hydrogen technologies are very similar and bioSNG plants could be converted to produce hydrogen using the same biomass and waste supply chains and gasification technology.

Biomass gasification to hydrogen is still at the pilot stage, with a lack of RD&D focus due to lack of demand for bulk, low carbon hydrogen. Demonstrating this technology alongside bioSNG, hydrogen and CCS infrastructure is the next step to determining the future role of this option for hydrogen production and negative emissions

Producing hydrogen from biomass gasification is a similar technology to bioSNG production, with both requiring feedstock pre-treatment, gasification and syngas clean-up, followed by catalysis steps. Hydrogen production remains at the pilot stage, however, as to date there has been little demand for sources of bulk, low carbon hydrogen. Industrial hydrogen today is often produced from fossil fuels, and hydrogen for transport is often produced onsite through electrolysis. Once a demand for bulk low carbon hydrogen exists, for example through gas grid blending or conversion, biomass gasification to hydrogen is anticipated to be a higher cost option in the near term than reforming of natural gas with CCS. Nevertheless, there is potential for cost reduction through scale and innovation to a hydrogen production cost of less than 4p/kWh, which is comparable to that of steam methane reforming with CCS. In addition, if the CO_2 produced is captured and stored, hydrogen production from gasification would be a carbon negative route.

In the near term, cost reductions and improvements in biohydrogen production could be realised through larger demonstration-scale plants, either in a dedicated plant or as a slipstream from a bioSNG plant. Innovative technologies could also contribute to reduced costs and increased efficiency and/or sustainability. Several of these cross-over from bioSNG technology development, but specifically for biohydrogen, improved or alternative water-gas-shift reactors have the potential to increase the efficiency of feedstock conversion to hydrogen, as well as reducing energy consumption of the hydrogen separation process, which can be one of the key contributors to energy consumption in the plant. These hydrogen-specific innovations are applicable to processes using any gasification and gas cleaning technology, and therefore could be the focus of R&D efforts today, and be applicable irrespective of which gasification technology is ultimately most widely deployed in the UK. To develop these, an increased research focus on biomass gasification routes to hydrogen would be required, together with demonstration facilities to allow scale up. Proving this route at demonstration scale of around $4MW_{hydrogen}$ could be the next step, either in a dedicated plant, or as a slipstream from a bioSNG plant. In addition, research on gasification, development of reliable and sustainable biomass supply chains and CCS infrastructure will benefit biohydrogen as well as bioSNG.

Achieving a significant expansion of energy crops to biomass supply would require an acceleration in planting rates, together with continued research on higher yielding and more cost effective breeds

Woody crops (such as short rotation coppice (SRC) and short rotation forestry (SRF)) and grassy crops (such as Miscanthus) can be specifically grown for energy purposes, with high yields and relatively low inputs. Developing improved and higher yielding breeds of energy crops is a priority to reduce costs, increase planting rates and improve sustainability performance. The crop yield (tonnes of crop per hectare of land) has a significant influence on the crop production cost, given that many of the costs are related to the area of land used or the quantity of planting material needed. Innovation could lead to increased yields in 2050 of 67% for Miscanthus compared with 2017 yields to reach 18 oven dried tonnes per hectare per year (odt/ha/yr) and 64% for SRC to reach 14 odt/ha/yr. Higher yielding breeds could lead to a 33% reduction in feedstock production cost for Miscanthus to £45/odt and 34% reduction for SRC to £52/odt by 2050. Development of new breeds could also focus on improving sustainability, such as increasing water and nutrient efficiency, and allowing use of poorer quality or contaminated land.

For Miscanthus, developing breeds that can be planted from seed would also allow a faster rate of planting and reduce establishment costs, which are a major contributor to production costs. UK research institutions are world leaders in Miscanthus R&D and breeding and in collaboration with other countries have led the advancement in Miscanthus breeding over the last decade. To commercialise new breeds of Miscanthus, seed production programmes would be needed as well as follow up research projects to capitalise on advances made to date.

Improving planting methods could lead to reductions in planting material and planting contractor costs for both SRC and Miscanthus, which in both cases is a significant contributor to production cost. Enhancing agronomic practices such as optimising supply chains to specific end-uses, improving harvesting, fertiliser and weeding techniques can also significantly improve yield and cost. This is particularly true for SRC willow which requires specialised machinery and is highly sensitive to weed control.

Although some of these crops are grown extensively in other regions, current planted areas are small in the UK. Nevertheless, both in the UK and globally, energy crops are expected to be a major source of biomass to 2050, and can be used for all bioenergy routes, including to heat, power, transport fuels and chemicals. This relies primarily on significantly increasing the rate of planting from today, as well as increasing yields to reduce costs and increase output. In the UK context, increasing planting rate requires supporting farmers to overcome initial costs and delayed payback from these crops, together with consistent policy to maintain stable market demand.

Although pretreatment technologies for anaerobic digestion of straw are being commercialised today, better comparable information on their performance could help to speed their uptake

Anaerobic digestion (AD) is a commercially available and widely used biological process for converting biomass into biogas. Typical feedstocks for AD are wet materials such as manures, sewage sludge, food wastes and some crops such as maize and agricultural residues such as grass silage. The biogas potential would be greatly increased by the ability to use lignocellulosic feedstocks which have a higher potential supply in the UK and globally, such as grassy and woody energy crops, straw and wood. However, these feedstocks are not commonly used in AD today, as they are very slow to break down. Use of straw in AD is at the early stages of commercialisation, with a range of technology options being commercialised in the UK and elsewhere. Adoption of straw pretreatment technologies could be accelerated by coordinated and monitored demonstrations of technologies which are currently available, to provide better information for potential adopters. In addition, further research could assess the potential impact of this technology for the UK and could aim to widen AD pretreatment to other feedstocks such as grassy energy crops and wood. Importantly, enabling these materials to be used in biological processes would increase the potential for biological routes to hydrogen by fermentation, an area where the UK has leading research.

The benefits of innovative pretreatment technologies for thermochemical routes are not yet clear and so a watching brief on these technologies is recommended

There is a wide range of biomass pre-processing technologies available today used to clean up, dry and/or densify biomass prior to thermochemical conversion. Processes such as chipping and pelletising are commercially mature, with little scope for innovation. More novel processes such as water washing, chemical washing, pyrolysis, torrefaction and steam explosion are at the demonstration to early commercial stage. However, none of these novel routes have yet been proven to have benefits to UK supply chains in terms of cost reductions in biomass transport or conversion that outweigh the costs and efficiency loss of the pre-processing itself. Research on the value of these routes is ongoing and should be reviewed before determining the direction of future support for RD&D. The commercial driver for novel pretreatment routes will increase with the increasing scale of biomass supply chains.

For each technology or feedstock, this report details opportunities for innovation, the impact of that innovation and possible actions to overcome barriers to their development and deployment

This report assesses the state of development of these technologies and feedstocks today, what the potential for innovation could be, and the impact that the innovation would have on deployment, cost, and sustainability, based on literature data and over 30 interviews with stakeholders. Wherever possible, data is given to allow the impacts to be quantified using the tool developed in the parallel project. Barriers to these innovation activities are discussed, and a range of actions which could be deployed to reduce them. These actions are intended to assist BEIS in considering the long term direction of innovation funding for bioenergy in heating.

1 Introduction and approach

E4tech and Ecofys were commissioned to support the UK Department of Business, Energy and Industrial Strategy (BEIS) in assessing the potential impact of innovation on bioenergy heat pathways to 2050. This project focuses on those pathways that are most relevant to decarbonising heat to 2050 – in particular, those options that relate to decarbonisation of the GB gas grid using **biomethane**, produced by anaerobic digestion of biomass, **bioSNG or biohydrogen**, both produced by gasification of biomass and downstream reaction of the syngas.

Innovation could occur in any part of the bioenergy value chain, from feedstock production to heat delivery. However, this project only considers innovations that are specific to biomass heat supply chains alone, and not those related to non-biomass parts of the chain such as gas grid conversion, CO_2 transport and storage, gas clean up after transportation via the gas grid for use in appliances, or end use appliances for methane or hydrogen.

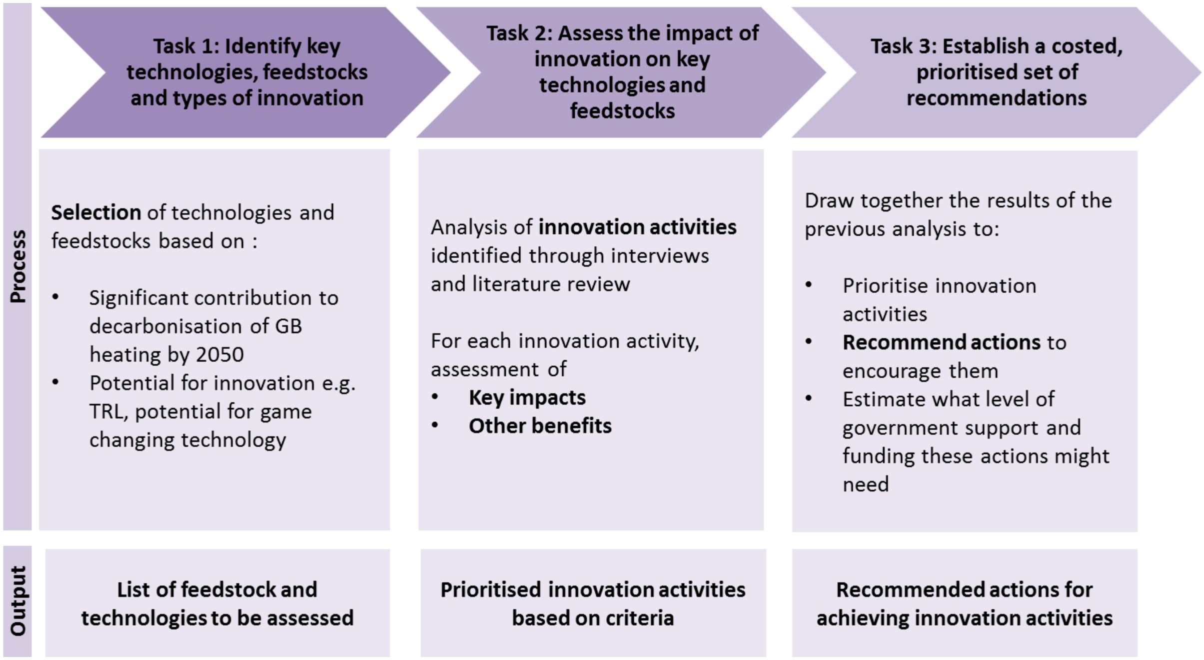
The project's aims are to:

- Identify those technologies and feedstocks where innovation is likely to accelerate and increase the potential for substantial bioenergy use in GB heating
- Assess the state of development of these technologies and feedstocks today, and assess what the potential for innovation is for each, including both what types of innovation are needed, and the impact that the innovation would have in terms of outcomes such as increased deployment, cost reduction, and improved sustainability
- Consider when these innovations need to happen, what barriers exist, and what actions are needed to overcome them
- Set out how the actions needed could be prioritised, and for those that are most important, how they could be delivered, by whom, and with what funding needs.

This will enable the Government to better consider the long term direction of innovation funding for bioenergy in heating, and set innovation priorities for bioenergy in heating within the context of a wider set of energy system priorities.

Note that this project does not aim to assess which biomass conversion technology is best, assess what the potential for a particular biomass feedstock is, or assess the relative costs of bioenergy pathways. Instead this project focuses on how innovation activities change the characteristics of individual technologies and feedstocks. As such, the actions required to promote innovation in each technology or feedstock selected are prioritised only within that technology or feedstock, and not between them.

The overall project approach is shown in the graphic below.



	Task 1: Identify key technologies, feedstocks and types of innovation	Task 2: Assess the impact of innovation on key technologies and feedstocks	Task 3: Establish a costed, prioritised set of recommendations
Process	**Selection** of technologies and feedstocks based on : • Significant contribution to decarbonisation of GB heating by 2050 • Potential for innovation e.g. TRL, potential for game changing technology	Analysis of **innovation activities** identified through interviews and literature review For each innovation activity, assessment of • **Key impacts** • **Other benefits**	Draw together the results of the previous analysis to: • Prioritise innovation activities • **Recommend actions** to encourage them • Estimate what level of government support and funding these actions might need
Output	**List of feedstock and technologies to be assessed**	**Prioritised innovation activities based on criteria**	**Recommended actions for achieving innovation activities**

In Task 1, the technologies and feedstocks to be considered in more detail are selected, based on their potential contribution to decarbonisation of heat by 2050, and their potential for innovation. The results of this selection are given in Appendix B. It is important to note that not selecting a technology or feedstock for this project **does not mean that the technology or feedstock is not an important contributor to UK decarbonisation**. Feedstocks that have not been taken forward in this project include:

- feedstocks and technologies that make too small a contribution to make a focus on innovation a priority
- feedstocks that are more suitable for uses other than heat
- feedstocks and technologies that are already commercially mature.

Most of these feedstocks and technologies are nevertheless likely to be important in realising the full potential of bioenergy to contribute to decarbonisation. The bioenergy sector will need a diversity of feedstock and technology options in order to provide different energy services in the most cost and GHG efficient way.

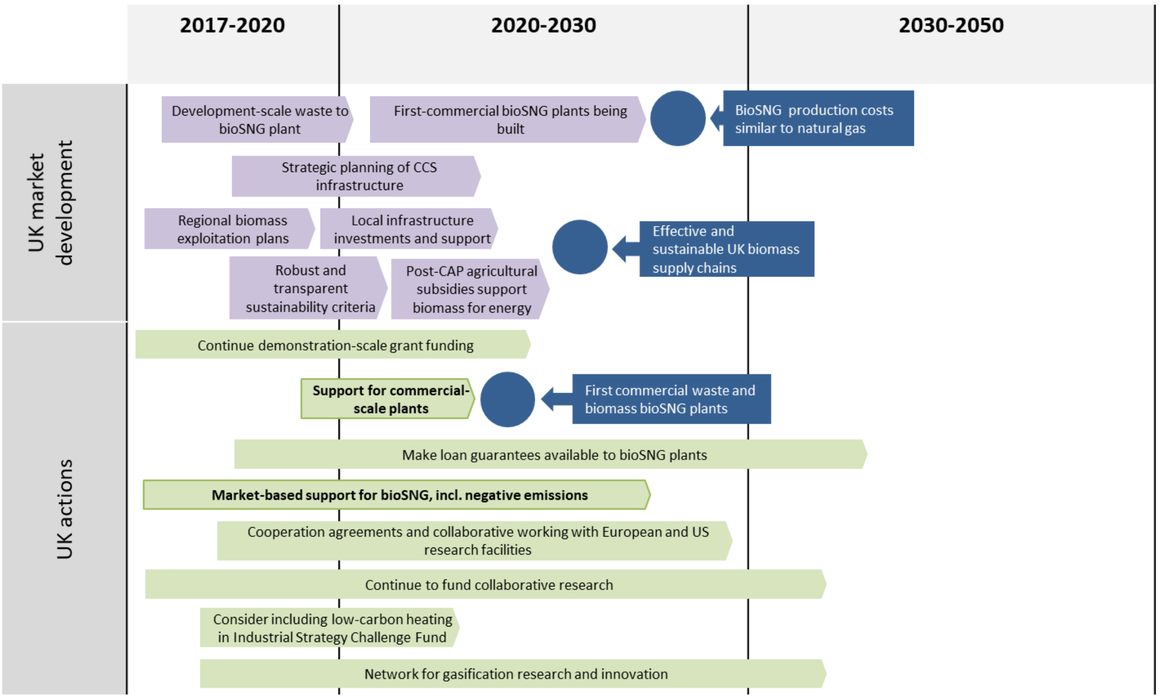
Each chapter of this report then gives results of Tasks 2 and 3 for each technology or feedstock, including establishing the current status of development and deployment, outlining UK and global activities in each area, and identifying innovation activities and their impacts. This is based on introductory information drawn from review papers and reports on each topic, new industry reports and scientific literature searches on specific topics (as referenced), and interviews with stakeholders and experts in each area. Innovation activities identified are areas where interviewees or the literature considered that there was significant potential for cost reduction, increase in supply, or improvement in sustainability. Where possible, the impacts of innovation are quantified. This research also revealed barriers to these innovation activities, for which proposed actions to overcome them are then proposed. The actions are prioritised and shown on a timeline. Appendix A includes a list of interviewees consulted, and literature sources are given in footnotes, for ease of reference.

2 BioSNG (with CO_2 capture)

Summary

- **B**iomass or waste feedstocks can be gasified to produce syngas, which is then converted to methane - termed **biomass-derived synthetic natural gas or bioSNG**. BioSNG is at the early commercial stage globally, with the UK having one of the main developers of this technology.
- In the near term, the main cost reductions are expected through **deployment and scale up**, rather than new technologies. Deployment of multiple plants, plus scale up of these plants from $38MW_{SNG}$ to $77MW_{SNG}$, is expected to bring down plant capex by 30% and opex by 19%. Further deployment will also give improved clarity on the technology improvements that could bring future gains.
- A range of **potential improvements to today's bioSNG technologies** could reduce costs, improve efficiency and reduce GHG emissions. Key improvements are: improving feedstock handling and flexibility, improving the efficiency of syngas clean up and air separation, developing new gasification options, and improving plant integration. These innovations are likely to reduce costs, and may increase conversion efficiency, for example alternative air separation techniques could reduce capex by 2.5% and opex by 6%.
- However, it is **not possible or desirable to prioritise between these potential improvements** today, to prioritise R&D efforts. This is because the impact of each improvement will vary considerably depending on the bioSNG technology used, and in many cases require further R&D in order to quantify benefits where they exist. In addition, some technology developers claim to have already made these improvements, although the early stage of commercialisation of the technology means that this has not yet been clearly demonstrated.
- As a result, support for innovation in bioSNG in the UK could focus on boosting UK capabilities through access to **larger scale research and testing facilities**, to allow these innovation options to be investigated further and their benefits quantified, in close collaboration with industry partners to ensure their relevance. Collaboration between work on gasification for heat, power and transport fuels is key. Importantly, interest in bioSNG R&D will only be maintained with a clear route to market, which relies on continued progress in bioSNG deployment.
- The barriers to bioSNG deployment include high capital costs and technology risk, and higher biomethane production costs than the wholesale natural gas price. In addition, the value of negative emissions if bioSNG were combined with CCS cannot currently be monetised. Providing **support for first commercial scale plants** could reduce project risk, coupled with improved market-based support for bioSNG that reflects its development status, GHG benefits and potential scale of contribution to decarbonisation. For bioSNG to be widely successful, development of **reliable and sustainable biomass supply chains** will be required, and to maximise decarbonisation, **CCS infrastructure.**

- An indicative timeline for bioSNG development:



2.1 Introduction

2.1.1 Technology description

Process introduction

BioSNG refers to the production of biogenic synthetic natural gas, via gasification of biomass or waste feedstocks to produce syngas, and subsequent methanation to produce methane. The production of bioSNG requires the following key steps:

1. **Feedstock pre-treatment** – requirements depend on gasifier technology and feedstock being used, but may include biomass drying and/or chipping.
2. **Biomass gasification** – this produces syngas (a mixture of H_2, CO, CO_2, CH_4, and other trace compounds). Several different types of gasifiers can be used, as discussed in more detailed below.
3. **Syngas clean-up** – tars and particles are removed from the syngas.
4. **Syngas conditioning** – trace compounds such as ammonia, hydrogen sulphide, COS, halides and alkaline metals must be removed to avoid damaging components and poisoning the methanation catalyst. CO_2 can also be captured at this stage.
5. **Water-gas-shift (WGS) reaction** – this increases the H_2:CO ratio to nearer 3:1, which is the optimum for methanation. This process consumes steam and produces CO_2.
6. **Methanation** – syngas is compressed to high pressure, and passed over a catalyst to produce methane. There are a number of different methanation processes that can be used, as discussed in more detail below.
7. **Purification** – the gas mixture exiting the methanation reactor is mostly CH_4 and water, but may contain CO_2 if this has not already been removed or the methanation catalyst has WGS activity. This mixture is cooled to separate the water. If CO_2 is present in any significant quantity, it must now be separated.

Gasifier types and process variants

There are several types of gasifier which can be used for production of syngas from biomass, but only a subset of these are appropriate for integration with a downstream methanation process, which ideally requires: minimal tar production, high methane concentration in the syngas, high H_2:CO ratio, high pressure operation and no nitrogen dilution of the syngas (Knoef, 2012). More technical information on the operation of each type of gasifier is available from E4tech (2009)[2].

Fluidised bed gasifiers: Of the gasifiers suitable for bioSNG production, there is most experience with fluidised bed gasifiers. Within this gasifier type, there are three sub-types commonly used: bubbling fluidised bed gasifiers, circulating fluidised bed gasifiers and dual fluidised bed gasifiers. Both the Repotec-CTU gasifier (used at GoBiGas, GAYA, and Güssing), and the ECN gasifier (used in the Ambigo project) are indirectly-heated dual fluidised bed gasifiers. The Advanced Plasma Power (APP) gasifier in Swindon is a bubbling fluidised bed gasifier followed by a plasma convertor to crack tars. Fluidised bed gasifiers can accept a wide range of biomass and waste feedstocks. Fluidised bed biomass gasifiers have been built up to around 150MW_{th} biomass input to-date, and it is likely that pressurised fluidised bed gasifiers would be able to operate up to around 350MW_{th} biomass input.[3]

Plasma gasifiers: Plasma gasifiers can accept almost any type of feedstock, and so could be more appropriate for bioSNG production from waste.[4] They can operate up to around 100 MW_{th} biomass input, based on technology limitations of current designs, and have been used for small commercial scale waste treatment (up to around 40 MW_{th} input).[5] However these gasifiers have mostly been used for waste disposal with some focus on electricity production, and have not been widely investigated for bioSNG or biohydrogen production. The 50 MW_{el} plasma gasifiers at the Air Products Tees Valley plants were not successfully commissioned.

Entrained flow gasifiers: Entrained flow gasifiers are widely established for coal gasification, and could potentially operate at scales of up to 2GW_{th} biomass input, based on the limitations of current technology.[5] However, companies have struggled to commercialise this technology for biomass and there are currently no successful demonstration-scale units using biomass – past biomass testing campaigns were conducted at fossil entrained flow gasifiers (Buggenum, Schwartze Pumpe). CHOREN attempted to develop this technology, but became insolvent in 2011. However subsequent analysis by Linde Group, who bought the technology, suggested that there were no fundamental problems with the technology.[6]

Several methanation techniques have been developed for the production of synthetic natural gas from syngas derived from coal gasification, such as Amec Foster Wheeler's VESTA technology,[7] which could also be used for

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[2] E4tech (2009) Review of technologies for gasification of biomass and wastes, Available from: http://www.e4tech.com/reports/review-of-technologies-for-gasification-of-biomass-and-wastes/

[3] E4tech (2009) Review of technologies for gasification of biomass and wastes, Available from: http://www.e4tech.com/reports/review-of-technologies-for-gasification-of-biomass-and-wastes/

[4] Sikarwar et al. (2017) Progress in biofuel production from gasification, Progress in Energy and Combustion Science (61) 189-248, http://www.sciencedirect.com/science/article/pii/S036012851630106X

[5] E4tech and Element Energy (2016) Hydrogen and Fuel Cells: Opportunities for Growth, Mini roadmaps (appendix to roadmap report)

[6] Kittelmann (2014) Carbo-V® Biomass Gasification Technology. Status after Application of Sound Engineering Practices http://www.ieatask33.org/app/webroot/files/file/2014/WS2/Kittelmann.pdf

[7] Romano, L., Ruggeri, F. (2015), Methane from Syngas – Status of Amec Foster Wheeler VESTA Technology Development, Energy Procedia, 249-254, http://www.sciencedirect.com/science/article/pii/S1876610215027411

biomass-derived syngas (as being demonstrated by APP). Rönsch et al. (2016)[8] summarise the main methanation reactor types that are currently used for bioSNG projects.

In the usual bioSNG production process, a relatively pure CO_2 stream is produced, which could potentially be captured, compressed and stored with minimal additional processing, achieving negative CO_2 emissions (BECCS). Because the CO_2 must already be separated, little additional technology is required for integration of bioSNG with CCS. Carbo et al. estimate that in a bioSNG plant based on indirect gasification, around 20% of the initial carbon is emitted as CO_2 in flue gas, 40% as methane in bioSNG and 40% as a high-purity CO_2 stream that could be captured, compressed and stored.[9] Directly-heated gasifiers, which do not have a separate combustion chamber, do not have a separate flue gas stream.

The technology used for CO_2 capture is similar to that used in industrial natural gas sweetening (and as proposed for pre-combustion IGCC plants), and is usually based around physical absorption solvents.[10] Other methods such as vacuum swing adsorption which is suitable for small to medium CO_2 sources have also been investigated.[11] The purity of the CO_2 produced will depend on a number of factors, but one plant developer interviewed stated that the CO_2 from their plant is already at the levels of purity required for industrial or food applications.

2.1.2 Global deployment status

Biomass gasification to provide syngas for heat and power applications, which does not require subsequent methanation, is at a more advanced stage of development than gasification for bioSNG production, due to the usually lower syngas clean-up requirements for heat and power applications. Therefore, while there are globally around 100 - 150 biomass and/or waste gasifiers in operation[12], only a small subset of these are targeting bioSNG production. Table 1 summarises the current global status of bioSNG gasification plants, arranged from largest to smallest bioSNG production capacity.

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[8] Rönsch, S. et al (2016) Review on methanation – From fundamentals to current projects, Fuel (166) 276-296, http://www.sciencedirect.com/science/article/pii/S0016236115011254

[9] Carbo et al. (2010), Bio energy with CO2 capture and storage (BECCS): conversion routes for negative CO2 emissions, http://tu-freiberg.de/en/fakult4/iec/evt/04-1-bio-energy-with-co2-capture-and-storage-beccs-conversion-routes-for-negative-co

[10] European Biofuels Technology Platform ZEP, (2012) Biomass with CO_2 Capture and Storage (Bio-CCS), www.biofuelstp.eu/downloads/bioccsjtf/EBTP-ZEP-Report-Bio-CCS-The-Way-Forward.pdf

[11] Ahn, H. (2016) Process Configuration Study on a Biomass Gasification CHP Plant with Carbon Capture, http://www.all-energy.co.uk/RXUK/RXUK_All-Energy/2016/Presentations%202016/Bioenergy%202/Hyungwoong%20Ahn.pdf?v=635993474783748594

[12] Gasification and Syngas Technologies Council (n.d.) http://www.gasification-syngas.org/resources/the-gasification-industry

Table 1: Pilot, demonstration and commercial-scale bioSNG projects

Project name (location)	Companies involved	Technology type	Feedstock	Size (MW_{SNG})	Status (start-up year)
Bio2G (Sweden)	EON, Andritz Carbona Oy, Haldor Topsoe AS	Pressurised O_2 blown fluidized bed gasifier; hot gas cleaning (tar reforming, HAT filter), water scrubber, acid gas removal	Woody biomass	200	Cancelled
GoBiGas – Phase 2 (Göteborg, Sweden)	Göteborg Energi, Repotec, Metso	Repotec technology: indirect dual fluidized bed gasifier	Forest residues	80-100	Planned – on hold
GoBiGas – Phase 1 (Göteborg, Sweden)	Göteborg Energi, Repotec, Metso	Repotec technology: indirect dual fluidized bed gasifier[13]	Forest residues[14]	20	Operational (2013)
GoGreenGas (Swindon, UK)[15]	Advanced Plasma Power, National Grid, Progressive Energy	Oxygen-blown bubbling fluidised bed gasifier (BFB), then plasma torch to clean the syngas	RDF and waste wood	2.7 (of which ~50% biogenic)	Under construction (2018)
Ambigo (Alkmaar, Netherlands)[16]	ECN, Gasunie, Royal Dahlman, PDENH, Engie	MILENA technology: Indirect dual fluidized bed gasifier; OLGA tar removal technology; ESME methanation[17]	Biomass - waste wood	2.6	Planned (2019)
Güssing, Austria	Repotec, Biomassekraftwerk Güssing GmbH etc	Repotec technology: indirect dual fluidized bed gasifier [18]	Wood chips, straw pellets[19]	1.0	Operational (2009)
GAYA (Lyon, France)	Repotec, GDF Suez, and others	Circulating fluidized bed reactor[20]	Lignocellulosic crops[21]	0.40 [22]	Under construction (2018)
GoGreenGas (Swindon, UK)	Advanced Plasma Power, National Grid, Progressive Energy	Oxygen-blown bubbling fluidised bed gasifier (BFB) and plasma torch to clean the syngas	Wastes	0.050 (of which ~50% biogenic)[23]	Operational (2015)

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[13] Hedenskog, L. (2014) Gasification of forest residues – IRL in a large demonstration scale, www.ieatask33.org/app/webroot/files/file/2014/WS2/Hedenskog.pdf

[14] Haldor Topsoe (2015) First ever large-scale demonstration biogas plant goes on-stream in Sweden with technology from Topsoe, https://www.topsoe.com/news/2015/01/first-ever-large-scale-demonstration-biogas-plant-goes-stream-sweden-technology-topsoe

[15] Go Green Gas (2017) http://gogreengas.com/

[16] Guerrini, (Engie) (2017) Gasification technologies and their contribution to Biomethane development, http://european-biogas.eu/wp-content/uploads/2017/02/12-ENGIE-OLlivier.pdf

[17] Rabou, L. and Overwijk, M. (2016) The Alkmaar 4 MW bio-SNG demo project, https://www.ecn.nl/publicaties/PdfFetch.aspx?nr=ECN-M--16-032

[18] Introduction (n.d.) http://www.ficfb.at/renet_d.htm

[19] DBFZ (2009) D1.4 Final Project Report, https://www.dbfz.de/fileadmin/user_upload/Referenzen/Berichte/Final_project_report_biomethan.pdf

[20] Engie (2016) http://www.engie.com/en/journalists/press-releases/innovative-green-gas-production-methods-europe/

[21] ETIP Bioenergy (n.d.) http://www.etipbioenergy.eu/databases/production-facilities

[22] Guerrini, (Engie) (2017) Gasification technologies and their contribution to Biomethane development, http://european-biogas.eu/wp-content/uploads/2017/02/12-ENGIE-OLlivier.pdf assuming 67% efficiency from 600kW biomass input

[23] Go Green Gas (2017) http://gogreengas.com/pilot-plant/achievements/

The Bio2G project was a 200 MW$_{SNG}$ plant planned by E.ON, which had been accepted for NER300 funding. However, the project has been cancelled, because of a lack of long-term biofuel policy in Sweden.[24]

The GoBiGas project aimed to build two gasification plants: a Phase 1 20 MW$_{SNG}$ demonstration plant, followed by a Phase 2 commercial plant. The Phase 1 plant was completed in 2013, but had problems with start-up, including clogging of tar meaning it was not possible to activate the bed material[25], so it did not start delivering gas to the grid until 2015. The problems were largely solved with the initial feedstocks (wood pellets) and performance testing moved to wood chips.[26] Despite much improved operational performance, it was announced in April 2017 that Göteborg Energi is aiming to sell this plant, as they do not want to continue to finance research on the Phase 1 plant and cannot commit to constructing the Phase 2 plant.[27]

A consortium including ECN and Engie are planning the 2.6 MW$_{SNG}$ Alkmaar bioSNG plant, which will be located at the Energy Innovation Park in Alkmaar, the Netherlands. At this same location, the InVesta expertise centre for biomass gasification is being established, which will give the opportunity for further R&D. An indirect fluidized bed (ECN MILENA) gasifier will be used, and the SNG produced injected into the regional gas distribution grid. Basic engineering on this plant has begun, but the final investment decision has not yet been made by the consortium.[28]

The Güssing plant is an 8 MW$_{th}$ CHP plant which started up in 2002. Initial research was carried out on a syngas slipstream of the plant, to produce around 10 kW$_{SNG}$. In 2008 a 1 MW$_{SNG}$ pilot unit was built onto the gasifier, which had some delays in commissioning due to technical issues and was completed in June 2009. The bioSNG produced met the requirements of the Austrian regulations for gas fed into the natural gas grid.[29] Research continues on this plant, under the remit of the Bioenergy 2020+ competence centre.

A research bioSNG plant is under construction in France as part of the GAYA project, which will have a capacity of 600 kW$_{th}$ of biomass, capable of producing ~400 kW$_{SNG}$.[30] The technology is based on that developed by Repotec at the Güssing plant, and aims to develop small module reactors that can accept a variable biomass feedstock.[31]

In the USA, West Biofuels is developing pilot-scale gasifiers, for example the FICFB gasifier at Woodland, California in collaboration with the University of California. This plant was proposed to be used for research into bioSNG and ethanol production, but further details about this research are unclear.[32]

There has been no commercial deployment of bioSNG with CO_2 capture, although some research has been carried out into capture options. ECN carried out techno-economic analysis of a 500 MW$_{th}$ (biomass input) commercial

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[24] IEA, Task 39 Newsletter Issue #38 (2016) http://task39.sites.olt.ubc.ca/files/2012/01/IEA-Bioenergy-Task-39-Newsletter-Issue-42-April-2016.pdf

[25] Thunman, Larsson, Hedenskog, 2015, http://www.gastechnology.org/tcbiomass/tcb2015/Thunman_Henrik-Presentation-tcbiomass2015.pdf

[26] Hedenskog, 2015, https://energiforskmedia.blob.core.windows.net/media/21800/gobigas_internationalseminariegasification_161020_mh.pdf

[27] Bioenergy International (2017) https://bioenergyinternational.com/biogas/gobigas-gasification-plant-sale

[28] Rabou, L. and Overwijk, M. (2016) The Alkmaar 4 MW bio-SNG demo project, https://www.ecn.nl/publicaties/PdfFetch.aspx?nr=ECN-M--16-032

[29] DBFZ (2009) D1.4 Final Project Report, https://www.dbfz.de/fileadmin/user_upload/Referenzen/Berichte/Final_project_report_biomethan.pdf

[30] Repotec (n.d.) http://www.repotec.at/index.php/gaya-rd.html

[31] Bioenergy insight (2016) http://www.bioenergy-news.com/display_news/11439/engie_announces_two_dry_biomasstogas_project_collaborations/

[32] WestBiofuels (n.d.) http://www.westbiofuels.com/projects#

plant, concluding that the additional cost of capturing CO_2 is small, and that with a CO_2 price above €25/tonne, the biomethane production cost is lower for the process with CO_2 capture than for the unabated process.[33]

2.1.3 UK deployment status

There are over 20 operating and planned gasification plants in the UK focussed on waste disposal and/or power production,[34] but only Advanced Plasma Power (APP) have constructed an operating bioSNG production plant.

APP are developing bioSNG technology in the UK, based on gasification of mixed wastes. APP use an Outotech oxygen-blown bubbling fluidised bed gasifier (BFB) to produce syngas, and then a plasma torch cleans the syngas, producing a solid by-product called Plasmarok. APP completed construction of their $0.05MW_{SNG}$ bioSNG pilot plant in 2015. They are currently constructing their first demonstration plant ($2.7MW_{SNG}$), within the GoGreenGas consortium which is anticipated to start up in 2018.[35] Unlike the GoBiGas, GAYA and Alkmaar bioSNG projects under development in Europe, the APP plant uses refuse-derived fuel and waste wood as feedstocks, and claims to be able to accept a wide range of wastes including MSW, RDF and SRF, commercial waste, wood wastes and biomass, mined landfill, auto shredder residue, hazardous and special wastes. The SNG from the GoGreenGas demonstration plant will be injected into the gas network,[36] and will also be used in a local Compressed Natural Gas filling station, providing fuel for a fleet of 40 trucks.[37]

The APP plant will also operate a project to capture CO_2 from the bioSNG production process at the $2.7MW_{SNG}$ plant, capturing around 800kg/hour of CO_2. The project, running from January 2017 to July 2018 and costing £1.7 million, will be delivered by Go Green Fuels Ltd. with funding provided by the Network Innovation Allowance. The project will capture, purify and deliver CO_2 to an industrial customer, and the developers are also holding discussions with experts to understand the requirements for CO_2 in a future storage network, and how future bioSNG facilities could integrate into this.[38]

The Energy Technologies Institute (ETI) are currently investing £5 million to support the construction of Syntech Bioenergy's waste gasifier in the West Midlands. The plant will process 40 tonnes of RDF per day. Initially the syngas that is produced will only be used to produce power ($1.5\ MW_{el}$), but it has been suggested that future research will investigate the possibility of producing fuels from the syngas.[39]

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[33] Carbo, M.C., Smit, R., van der Drift, B., Jansen, D. (2011) Bioenergy with CCS (BECCS): Large potential for BioSNG at low CO_2 avoidance cost, Energy Procedia 4, 2950-2954, http://www.sciencedirect.com/science/article/pii/S1876610211004000

[34] ETI (2017) targeting new and cleaner uses for wastes and biomass using gasification, http://www.eti.co.uk/insights/targeting-new-and-cleaner-uses-for-wastes-and-biomass-using-gasification

[35] Go Green Gas (2017) http://gogreengas.com/

[36] Go Green Gas (2017) http://gogreengas.com/news/demonstration-plant-plans-underway/

[37] Institute of Mechanical Engineers (2016) https://www.imeche.org/news/news-article/construction-to-start-on-world-s-first-commercial-bio-substitute-natural-gas-plant

[38] Smarter Networks Portal (2017) http://www.smarternetworks.org/Project.aspx?ProjectID=2034

[39] Power Engineering International (2017) http://www.powerengineeringint.com/articles/2017/04/uk-waste-to-energy-gasification-project-gets-underway.html

There are a range of other gasifier projects in the UK aimed at waste management or the production of power. Although not specifically targeting the production of bioSNG, these plants provide the UK with valuable learning and experience in gasification technologies that could be applied to bioSNG systems. Examples include:

- Energy Works in Hull have built a gasifier producing 25 MW_{el} of electricity from waste, processing 200,000 t/yr of waste wood, commercial and industrial waste and eventually municipal solid waste.[40]
- A gasifier built by Amey in Milton Keynes is processing the residual fraction of MSW to produce electricity.[41] The plant combines AD and gasification technology, and processes 132,000 t/yr of MSW to produce 5.8 MW_{el} of electricity from both processes.
- Air Products completed construction of the Tees Valley One (TV1) plant in 2015, including an Alter-NRG plasma gasifier designed to use 350 kt/yr of RDF, producing 50 MW_{el}. However design and operational problems in commissioning meant that the plant is yet to operate, and construction on the planned second plant (TV2) was stopped in 2015.[42]

2.1.4 Enabling factors for innovation

This section describes the capabilities for bioSNG technology development, and the factors driving that development, both globally and in the UK.

Global capabilities and support

Europe has strong capabilities in biomass gasification to produce bioSNG, with the development of two competing dual fluidised bed gasifier technologies, the Repotec-CTU gasifier and the ECN MILEA gasifier. Both development programmes involve a consortium of European companies and universities, including the Vienna University of technology (TUV), Paul Scherrer Institut (PSI), Biomasse Kraftwerk Güssing, Conzepte Technik Umwelt (CTU), ECN, Repotec, Royal Dahlman and others. Interviewees emphasised the importance of the pilot-scale research plants at ECN and Güssing in the development of these technologies.

European research funding schemes, including NER300 and H2020 have aided bioSNG projects, for example the Bio2G project in Sweden was awarded an NER300 grant. In addition, more specific funding for biomass or gasification projects is available, such as the European Bioenergy Securing the Future (BESTF) ERANET programme which supported Advanced Plasma Power[43], and the BioProGReSs project in developing syngas cleaning technology.[44]

Outside Europe, there has been limited focus on bioSNG production. However, NETL in the USA has a large coal to SNG gasifier[45], and China also has several coal to SNG plants developing this technology,[46] suggesting the

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[40] Power-technology.com (2017) Energy works power plant project, Hull, United Kingdom, http://www.power-technology.com/projects/energy-works-power-plant-project-hull/

[41] Trading Products (2016) Milton Keynes Recovery Park begins taking waste, http://www.tradingproducts.co.uk/news/milton-keynes-recovery-park-begins-taking-waste/

[42] Waste Management World (2016) Air products to ditch plasma gasification waste to energy plant in Teesside, https://waste-management-world.com/a/air-products-to-ditch-plasma-gasification-waste-to-energy-plants-in-teesside

[43] BESTF (n.d.) http://eranetbestf.net/call/bestf1/

[44] BioProGReSs (n.d.) http://bioprogress.se/

[45] National Energy Technology Laboratory (n.d.) Great Plains Synfuels Plant, https://www.netl.doe.gov/research/coal/energy-systems/gasification/gasifipedia/great-plains

[46] ECEC (2015) Coal to Natural Gas, http://www.chinaecec.com/en/fields04.htm

expertise for bioSNG production is present in these countries even if there has been little interest so far. Expertise in gasification to high quality syngas is also being developed globally aimed at liquid fuels production.

UK capabilities

As outlined above, the UK has experience in gasification to power applications, with bioSNG application development currently limited to APP. The UK has some research activity in gasification and bioSNG technologies, but does not have any large pilot scale gasifiers for R&D, such as the Bioliq or Güssing projects in Europe. Several UK-based companies are working on aspects of the technology and there are also several universities working on aspects of gasification research, although few focussed specifically on bioSNG production:

- Johnson Matthey, a global technology company with a significant UK presence, is developing technology for biomass-derived syngas purification and conditioning, although primarily targeting methanol production.[47] They worked on novel syngas cleaning in the EU project 'GREENSYNGAS' from 2010 to 2011, primarily providing materials including absorbents, reforming catalysts and water-gas shift catalysts.[48]
- Commercial methanation catalysts are available from companies such as Johnson Matthey, Sud-Chemie and Haldor Topsoe. Velocys' micro-channel reactor is also being developed by Oxford Catalysts, which could be applicable to methanation process intensification (although not a current focus).
- Research into gasification technologies is being done at several UK universities including, but not limited to:
    - Glasgow University – research into biomass gasification includes the EPSRC SUPERGEN Bioenergy Challenge II "Real time control of gasifiers to increase tolerance to biomass variety and reduce emissions" which runs from 2015 to 2018.[49]
    - Aston University – The European Bioenergy Research Institute (EBRI) at Aston University carries out research into gasification, with a focus on enhancing syngas quality.[50] Aston University is also involved in the EPSRC SUPERGEN Bioenergy Challenge II project alongside Glasgow.
    - Imperial College London – the Clean Fossil and Bioenergy Research Group carries out research on gasification of coal and biomass with carbon capture and storage, including pre-combustion CO_2 capture by chemical looping.[51]
    - Nottingham University – research into thermochemical biomass conversion in the Cleaner Fossil Energy and Carbon Capture technologies Research Group.[52]
    - Sheffield University – research into pyrolysis and gasification within the Environmental and Energy Engineering Research Group.[53]
    - The University of Bath – work on biomass gasification includes some projects focussed specifically on bioSNG production.[54]

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[47] Abbott, J., JMPT (2015) Syngas from renewables: Production of green methanol, 2015 European Methanol Policy Forum, https://eu-ems.com/event_images/presentations/Jim%20Abbott%20presentation.pdf

[48] GREENSYNGAS Report Summary

[49] Bioenergy Research at the University of Glasgow (2016) http://bit.ly/2r7YyAn

[50] Gasification, http://www.aston.ac.uk/eas/research/groups/ebri/research/gasification/

[51] Research Staff, https://www.imperial.ac.uk/a-z-research/clean-fossil-and-bioenergy/people/research-staff/

[52] Cleaner Fossil Energy and Carbon Capture Technologies Research Group, https://www.nottingham.ac.uk/research/groups/cleaner-fossil-energy-and-carbon-capture-technologies/research/projects.aspx

[53] Environmental and Energy Engineering Research Group, https://www.sheffield.ac.uk/cbe/research/envenergyeng

[54] Dr Paul Adams, http://www.bath.ac.uk/mech-eng/research/sert/people/adams/index.html

- University of Newcastle – lead partners on the Supergen Gasification Integration project[55] and have a 50kW gasifier.[56]
- University College London – Work on gasification is carried out in the Department of Chemical Engineering,[57] and they have collaborated with APP on plant studies.[58]

UK support

UK support for bioSNG production is mainly focussed on R&D in universities, and demonstration-scale projects, and has been criticised by some interviewees for not encompassing research at large-scale pilot plants, or supporting technologies to move from demonstration to commercialisation.

Much of the research into biomass gasification in the UK is funded by the EPSRC, and the Supergen Bioenergy Hub brings together industry, academics and other stakeholders in this area.[59] The CombGEN network, funded by the Carnegie Trust and EPSRC, also brings together researchers in the field of cleaner and more efficient combustion and gasification technologies.[60]

Bridging the gap between research and industry, Innovate UK provide grant funding towards industrial research.[61] In the 2016/17 financial year the Innovate UK research budget was £561 million, of which 27% was targeted towards Infrastructure Systems, which includes energy technologies. However from April 2016 to August 2017 only one collaborative R&D project and two feasibility studies on gasification were funded.[62] Also Ofgem's annual Network Innovation Competition, with a total annual budget of up to £81 million, offers funding for innovative project delivering environmental benefits for gas customers, up to a maximum of £18 million per project,.[63] The Gas Network Innovation Allowance is an allowance that the regulator allows gas network operators to spend on either small projects or submissions to the Network Innovation Competition.[64]

Support for developers to scale-up their technology is available through several channels in the UK. The Department for Transport (DfT) Advanced Biofuels Demonstration Competition provided grant funding to Advanced Plasma Power for their 2.7 MW_{SNG} plant. The upcoming Future Fuels for Flight and Freight Competition (F4C), which is also funded by DfT, could also offer similar opportunities for grant funding for bioSNG technologies, although the F4C is more targeted at jet and diesel replacements.[65] In addition, the ETI has provided funding to SynTech Bioenergy for construction of their demonstration-scale gasification plant.

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[55] SuperGEN Bioenergy Hub (n.d.) Gasification integration, http://www.supergen-bioenergy.net/research-projects/gasification-integration/

[56] Bioenergy Research at Newcastle University (2016) http://www.supergen-bioenergy.net/media/eps/supergen/Bioenergy-at-Newcastle.pdf

[57] Energy and CO_2 (2017) http://www.ucl.ac.uk/chemeng/research/energy

[58] Morrin, S., Lettieri, P., Chapman, C., Taylor, R. (2013) Fluid bed gasification – Plasma converter process generating energy from solid waste: Experimental assessment of sulphur species, Waste Management, 34, 28-35, http://discovery.ucl.ac.uk/1396516/

[59] Supergen Bioenergy Hub (n.d.) http://www.supergen-bioenergy.net/

[60] Combustion and Engineering Gasification (n.d.) http://www.combgen.gla.ac.uk/

[61] Innovate UK (2016) https://www.gov.uk/government/publications/innovate-uk-open-funding-competition/innovate-uk-open-funding-competition-brief

[62] Innovate UK (2017) Innovate UK funded projects since 2004, Available from: https://www.gov.uk/government/publications/innovate-uk-funded-projects, Data based on filter by grant year (2016/2017 and 2017/2018) and description 'gasif' or 'SNG' in public description.

[63] Network Innovation Competition (n.d.) http://www2.nationalgrid.com/UK/Our-company/Innovation/NIC/

[64] Gas Network Innovation Allowance (2017) https://www.ofgem.gov.uk/network-regulation-riio-model/network-innovation/gas-network-innovation-allowance

[65] Future Fuels for Flight and Freight Competition (F4C) (2017) http://ee.ricardo.com/en/transport/case-studies/f4c

2.2 Innovation activities and their impacts

In this section, potential innovation activities suggested by interviewees and the literature are discussed, and where possible quantified.

Among interviewees and literature reviewed, there was a considerable emphasis on the need for increased deployment of bioSNG technologies in order to bring down costs and accelerate further uptake. It was particularly noticeable that technology developers emphasised the importance of further deployment of the technology, whilst academics tended to focus more on technology innovation needs. In the section below, we outline the innovations identified by interviewees and in the literature that could reduce costs, improve efficiency or sustainability of bioSNG production, grouped together under sub-headings for ease of navigation. Where there was disagreement between interviewees on the innovations required we have highlighted these. Note that there is some overlap in benefits from these innovations: for example, improvements in gas clean-up could reduce the benefit that can be obtained by more robust methanation catalysts, as both of these innovations address the problem of methanation catalyst poisoning.

2.2.1 Construction of multiple plants

The construction of more gasification plants could bring multiple benefits, independently of the benefits that could be gained through scale-up. One interviewee emphasised that the benefits from the construction of multiple plants could be gained even though the construction of gasification plants for different applications: for example construction of gasification plants for liquid biofuel production would create benefits for bioSNG production. The main benefits from the construction of multiple gasification plants are anticipated to come from:

- Improved operations, as processes are optimised to operate at higher reliability and efficiency, which lowers costs.
- Two UK-based interviewees emphasised the need for greater engineering, procurement and construction (EPC) experience in gasification to bring down costs. A lack of knowledge or experience with the construction of gasification plants means that EPC contractors perceive these projects as risky, and consequently charge more for project construction. One interviewee who had been involved in project development estimated that EPC costs currently add 40% on top of plant capex, compared with the 15-20% commonly charged for established technologies. Therefore additional EPC experience with gasification technologies could significantly reduce EPC costs, and hence overall cost of bioSNG production.
- Construction of more bioSNG plants and proven reliable operation would reduce the perceived riskiness of the technology to developers, meaning reduced hurdle rates (and reduced capital contingencies) would be required for financing future plants.
- Construction of multiple plants would likely result in lower cost of components because of more mature designs, higher utilisation of equipment manufacturing facilities, and a more competitive supply landscape. One UK-based developer stated that suppliers are currently making large mark-ups on equipment (e.g. 30-50% above production costs). With more competition in the market, this could be reduced to ~5% above the true cost of production.
- One interviewee suggested that modularising and mass producing gasification equipment, which would be made possible through increased deployment, could significantly reduce the capital cost of the gasifier. However other interviewees disagreed with this on the grounds that each gasifier would likely be unique in its design (and would be very large, with only 1 or maximum 2 gasifiers installed at each bioSNG plant), so that mass manufacture would be unlikely.

As an example, industry data[66] shows the cost reductions that could be achieved by constructing multiple first-of-a-kind waste gasifiers at scale of 38.3MW_{SNG}. Capex costs will reduce by 15% from £2.82m/MW_{SNG} to £2.40m/MW_{SNG}, opex costs will reduce by 6.1% from £266,000/MW/year to £250,000/MW/year and plant availability will increase from 85% to 90%. These reductions would reduce the levelised cost of bioSNG production from a waste-based gasifier from £55/MWh to £39/MWh (LHV basis).[67]

Construction of multiple gasifiers may result in small improvements in conversion efficiency due to improved operations, which would result in slightly larger overall supply potential of bioSNG and improved sustainability of bioSNG, but these impacts are anticipated to be small.

2.2.2 Plant scale-up

Larger-scale gasification plants will have lower costs through economies of scale. One interviewee suggested that bioSNG plants are only likely to be viable without subsidies at scales above 80 MW_{SNG}. Analysis by APP anticipates an 84 MW_{SNG} commercial-scale plant converting wastes.[68] E.ON previously targeted projects at 200 MW_{SNG} and above. Scales in excess of around 400 MW_{SNG} are not appropriate for waste gasifiers which are likely to be limited by feedstock availability. In addition, use of low bulk-density feedstocks such as Miscanthus bales may limit gasifier scale-up, as above a certain scale transport costs and sustainability implications may outweigh economies of scale from building larger plants.

Construction of larger-scale plants is likely to be realised after further deployment: investors are unlikely to risk the significant amounts of capital for large-scale plants before they can see the technology operating reliably at smaller-scale, and a gradual scale-up is required in order to tackle technology issues at smaller scales to prevent these issues becoming a major challenge in a larger-scale plant.

An industry source estimates the cost reductions that can be achieved by moving from improved (i.e. several identical plants have been constructed) waste gasifiers at scale of 38.3 MW_{SNG} to nth of a kind plants at 76.6 MW. They anticipate that capex costs will reduce by 18% from £2.40m /MW_{SNG} to £1.97m/MW_{SNG}, and opex costs will reduce by 14% from £250,000/MW/year to £215,000/MW/year. These reductions would reduce the levelised cost of bioSNG production from a waste-based gasifier from £39/MWh to £23/MWh (LHV basis).[69]

Similarly for clean gasifiers, on scale-up from 60MW to 200MW there is a 35% reduction in capex and a 36% reduction in opex for each year, and on scale-up from 200MW to 400MW there is a 20% reduction in capex and an 18% reduction in opex.

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[66] Advanced Plasma Power (2016) The Renewable Heat Incentive: A reformed and refocused scheme Response to Consultation, Appendix C levelised cost calculation

[67] Gogreengas (2016) First project progress report, http://gogreengas.com/wp-content/uploads/2015/11/BioSNG-Demonstration-Plant-June-2016-Project-Progress-Report.pdf

[68] Gogreengas (2016) First project progress report, http://gogreengas.com/wp-content/uploads/2015/11/BioSNG-Demonstration-Plant-June-2016-Project-Progress-Report.pdf

[69] Advanced Plasma Power (2016) The Renewable Heat Incentive: A reformed and refocused scheme Response to Consultation, Appendix C levelised cost calculation

It is likely that plant scale-up would allow some improvements in efficiency due to improved thermal integration, but this is captured separately in innovation 2.2.9 Improve plant integration.

2.2.3 Improved feedstock handling

Feedstock handling is a challenging aspect of the bioSNG production process, and one interviewee stated that for good performance and operational reliability, skilled personnel and high quality equipment are required. A gasifier developer stated that for their technology, the screw feed to the gasifier needed to be tuned to each feedstock, meaning that they would likely require specific screw feeders for each type of biomass if they were to use mixed feedstocks.

Improved feedstock handling would improve the reliability of the gasifier, and therefore increase availability of the plant so that more bioSNG can be produced in a given year. In addition, opex costs are likely to be lower if feedstock handling is more reliable. It was not possible to find data quantifying the impact of improved feedstock handling, despite the widespread agreement that it is an important improvement to make.

2.2.4 Feedstock flexibility

The acceptability of different feedstocks depends on the gasifier type, and to a certain extent on the downstream technologies, and so there were widely differing opinions among interviewees on the need for improvements in feedstock flexibility of the gasifier. One developer was confident in the ability of their gasifier to handle RDF while another considered that more work needed to be done in this area. One interviewee stated that the GoBiGas plant needed to be able to use biomass residues instead of just high quality wood chips or pellets, suggesting that further development is required in this area. A gasifier developer suggested that using alternative feedstocks was not inherently difficult – it just required optimisation of the gasification conditions. Some interviewees considered it important to develop one individual gasifier which can take a range of different feedstocks, while others thought that it would be easier to develop a range of gasifier types that can accept different feedstocks.

Despite differing opinions on this topic, it is likely that improved feedstock flexibility will allow a greater range of feedstocks to be able to be processed by gasification, which could increase the supply potential of bioSNG. In addition, widening the range of available feedstocks could enable lower cost or more sustainable feedstocks to be used, and improved feedstock flexibility may enable plants to use more UK-based feedstocks rather than having to import biomass, contributing to improved UK energy security.

Innovation could allow a wider range of wastes to be processed by ‘waste’ gasifiers, and could allow some more challenging feedstocks to be processed by gasifier’s that are targeted towards ‘clean’ streams of biomass. Given that estimated capex and opex of clean gasifiers are currently less than for waste gasifiers, this would likely reduce the cost of bioSNG production. However it should be noted that widening the scope of feedstocks that can be accepted by a ‘clean’ gasifier may also increase the costs associated with bioSNG production by this route. In practice, improved feedstock flexibility could also reduce the need for complex and costly pre-processing.

2.2.5 High-pressure gasification

Interviews suggested that the development of high-pressure gasification could reduce the overall system costs and improve efficiency by reducing the need for energy-intensive gas compression, and through smaller downstream equipment. Entrained flow gasifiers currently routinely operate at high pressures, but generally require a biomass feedstock that has undergone pyrolysis (such as that used in the Bioliq project[70]), or torrefaction (for easier grinding). High-pressure fluidized bed gasifiers are at an early stage of development - a pressurised circulating fluidised bed gasifier for IGCC power generation was developed by Sydkraft and Foster Wheeler Energy International and constructed in Värnamo, Sweden in 1993. Testing with a range of feedstocks was considered successful,[71] but the demonstration was concluded in 2000[72] and a follow-on project to create clean hydrogen-rich synthesis gas (CHRISGAS) for fuel synthesis applications could not raise sufficient funds to rebuild the plant.[73]

Whether high-pressure biomass gasification is as advantageous as high-pressure coal gasification, which usually takes place at much larger scales, is still a topic of research.[74] In a review of gasification technologies, the US DoE[75] suggest that high-pressure gasifiers may not have a significant overall advantage as the higher capital cost of pressure vessels and complexity of feed systems cancels out gains in efficiency from operating at high pressure. Nevertheless, future developments may prove some of the advantages of high-pressure gasification.

2.2.6 Sorption-enhanced gasification

Both literature[76] and interviews suggest that sorption enhanced gasification (also known as absorption enhanced reforming, AER) could improve the efficiency of bioSNG production. Here, a CaO-based CO_2 sorbent is used in the gasifier to remove CO_2 as soon as it is formed, creating a higher concentration of hydrogen in the syngas and lower concentration of tars. Martinez et al (2016) suggest that sorption enhanced indirect gasification can eliminate the need for an intermediate water-gas-shift reaction and downstream CO_2 separation before synthetic fuel production. However, some interviewees considered that this technology could be challenging to develop and may encounter difficulties with thermal management and calcining. Calcium looping gasification (CLG) would help to regenerate the CaO, reducing the cost and environmental impacts of sorption enhanced gasification.[77] The technology was tested at the Güssing plant in 2007/2008, but is not currently being widely developed.[78] Advancements in chemical looping

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[70] High pressure entrained flow gasification (2016) https://www.bioliq.de/english/67.php

[71] Waldheim Consulting (2012) Industrial Biomass Gasification Activities in Sweden 1997-2009 ANNEX 1 to IEA Biomass Agreement Task 33 Country Report Sweden 2012, http://www.ieatask33.org/app/webroot/files/file/country_reports/Sweden1997-2009.pdf

[72] IEA Bioenergy Task 33, Gasification of Biomass and Waste (2015) https://www.energimyndigheten.se/contentassets/cd52a310d29b435789d86f5caeb1d5d1/dokument-utlysning-iea-bioenergy/task-33-final-prolongation-proposal-for-new-triennium-2016-2018.pdf

[73] CHRISGAS Report Summary (2012) http://cordis.europa.eu/result/rcn/47384_en.html

[74] Newalkar (2015) High pressure pyrolysis and gasification of biomass, PhD dissertation, Georgia Institute of Technology, https://smartech.gatech.edu/handle/1853/53917

[75] United States. Department of Energy. Office of Energy Efficiency and Renewable Energy (1997) Renewable Energy Technology Characterizations - December 1997 - Gasification-based Biomass, https://www1.eere.energy.gov/ba/pba/pdfs/bio_gasification.pdf

[76] Martinez, I., Romano, M.C. (2016) Flexible sorption enhanced gasification (SEG) of biomass for the production of synthetic natural gas (SNG) and liquid biofuels: Process assessment of stand-alone and power-to-gas plant schemes for SNG production, Energy, 113, 615-630, http://www.sciencedirect.com/science/article/pii/S0360544216309501

[77] Sikarwar, V.S., Zhao, M., Clough, P., Yao, J., Zhong, X., Memon, M.Z., Shah, N., Anthony, E.J., Fennell, P.S. (2016) an overview of advances in biomass gasification, Energy Environ. Sci., 2016, 9, 2939-2977, http://pubs.rsc.org/en/content/articlehtml/2016/ee/c6ee00935b#cit100

[78] Koppatz, S., Pfeifer, C., Rauch, R., Hofbauer, H., Marquard-Moellenstedt, T., Specht, M. (2009) H2 rich product gas by steam gasification of biomass with in situ CO2 absorption in a dual fluidized bed system of 8 MW fuel input, Fuel Processing Technology, 90, 914-921, http://www.sciencedirect.com/science/article/pii/S0378382009000708

combustion, for example the 1.7MW$_{th}$ calcium looping pilot plant developed by the FP7 CAOLING project,[79] could also benefit sorption enhanced gasification development.

It was been shown experimentally that tar production is five times lower with sorption enhanced gasification compared with conventional gasification.[80] In a modelling analysis of a complete absorption-enhanced gasification to bioSNG process using an atmospheric dual fluidized bed system at 62MW$_{SNG}$, Martinez et al. estimate that the efficiency of SNG production (on an LHV basis) could reach 62.2%. This is within the range of efficiencies reported in that paper for SNG production based on other modelling studies, and given that the Martinez model produced higher purity SNG than many other studies and exported some electricity, this is a promising result.

Rasmussen (2013)[81] modelled a plant that is pyrolysis followed by indirect gasification, comparing two processes using limestone (CaO) in the gasifier, which is used for CO_2 removal in one of the processes. The results demonstrate that by introducing AER the cold gas efficiency of the plant (net bioSNG output / dry wood input) increases by around 3 percentage points from approximately 80% to 83%. Therefore increased conversion efficiency with AER seems likely, which would improve the sustainability of the process and increase overall bioSNG supply from a given quantity of biomass.

In addition, integrating CO_2 removal in the gasifier could reduce the requirement for downstream CO_2 removal equipment, therefore reducing overall plant capex. Heffels et al. estimate that the capital costs of a 6.76MW$_{SNG}$ plant with AER, using wood chips as a feedstock, would be around £1,698,000/MW$_{SNG}$. They do not carry out a comparison with a similar gasifier without AER.

Heffels et al (2014)[82] examined the environmental and economic impacts of bioSNG production using absorption enhanced gasification. Excluding any credit given for use of waste heat, the GHG emissions intensity for bioSNG produced using this method was calculated to be around 23.6gCO_2eq./MJ$_{SNG}$. However, no comparison is given with bioSNG produced without AER.

2.2.7 Develop more efficient hot gas clean-up

The extent of gas clean-up required for bioSNG production depends on a number of factors – the level of contaminants in the feedstock, the type of gasifier used, and the robustness of the downstream methanation catalyst. Therefore there was some disagreement between interviewees on the level of improvement or innovation

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[79] European Commission Cordis (2014) CAOLING Report summary, http://cordis.europa.eu/result/rcn/142991_en.html (Accessed 24th July 2017)

[80] Soukup, G., Pfeifer, C., Kreuzeder, A., Hofbauer, H. (2009) In Situ CO2 Capture in a Dual Fluidized Bed Biomass Steam Gasifier – Bed Material and Fuel Variation, Chem. Eng. Technol, 32 (3) 348-358 http://onlinelibrary.wiley.com/doi/10.1002/ceat.200800559/abstract;jsessionid=24A1A258720905013275990EB44E36E5.f02t03?systemMessage=Wiley+Online+Library+%27Journal+Subscribe+%2F+Renew%27+page+will+be+down+on+Wednesday+05th+July+starting+at+08.00+EDT+%2F+13.00+BST+%2F+17.30+IST+for+up+to+75+minutes+due+to+essential+maintenance.

[81] Rasmussen, N.B.K. (2013) Bio-SNG and RE-gases Detailed analysis of bio-SNG technologies and other RE-gases ForskNG 10689, Sub-section: "Process analysis of gasification technologies", *www.dgc.eu/sites/default/files/filarkiv/documents/R1308_BioSNG_REgases.pdf*

[82] Heffels, T., McKenna, R., Richtner, W. (2014) An ecological and economic assessment of absorption-enhanced reforming (AER) biomass gasification, Energy Conversion and Management (77) 535-544

required in gas clean-up technologies, with some claiming that this challenge had largely been solved, and some stating that it was a key area requiring improvement.

Tar reduction is still the key consideration, and whilst mechanical filtering and oil/water scrubbers (e.g. OLGA) are proven methods to reduce tars (for example the GoBiGas Phase 1 plant uses an oil scrubber to remove tars), these require syngas cooling before tar removal, producing a large amount of heat that can only be partially recovered. Keeping the syngas at higher temperatures during clean-up reduces energy losses in the plant, but more work is required on scaling up and improving the efficiency of thermal cracking, catalytic cracking and plasma cracking methods. Whilst there are bioSNG projects which will be using hot gas clean-up technologies, including APP's demo plant in the UK, improvements could be made in order to reduce the energy required for this stage, therefore further improving the efficiency, and reducing the cost and GHG emissions associated with gas clean-up. Reducing the number of gas clean-up steps would also be advantageous, but is likely to be challenging.

Asadullah (2014) carried out a comparison of cold gas clean up with hot gas clean-up technology, considering both thermal and catalytic tar cracking. Although he was not able to quantify the impacts of improved hot gas clean-up technology, he highlighted that hot gas clean-up eliminated both the gas cooling step for physical filtration and the reheating step for downstream applications.[83]

2.2.8 More robust methanation catalysts

The main methanation technologies in use by bioSNG plants today, including those developed by Air Liquide, Haldor Topsoe, Clariant and Foster Wheeler, Johnson Matthey and Linde, are fixed-bed methanation technology involving a cascade of between 1 and 5 reactors, with 5 being commonly used.[84]

Ronsch (2016)[85] suggests that key improvements to methanation catalysts are required in terms of their thermal stability and resistance to sulphur poisoning. However other interviewees did not identify methanation as a key challenge in bioSNG production. Amec Foster Wheeler's VESTA technology has already been optimised to simplify the methanation train to be more appropriate to smaller bioSNG plant scales, using once-through catalysts and low alloy steel walls that can handle a variety of syngas compositions, instead of needing more expensive recycle loops and refractory linings.

Improving methanation catalysts could increase the efficiency of methane production, also reducing the GHG emissions of the overall process. More efficient methane production reduces the cost per tonne of methane, and a more robust catalyst reduces opex costs and improves plant availability. If catalysts were developed to be more

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[83] Asadullah, M. (2014) Biomass gasification gas cleaning for downstream applications: A comparative critical review, Renewable and Sustainable Energy Reviews (40) 118-132, http://www.sciencedirect.com/science/article/pii/S136403211400584X?via%3Dihub#s0010

[84] Rönsch, S., Schneidera, J., Matthischkea, S., Schlütera, M., Götzb, M., Lefebvrec, J., Prabhakaranb, P.,Bajohrc, S., (2016) Review on methanation – From fundamentals to current projects, Fuel, 166, 276-296, http://www.sciencedirect.com/science/article/pii/S0016236115011254

[85] Rönsch, S., Schneidera, J., Matthischkea, S., Schlütera, M., Götzb, M., Lefebvrec, J., Prabhakaranb, P.,Bajohrc, S., (2016) Review on methanation – From fundamentals to current projects, Fuel, 166, 276-296, http://www.sciencedirect.com/science/article/pii/S0016236115011254

robust to thermal degradation, then the methanation reactor design (which can be very complex in current large-scale coal SNG facilities[86]) could be simplified, further reducing capex costs.

There is significant ongoing research into improving methanation catalysts (e.g. Hogskolan, 2015[87]), and authors such as Gao (2015)[88] suggest the developments that are required to improve SNG production, but there is not sufficient research quantifying the impact of these improvements on the overall bioSNG production.

2.2.9 Improve plant integration

Two interviewees developing gasification technology in the UK identified the thermal integration of the plant as a key challenge. One emphasised that whilst the overall bioSNG production process is exothermic, careful process design and optimisation is required in order to efficiently use the heat generated, and waste heat can even be used for cogeneration of electricity. Achieving efficient thermal integration is quite specific to each plant, so while some project developers have put considerable time and effort into optimising this, other developers are likely to still require significant improvements in this area. Whilst the technology components involved are well known, the changes in control systems and operating parameters involved with scaling up and including new innovations (as discussed above, particularly hot gas clean-up) can have significant impacts on the thermal integration choices made.

Ahmad et al (2011)[89] carried out a modelling exercise to investigate the impact of heat integration in a hydrogen gasification plant, which indicates the order of magnitude of changes anticipated in a bioSNG plant, although the methanation process is omitted. They propose that adding three heat exchangers to the plant saves approximately 72% of the heat energy required by the plant, compared to a process without these, which would improve overall plant conversion efficiency, reducing costs and GHG emissions. Nevertheless, it would be standard engineering practice to include heat integration in a commercial bioSNG plant, so gains from improved thermal integration are likely to be much smaller in magnitude.

Increased energy efficiency from the integration of different conversion technologies is investigated by Heyne (2013), along with the integration of the bioSNG plant with a biomass CHP steam turbine enabling cascading use of high-temperature process heat. Feedstock drying using internal process heat recovery is important for increasing the process energy efficiency, and integration of a bioSNG plant with an existing biomass-fired CHP plant may lead to favourable overall energy system performance compared to stand-alone plants (resulting in lower GHG emissions), although decreases the process energy efficiency.[90]

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[86] GoGreenGas (2017) BioSNG demonstration plant summary of technical results

[87] Högskolan, K.T. (2015) FT and methanation catalysts new formulations and their properties, Fuel from Waste Project, *www.fuelfromwaste.eu/download/D4.2.pdf*

[88] Gao, J., Liu, Q., Gu, F., Liu, B., Zhong, Z., Su, F. (2015) Recent advances in methanation catalysts for the production of synthetic natural gas, RSC Advances (5) 22759, DOI: 10.1039/c4ra16114a

[89] Ahmad, M.M., Aziz, M.F., Inayat, A., Yusup, S. (2011) heat integration study of biomass gasification plant for hydrogen production, Journal of Applied Sciences, 11 (21) 3600-3606

[90] Heyne, S., Thunman, H., Seemann, M., Harvey, S. (2013) Bio-SNG Production via Gasification – Process Integration Aspects for Improving Process Performance, Conference paper, DOI: 10.5071/21stEUBCE2013-3DP.1.3

The benefit to be gained from heat integration of bioSNG plants is very specific to each particular plant, but in all cases where there are innovations in plant heat integration a reduction in the overall energy use of the bioSNG plant is anticipated to reduce both the opex cost and GHG emissions.

2.2.10 Reduce plant complexity

Haro et al. (2016)[91] investigated improvements that could be made to the GoBiGas Phase 2 plant, and concluded that the reduction of process equipment and the combination of some units into combined processes could reduce the capital cost of the plant by 29% and increase efficiency of biomass to SNG conversion (on HHV basis) by 6.3 percentage points. Interviewees also identified a reduction in plant complexity as important to achieving cost reductions.

The work of Haro et al. investigated the impact of several key modifications to increase the process intensity of the GoBiGas Phase 2 plant, planned at $100MW_{SNG}$, significantly reducing the complexity of the original design. They found that the biomass to SNG efficiency (HHV value basis) increases from 64.8% to 71.1%, although this is likely to be due to the process modifications rather than simply the reduction in complexity. The main impact of reducing plant complexity is anticipated to be in reducing plant capex costs, which in the modelling of Haro et al. decreases by 29% from around £660,000/MW to £470,000/MW (converted from euros).

A reduction in plant capex costs of 29% could be applied to the capex of a clean biomass gasifier, but it should be noted that the benefits from reducing plant complexity are highly specific to the starting configuration of the particular gasifier.

2.2.11 Couple BioSNG with renewable hydrogen

Injecting additional renewable hydrogen into the methanation reactor could increase the yield of bioSNG (and reduce the need for water-gas shift reactions), as well as potentially using the plant gas storage buffers or the gas grid as a storage mechanism for excess or very low price renewable electricity if the hydrogen is produced via electrolysis. The oxygen produced as a by-product in electrolysis could also be used in the gasification unit, potentially reducing the requirements for separate oxygen production. This was identified by several interviewees as a possible innovation in the medium to long term. Interviewees were positive about the economics and technical ease of doing this, but investigation of this has been largely theoretical to-date, such as Hannula (2016).[92]

Hannula estimates that enhancement of bioSNG yields with external hydrogen supply could result in a 3.1-fold increase in methane output compared to the reference plant configuration, with yield increasing by 207% from 226kg per oven dried tonne (odt) of biomass to $694kg/odt_{biomass}$ in the case of an oxygen gasifier and by 120% from $215kg/odt_{biomass}$ to $473\ kg/odt_{biomass}$ in the case of a steam gasifier. This innovation significantly increases the supply potential for bioSNG, but with likely higher opex costs.

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[91] Haro, P., Johnsson, F., Thunman, H. (2016) Improved syngas processing for enhanced Bio-SNG production: A techno-economic assessment, Energy, 101, 380-389, http://www.sciencedirect.com/science/article/pii/S0360544216300809

[92] Hannula, I. (2016) Hydrogen enhancement potential of synthetic biofuels manufacture in the European context: A techno-economic assessment, Energy, 104, 199-212, http://www.sciencedirect.com/science/article/pii/S0360544216303668

Hannula (2016) also examines the total capital investment and levelised cost of fuel (LCOF) production, calculating that to achieve the same LCOF with hydrogen-enhanced bioSNG production compared to conventional bioSNG production, a hydrogen cost of between 2.2 and 2.4 €/kg (18.7-19.7€/GJ) is required. If this hydrogen is produced from electrolysis (off-site) the break-even electricity price, accounting for electrolyser capex, opex and efficiency, is between 25.1€/MWh and 27.7€/MWh. Hydrogen / electricity costs below this would further reduce the levelised cost of the fuel to below that of conventional bioSNG production. Total capital investment, excluding equipment needed for external hydrogen generation, is anticipated to increase by around 4% when bioSNG is coupled with hydrogen input, compared to stand-alone bioSNG. Lower capital costs of CO_2 removal equipment and the air separation unit are outweighed by the higher cost of larger methanation equipment.

Hannula (2017)[93] examines the GHG implications of this innovation and concludes that with hydrogen production from 100% renewable energy, the GHG emissions of the final bioSNG would be between 7 and 9 $gCO_{2eq.}$/MJ. This is significantly lower than the GHG emissions of bioSNG produced solely from biomass gasification, but whether these low emissions factors can be realised in practice depends on the production method of the hydrogen.

2.2.12 Alternative air separation technologies

Oxygen-blown gasifiers require a high-purity oxygen stream to be generated for injection into the gasifier, which is separated from air. Of the three main types of air separation units (cryogenic units, adsorption units such as PSA, and membrane units), cryogenic air separation units are most commonly used as they provide the highest purity oxygen,[94] however they have a very high electricity demand. It has been suggested that development of improved air separation units could significantly reduce the energy demand and hence the cost of oxygen production.[95]

One novel membrane separation technology is projected to reduce the cost (including capital, operating and energy use) from around $35.8/ton O_2 (~£26/tonne) for cryogenic air separation to around $19.97/ton O_2.[96] (~£14/tonne). This represents a cost of oxygen that is 45% lower than that provided by a cryogenic ASU.

Air Products is developing a membrane separation technology called Ion Transport Membranes (ITM). Oxygen produced via this method could have a 25% to 35% cost reduction compared with the cost of conventional oxygen production by the cryogenic method.[97] This is based on a 35% capital cost reduction and 35-60% less compression energy use compared to cryogenic air separation.[98]Air Products compare their ITM system with traditional ASU in power plants with carbon capture, and see an efficiency advantage of between 1.8 and 7.6 percentage points and a

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[93] Hannula, I., Koponen, K. (2017) GHG emission balances and prospects of hydrogen enhanced synthetic biofuels from solid biomass in the European context, Applied Energy (200) 106-118

[94] UIG (n.d.) Air Separation Process Technology and Supply System Optimization Overview http://www.uigi.com/compair.html

[95] IEA Greenhouse Gas R&D Programme (2007) Improved Oxygen Production Technologies, http://bit.ly/2rMWDCM

[96] https://www.netl.doe.gov/File%20Library/Events/2015/gas-ccbtl-proceedings/Gasification-Workshop-2015-final-Yu.pdf

[97] Air Products (2011) Enabling clean coal power generation: ITM oxygen technology, http://www.airproducts.com.tw/~/media/files/pdf/industries/enabling-clean-coal-power-generation-280-11-005-glb.pdf

[98] Air Products (2007) http://bit.ly/2sJndIZ

unit capital cost advantage of between 12% and 34%.[99] Based on this assessment, increased efficiency of biohydrogen production with ITM compared to ASU would be anticipated, but with little specific research in this area it is not possible to quantify this benefit.

An alternative new chemical adsorbent-based air separation process being developed by TDA Research Inc. is estimated to reduce the cost of oxygen from \$32/ton O_2 (~£21/tonne) when large-scale cryogenic separation units are integrated in an IGCC plant, to \$17/ton O_2 (~£11/tonne) for the new system integrated in an IGCC plant.[100] This represents a cost of O_2 that is 47% lower than that provided by a cryogenic ASU. Other innovative oxygen-supply solutions are being developed, although their early stage of development makes their impact difficult to quantify.[101]

Based on the technology-specific cost reductions given above, and the cost breakdown for a waste bioSNG plant[102] a 35% reduction in the capital cost of the oxygen production unit would give a reduction in the total capex of the plant of 2.5% from £1.97m/MW_{SNG} to £1.92m /MW_{SNG}. A 47% reduction in the power consumption of the ASU, taken as an average of the technology-specific data given above, would result in a 6% reduction in plant opex from £215,000/MW/year to £203,000/MW/year. This would also result in 17% reduction in the net power required by the plant, which could significantly reduce GHG emissions.

There are other novel air separation technologies that may be less applicable to gasification systems, for example, research on new classes of high temperature ceramic oxygen transport membranes (OTMs) for oxy-fuel combustion power plants by Imperial College, Shell, Linde and others[103] suggests that whilst reductions in parasitic power demands could be possible compared to cryogenic oxygen separation, the overall system benefits could be limited due to low scaling factors in membrane design, membrane stability & permeation issues with the recycled flue gas, and the high operating temperatures required. This GREEN-CC project has already identified that Integrated Gasification Combined Cycle (IGCC) power plants using ceramic OTMs would be "inefficient due to additional technology required independent of membrane performance and cost"[104]. It therefore appears unlikely that these high temperature ceramic OTMs would be applicable to bioSNG or biohydrogen applications.

2.2.13 Summary of innovation impacts

Table 2 gives a summary of the potential impacts of the innovation activities discussed in this section on the cost, supply potential and sustainability of bioSNG supply.

Overall, the largest and most near term potential for cost reduction across all bioSNG configurations and feedstock types is expected to result from construction of multiple plants, and from an increase in plant scale. These reductions arise primarily from economies of scale in the major capital cost components (gasifier, methanation) and

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[99] Repasky, J., McCarthy, D., Armstrong, P., Carolan, M. (2014) ITM Technology for Carbon Capture on Natural Gas and Hybrid Power Systems, https://www.usea.org/sites/default/files/event-/140417_140422_USEA%20NG%20CCS_WashDC_Repasky%20-no%20backup.pptx

[100] NETL (n.d.) Cost-effective air separation systems, https://www.netl.doe.gov/research/coal/energy-systems/gasification/project-information/proj?k=FE0024060

[101] NETL (n.d.) https://www.netl.doe.gov/research/coal/energy-systems/gasification/feed-systems

[102] Progressive Energy and APP (2016) RHI consultation submission

[103] Green-CC (2015) Green-CC, Available from: www.green-cc.eu

[104] Green-CC Report Summary (n.d.), “Periodic Report Summary 2 - GREEN-CC (Graded Membranes for Energy Efficient New Generation Carbon Capture Process)”, Available from: http://cordis.europa.eu/result/rcn/195587_en.html

labour, and reduction of real and perceived risk leading to reduction in EPC and construction management costs. There are also likely to be improvements both to gross efficiency (bioSNG output per unit feedstock input) as well as the net efficiency when energy use is taken into account, as improvements are made to process integration. Proving **reliable production at scale** is considered a priority for the industry, required before improvements to performance can be prioritised.

All of the other innovation activities listed could have benefits for the cost, supply potential and sustainability of bioSNG production, but it is not possible or desirable to prioritise between them at this time, because:

- The impact of each activity will vary considerably between bioSNG technologies: for example, air separation technologies only benefit oxygen-blown gasifiers. Those that are of most benefit to the UK will depend on which technologies are deployed in the UK, which in the near term depends on the priorities of technology developers and in the longer term depends which are shown to have most reliable and lowest cost operation at scale
- Some technology developers claim that they have already made progress in these areas such that innovation is not needed, although this is impossible to prove without successful demonstration at scale, and may not apply to all feedstock types
- The impact of many of the activities has not been quantified, or has not been quantified for the technologies that are in or closest to commercial deployment today

As a result, the barriers and gaps discussed below cover all of these innovation activities, with actions proposed to take account of the uncertainties described above.

Table 2: Summary of impacts of bioSNG innovations identified. Shading refers to impact of innovation in each category. Dark blue = strong impact, light blue = some impact, white = low impact

	Cost	Supply	Sustainability	Other
Construction of multiple plants	Waste gasifier capex falls 15%, opex reduces by 6% and plant availability increases from 85% to 90%.	Small efficiency improvement	Small efficiency improvement	
Plant scale up	Waste gasifier capex falls 18%, opex reduces 14%	Small efficiency improvement	Small efficiency improvement	
Improved feedstock handling	Improved reliability			Lower risk
Feedstock flexibility	Access lower-cost feedstocks	Access to a greater range of feedstocks	Access more sustainable feedstocks	Increased use of UK feedstocks
High-pressure gasification	Cost impacts uncertain		May increase net efficiency through decreased energy consumption	

Sorption-enhanced gasification	Capex costs may reduce	Increased conversion efficiency	Increased conversion efficiency	
Develop more efficient hot gas clean-up	Increased efficiency and reliability	Increased conversion efficiency	Increased net efficiency through decreased energy consumption	
More robust methanation catalysts	Improved reliability increases availability			Lower technology risk
Improve plant integration	Reduce opex costs		Improved net efficiency through decreased energy consumption	
Reduce plant complexity	Potential for 29% capex reduction			Faster construction
Couple BioSNG with renewable hydrogen	Capex costs likely to increase, opex may decrease	Yield of bioSNG increases by 120% - 207%		Improved integration with energy system
Alternative air separation technologies	For oxygen blown gasifiers, capex falls 2.5%, opex falls 6%.		For oxygen blown gasifiers, 17% reduction in net power input	

2.3 Barriers and gaps

The barriers and gaps to innovation in bioSNG technology in the UK are outlined in this section. We focus initially on those barriers or gaps which hinder the development of the industry as a whole, and then outline particular barriers which hinder the realisation of particular innovations outlined in section 3.2.

2.3.1 **High capital cost and technology risk**

Scaling up gasification plants requires significant capital investments, and because the technology is largely untested at larger scales, there is technology risk in scale-up. As a result, it can be hard for developers to access the required capital. Investors are particularly unwilling to take on the risk of scale-up coupled with the risk of new technology or components, meaning that bioSNG with the added risk of CO_2 capture and storage is likely to be particularly difficult to fund.

Capex costs for commercial-scale plants are anticipated to be in the order of hundreds of millions of pounds. There is the perception that while UK funding for pilot and development-scale projects is available as outlined above there is insufficient support for the capex costs of first commercial-scale projects – either in terms of financial support or loan guarantees. As a result of the very broad definitions in the UK Infrastructure Act, it is not clear whether the UK's infrastructure loan guarantee programme would support an individual bioSNG project, and it is uncertain whether following Brexit, EU funding sources such as the New Entrants Reserve (NER300, NER 400) and the BioBased Industries Joint Undertaking (BBI) will be available to UK actors.

2.3.2 Competitiveness with fossil natural gas

Currently the cost of producing bioSNG is substantially higher than the cost of producing natural gas[105]. A review by the Sustainable Gas Institute in 2017 estimated that the cost of producing bioSNG is between 3 and 6p/kWh, compared with an average EU wholesale gas price of approximately 1.5 p/kWh in 2015.[106] This implies that support will be needed whilst the technology comes down the cost curve to approach the cost of natural gas, however weak market-based support policies can be a strong barrier to the development of additional plants and low natural gas prices can magnify this problem.

In the UK the Renewable Heat Incentive (RHI) would provide support for bioSNG injection into the gas grid. The current grandfathering arrangements and the pre-approval process that is being introduced mean that this provides a relatively high level of certainty to investors in bioSNG. Nevertheless interviewees from outside the UK highlighted the inadequacy of bioSNG production support in many regions. In particular, treating bioSNG from gasification under the same subsidy regime as biomethane from AD can be a barrier because of the earlier technical maturity of gasification technology, and the different scales at which these processes typically operate. Lack of policy support outside the UK will mean less interest in the technology, slower global deployment and slower cost.

2.3.1 Investment climate not favourable for development and deployment of negative emissions technologies

Current market conditions do not make it commercially attractive for industry to invest in CO_2 capture technologies and infrastructure, which represents a barrier to the development of bioSNG + CCS. Under policies such as the RHI, emissions reductions thresholds provide some incentive to producers to capture CO_2, to achieve the required CO_2 emission reductions to gain support. However, there is no financial incentive for producers to increase the amount of CO_2 captured above that required to meet the thresholds, so the current incentive framework does not act as a driver towards developing negative emissions technology.

2.3.2 Poor coordination of support for gasification

Gasification technology is cross-sectoral in its application: gasification can be used simply as a waste-disposal technique, to provide heat and power, to provide fuels such as bioSNG for heating, or to provide fuels such as Fischer-Tropsch diesel for transportation. Developments in gasification for each of these applications provide learnings that can benefit gasification across all applications, for example in terms of building up EPC experience and de-risking the project. However, there are a limited number of gasifier developers and a limited amount of government support that can be offered to this technology. The separation of policy support between transport, heat, power and waste, without an overall strategy for gasification development, could therefore be a barrier to the most effective development of the industry as a whole.

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[105] Progressive Energy (2016) The Renewable Heat Incentive: A reformed and refocused scheme Response to Consultation

[106] Sustainable Gas Institute (2017) White Paper 3 -A Greener Gas Grid: What Are The Options? Available from: http://www.sustainablegasinstitute.org/a-greener-gas-grid/

2.3.3 Feedstock cost and supply chain

Several interviewees identified the high cost of biomass (and the variability in its cost) as a key barrier to the development of bioSNG technology. Figure 1 illustrates the strong dependency of production cost of bioSNG on biomass prices for a wood-based gasifier – two different process configurations are shown.

Figure 1 Dependency of bioSNG production cost on biomass price for a 100MW$_{\text{bioSNG}}$ plant. (figure from Haro, 2016)[107]

It should be noted that for gasifiers processing waste, the cost of the biomass is not a barrier, indeed there is currently often a gate fee associated with receiving the waste that forms an important part of project revenues.

For many feedstocks, securing an adequate and reliable feedstock supply can be a barrier. In the UK, straw and forest residue supply chains are relatively immature, making it challenging to secure supplies of these feedstocks, particularly in the form of long-term supply contracts. For example, a regional assessment of biomass supply chains in the South of England cited lack of local demand, lack of space for storage and processing, and the high cost of specialist equipment as key barriers to the development of the local wood fuel supply chain.[108]

The supply chain for MSW is well-established, but a key barrier to securing supplies of this feedstock is that it is often locked up in existing long-term (up to 25 years) contracts. In addition, the waste hierarchy states that reuse and recycling should occur in preference to energy recovery of waste, therefore improvements in recycling technology or a fall in waste arisings may reduce the amount of waste available to bioSNG production. The current waste supply chain makes accessing construction and demolition waste challenging, which could be a barrier to innovations in improved feedstock flexibility of gasifiers in using wastes other than MSW or RDF. Lack of standardisation of feedstocks can be a barrier to use of feedstocks such as commercial and industrial waste, which

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[107] Haro, P., Johnsson, F., Thunman, H. (2016) Improved syngas processing for enhanced Bio-SNG production: A techno-economic assessment, Energy, 101, 380-389, http://www.sciencedirect.com/science/article/pii/S0360544216300809

[108] Biomass supply chains in South Hampshire (2009) *www.push.gov.uk/biomass_supply_chains_in_south_hampshire.pdf*

are not currently widely used in the energy sector. Securing long-term and reliable supply contracts for these feedstocks can therefore be a key challenge.

2.3.4 Development of enabling industries

In the UK, CO_2 transport and storage infrastructure is at an early stage of development, presenting a barrier to the scale-up of bioSNG + CCS. The slow progress being made in the UK to develop CO_2 transport and storage infrastructure is not providing the signal to project developers that CCS will be a viable option for their technology in the medium-term, meaning that technologies might not be optimised for CO_2 capture at the point that widespread storage becomes available. There are few users in the UK of industrial CO_2, and this market is becoming increasingly saturated. Therefore CCU is not a large-scale solution to the challenge of utilising captured CO_2.

The global gasifier market is currently relatively small, which presents barriers to development of bioSNG in the UK as there are relatively few manufacturers of equipment, and risk of delays in manufacturing and importing components. In addition, the current small size of the gasification industry limits the development of some of the innovations outlined above because the large investment required to bring these research concepts to commercialisation is not worth it if the gasifier market is very small. For example, developing high-pressure gasification would require a large development operation: pilot plants, demonstration plants, and first commercial plants, which are quite different to those seen today. It would also require working with component manufacturers to ensure that the components could work at pressure. It should be noted that this barrier is not specific to the UK – even Scandinavian countries, where gasification technology is more widespread, have failed to commercialise high-pressure gasification. A key barrier therefore to realising this innovation is that a large existing global gasification industry is required to make the development effort worthwhile.

2.3.5 Bringing research from laboratory to demonstration

Many of the innovation activities identified above, including high pressure gasification, sorption enhanced gasification, alternative hot gas clean up and air separation technologies and improved methanation catalysts require further development at lab/pilot scale followed by successful scale up to demonstration scale. UK-based researchers emphasised the difficulty in scaling up in this way. This may be because they do not have research and testing facilities at the required scale, or because legislation or logistics can limit the operating hours of test facilities in universities. A UK-based researcher also highlighted that there is a gap in terms of the interaction between industry and academia in the UK, which made it more difficult to bring research to commercialisation.

2.4 Potential options to mitigate innovation barriers

2.4.1 Coordinated support for first commercial plants

BioSNG in the UK is currently moving to demonstration scale for waste biomass, with the next step being an increase to commercial scale. This demonstration plant is under construction by Advanced Plasma Power, and will process 10,000 tonnes/year of waste producing 2.7MW of SNG. The project received an £11M grant from the Department for Transport, £5.4M from Ofgem's Network Innovation Competition and £600,000 from National

Grid.[109]. BioSNG plants using clean biomass have been constructed and operated at demonstration scale outside the UK, (e.g. GoBiGas, see section 2.1.2), and therefore UK demonstration scale plants may not be needed for some technologies, where a UK commercial scale plant could be built based on non-UK experience. However, given that the innovations set out above will require demonstration before a move to commercial scale, continued availability of UK funding for demonstration-scale plants, such as that outlined above, could be important in supporting new technologies.

Actions to support the first commercial scale plants could help overcome technology risks and attract investment. This could be achieved for example through capex grants or regional industrial development schemes, loans, loan guarantees, or other financial de-risking mechanisms.

The capex costs will be significantly larger for first commercial plants compared to the demonstration-scale plants funded to-date in the UK. For example in 2009 the Swedish Energy Agency invested SEK220M (around £18M) in the GoBiGas project[110] to construct the Phase one 20$\mathrm{MW_{SNG}}$ gasifier, and developers had agreed €59M (around £51M) in NER300 funding for the Phase two 90$\mathrm{MW_{SNG}}$ plant.[111] It is uncertain whether the successor scheme to NER300 funding (NER400) will be available to UK developers after the UK leaves the EU.[112] One option to promote the development of projects at first commercial scale, would be to establish a fund for commercial-scale bioSNG plants, awarding grants of up to £50M. This would provide a significant proportion of the capital costs of a first commercial plant, which are anticipated to be of the order of £100M.[113] It could be focused on innovative technologies where the grant is needed for de-risking first commercial plants, but should require industry to prove that once the technology has been proven at a given scale, subsequent plants could proceed with market-based support only, i.e. without capex support.

Other policies to de-risk commercial-scale plants in order to bring in private investment include regional industrial development schemes, loans and loan guarantees. Such mechanisms have been used in other gasification projects, for example Göteborg Energi, which owns the GoBiGas plant, is owned by Gothenburg City Council; and the Ambigo project is located in the Alkmaar Energy Innovation Park which is a regional initiative to promote energy innovation in the area[114]. Such schemes do have precedent in the UK, for example the UK guarantees scheme, which currently runs to March 2021[115] and has the potential to award up to £40bn in support to projects. Loan guarantee schemes such as this one could be tailored to enable early commercial development of bioSNG or the supporting supply chain, especially if tailored to cater for projects with a significant level of technology risk. Lessons

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[109] Waste Management World (2015) £6m for waste gasification biomethane to grid project in Swindon, https://waste-management-world.com/a/6m-for-waste-gasification-biomethane-to-grid-project-in-swindon, accessed 19th July 2017

[110] Dahl, J. (2015) GobiGas - Bio-Methane from Forest Residues, http://www.forgasning.dk/sites/default/files/sites/default/files/filarkiv/08_Seminar_forgasning_nov15_Dahl.pdf

[111] NER300 (2017) Three further projects withdrawn from NER300, http://www.ner300.com/?m=201705 (accessed 18th July 2017)

[112] Schuman Associates (2017) The NER400 innovation fund – future EU funding for renewable energy, http://www.schumanassociates.com/newsroom/333-the-ner400-innovation-fund-future-eu-funding-for-renewable-energy Accessed 19th June 2017

[113] Advanced Plasma Power (2016) The Renewable Heat Incentive: A reformed and refocused scheme Response to Consultation

[114] Holland (2014) Made in Holland Energy Innovation, https://www.alkmaar.nl/gemeente/webcms/site/files/Brochure%20energieregio%20DEF.pdf

[115] UK guarantees scheme key documents (2015) https://www.gov.uk/government/publications/uk-guarantees-scheme-key-documents (Accessed 19th July 2017)

could be learned from the US DoE loan guarantee programme which is focused towards projects with high technology risk and has supported a significant number of advanced biofuel projects to-date.[116]

2.4.2 Improved market-based support for bioSNG

Currently bioSNG is not cost competitive with fossil natural gas, even with support from the RHI. Competitiveness with natural gas is expected to improve with technology deployment and innovation over the next decade. Market-based support for bioSNG could enable commercial viability of early plants by making market adjustments which enable bioSNG to compete with natural gas to compensate for the premium in production costs, recognising the GHG benefits of bioSNG in the longer term. Actions to improve market conditions for bioSNG are likely to be more effective if they provide certainty over the medium to long term, to reduce risk for larger-scale bioSNG projects which have long lead times for development. A range of policy mechanisms could be used to achieve this aim, including contracts for difference, incentives similar to those currently offered in the RHI, a carbon tax, or a supply obligation.

- Contracts for difference are a mechanism currently used in the electricity sector. If introduced for bioSNG, this type of mechanism could top up the price received by low-carbon fuel producers from an agreed ‘strike price’ to the market level, with negative payments if the market price drops lower than the agreed strike price. However, in this type of mechanism, contracts are awarded by auction to the producer with the lowest strike price. As a result, this mechanism is unlikely to be the most appropriate for supporting bioSNG production at this point in time, as there are very few producers currently operating in the UK (or globally) and they are at a pre-commercial TRL.
- A carbon tax could be used to increase the cost of natural gas, allowing bioSNG to be more competitive. This could be designed to also promote negative carbon emissions.
- Incentives similar to the current RHI for biomethane grid injection. This could be done through modification to the RHI tariff, which would involve relatively small changes to the existing policy, and has been previously supported by the industry. Alternatively a different scheme could be established. Any scheme would need to ensure that bioSNG was incentivised, through recognising the earlier TRL and higher current cost of bioSNG compared with biomethane production from AD. Industry sources propose that a support of 5.87p/kWh for the whole production of a bioSNG plant would provide the support required for a first commercial bioSNG plant.[117] In addition, the scheme would need a long enough time horizon to facilitate the construction of new plants at larger scale which are likely to have long lead times.
- An obligation to supply low carbon gas could incentivise bioSNG alongside other low carbon gas options. This type of mechanism gives a reasonable level of longer term direction to the market. This approach has been used for bioSNG in the transport sector, where the Renewable Transport Fuels Obligation (RTFO) obliges fuel suppliers to supply biofuels. The forthcoming RTFO development fuel sub-target, which gives an additional value to particular supply routes, will incentivise bioSNG for transport.

For all of these mechanisms, the level of support would need to be sufficient to incentivise bioSNG production, rather than biomethane from AD alone. This can be justified by bioSNG’s earlier stage of technology development, larger scale, and larger potential contribution to heat supply. Also, in order to support bioSNG with CO_2 capture, policies will need to address market failures to enable monetisation of negative emissions. This could be done either by introducing a separate rate or obligation for bioSNG with carbon capture which is set at a higher level, or a market payment per tonne of CO_2 captured. Given that investments in CO_2 capture technology are likely to be costly

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[116] US Department of Energy (n.d.) US Department of Energy – Loan Guarantee Program, https://energy.gov/savings/us-department-energy-loan-guarantee-program (Accessed 26th July 2017)

[117] Advanced Plasma Power (2016) The Renewable Heat Incentive: A reformed and refocused scheme Response to Consultation

and involve significant technology risk, and will depend substantially on policy for revenue from the captured CO_2, it is especially important that actions to foster the generation of negative carbon emissions are robust and long-term.

2.4.3 Larger-scale research facilities

The test facilities at Güssing in Austria and ECN in the Netherlands have been instrumental in several key technology developments for gasification, and their important role was emphasised by several interviewees. One researcher emphasised that a test facility such as this, at a scale of a few MW's, where different technologies and new processes could be trialled and developed, would be very advantageous to the UK. This could be justified by the value of exploiting the UK's research strengths in gasification, and the policy interest in gasification based bioenergy routes, for heat and for transport fuels, as well as the potential for bioenergy with CCS (BECCS).

The Gussing gasifier (which was originally $8MW_{\text{biomass input}}$ for CHP) had a total investment cost (in 2001) of €10M and an annual operational cost of 10 to 15% of investment costs.[118] The project was realised by a consortium of academic and industrial partners and received significant EU and national funding. The ECN research gasifier was considerably smaller – $800kW_{\text{biomass input}}$.[119]

A large-scale research facility would help to tackle the difficulty of proving research at larger-scales and high availabilities, which were identified as barriers. It would therefore facilitate several innovations that rely on larger-scale research to move towards commercialisation including improved feedstock handling, feedstock flexibility, sorption-enhanced gasification, the development of more efficient hot gas clean-up and more robust methanation catalysts. The facility should be designed specifically to address the uncertainties identified in the Summary of Innovation impacts above and to address the barriers identified, i.e.

- to allow testing of innovations that could benefit different bioSNG technologies, rather than focusing on one technology and configuration alone
- to allow collaboration between researchers and technology developers, both to validate technology developers claims and to strengthen the link between research and industrial needs
- to allow quantification of the benefits of innovative activities, and comparison between them in order to prioritise future RD&D

In 2011 the Centre for Process Innovation (CPI) and Tata Steel attempted to establish a $350kW_{el}$ demonstration gasifier at the Teesside Technology Centre, but this was not completed due to budget limitations. The complexity of the proposed gasifier, which was designed to operate in a number of different 'modes' including updraft, downdraft and fluidised bed, along with limited engineering and construction experience of the team in gasifiers of this type, led to the project overrunning and ultimately being abandoned. Nevertheless, an open-access demonstration gasifier would not be unfeasible in the UK today. Sufficient funding would be required, and focus should be placed on recruiting experienced team members, which may be more feasible today than in 2011 given the larger number of gasifiers in operation in the UK and Europe. In order to avoid undue complexity in the testing facility, a single gasifier

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[118] Simader, G.R. (2004) Case Study: 2 MWel biomass gasification plant in Güssing (Austria) http://www.opet-chp.net/download/wp3/g%FCssingaustria.pdf

[119] Can der Meijden, C.M., Veringa, H.J., van der Drift, A., Vreugdenhil, B.J. (2008) The 800 kWth allothermal biomass gasifier MILENA, Presented at the 16th European Biomass Conference, 2-6 June 2008, Valencia, Spain , http://www.milenatechnology.com/publications/

technology would need to be agreed between funders and potential users of the facility. Given that all major bioSNG developers currently focus on fluidised bed technologies, this is likely to be an appropriate choice.

Given that there are already large-scale research facilities in operation in Europe and the USA, encouraging and facilitating more cooperation and co-working with these facilities could also help make best use of existing assets. This could take the form of research funding for collaborative projects, and/or cooperation agreements with the institutions which operate these facilities.

2.4.4 R&D funding for bioSNG gasification

Additional research funding could help to accelerate many of the innovations outlined in section 3.2 including the development of alternative air separation technology, high-pressure gasification, sorption-enhanced gasification, more efficient hot gas clean-up and more robust methanation catalysts. Given the uncertainties outlined above, it would be more appropriate to launch funding calls that are open to all of these areas, with a requirement to estimate potential benefits as part of the application, rather than to prioritise between topics at this stage. Linking academic research to funding for demonstration plants (for example by placing a requirement on demonstration-plant funding that there is collaboration with academics to facilitate better data-sharing between industry and academia) could also help to bring these innovations to commercialisation more quickly.

In the UK around 0.5% of the EPSRC research portfolio (around £21 million) is currently in the research theme of bioenergy,[120] with a key focus on thermochemical conversion of biomass to energy vectors within this theme. The strategic connection of bioenergy with CCS and BECCs is highlighted, but currently only two grants operate across bioenergy and CCS. The EPSRC aims to maintain the current level of bioenergy funding as a proportion of its portfolio, and BEIS could aim to encourage increased collaboration across research areas relevant to bioSNG. The Supergen Bioenergy hub could also continue to fund research into bioSNG.

In order to achieve a step-change in research activity in bioSNG technology, the Industrial Strategy Challenge Fund could prioritise the development of technologies for low-carbon heating, either through their inclusion in the Clean and Flexible Energy challenge, or through the introduction of a new challenge focused solely on low-carbon heat provision.[121] The industrial strategy challenge fund tends to focus on broad areas, but specific inclusion of BioSNG technology within the low-carbon heating challenge could increase the chances of it receiving funding amongst competition from other low-carbon heating technologies. This would promote research into bioSNG and other low-carbon heating technologies in the UK, and would help to mitigate the shortfall in research funding that is likely to occur if the UK no longer has access to Horizon2020 grants on leaving the EU.

Finally, collaboration between researchers in different disciplines and between researchers, industry and policy-makers could be facilitated by establishing a network for gasification research and innovation, with a focus on technologies for the production of clean syngas. This should include academics, grid operators, policy-makers and plant developers and should aim to promote collaboration and fund collaborative projects.

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[120] EPSRC (2017) https://www.epsrc.ac.uk/research/ourportfolio/researchareas/bioenergy/

[121] Industrial Strategy Challenge Fund: joint research and innovation, https://www.gov.uk/government/collections/industrial-strategy-challenge-fund-joint-research-and-innovation (Accessed 21st July 2017)

2.4.5 Development of CO_2 transport and storage infrastructure

Infrastructure for CO_2 transport and storage is essential to allow the scale-up of bioSNG with CCS. Given the small-scale of bioSNG plants compared to the likely scale of CO_2 transport and storage infrastructure, and the technology risk already incurred by bioSNG processes, investment in such infrastructure is unlikely to come directly from bioSNG plant developers. Therefore government investment, and coordination of disparate stakeholders, is considered essential to bring carbon capture and storage to reality. Actions to achieve this goal are applicable to the development of CCS infrastructure for both bioSNG and biohydrogen, but as a roadmap for roll-out of CCS infrastructure is not the focus of this report, these actions are not considered in detail here.

- Ongoing policymaker consideration of CCS should consider the role and benefits of biohydrogen and bioSNG with CCS
- Strategic planning of infrastructure for CCS over the next 3 to 5 years should include the role of biohydrogen and bioSNG with CCS
- Review of progress in CCS is required in around 2020 to determine whether it is feasible to progress with bioSNG production plus CCS

2.4.6 Support the development of biomass supply chains

The development of strong biomass supply chains would benefit bioSNG, biohydrogen and other biomass to heat, power and transport fuel technologies. Note that actions to support energy crop development and innovation are provided in section 5.

Awareness raising of locally available biomass resources, including strategies for their sustainable mobilisation and use, could be achieved through the development of regional biomass exploitation plans. Plans could be developed by national governments or regional councils, in consultation with local stakeholders, to assess the biomass resource available in each region, current and potential uses, and what gaps or barriers are in place to mobilising that resource.

Based on this assessment, appropriate investments in infrastructure can be made in order to develop strong biomass supply chains across the UK and for key import sites. Infrastructure investments are likely to be very regionally specific, and might include for example loans for new equipment for harvesting and removing forestry residues or investments in upgrading of port facilities to enable increased biomass import. Some actions may also be policy-based, such as making changes to the way local councils enter into MSW and waste biomass disposal contracts to facilitate use for energy, and research into innovative business models to encourage long-term and reliable biomass supply contracts. [122] In addition, changes to agricultural subsidies which are anticipated with the UK leaving the EU could be implemented to support the use of biomass, particularly residues, for energy.

Finally, it is important for investors to have certainty in the UK's biomass sustainability criteria. This particularly applies to gasifiers using non-waste material because there has been considerable recent debate in the UK over the

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[122] IEEP (2012) MOBILISING CEREAL STRAW IN THE EU TO FEED ADVANCED BIOFUEL PRODUCTION, https://ieep.eu/publications/mobilising-cereal-straw-in-the-eu-to-feed-advanced-biofuel-production

use of wood for energy. A review of biomass sustainability criteria for heating, could help to ensure that they are robust and transparent to at least 2030 (and ideally beyond).

2.5 Indicative timeline

The actions identified above to stimulate innovation and support the development of the bioSNG industry are shown over time to demonstrate their prioritisation and interaction with wider developments in the UK bioenergy or low-carbon heating market (Figure 2). Near-term actions are prioritised either because they facilitate commercialisation and scale up for bioSNG plants today, or because they are likely to require significant time to develop the outcome that will be required in the future such as regional biomass exploitation plans to build up biomass supply chains.

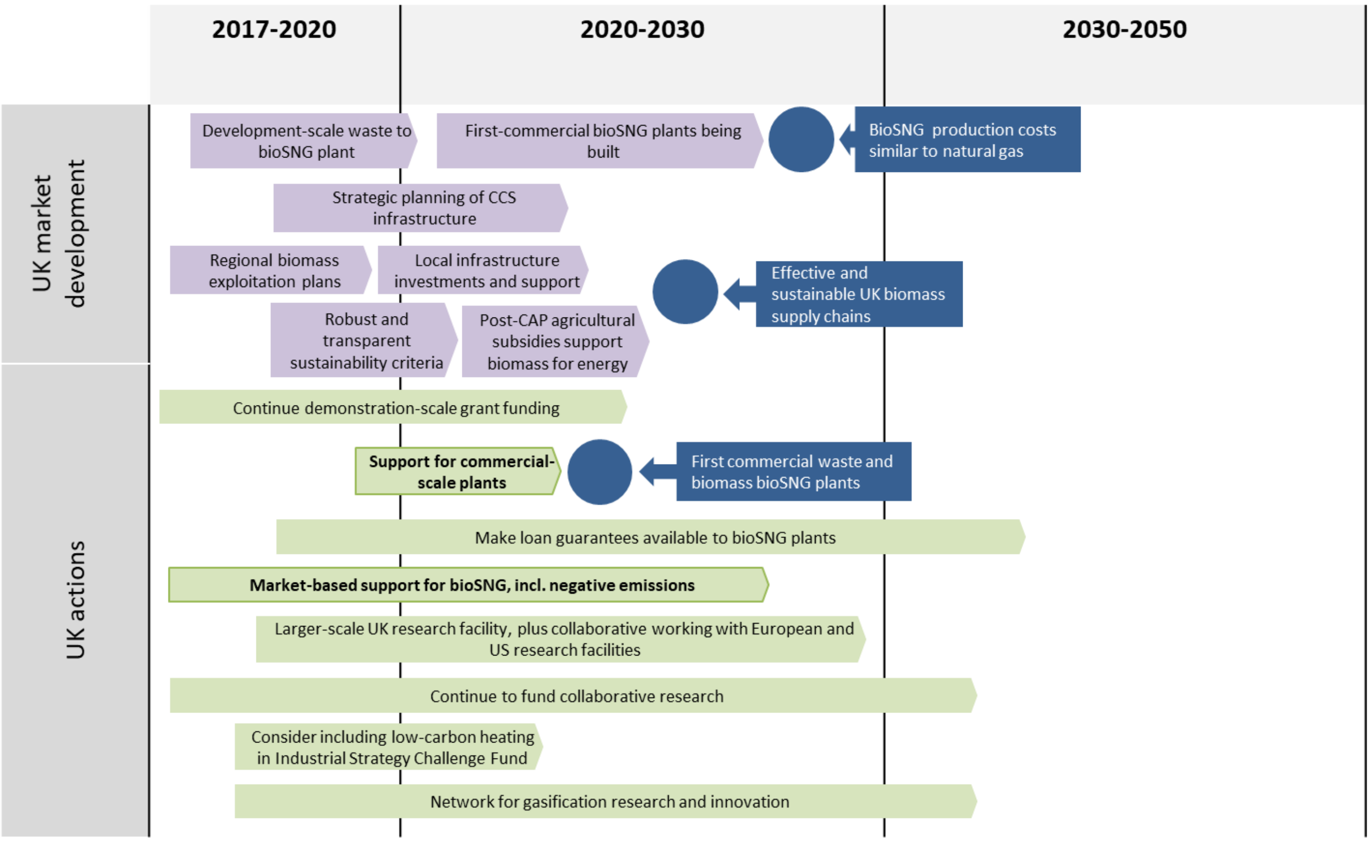


Figure 2 Actions for the support of bioSNG production, as required over time (green chevrons) in the context of wider UK market developments (purple chevrons)

Given that bioSNG is currently at demonstration-scale, the near-term actions which focus on scaling-up to commercial-scale to bring costs down towards parity with natural gas will have the greatest long-term impact stimulating cost reduction and improvements in performance. Support on both supply and demand would be required. Grant funding and loan guarantees for first commercial plants would provide the support required, alongside a long-term heat strategy and market-based support to de-risk these initial plants and provide additional revenue.

In the medium to long term, development of enabling infrastructure for bioSNG will become increasingly important. In order to reach large scale, reliable and sustainable biomass supply-chains will be required, and to maximise decarbonisation, CCS infrastructure will be necessary. Near term actions to build up these capabilities will also benefit many other heat, power and transport fuels routes.

Investment in bioSNG plants today should not be constrained by the concern that bioSNG plants could be a stranded asset if a decision is made to progressively convert gas grids to hydrogen in the early 2020s. Depending on plant siting and local demand, the few bioSNG plants that would be built in this time might continue to supply methane to parts of the grid that would not be converted until later in the roll out of hydrogen, be converted to hydrogen plants, or potentially even be converted to liquid biofuel production plants. Given that the challenges to bioSNG include areas like feedstock supply, feedstock handling and successful operation of gasification at scale, bioSNG plants can be seen as helping to overcome barriers for all gasification-based routes.

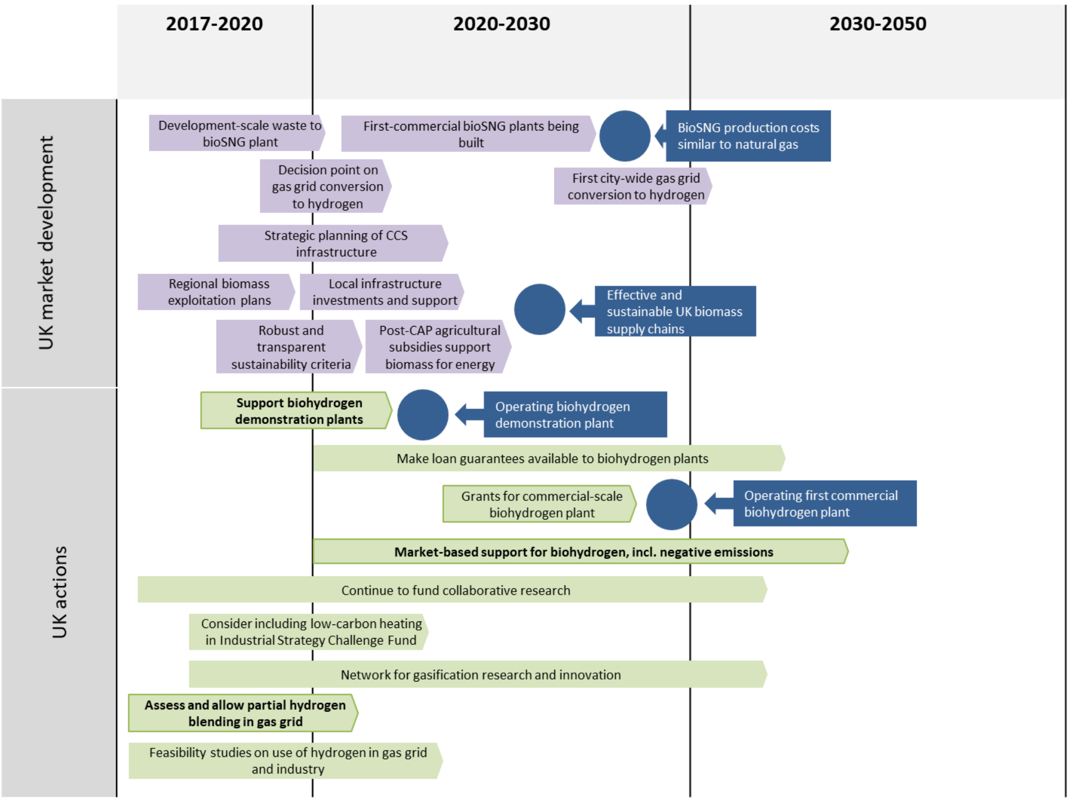
Long-term support for research will be important both to facilitate gasification-based routes as a whole, and the specific innovation activities identified above for bioSNG. Given the current uncertainty over the bioSNG technologies that are most likely to be deployed in the UK in the long term, research allowing investigation of multiple innovative options would enable the most effective options to be determined, and would build up the UK research community through better access to larger scale facilities and industrial collaboration.

3 Biohydrogen from gasification (with CO_2 capture)

Summary

- Producing hydrogen from biomass gasification is a similar technology to bioSNG production, with both requiring feedstock pre-treatment, gasification and syngas clean-up, followed by catalysis steps. Hydrogen production is at the pilot stage, however, as to date there has been little demand for bulk, low carbon hydrogen.
- Near-term, cost reductions and improvements in biohydrogen production could be realised through larger demonstration-scale plants, either in a dedicated plant or as a slipstream from a bioSNG plant.
- Innovative technologies could also contribute to reduced costs and increased efficiency and/or sustainability. Several of these cross-over from bioSNG technology development, but specifically for biohydrogen improved or alternative water-gas-shift reactors have the potential to increase the efficiency of feedstock conversion to hydrogen, as well as reducing energy consumption of the hydrogen separation process, which can be one of the key contributors to energy consumption in the plant. These hydrogen-specific innovations are applicable to processes using any gasification and gas cleaning technology, and therefore could be the focus of R&D efforts today, and be applicable irrespective of which gasification technology is ultimately widely deployed in the UK. To develop these, an increased research focus on biomass gasification routes to hydrogen is required, together with demonstration facilities to allow scale up.
- Support for biohydrogen demonstration plants at a scale of around 4MWhydrogen, and market-based support for low-carbon hydrogen, could help to reduce technology risk and achieve lower production costs. In addition, research on gasification, development of reliable and sustainable biomass supply chains and CCS infrastructure will benefit biohydrogen as well as bioSNG.
- Building up demand for bulk, low carbon hydrogen is an important step to encourage biohydrogen development. Once demand for bulk low carbon hydrogen exists, for example through gas grid blending or conversion, biomass gasification to hydrogen is anticipated to be a higher cost option in the near term than reforming of natural gas with CCS. Lack of market value for negative emissions is an additional barrier. Nevertheless, there is potential for cost reduction through scale and innovation to a hydrogen production cost of less than 4p/kWh, which is comparable to that of reforming with CCS.

- An indicative timeline for biohydrogen development in the UK:



3.1 Introduction

3.1.1 Technology description

Process introduction

Hydrogen production from gasification of biomass is produced by the following key steps:

1. **Feedstock pre-treatment** – requirements depend on gasifier technology and feedstock being used, but may include biomass drying and/or chipping.
2. **Biomass gasification** – this produces syngas. Several different types of gasifiers can be used, as discussed in more detailed below.
3. **Syngas clean-up** – Removal of tars is required. Other contaminants such as H_2S may need to be removed, depending on feedstock characteristics, gasifier type and downstream water-gas-shift (WGS) reactor.
4. **Steam reformer** – A separate steam reforming step may be used to convert methane in the syngas into CO and H_2. In some plant configurations this may not be required.[123]

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[123] https://link.springer.com/article/10.1007/s13399-011-0004-4

5. **Water-gas-shift (WGS) reaction** – In order to maximise the amount of hydrogen in the syngas. This consumes steam and produces CO_2.
6. **Purification** – This could be done through a number of different systems including cryogenic separation, pressure swing absorption (PSA) and membrane separation,[124] and aims to remove traces of CO and CO_2, leaving hydrogen of sufficient purity for the end application or grid injection. H_2 compression may be required.

Hydrogen production from biomass gasification has many parallels with bioSNG production, as both require feedstock pre-treatment, gasification and syngas clean-up steps to produce a relatively clean syngas. The three gasification technologies discussed above in relation to bioSNG could also be used for hydrogen production. Given the limited experience of hydrogen production via biomass gasification, it is not yet clear which would be the optimum gasifier type to use. As for bioSNG production, the process for using wastes and biomass is broadly similar, but the choice of feedstocks is likely to influence the gasifier technology choice and downstream processing requirements.

As there is no catalytic methanation step for the production of hydrogen, only a catalytic water-gas-shift reaction to increase the proportion of hydrogen in the syngas, the syngas clean-up requirements may be less stringent for hydrogen production compared to bioSNG. However, more extensive WGS is required to maximise the hydrogen component, and minimise the CO remaining in the syngas, compared with bioSNG production. It is likely that existing bioSNG plants could even be converted/retrofitted to hydrogen production relatively easily and cheaply, requiring alternative catalysts and control systems, but able to use largely the same physical equipment. [125]

As with bioSNG production, CO_2 must be removed from the gas streams, meaning that integration with CO_2 capture should only require minimum modifications to the process. In contrast to bioSNG production, where there are CO_2 emissions at the point of combustion of the bioSNG (in the end application), in biohydrogen production all of the carbon contained in the biomass is released at the production plant, so a much higher percentage of the initial biogenic carbon can be captured and stored.

Capture of CO_2 from the biohydrogen production process is technically possible, but has not been extensively investigated for the purpose of CO_2 capture rather than simply gas purification. Carbo (2010) [126] suggests that 80 to 90% of the initial carbon input can be captured as high-purity CO_2 using commercially-available absorption technologies for acid gas removal. Other studies suggest that vacuum swing adsorption could also be used (Oreggioni et al., 2015)[127]. The choice of technology is likely to be based on the CO_2 purity and pressure requirements of downstream CCS infrastructure.

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[124] Müller et al. (2011) Hydrogen from biomass: large-scale hydrogen production based on a dual fluidized bed steam gasification system, Biomass Conv. Bioref. (1) 55-61

[125] Cadent, Advanced Plasma Power, Progressive Energy (2017) Biohydrogen: Production of hydrogen by gasification of waste

[126] Carbo (2011), Global Technology Roadmap for CCS in Industry: Biomass-based industrial CO2 sources: biofuels production with CCS, https://www.ecn.nl/publicaties/PdfFetch.aspx?nr=ECN-E--11-012

[127] Oreggioni, G.D. et al. (2015) CO2capture from syngas by an adsorption process at a biomass gasification CHP plant: Its comparison with amine-based CO2 capture, International Journal of Greenhouse Gas Control (35) 71-81, http://www.sciencedirect.com/science/article/pii/S1750583615000249

3.1.2 Global status

Currently there is no commercial hydrogen production from biomass gasification. The projects and research programmes which are producing bioSNG will contribute to the development of gasification, syngas clean-up and WGS technology which could be used for hydrogen production.

Although no developers are currently targeting commercial biohydrogen production, there is research activity in the EU and globally, for example at TUV, the Technical University of Vienna.[128]

The BioH2 4 Refineries project, with partners OMV, Repotec, Bioenergy2020+ and TUV, carried out an economic evaluation into the production of hydrogen for a refinery on a 50MW scale[129] using a dual fluidised bed gasifier with wood chips and short-cycle energy crops.[130] This project was within the Austrian funding scheme "Energies 2020".

The FP7-funded UNIfHY project (2011-2016) developed an integrated system capable of producing 100 - 500 kg/day of hydrogen from various feedstocks.[131] This project was carried out by a consortium of four universities, four industrial companies and one research organisation, with the pilot plant located at the CIRPS research centre in Civitavecchia (near Rome).[132]

The USA National Renewable Energy Laboratory (NREL) have carried out research into hydrogen production using an indirect steam gasifier[133] and have produced a detailed design and economic analysis of a hydrogen production plant.[134] The Gas Technology Institute in the USA have also carried out research into hydrogen production from biomass gasification.[135]

3.1.3 UK status

There is currently no commercial or demonstration scale production of hydrogen from biomass gasification in the UK, but current activities in gasification give rise to capabilities which are also applicable to hydrogen production.

Air Products' Tees Valley 1 plant was at one point considering the use of syngas to produce hydrogen,[136] and had initial plans with Waste2Tricity to integrate the plasma gasification technology with AFC Energy's hydrogen-powered

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[128] Project Group: Synthetic Biofuels (2015) http://www.vt.tuwien.ac.at/chemical_process_engineering_and_energy_technology/future_energy_technology/synthetic_biofuels/EN/

[129] Rauch, R. (2011) Conversion of biomass over steam gasification to biofuels and chemicals – actual status of work, http://www.ieatask33.org/app/webroot/files/file/2013/Workshop_Gothenburg/19/Rauch.pdf

[130] Repotec (n.d.) Research-Projekt: BioH2-4Refineries http://www.repotec.at/index.php/hydrogen-generation.html

[131] Unifhy (n.d.) Unique gasifier for Hydrogen Production, http://www.unifhy.eu/index.asp

[132] Final Report Summary - UNIFHY (UNIQUE gasifier for hydrogen Production) (2016) http://cordis.europa.eu/result/rcn/193089_en.html

[133] Bain, 2009, https://www.hydrogen.energy.gov/pdfs/review09/pd_27_bain.pdf

[134] Spath et al., 2005, http://neotericsint.com/pubs/BCL%20Gasifier.pdf

[135] Gas Technology Institute (2007) Direct Hydrogen Production from Biomass Gasifier Using Hydrogen-Selective Membrane, https://www.xcelenergy.com/staticfiles/xe/Corporate/RDF-DirectHydrogenProduction-Report%5B1%5D.pdf

[136] Air Products (2010) http://www.airproducts.co.uk/Company/news-center/2010/07/0720-air-products-plans-renewable-energy-plant-in-tees-valley.aspx

alkaline fuel cells.[137] However these plans never came to fruition, with the Tees Valley projects being constructed for syngas turbine operation (but not successfully commissioned).

The consortium of Cadent, Progressive Energy and APP have performed laboratory-scale and pilot-scale testing of biohydrogen production using their 50kW bioSNG plant. The consortium has also produced a feasibility study for a commercial scale biohydrogen plant within an assessment of biohydrogen production and opportunities for implementation on the gas network, funded by the Network Innovation Allowance[138].

3.1.4 Enabling factors for innovation

Global capabilities and support:

As outlined above, there have been some European and US research programmes into hydrogen production from gasification. The support available to research and development activities for biohydrogen are largely the same as those identified for supporting bioSNG production. In addition, the Fuel Cells and Hydrogen Joint Undertaking (FCHJU) is a public private partnership supporting research, technological development and demonstration (RTD) activities[139], which supported the UNIFHY project discussed above.

UK capabilities and support:

Many of the UK gasification technology capabilities identified for bioSNG are also relevant to biohydrogen. In addition to these, there are researchers in the UK with specific interests in hydrogen, including the University of Hull on nickel gasification catalysts[140], University of Cambridge on gasification to hydrogen[141], and the University of Leeds on pyrolysis-gasification of biomass and plastic mixtures to produce hydrogen.[142] EPSRC have supported biohydrogen research in the past,[143] but do not have a research focus in this area.

3.2 Innovation activities and their impacts

Biohydrogen production is similar to bioSNG production at the feedstock, gasification, and syngas clean-up stages, so many of the innovations identified in section 2.2 (as discussed below), also apply to biohydrogen production:

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[137] Waste Management World (2012) Fuel Cell Demonstration Facility at 50 MW Plasma Gasification Plant, https://waste-management-world.com/a/fuel-cell-demonstration-facility-at-50-mw-plasma-gasification-plant

[138] Cadent, Advanced Plasma Power, Progressive Energy (2017) Biohydrogen: Production of hydrogen by gasification of waste http://gogreengas.com/wp-content/uploads/2015/11/Biohydrogen-Cadent-Project-Report.pdf

[139] Fuel Cells and hydrogen Joint Undertaking (n.d.) http://www.fch.europa.eu/page/vision-objectives

[140] Ni-based catalyst development for hydrogen enrich syngas production from biomass gasification (n.d.) http://ukchinaenergy.com/presentation/ni-based-catalyst-development-for-hydrogen-enrich-syngas-production-from-biomass-gasification/

[141] Professor John Dennis, http://www.energy.cam.ac.uk/directory/jsd3@cam.ac.uk

[142] Alvarez, J., Kumagai, S., Wu, C., Yoshioka, T., Bilbao, J., Olazar, M., Williams, P.T. (2014) Hydrogen production from biomass and plastic mixtures by pyrolysis-gasification, International Journal of Hydrogen Energy, 39 (21) 10883-10891, http://eprints.whiterose.ac.uk/80746/1/AS%20RE-SUBMITTED-JAN%202014.pdf

[143] EPSRC (n.d.) http://gow.epsrc.ac.uk/NGBOViewGrant.aspx?GrantRef=EP/F027435/1

- **2.2.3 Improved feedstock handling** – This was not mentioned specifically in relation to biohydrogen production in the interviews we conducted and literature searched, but given its importance in gasification, would also be applicable to this technology.

  Improved feedstock handling should enable existing feedstocks to be used more efficiently and plants to run more reliably, therefore reducing costs.
- **2.2.4 Feedstock flexibility** – The LBS and Hinicio S.A. estimate that biomass costs would be 20-30% of the hydrogen costs (when using solid lignocellulosic biomass), and identifies that this could be tackled by increased flexibility of the gasifier to use variable feedstocks with lower quality (and hence lower costs).[144] As for bioSNG, however, this will depend on the gasifier type, with some developers already considering that their technologies can accept a sufficiently wide range of feedstocks. As well as reducing costs, the ability to use a wider range of feedstocks enables biohydrogen to be produced from waste and residue feedstocks with lower GHG emissions.
- **2.2.5 High-pressure gasification** - Process modelling of a biomass gasification to hydrogen plant by Müller et al (2011)[145] predicted a very high electricity consumption, over half of which was for compression of the gas prior to membrane-based hydrogen separation. This electricity demand for compression could be reduced if the gasification process itself could operate at elevated pressure, but it should be noted that the benefits of pressurised operation depend on the operating conditions downstream of the gasifier.
- **2.2.6 Sorption-enhanced gasification** - Use of chemical looping in the gasifier was identified by two interviewees and in the literature[146,147] as being a significant potential innovation for hydrogen production.

  Modelling of a biohydrogen production process from wood residue using a CaO/$CaCO_3$ chemical looping process suggests that under optimum steam to carbon ratios and gasifier temperatures the maximum energy efficiency of the hydrogen production process from biomass is 57.7% (LHV basis).[148]

  By improving the efficiency of the process, sorption-enhanced gasification could increase overall supply of biohydrogen and could also reduce the GHG emissions per tonne of hydrogen.
- **2.2.7 Develop more efficient hot gas cleaning** – The UNIfHY project has developed hot gas cleaning technology for biohydrogen production, noting that the limitations of existing cold-gas cleaning technologies are their inability to convert tar into additional hydrogen and the fact that they require a cooling step. However the UNIfHY hot gas cleaning technologies failed testing at pilot-industrial scale, suggesting further work is needed in this area.[149] However it should be noted that other interviewees developing bioSNG plants considered hot gas cleaning to now be operational. A review of the high-temperature catalytic candles used in the UNIQUE project suggests that compared to reference values with no filter candle the syngas yield increased by 110%, the percentage by volume of hydrogen increased by 17 percentage points and the tar content decreased by 96%.[150]

  The development of hot gas clean-up and conditioning technologies therefore significantly improves the process efficiency compared to cold gas clean-up, which would also result in lower GHG emissions of hydrogen production. The UNIfHY project aimed to reduce both capex and opex costs of the gas clean-up process, so that

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[144] Ludwig-Bölkow-Systemtechnik GmbH (LBST) and Hinicio S.A., for the FCHJU (2015) Study on hydrogen from renewable resources in the EU, http://www.fch.europa.eu/studies/study-hydrogen-renewable-resources-eu

[145] Müller, S., Stidl, M., Pröll, T., Rauch, R., Hofbauer, H. (2011) Hydrogen from biomass: large-scale hydrogen production based on a dual fluidized bed steam gasification system, Biomass Conv. Bioref. (1) 55-61

[146] Müller, S., Stidl, M., Pröll, T., Rauch, R., Hofbauer, H (2011) Hydrogen from biomass: large-scale hydrogen production based on a dual fluidized bed steam gasification system, Biomass Conv. Bioref. (1) 55-61

[147] UNIfHY (2016) Deliverable 5.3: Techno-economic analysis of UNIFHY hydrogen production system, http://www.unifhy.eu/deliver_pro.asp

[148] Detchusananard, T. Ponpesha, P. Saebea, D. Authayanun, S. Arpornwichanop, A. (2017) Chemical Engineering Transactions Vol 57, Modeling and Analysis of Sorption Enhanced Chemical Looping Biomass Gasification, *www.aidic.it/icheap13/program/159detchusananard.pdf*

[149] UNIfHY (2016) Deliverable 5.3: Techno-economic analysis of UNIFHY hydrogen production system, http://www.unifhy.eu/deliver_pro.asp

[150] Foscolo, P.U., Bocci, E. (2012) Summary Of Research And Technology Development Experience On Gasification And Hot Gas Conditioning UNIQUE (7pq-Energy-2007/2010-211517) And UNIfHY (7fp-Fch-Ju-2012/2015-299732) Projects, http://www.fast.mi.it/een/energia_idrogeno2012/bocci.pdf

the gas clean-up and conditioning system cost is reduced to 30% of that of a standard free-standing conditioning system.[151] More effective tar removal is also likely to reduce downstream costs.

Biohydrogen production is at an earlier stage of deployment than bioSNG, and has different requirements for the water-gas-shift reaction and hydrogen separation, so there are also specific innovations to biohydrogen technology.

3.2.1 Larger demonstration scale plants

LBST and Hinicio (2015), identified that a key gap in the commercialisation of biohydrogen technologies is the lack of experience with larger demonstration plants.[152] A key step towards understanding the potential for biohydrogen, bringing down costs and improving efficiency is to carry out more experimental work at large demonstration scale.

Larger scale plants are anticipated to have significantly lower capex and opex costs than are seen with existing pilot-scale plants. They may also have a slightly higher efficiency, with a small impact on total potential biohydrogen supply and sustainability. Nevertheless, the real value of larger demonstration-scale plants is in proving the technology and solving challenges of scale-up so that plants can ultimately reach commercial-scale, where the cost of hydrogen is anticipated to be around 4p/kWh (at modelled scale of 82MW$_{th}$ and assuming a gate fee of £75/tonne for feedstock).[153] This is comparable to hydrogen production by steam methane reforming with CCS.[154]

Interviewees also considered that there is potential to demonstrate hydrogen production alongside bioSNG production, as a slipstream or alternative product of bioSNG plants. Some interviewees suggested that the syngas production step is the most technically challenging, and therefore developments in gasification for bioSNG production would substantially benefit biohydrogen.

3.2.2 Improved WGS reactors

With limited research on biohydrogen production from gasification, more research is needed to understand the limitations and innovation needs around existing water gas shift reactors. The WGS reaction is usually carried out in two stages: a high-temperature shift reactor to increase reaction rate and a lower-temperature shift reactor to increase the conversion efficiency.[155] Recent research on the Güssing gasifier demonstrates reliable operation of a catalytic water gas shift reactor with tar-rich syngas over 2250 hours, converting CO content in the syngas to below 2%.[156]

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[151] Foscolo, P.U., Bocci, E. (2012) Summary Of Research And Technology Development Experience On Gasification And Hot Gas Conditioning UNIQUE (7pq-Energy-2007/2010-211517) And UNIfHY (7fp-Fch-Ju-2012/2015-299732) Projects, http://www.fast.mi.it/een/energia_idrogeno2012/bocci.pdf

[152] Ludwig-Bölkow-Systemtechnik GmbH (LBST) and Hinicio S.A., for the FCHJU (2015) Study on hydrogen from renewable resources in the EU, http://www.fch.europa.eu/studies/study-hydrogen-renewable-resources-eu

[153] Cadent, Advanced Plasma Power, Progressive Energy (2017) Biohydrogen: Production of hydrogen by gasification of waste

[154] SGI (2017) A Greener Gas Grid: What are the Options – White Paper

[155] Chein, R., Yu, C.T. (2016) Thermodynamic analysis of sorption-enhanced water–gas shift reaction using syngases, Energy Research, 40 (12) 1699-1703

[156] Kraussler, M., Binder, M., Hofbauer, H. (2016) 2250-h long term operation of a water gas shift pilot plant processing tar-rich product gas from an industrial scale dual fluidized bed biomass steam gasification plant, International Journal of Hydrogen Energy, 41, 6247-6258, http://www.sciencedirect.com/science/article/pii/S0378382016304866

Moneti et. al (2016)[157] state that conventional WGS reactors usually operate at large scales and high pressures, hence a key innovation to result from the UNIfHY project has been the development of an atmospheric-pressure WGS reactor. Chein et al. (2016) suggest that the development of high-temperature WGS catalysts with improved yield could improve efficiency and reduce capital cost if a low-temperature shift stage is removed[158].

Improving water gas shift reactors will increase the conversion of CO to hydrogen, resulting in higher overall conversion efficiencies from biomass to hydrogen, and potentially lowering the requirements for downstream CO removal. In addition, if WGS catalysts can be developed which have higher tolerance for syngas contaminants such as VOCs, tars, sulphur and chlorine then the upstream syngas cleaning requirements could be reduced. Given that the lifetime of existing WGS catalysts is currently limited to 2 – 5 years,[159] higher tolerance to contaminants could also improve catalyst lifetimes. These improvements could lower both capex and opex costs. Currently this is not possible to quantify exactly, but considering that capex cost of the WGS reactor is around 15% of total capex in the water to biohydrogen gasification plant modelled by Progressive Energy[160], even halving the total capex cost of the WGS reactor would only reduce total capex costs by 8%.

3.2.3 Sorption enhanced water gas shift (SEWGS)

Sorption enhanced water gas shift (SEWGS) combines the water gas shift reaction with CO_2 capture in a single process, operating at high temperature and pressure. There has been research into SEWGS, including the FP7-funded CAESAR project (2008)[161] which focussed on CO_2 capture from fossil fuels, work being done by ECN in the Netherlands[162], and the EU Stepwise project.[163] However few of these studies or projects are focused specifically on use of SEWGS with biomass-derived syngas, suggesting this field of research still has important innovation potential. Given the current pre-commercial status of SEWGS, this innovation would start to have an impact upon UK biohydrogen production only in the medium to long term.

Chein (2016) suggests that a key advantage of SEWGS is that it may reduce or even eliminate the need for catalysts in the WGS reaction, and may eliminate the need for syngas cooling.[164] Both the absorption and the regeneration process operate at high temperature, meaning that high temperature waste heat can therefore be used elsewhere in the plant and the overall system efficiency can be increased. It has also been suggested that a SEWGS reactor could tolerate higher levels of H_2S and COS in the syngas than conventional WGS processes.[165] Together these changes contribute to higher efficiency of the overall hydrogen production process, which could

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[157] Moneti, M., Di Carlo, A., Bocci, E., Foscolo, P.U., Villarini, M., Carlini, M. (2016) Influence of the main gasifier parameters on a real system for hydrogen production from biomass, International Journal of Hydrogen Energy, 41 (28) 11965-11973, http://www.sciencedirect.com/science/article/pii/S036031991531644X

[158] Chein, R., Yu, C.T. (2016) Thermodynamic analysis of sorption-enhanced water–gas shift reaction using syngases, Energy Research, 40 (12) 1699-1703

[159] LeValley, T.L., Richard, A.R., Fan, M. (2014) The progress in water gas shift and steam reforming hydrogen production technologies - A review, International Journal of Hydrogen Energy (39) 16983 - 17000

[160] Cadent, Advanced Plasma Power, Progressive Energy (2017) Biohydrogen: Production of hydrogen by gasification of waste

[161] CAESAR (n.d.)The SEWGS process http://caesar.ecn.nl/the-sewgs-process/

[162] ECN (2015) Process intensification: SEWGS case, https://www.ecn.nl/news/item/process-intensification-sewgs-case/, accessed 1st June 2017

[163] Stepwise http://www.stepwise.eu/

[164] Chein, R., Yu, C.T. (2016) Thermodynamic analysis of sorption-enhanced water–gas shift reaction using syngases, International Journal of Energy Research, 40 (12) 1688-1703, http://onlinelibrary.wiley.com/wol1/doi/10.1002/er.3554/full#er3554-bib-0031

[165] Cadent, Advanced Plasma Power, Progressive Energy (2017) Biohydrogen: Production of hydrogen by gasification of waste

increase the overall supply of hydrogen and is likely to reduce GHG emissions. Cost benefits are likely to be realised by combining multiple reaction stages in a single-stage reaction, in order to lower capex and opex costs.

3.2.4 Water gas shift membrane reactors

The US Department of Energy states that a key research need to lower the capital cost of biohydrogen production is the development of new membrane technologies to better separate and purify hydrogen from the gas stream that is produced from the WGS reactor.[166] A hydrogen-selective membrane could be integrated within the WGS reactor to combine the conventionally separate WGS and H_2-separation stages, using significantly less energy than existing H_2 separation technologies such as pressure swing absorption (PSA). Use of membrane reactors can also reduce the cooling demand in the WGS reactor as they enable higher-temperature operation.[167] In addition, some membrane WGS reactors can produce high-pressure hydrogen, reducing the requirement for downstream compression.[168]

Chein et al. (2016) report that the development of cost-effective membrane WGS reactors for H_2/CO_2 separation could improve efficiency and reduce capital costs.[169] Two interviewees also identified the further development of membrane WGS reactors as being key to improving the efficiency of the overall plant, stating that they could reduce the total levelised cost of hydrogen production by 10-20%.

The research on WGS membrane reactors is currently at lab-scale, and a particular focus is on the development of new WGS catalysts that are more compatible with membrane reactors than the current catalysts.

3.2.5 Other thermo-chemical routes to biohydrogen

In addition to gasification, there are several alternative routes to biohydrogen which are at early TRL, hence have not been considered as separate hydrogen production routes, but are included here as potential innovations:

- **Supercritical water gasification** – This technique uses super-critical water as the gasification agent to produce syngas with a high hydrogen content. It can use feedstock with a high moisture content (at least 30%, and potentially up to 90%), hence could expand the amount of potentially available feedstock that can be used for thermochemical hydrogen production. The impact of supercritical water gasification on the cost and sustainability of biohydrogen production is not possible to assess until the technology is further developed. Current challenges to this technology include the need to use expensive construction materials that are resistant to supercritical water, and the high cost and energy use from producing supercritical steam.[170] Supercritical water gasification could also potentially be used for bioSNG production.[171]

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[166] US Department of Energy (USDoE) (n.d.) Hydrogen production: biomass gasification, https://energy.gov/eere/fuelcells/hydrogen-production-biomass-gasification, accessed on 1st June 2017

[167] Cadent, Progressive Energy, APP (2017) Biohydrogen: Production of hydrogen by gasification of waste

[168] US Department of Energy (2011) Process intensification with integrated water-gas-shift membrane reactor, *https://energy.gov/sites/prod/files/2013/11/f4/water-gas-shift.pdf*

[169] Chein, R., Yu, C.T. (2016) Thermodynamic analysis of sorption-enhanced water–gas shift reaction using syngases, Energy Research, 40 (12) 1699-1703

[170] E4tech et al. (2016) "Review and benchmarking report", Deliverable 1 for the Energy Technologies Institute (ETI)'s *Techno-Economic Assessment of Biomass Pre-Processing* (TEABPP) project. Authored by E4tech, Black & Veatch, Imperial College Consultants, University of Sheffield and University of Leeds.

[171] Mozaffarian, M., Deurwaarder, E.P., Kersten, S.R.A.(2004) "green gas" (SNG) production by supercritical gasification of biomass, *www.ecn.nl/docs/library/report/2004/c04081.pdf*

- **Aqueous phase reforming** – this technology also enables processing of wet biomass, hence could expand the available feedstock for hydrogen production. However, the process typically produces a wide range of gaseous and liquid output products, and would need significant optimisation.
- **Chemical looping combustion** – Several academics have also looked at the potential to generate hydrogen as a by-product from the chemical looping combustion of fossil fuels and/or biomass (to generate electricity), where steam instead of air carries out the re-oxidation of the metal oxide[172,173,174]. This process may have higher efficiency than alternative biohydrogen production methods, particularly when CO_2 capture is required, but the technology is too early-stage to quantify these impacts.

3.2.6 Summary of innovation impacts

Table 3 summarises the innovation activities identified above which are applicable specifically to biohydrogen plants. Those which are also applicable to bioSNG plants are summarised in Table 2.

Even more so than for bioSNG, lack of experience of biohydrogen production at scale leads to considerable uncertainty about where improvements will be needed, or will be most effective, in the innovative activities that are common with bioSNG, with this being highly dependent on the technologies used. As described, there is also relatively little literature detailing the costs and benefits of the innovation activities identified above in the context of hydrogen production. As a result, the barriers and gaps discussed below cover all of these innovation activities, with actions proposed to take account of these uncertainties.

However, some of the innovation activities below that are specific to hydrogen production are likely to benefit any gasification to biohydrogen route: improved WGS reactors, SEWGS, and WGS membrane reactors. All of these would increase the efficiency of conversion of feedstock to hydrogen production, thereby increasing supply of gas per unit of biomass as well as reducing costs and emissions. As shown in the indicative energy consumption diagram above, separation is also a key contributor to energy losses in the process.

Alternative thermo-chemical routes to hydrogen are diverse, do not have clearly identified benefits, and are at an early stage of development, and are therefore a lower priority for further development.

Table 3: Summary of impacts of biohydrogen innovations identified. Shading refers to impact of innovation in each category. Dark blue = strong impact, light blue = some impact, white = low impact

	Cost	**Supply**	**Sustainability**
Larger demonstration scale plants	Lower capex and opex		
Improved WGS reactors	Lower capex and opex	Increased conversion efficiency	Increased conversion efficiency

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[172] Rydén M, Lyngfelt A. Using steam reforming to produce hydrogen with carbon dioxide capture by chemical-looping combustion. International Journal of Hydrogen Energy 2006;31(10):1271-1283

[173] Wiltowski T, Mondal K, Campen A, Dasgupta D, Konieczny A. Reaction swing approach for hydrogen production from carbonaceous fuels. International Journal of Hydrogen Energy 2008;33(1):293-302

[174] Chiesa P, Lozza G, Malandrino A, Romano M, Piccolo V. Three-reactors chemical looping process for hydrogen production. International Journal of Hydrogen Energy 2008;33(9):2233-2245

Sorption enhanced water gas shift (SEWGS)	Lower capex and opex	Increased conversion efficiency	Increased conversion efficiency and reduced energy consumption
Water gas shift membrane reactors	Reduction of capex and opex – reduce total levelised cost of H_2 production by 10 – 20%	Increased conversion efficiency	Increased conversion efficiency and reduced energy consumption
Other thermo-chemical routes to biohydrogen		Use of wet feedstocks increases potential supply	

3.3 Barriers and gaps

Here we outline the barriers and gaps to the development of biohydrogen technology. There are some barriers to expanding the production and use of all types of low-carbon hydrogen, which therefore impact biohydrogen. As these have been addressed elsewhere (e.g. E4tech, 2017)[175] and are not the focus of this report, the barriers have been listed but further actions for addressing these barriers have not been identified.

3.3.1 Lack of demand for bulk low-carbon hydrogen

Hydrogen has potential to be used in transport, power, heating and as an industrial process feedstock. For there to be a demand for low-carbon hydrogen, it is necessary for there to be both the infrastructure in that sector that can use hydrogen, and the policy to ensure that low-carbon hydrogen routes are used. Across these four sectors, demand does not currently exist, presenting a barrier to the uptake of low-carbon hydrogen such as biohydrogen.

The Renewable Transport Fuel Obligation (RTFO) is currently being revised to incentivise low-carbon hydrogen for use in transport. However, in transport, the hydrogen demand is currently very small due to the limited number of fuel cell vehicles currently on the road. Growing demand in transport is likely to be predominantly supplied by hydrogen from electrolysis in the near future, given that electrolysers can be sited at refuelling stations, with scales matched to the scale of demand, rather than hydrogen produced centrally and transported to refuelling stations.

There is interest in the potential supply of hydrogen to the heat and power sectors via the gas grid, although this is at an early stage of development. Current UK regulations for natural gas transported via the gas grid limit the percentage of hydrogen to 0.1mol%.[176] Ongoing projects such as HyDeploy are investigating blending higher percentages of gas into the network – up to 20% by volume.[177] 100% conversion of the gas grid is also being considered: the Leeds City Gate H21 feasibility study was the first major project to consider the feasibility of a city-scale gas grid conversion. Although there is no current policy to ensure that the hydrogen injected would be low carbon (e.g. this is not currently incentivised under the RHI[178]), the aim of these activities is decarbonisation, and

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[175] E4tech (2017) Hydrogen and fuel cells: opportunities for growth

[176] National Grid (n.d.) Gas quality, http://www2.nationalgrid.com/uk/industry-information/gas-transmission-system-operations/gas-quality/

[177] National Grid (2017) Hydrogen in the mix http://nationalgridconnecting.com/hydrogen-mix/ (accessed 12th July 2017)

[178] Ofgem (2017) Non-domestic Renewable Heat Incentive (RHI) Guidance Volume One: Eligibility and how to apply (version 9) https://www.ofgem.gov.uk/publications-and-updates/non-domestic-rhi-main-guidance

therefore it is likely that projects would only be justified on the grounds of GHG reduction. Nevertheless, if these routes are established, policy will be necessary to incentivise lower (and negative) carbon routes.

The largest use of hydrogen in the UK is currently in industry. The FCHJU estimates that across Europe industrial uses account for more than 90% of the hydrogen market[179], predominantly in the chemicals sector and in refineries. For example in the Tees Valley, the BOC SMR facility provides more than 50% of total UK hydrogen production to industrial users.[180] There is no current policy driver for existing industrial users to switch to low-carbon hydrogen.

3.3.2 Competitiveness with other bulk hydrogen production options

Even once a demand for bulk, low carbon hydrogen has been established, the competitiveness of biomass gasification to hydrogen will depend on the cost and scale of plants, and on the treatment of negative emissions.

Previous E4tech analysis[181] has shown that hydrogen produced from biomass gasification, either with or without CCS, is currently more expensive on a per kg basis than fossil hydrogen produced from steam methane reforming (SMR), or low-carbon hydrogen produced from steam methane reforming with CCS (Figure 3), although with potential for cost reduction by 2030 to produce hydrogen in a similar cost range. This assertion is supported by the Sustainable Gas Institute (SGI)[182] although they are more optimistic on the cost-competitiveness of biohydrogen compared to hydrogen from SMR, suggesting that while it may be possible to produce hydrogen significantly cheaper by SMR than by gasification, the average cost of both production methods in $p/kWh_{hydrogen}$ is very similar.

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[179] FCHJU (2015) Overview of the market segmentation for hydrogen across potential customer groups, based on key application areas, http://bit.ly/2tiu4yy

[180] E4tech and Element Energy (2014) Tees Valley and North East Hydrogen Economic Study

[181] E4tech (2016) Hydrogen and fuel cells: opportunities for growth

[182] SGI (2017) A Greener Gas Grid: What are the Options – White Paper

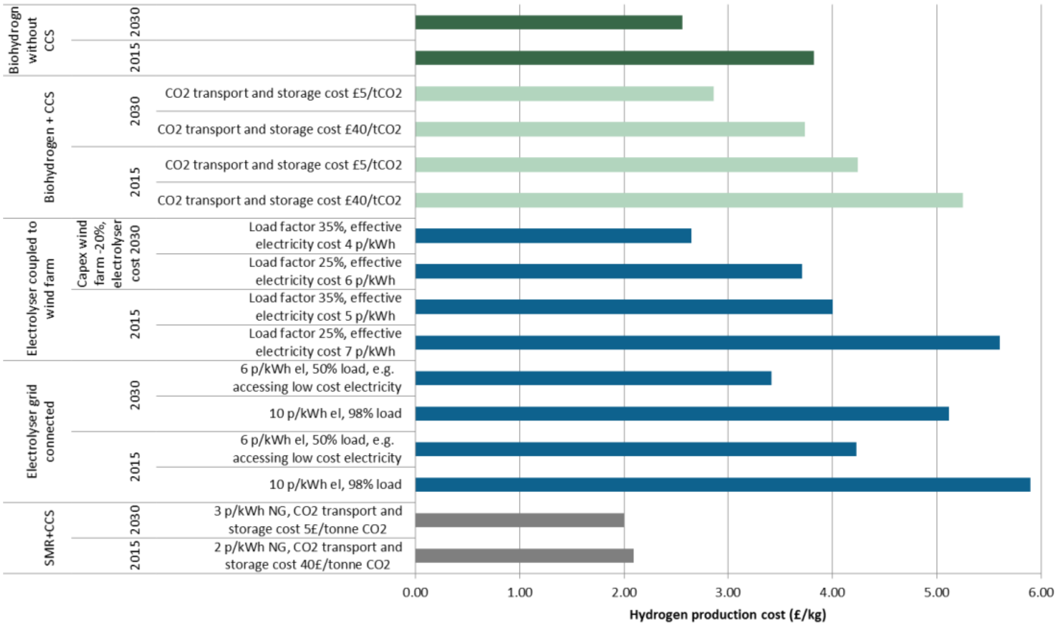

Figure 3 Comparison of costs of low-carbon hydrogen production technologies (data from E4tech, 2016)[183]

Nevertheless, analysis by Progressive Energy has shown that the cost per tonne of CO_2 saved could be significantly lower for biohydrogen compared to other low-carbon hydrogen production methods: £25/tonneCO_2eq for biohydrogen without CCS and £39/tonneCO_2eq for biohydrogen with CCS, compared with £163/tonneCO_2eq. for SMR + CCS. [184] Moreover, larger carbon savings in terms of kgCO_2eq./$MWh_{hydrogen}$ can be achieved with biohydrogen compared to SMR + CCS. Therefore, not valuing all CO_2 savings on a per kgCO_2 saved basis, particularly with no market incentive for negative emissions, presents a barrier to realising the full benefits of biohydrogen.

If hydrogen was blended into the gas grid at low levels, it would be possible for all bulk hydrogen technologies, including biomass gasification, to compete on the basis of cost, including potential policy incentives towards lower carbon options. For conversion of parts of the gas grid to 100% hydrogen, the current industry view is that this would only be likely using SMR + CCS, given that this is the only route that could currently deliver the quantities of hydrogen needed to convert a city or region. As such, plans for conversion of the first cities or regions are likely to be based on this technology, and SMR + CCS planned at a scale to supply it. Nevertheless, there could be a role for biomass gasification to hydrogen in supplying 100% hydrogen areas as conversion expands, given that by this time there may be greater storage on the system, and greater experience with biomass gasification, meaning reduced costs and technology risk.

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[183] E4tech (2016) Hydrogen and fuel cells: opportunities for growth

[184] Cadent, Progressive Energy, APP (2017) Biohydrogen: Production of hydrogen by gasification of waste

3.3.3 Investment climate not favourable for development and deployment of negative emissions technologies

This barrier is also applicable to bioSNG technology and was discussed in more detail in section 3.3, but for biohydrogen it is particularly important. The GHG intensity of biohydrogen with CCS is much more negative than bioSNG with CCS, hence the potential benefit from incentivising negative emissions is greater for biohydrogen compared to bioSNG. In addition, there are several other potentially lower-cost low-carbon hydrogen production methods that will outcompete biohydrogen if its negative emissions do not hold a market value.

3.3.4 Feedstock cost and supply chain

This is a barrier for biohydrogen development, as it is for bioSNG, and is discussed in more detail in section 3.3. This barrier is less severe for biohydrogen due to its earlier stage of development, but will become increasingly important as it moves towards larger-scale and commercialisation.

3.3.5 Development of enabling industries

As for bioSNG the lack of development of carbon capture and storage / utilisation infrastructure, and the limited maturity of the global gasification industry presents a barrier to biohydrogen development. Due to the earlier TRL stage of biohydrogen compared to bioSNG, these barriers are less severe. However, the substantial negative emissions benefits from biohydrogen can only be realised if CCS infrastructure develops, so this will be a severe barrier for biohydrogen in the future if CCS does not develop.

3.3.6 Limited research focus on biomass gasification to hydrogen

Interviewees commented that there was a specific lack of research bringing together expertise in biomass, hydrogen and CCS, which is holding back the development of biomass gasification + CCS. The key benefit of biohydrogen technology compared to other hydrogen production methods is the ability to achieve negative emissions, which is widely used in long-term climate scenarios to achieve deep decarbonisation and solve global temperature overshoot. However, this important long term role is not currently being translated into biomass gasification to hydrogen + CCS being seen as a research priority, with the biomass research community often seeing it as too far off, with no near term demand, and the hydrogen research community often seeing it as an expensive option complicated by questions over biomass resources and sustainability.

3.4 Potential options to mitigate innovation barriers

A series of actions that could be used to enable the development of biohydrogen technology are suggested and explained here and are shown over time on Figure 4. Because of the more advanced state of bioSNG technology we anticipate that the innovation activities identified above as being relevant to both bioSNG and biohydrogen technology will be addressed first through developments in bioSNG.

3.4.1 Funding for biohydrogen demonstration plants

A biohydrogen demonstration plant could be built in order to confirm the expected performance of biohydrogen plants, and allow assessment of the potential role biohydrogen could play in the future heating and transport systems. Construction and operation of a demonstration plant for biohydrogen would also be likely to identify further areas for improvement and innovation, which are not yet apparent given the early stage of development and lack of research focus. The plants could also act as a focal point for UK research activity, and allow research/industry collaboration.

LBST and Hinicio suggest that in the next few years, large demonstration-scale plants of up to 24tonnes$_{\text{hydrogen}}$/day (equivalent to roughly 42MW hydrogen production on LHV basis) should be built in order to accelerate commercialisation.[185] However, this represents a significant scale-up from current biohydrogen production, which is largely at pilot scale. Therefore, to reduce technology risk and give investors the confidence to invest in larger demonstration plants, which may cost £100’s millions, a smaller-scale demonstration plant would be likely to be more effective.

There are several plausible options for a biohydrogen demonstrator: a dedicated biohydrogen production plant or a slipstream from a commercial bioSNG plant. A small-scale biohydrogen demonstration plant of around 4MW$_{\text{th}}$ has been estimated to cost around £25M, while an alternative option of using the slipstream from an operating bioSNG plant to demonstrate biohydrogen production might cost between £3M and £15M.[186] There could also be the potential for demonstration as part of the large scale bioSNG research facility discussed above.

Due to technology risk and high production costs of biohydrogen associated with a small plant, a demonstration plant at this scale would be likely to require support. This could be provided by a demonstration plant competition, such as those currently run in the UK for advanced transport fuels which offer fuel producers up to £20M in capital grant funding over 3 years,[187] or other grant mechanisms such as Ofgem’s Gas Network Innovation Competition. Coordination between different organisations would be needed depending on the end use of the hydrogen: including Ofgem if for gas grid injection, and/or DfT if the project included use in transport. Combining a demonstration-scale biohydrogen plant with a wider hydrogen infrastructure demonstration project, for example as part of bus fleet trial, could bring more value to a demonstration plant.[188] The earliest operation of a commercial bioSNG facility in the UK is in 2021, so this represents the likely earliest possible operation of a hydrogen slipstream. If a stand-alone hydrogen demonstration plant were to be built then project development could start immediately. A competition run from 2018 – 2022 would provide opportunity for both of the options outlined above, recognising that each has advantages and disadvantages. The HyDeploy project, which is due to finish in March 2020, will be important in determining the feasibility of hydrogen blending into the gas grid. Therefore, if the biohydrogen demonstration plant is constructed before this date then it could also target hydrogen use in transport or industry so focus is not solely on the heat sector before the feasibility of hydrogen blending in the gas grid has been proven.

Following construction of a demonstration plant at the scale mentioned above, a subsequent biohydrogen plant would likely be at a large demonstration / first commercial scale of 40-50MW$_{\text{hydrogen.}}$ This could cost around

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[185] Ludwig-Bölkow-Systemtechnik GmbH (LBST) and Hinicio S.A., for the FCHJU (2015) Study on hydrogen from renewable resources in the EU, http://www.fch.europa.eu/studies/study-hydrogen-renewable-resources-eu

[186] Progressive Energy (2017) Biohydrogen: Production of hydrogen by gasification of waste

[187] Ricardo Energy and Environment (2017) Future Fuels for Flight and Freight Competition , https://ee.ricardo.com/transport/case-studies/f4c

[188] Progressive Energy (2017) Biohydrogen: Production of hydrogen by gasification of waste

£100M[189], and would require support as outlined for first commercial bioSNG plants in section 3.4.1. Therefore, financial support for first commercial plants would become important actions for the promotion of biohydrogen plants from around 2025. The nature of the scale-up of biohydrogen technology will be strongly influenced by the government's consideration of the costs and benefits of grid conversion to hydrogen compared with other decarbonisation options. If 100% conversion is considered preferable, then a clear policy signal on this would be required. The government's clean growth strategy has committed to making a decision on this in the mid-2020s. If 100% conversion is not chosen then there is still scope for biohydrogen use in partial blending of the gas grid, in industry or in transport, and innovation support suitably targeted towards the appropriate scale and hydrogen purity required in these alternative applications: hydrogen for fuel cells is generally required to be higher purity than hydrogen used for combustion.

It has been noted that at larger scales the development of flexible gasification plants which can produce both bioSNG and biohydrogen could enable plant scale-up even if grid blending of hydrogen is limited or 100% gas grid conversion is not adopted[190]: at times of lower natural gas demand the plant could switch to producing bioSNG so that it does not reach the blend limits of the grid. However, research into this concept has been limited and it is unclear how technically and economically feasible such plants would be.

3.4.2 Market-based support for low-carbon hydrogen for heating

A market-based support mechanism for biohydrogen would help to overcome barrier 4.3.2, the poor competitiveness of biohydrogen with other hydrogen production options. This support mechanism would be needed as soon as hydrogen in the gas grid is deployed, likely to be after the HyDeploy project has finished in March 2020. Specific inclusion of hydrogen within a low-carbon heat market support mechanism would also signal the long-term intention of the government towards increasing the use of hydrogen in the energy system, which could promote interest in research in this field in the other areas of innovation identified above.

Market-based support could be provided to biohydrogen by a number of different policy mechanisms, similar to those outlined in section 2.4.2 for support of bioSNG, including provision of a specific incentive, contracts for difference or a carbon tax. Providing long-term revenue certainty for plant developers is likely to reduce the risk of such projects and overcome the challenge of long lead times on large plants. As for bioSNG, the level of support for biohydrogen should recognise the stage of technology development of hydrogen production routes. Given that hydrogen produced from gasification is likely to be higher cost than that produced from SMR + CCS, while offering the potential for greater decarbonisation and a lower cost per kg of sequestered CO_2, a market-based support scheme which provides rewards on the basis of GHG savings would be appropriate. This would enable biohydrogen to compete with SMR + CCS and would also promote the development of biohydrogen with carbon capture.

3.4.3 R&D funding for biohydrogen from syngas

Funding for research and development could accelerate many of the innovations outlined in section 4.2, including the development of improved water-gas-shift reactors, sorption enhanced water-gas-shift, and water-gas-shift

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[189] Ludwig-Bölkow-Systemtechnik GmbH (LBST) and Hinicio S.A., for the FCHJU (2015) Study on hydrogen from renewable resources in the EU, http://www.fch.europa.eu/studies/study-hydrogen-renewable-resources-eu

[190] Progressive Energy (2017) Biohydrogen: Production of hydrogen by gasification of waste

membrane reactors. As described above, these would benefit biohydrogen routes irrespective of the feedstock and gasification option chosen. Despite limited industrial activity in biohydrogen, it will be important to encourage links between researchers and developers in order to help bring these innovations to commercialisation.

Currently in the UK, although there is research ongoing into thermochemical treatment of biomass including gasification, and some activity in water-gas-shift catalysis, there is limited research into biohydrogen production through gasification specifically. The EPSRC emphasise the strategic connection of bioenergy with CCS and BECCs, but currently only two grants operate across bioenergy and CCS, and only two operate across bioenergy and hydrogen and alternative energy vectors.[191] The H2FC Supergen hub aims to fund and promote multi-disciplinary hydrogen research, but current research focuses only on biological hydrogen production.[192] Therefore in the short term ongoing EPSRC funding for the energy sector could focus on cross-sectoral projects between bioenergy, CCS and gasification, either through the H2FC or Bioenergy Supergen hubs.

Inclusion of low-carbon heating within the Industrial Strategy Challenge Fund and the establishment of a network for gasification research and innovation, as outlined above to promote bioSNG, could also benefit the development of biohydrogen technologies.

3.4.4 CO_2 transport and storage infrastructure

As for bioSNG, the development of CO_2 transport and storage infrastructure will facilitate the deployment of biohydrogen production with CCS. This is not currently a barrier to biohydrogen production today, but will be vital in the longer-term for achieving large-scale commercialisation of this technology. Because of the significant cost of developing large infrastructure such as CO_2 transport and large-scale storage, this action is relevant in the near term, even though biohydrogen is unlikely to be at sufficient scale to require this infrastructure for several years.

These actions are detailed in section 3.

3.4.5 Build up demand for hydrogen in heating

The barriers to uptake of hydrogen in the heat sector are not specific to the development of biohydrogen, and are therefore not the focus on this report (see for example the UK HFC roadmap[193] for a comprehensive review of these issues). However, creating demand for hydrogen for heating is essential to the development of biohydrogen technologies, so we note above several actions that could be effective: allowing partial hydrogen blending in the gas grid, continuing feasibility work into gas grid conversion to hydrogen and continuing feasibility work into increased use of hydrogen in heating.

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[191] EPSRC (2017) https://www.epsrc.ac.uk/research/ourportfolio/researchareas/bioenergy/

[192] H2FC Supergen (n.d.) Hydrogen Production http://www.h2fcsupergen.com/research-type/hydrogen-production/ (Accessed on 24th July 2017)

[193] E4tech and Element Energy (2016) Hydrogen and Fuel Cells: Opportunities for Growth A Roadmap for the UK

3.4.6 Support the development of a strong biomass supply chain

Actions for the development of a strong biomass supply chain were detailed in section 2.4.6. These are also relevant for the development of the biohydrogen industry, but given the earlier TRL stage of biohydrogen, are less urgent for this technology.

3.5 Indicative timeline

Figure 4 outlines the actions that are required to promote the development of the biohydrogen industry, including supporting the innovations outlined in section 3.2. Actions which are required before 2020 should be prioritised in order for the long-term benefits to be realised, and actions highlighted in bold are anticipated to be particularly important to the development of the biohydrogen industry.

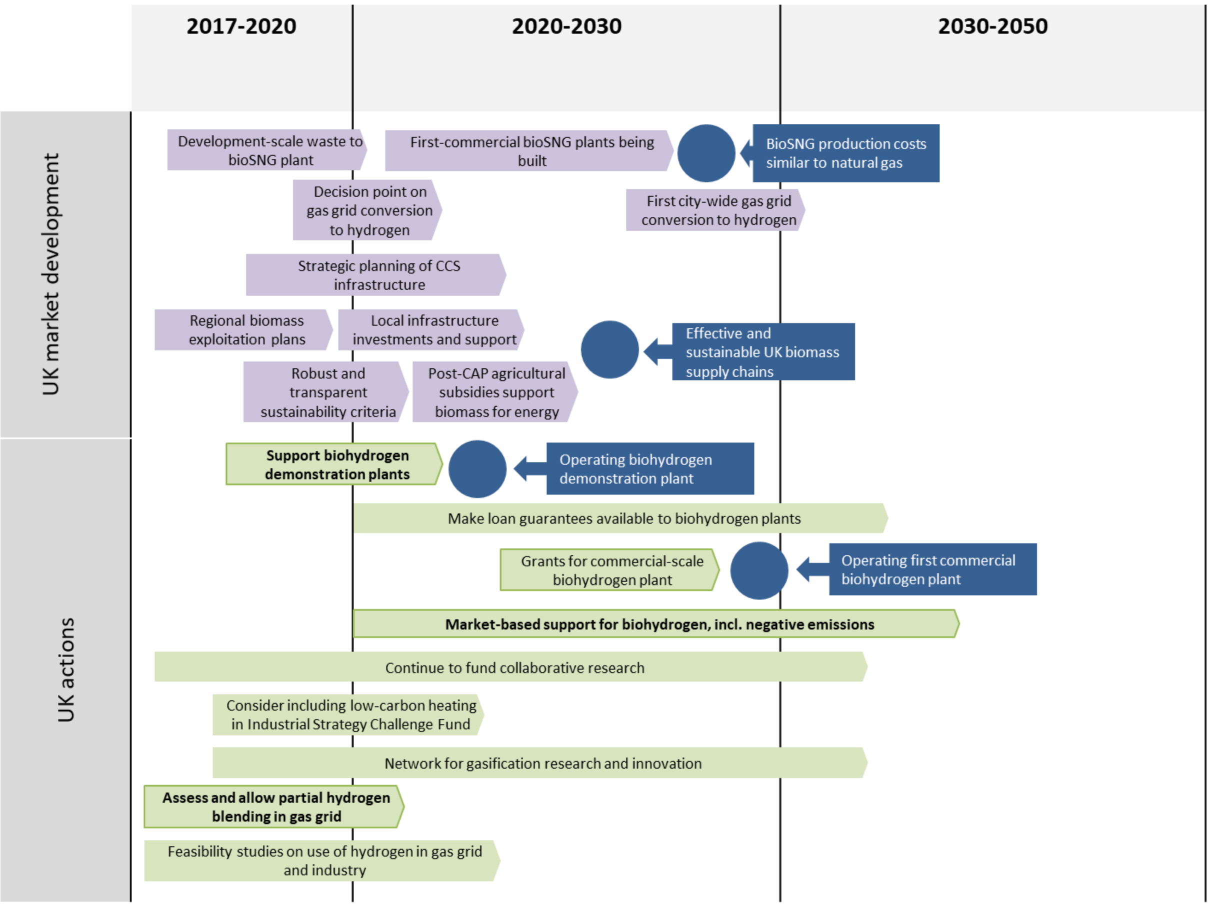

Figure 4 Actions for the support of biohydrogen production, as required over time (green chevrons) in the context of wider UK market developments (purple chevrons)

Currently, biohydrogen plants are at pilot scale. To establish the potential for the technology in the UK, and to focus R&D efforts, demonstration-scale plants are required. For these, both support for capex and market-based support for the biohydrogen are important, which could be via transport and/or heat policy mechanisms. This is broadly in line with what is suggested in the UK HFC roadmap,[194] which anticipates the planning and construction of two demonstration plants between 2020 and 2025 funded through a demonstration competition, with the second plant at larger scale than the first. Some learnings are anticipated to come from the development of bioSNG technology, which will be scaled up before biohydrogen, and may allow hydrogen production from a syngas slipstream. However, development of bioSNG is not sufficient alone, as there are several innovation activities detailed above that are specific to hydrogen production, and could have hydrogen production efficiency and energy benefits irrespective of the gasification technology used. To develop these, an increased research focus on biomass gasification routes to hydrogen would be required, together with the demonstration facilities above to allow scale up.

The substantial benefit of biohydrogen compared to other low-carbon hydrogen production methods, is its ability to achieve negative emissions when coupled with CCS. However even if CCS infrastructure is not in place, there is still value in developing biohydrogen production technology. If there is no CCS infrastructure in place, biohydrogen remains the lowest-cost way of producing low-carbon hydrogen because SMR without CCS is not low-carbon and biohydrogen is in general cheaper to produce than hydrogen from electrolysis (which can be low-carbon). Therefore, whilst decisions around the roll-out of CCS infrastructure in the UK are important for biohydrogen, development of the technology does not need to be delayed until these decisions have been made.

Of more critical importance to the development of the biohydrogen market is building up demand for hydrogen in heating, including compatibility with end-use appliances. Whilst it is not necessary for there to be a large market today, given that little biohydrogen is likely to be produced in the UK in the next 5 to 10 years, a UK heat strategy indicating a significant anticipated role for hydrogen in the future heating system would enable a build up of interest in biohydrogen technology from academics and gasification plant developers. Allowing low-volume hydrogen blends in the gas grid, and supporting feasibility studies into gas grid conversion would provide a clear signal that these large anticipated markets can be realised.

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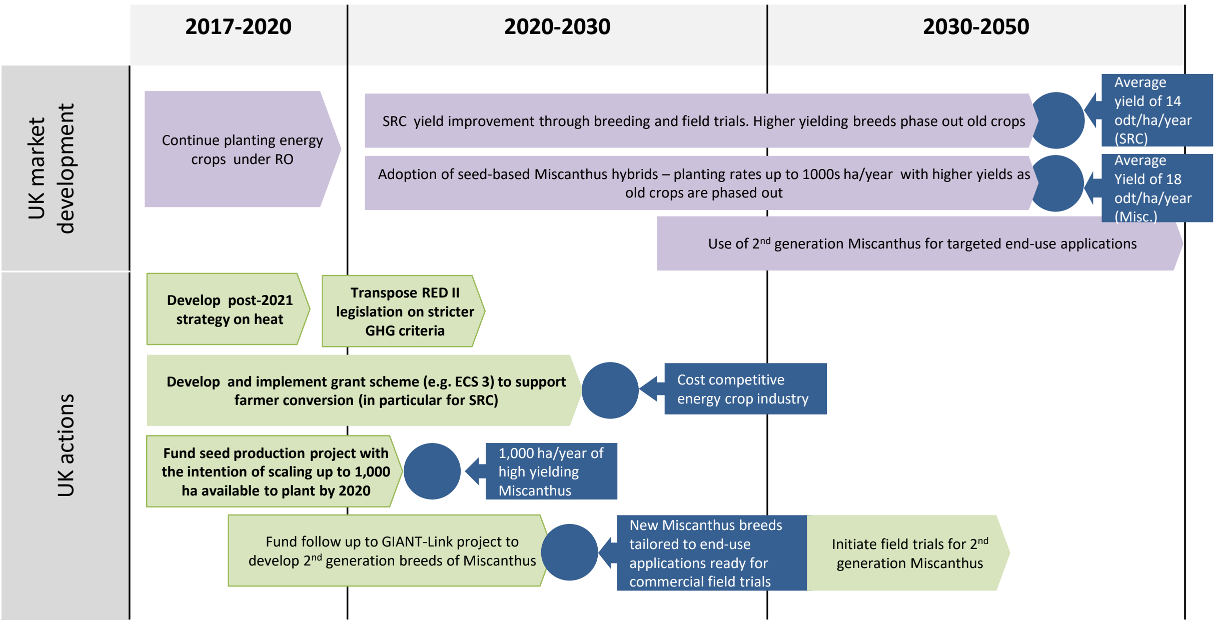
[194] E4tech (2016) Hydrogen and fuel cells: opportunities for growth, http://www.e4tech.com/reports/hydrogen-and-fuel-cells-opportunities-for-growth-a-roadmap-for-the-uk/

4 Woody and grassy energy crops

Summary

- Woody crops (such as short rotation coppice (SRC) and short rotation forestry (SRF)) and grassy crops (such as Miscanthus) can be specifically grown for energy purposes, with high yields and relatively low inputs.
- Although some of these crops are grown extensively in other regions, planted areas are small in the UK. Nevertheless, both in the UK and globally, energy crops have the potential to be a major source of biomass to 2050, and can be used for all bioenergy routes, including to heat, power, transport fuels and chemicals. This relies primarily on significantly increasing the rate of planting from today, as well as in parallel increasing yields to reduce costs and increase output from future planting.
- Developing improved and higher yielding breeds of energy crops would have a major impact on reducing costs, increasing planting rates and improving sustainability performance. The crop yield (tonnes of crop per hectare of land) has a significant influence on the crop production cost, given that many of the costs are related to the area of land used or the quantity of planting material needed. Innovation could lead to increased yields in 2050 of 67% for Miscanthus to reach 18 odt/ha/yr and 64% for SRC to reach 14 odt/ha/yr, compared with 2017 yields. Higher yielding breeds could lead to a 33% reduction in feedstock production cost for Miscanthus to £45/odt and 34% reduction for SRC to £52/odt by 2050. Development of new breeds could also focus on improving sustainability, such as increasing water and nutrient efficiency, and allowing use of poorer quality or contaminated land.
- For Miscanthus, developing breeds that can be planted from seed would also allow a faster rate of planting and reduce establishment costs, which are a major contributor to production costs. UK research institutions are world leaders in Miscanthus R&D and breeding and in collaboration with other countries have led the advancement in Miscanthus breeding over the last decade. To commercialise new breeds of Miscanthus, seed production programmes would be needed as well as follow up research projects to capitalise on advances made to date.
- Improving planting methods could lead to reductions in planting material and planting contractor costs for both SRC and Miscanthus, which in both cases is a significant contributor to production cost. Enhancing agronomic practices such as optimising supply chains to specific end-uses, improving harvesting, fertiliser and weeding techniques can also significantly improve yield and cost. This is in particular true for SRC willow which requires specialised machinery and is highly sensitive to weed control.
- In the UK context, increasing planting rate requires supporting farmers to overcome initial costs and delayed payback from these crops, together with consistent policy to signal and maintain stable market demand. This includes heat policy, but also clarity on the potential demand for energy crops for transport, power and chemicals. This planting today will lead to learning in agronomics and development of supply chains.

- An indicative timeline to increase innovation in energy crops in the UK is included in the figure below:



4.1 Introduction

4.1.1 Feedstock description

Crop types

This section considers woody and grassy energy crops that are specifically grown for energy purposes. Interest in these crops has stemmed from their ability to be grown on lower quality land than that used for food production, with low levels of maintenance and fertilizer input and high growth rates, as well as the potential to increase soil carbon.

Woody energy crops considered in the UK are short rotation coppice (SRC) willow, SRC poplar and short rotation forestry (SRF). These feedstocks are considered the most attractive UK biomass resource as they can provide a good mix of yield, cost effectiveness and greenhouse gas performance[195]. SRC usually consists of densely grown poplar or willow providing high yields. SRC aims to increase the rate at which harvesting can occur compared with traditional long rotation practices. SRC is planted as cuttings or rods in spring, using specialist equipment, and is normally ready for harvest after four years, depending on climatic conditions, after which point it can be harvested every three years. The life span of an SRC crop is typically 23 years.[196,197] SRF is an agricultural practice aimed at cultivating fast growing trees and uses a number of different species including birch, poplar and willow. Depending

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[195] Energy Technologies Institute (2015) "Bioenergy: Enabling UK Biomass" http://www.eti.co.uk/insights/bioenergy-enabling-uk-biomass/

[196] "Short Rotation Coppice establishment" Forest Research. Web. 24 May 2017. Available on: https://www.forestry.gov.uk/fr/infd-8a5kl3

[197] Energy Technologies Institute (2016) "Bioenergy crops in the UK. Case studies of successful whole farm integration" http://www.eti.co.uk/library/an-eti-perspective-bioenergy-crops-in-the-uk-case-studies-of-successful-whole-farm-integration

on the species, the trees will normally be ready for harvesting between four and twenty years. Currently SRF is only being trailed on a few plots in the UK.[198]

The grassy energy crop that has been considered in most detail for the UK is Miscanthus. Miscanthus is a high yielding perennial energy crop which can be harvested every year, although establishing the crop normally takes three years. Miscanthus is traditionally grown from rhizomes (roots that grow horizontally) [199]. Miscanthus requires low maintenance, e.g. requires few pesticides and fertilisers during establishment of the crop, and has a long life span (20 years or more). [200,201] These energy crops are complementary in the UK as they provide different yields and suitability with demand and supply chains in different parts of the country. SRC willow is optimal in the west and north-west whereas Miscanthus and SRF are optimal in the south and east.

Other notable energy crops, not grown in the UK, include switchgrass, giant reed, and eucalyptus. Switchgrass and giant reed are grassy crops with the latter predominantly found in dryer and warmer regions. As with other energy crops, giant reed can tolerate low quality soils. Switchgrass is well adapted for northern climates and varieties exist that are adapted to most regions of Europe and North America.[202] Switchgrass and giant reed can be planted as seeds, weeded and fertilized as needed and harvested annually. Eucalyptus is a woody crop with high growth rates and is grown as a short rotation forestry feedstock for the pulp industry.[203] Eucalyptus is intolerant of frost and is therefore grown in warmer climates such as South America and in parts of China. Compared to other energy grasses, Miscanthus was chosen as the ideal energy grass in the UK due to its high photosynthetic efficiency (80%) and that it grows well in the UK's temperate climate.

Indicative cost and emissions breakdown

The contributors to the cost of energy crops consist of pre-planting preparation (such as vegetation removal and ploughing), the planting material itself and the cost of contractors to plant it, other planting costs (herbicides, fertilisers, harrowing, fencing, topping), harvesting (which can include mowing/cutting, baling and carting) and land rent. The breakdown of costs between these steps varies considerably based on the crop type and on the location (previous land use, soil type, climate etc). As an example, Figure 5 shows an example breakdown of costs for UK Miscanthus production, based on a calculator developed for the ETI [204]. The levelised cost of Miscanthus production is £67/odt (oven dried tonne) Miscanthus, assuming 23 years of growth and a yield of 10.8 odt/ha. The main cost contributors are the land rent, planting material (rhizomes), and baling of the harvested Miscanthus. Where the grower owns the land, the land rent would not apply. The crop yield (odt/ha) has a significant influence on the levelised cost, given that many of the costs are related to the area of land used or the quantity of planting material: a 10% yield increase from the baseline used gives a 7% reduction in levelised cost.

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[198] Low Carbon Innovation Group, *Technology Innovation Needs Assessment: Bioenergy Summary Report* (2016) pg. 9

[199] Rhizomes are essentially horizontally growing rootstalks

[200] "Miscanthus, a revolutionary biomass crop" Recrops. Web. 24 May 2017. Available on: http://www.recrops.com/Miscanthus

[201] Energy Technologies Institute (2016) "Bioenergy crops in the UK. Case studies of successful whole farm integration"

[202] IEA Bioenergy Task 43 (2011) "Switchgrass Production in the USA" http://ieabioenergytask43.org/wp-content/uploads/2013/09/IEA_Bioenergy_Task43_PR2011-03.pdf

[203] IEA Bioenergy Task 43 (2011) "Short Rotation Eucalypt Plantations for Energy in Brazil" http://ieabioenergytask43.org/wp-content/uploads/2013/09/IEA_Bioenergy_Task43_PR2011-02.pdf

[204] E4tech Energy Crops Calculator from Taylor R, Ripken R, Montemurro F, Bauen A. Energy Crop Competitiveness and Uptake Report, version 5.4. Energy Technologies Institute, London, UK: 2013

Hastings et al (2017)[205] estimated the greenhouse gas emissions impacts of different stages of Miscanthus cultivation. This showed that for Miscanthus established from rhizomes, on light soil with moderate weed control and without fertilisation, the diesel used in planting contributes to 50% of GHG emissions from establishment, followed by 35% for ground preparation, and 10% from rhizomes. GHG emissions from harvesting and transport are highly variable depending on the form of the transported material (chopped material, bales, pellets) and the transport distance.

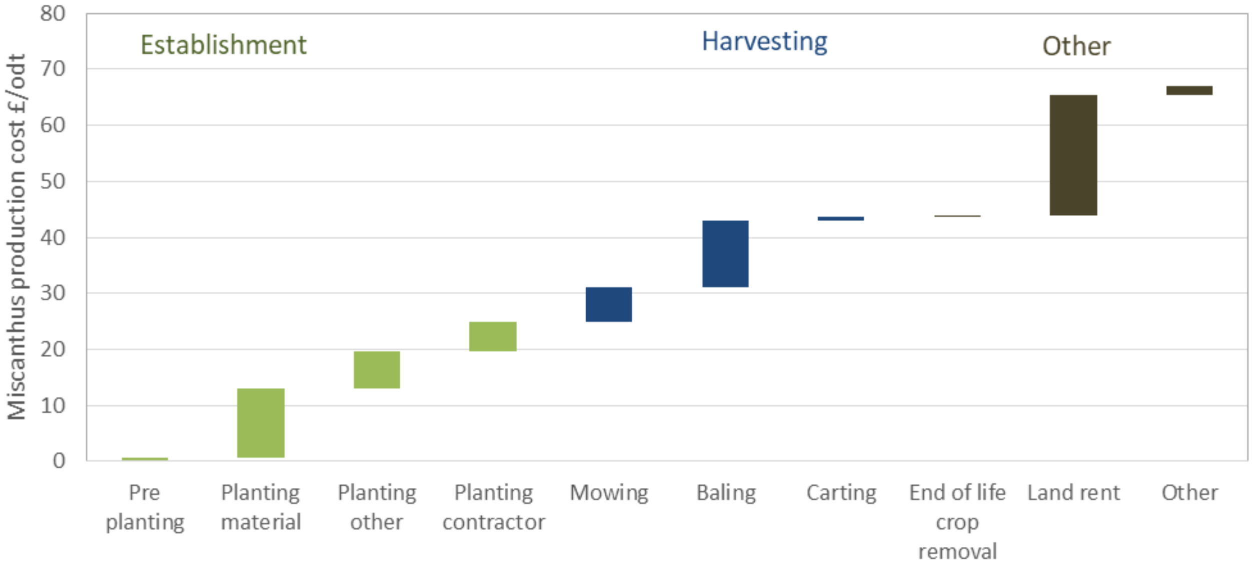

Figure 5: Indicative cost breakdown for Miscanthus production in the UK

Figure 6 shows an example breakdown of costs for UK SRC willow production, based on a calculator developed for the ETI [206]. The levelised cost of SRC production is £80/odt SRC, assuming 23 years of growth and a yield of 8.5 odt/ha. The main cost contributors are land rent, harvesting and carting, drying, planting material and other planting costs (herbicide, fertiliser, harrowing, fencing). Where the grower owns the land, the land rent would not apply. The crop yield (odt/ha) has a significant influence on the levelised cost, given that many of the costs are related to the area of land used or the quantity of planting material: a 10% yield increase from the baseline used gives an 8% reduction in levelised cost.

The B2C2 calculator[207] gives an indicative breakdown of GHG emissions for SRC cultivation and harvesting, based on a yield of 7 odt/ha. Emissions are split between diesel for harvesting (30%), nitrous oxide emissions from soil (22%), and fertiliser, pesticide and diesel for cultivation (each around 15%). As for cost, the emissions are highly dependent on crop yield, and vary considerably between soil and climate types.

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[205] Hastings et al (2017) Economic and Environmental Assessment of Seed and Rhizome Propagated *Miscanthus* in the UK. Front Plant Sci. 2017; 8: 1058

[206] E4tech Energy Crops Calculator from Taylor R, Ripken R, Montemurro F, Bauen A. Energy Crop Competitiveness and Uptake Report, version 5.4. Energy Technologies Institute, London, UK: 2013

[207] B2C2 https://www.ofgem.gov.uk/publications-and-updates/uk-solid-and-gaseous-biomass-carbon-calculator

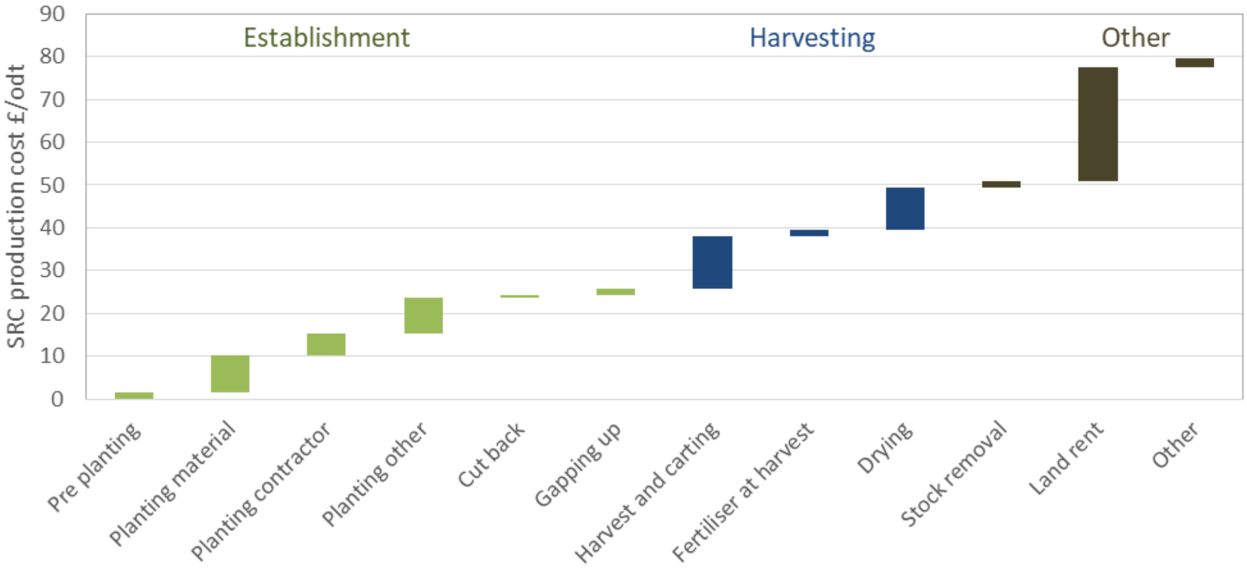

Figure 6 Indicative cost breakdown for SRC production in the UK

4.1.2 Global status

Global production of woody and grassy energy crops was 47 million odt in 2015.[208] Brazil is a major producer of SRF (including eucalyptus, pine and poplar) grown for the pulp and paper industry, charcoal, and wood products as well as for energy. 0.6% of Brazilian land area is forest plantations, predominantly eucalyptus and pine, totalling 6.3 mha.[209] SRC eucalyptus, with shorter rotation times than SRF, is also grown for energy purposes in Brazil although to a lesser extent than for traditional industries. South America is estimated to have the largest theoretical potential for woody and grassy energy crops, although there has been less interest in grassy crops than in SRF.

In the US, research on cultivation of switchgrass for energy purposes has been on-going since the late 1970s. Switchgrass is used as a forage crop for low grade feed and animal bedding, is broadly adapted to a range of climates and habitats, is native to North America (reducing concerns over use of an invasive species), has high yields with minimal inputs, and can be grown on marginal lands. Switchgrass in the US is used to produce pellets for and as a feedstock for cellulosic ethanol production[210] but there is only a small amount of land in the US dedicated

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[208] Calculated from (2009) de Wit and Faaij. European biomass resource potential and costs Biomass and Bioenergy, volume 34, issue 2, pp. 188 - 202

[209] Short Rotation Eucalypt Plantations for Energy in Brazil. IEA Task Force 43 (2011) http://ieabioenergytask43.org/wp-content/uploads/2013/09/IEA_Bioenergy_Task43_PR2011-02.pdf

[210] Penn State Extension: NEWBio Energy Crop Profile: Switchgrass (2012) Available on: www.newbio.psu.edu/Extension/switchgrass3.pdf

to it.[211] The Environmental Protection Agency expects 1.1 million ha of switchgrass in the US by 2022 depending on market demand.[212] Estimates for total potential US energy crop production in 2030 are 400 million odt/year[213].

According to the CORDIS 4F CROPS project, the EU has at least 100 kha of energy crops used for power and heat.[214] The crops mainly include Miscanthus, giant reed, switchgrass, reed canary grass and cardoon. A large portion of this is 20 kha of reed canary grass in Finland. According to the EU funded OPTIMISC project there is an estimated 20 kha of Miscanthus in Europe with most Miscanthus production occurring in the UK (10 kha), France (4 kha) and Germany (4 kha), Switzerland (0.5 kha) and Poland (0.5 kha). [215] The European countries with the largest areas of SRC production are Sweden, UK and Poland with Sweden being considered a leader in SRC willow.[216]

4.1.3 UK status

An estimated 135 kodt of Miscanthus and 23 kodt of SRC willow and poplar is grown annually in the UK. [217] There are no imports of energy crops to the UK although this may change if demand develops and global availability of energy crops increases. Uses of Miscanthus in the UK include livestock bedding, power generation, small scale CHP and use directly for heating buildings. Minor amounts of SRC are used for power generation. The UK potential for sustainable energy crop production by 2030 is estimated at 4.3 million odt/year. This compares to 12.42 million odt/year in France, 7.8 million odt/year in Germany, and 1.1 million odt/year in Sweden. [218]

4.1.4 Enabling factors for innovation

Global capabilities and support

Brazil has supported research into SRF and other energy crops since the 1960s with a focus on sugarcane and eucalyptus. The main research hub for agricultural research to date has been the Embrapa (Brazilian Agricultural Research Corporation) which is currently funding projects on napier grass and improving the genetic characteristics of various energy crops. Germany is a leader in Miscanthus research, through centres such as the Helmholtz Centre for Environmental Research, alongside the University of Illinois (American Institution for Research on Miscanthus) in the US. Several interviewees mentioned the UK as a global leader in energy crop R&D and breeding, in particular Miscanthus, and Sweden a global leader in SRC willow. The two countries have experience of collaboratively developing new types of SRC willow through the BREDNET-SRC project, led by Rothamsted Research and the

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[211] DOE (2016) 2016 Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy 2016 Billion-Ton Report: Advancing Domestic Resources for a Thriving Bioeconomy

[212] Cenusa Bioenergy (2012) *Sustainable Production and Distribution of Bioenergy for the Central USA* *https://cropwatch.unl.edu/documents/Switchgrass%20Cost%20of%20Production%20-%20Marty%20Schmer%20-%20USDA%20ARS.pdf*

[213] Union of Concerned Scientists (2012) *The Promise of Biomass – Clean Power and Fuel – if Handled Right* *http://www.ucsusa.org/sites/default/files/legacy/assets/documents/clean_vehicles/Biomass-Resource-Assessment.pdf*

[214] 4F CROPS (2015) *Report Summary*. Available on: http://cordis.europa.eu/result/rcn/162500_en.html

[215] OPTIMISC (2016) *Report Summary.* Available on: http://cordis.europa.eu/result/rcn/188169_en.html

[216] SRCPlus (2014) *About SRC* Plus Available on: http://www.srcplus.eu/en/about-srcplus.html

[217] Calculated based on estimated planted kha and average yields. Miscanthus planted area (10 kha) derived from OPTIMISC project and SRC from Defra (2016) "Crops Grown for Bioenergy in England and the UK: 2015" https://www.gov.uk/government/statistics/area-of-crops-grown-for-bioenergy-in-england-and-the-uk-2008-2015

[218] Calliope Panoutsou et al., *National roadmaps for lignocellulosic biomass and relevant policies for a bio-based economy in 2030:* (2016) Available on: http://www.s2biom.eu/en/publications-reports/s2biom.html

Swedish University of Agricultural Sciences. The project was backed by Lantmännen, an agricultural cooperative and marketer of willow.[219] There are also a few private companies involved in genetic research on energy crops including Swiss-based Syngenta, and US based CERES which works on developing different varieties of Miscanthus seeds.

UK capabilities[220]

UK is considered a global leader in energy crops (in particular Miscanthus and SRC) with capabilities throughout the supply chain from R&D, growers, intermediaries and end-users. Notable UK organisations involved in energy crop research include:

- **Aberystwyth University**: The Energy Crop Biology research group at Aberystwyth University is a world leading research centre focusing on Miscanthus growth and development. It maintains a breeding programme focusing on increasing the net energy yield per hectare on marginal lands. The programme involves managing one of the largest Miscanthus germplasm collections in the world. The group was also involved in the Carbo-BioCrop project which aimed to understand energy crops' impact on soil carbon balances together with the University of Southampton. In 2012 Aberystwyth University, University of Aberdeen and CERES finished mapping the genetics of Miscanthus with the aim of creating new breeds as part of the pioneering GIANT Link project.[221]
- **University of Southampton:** carries out world leading work in anaerobic digestion and energy crops. The Bioenergy and Organic Resources research group works on a number of international projects including the on-going WATBIO which aims to accelerate the breeding of energy crops for drought-stressed conditions while maintaining high yields. The project focuses on poplar, Miscanthus and arundo donax. [222]
- **Rothamsted Research**: is a world leading research centre focused on SRC willow and Miscanthus. Rothamsted is the programme lead for the BBSRC's energy crops programme and focuses on breeding through for example mapping Miscanthus populations and field experiments. Rothamsted also manages the UK's willow germplasm collection and breeding programme.
- **BBSRC Sustainable Bioenergy Centre (BSBEC)**: BSBEC was set up with £20 million funding from the Research Council UK's Energy Programme. [223] Researchers at BSBEC are aiming to improve biomass yields via genetic improvement of plants (e.g. by increasing the amount of sunlight plants are able to capture) and to develop tools for selecting genotypes.[224] To this end, BSBEC oversees one of UK's Miscanthus germplasm collections.
- **Centre for Ecology and Hydrology (CEH)**: is a research organisation focusing on the ecological impacts of energy crops including soil carbon impact and land use changes. CEH led the Ecosystem Land Use Modelling and Soil Carbon Flux Trial (ELUM[225]) together with University of Southampton, Aberystwyth and others. This was

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[219] "Towards targeted breeding of a European SRC willow crop for diverse environments and future climates (BREDNET-SRC) (2017)" Available on: http://gtr.rcuk.ac.uk/project/18EAF5A4-530C-40C2-867A-6B87E653083D. Accessed: May 24th 2016

[220] Taylor, R et al (2014) Version 1.1. UK Energy Crop Business Models – Task A report. For the Energy Technologies Institute London, UK

[221] Austin, Anna. "Ceres, UK University Complete Genetic Map of Miscanthus." Biomassmagazine.com. N.p., 20 Mar. 2012. Web. 24 May 2017.

[222] "Research Project: Development of Improved Perennial Non-food Biomass and Bioproduct Crops for Water-stressed Environments (WATBIO)." Development of Improved Perennial Non-food Biomass and Bioproduct Crops for Water-stressed Environments (WATBIO) | Biological Sciences | University of Southampton. N.p., n.d. Web. 24 May 2017

[223] "Bioenergy" Research Councils UK Web. 24 May 2017 Available on: http://www.rcuk.ac.uk/research/xrcprogrammes/energy/EnergyResearch/Bioenergy/

[224] "Perennial Bioenergy Crops." *BBSRC Author*. N.p., n.d. Web. 24 May 2017. Available on: http://www.bbsrc.ac.uk/research/institutes/bsbec/perennial-bioenergy-crops/

[225] ETI (2017) "Ecosystem Land-Use Modelling", Available from: http://www.eti.co.uk/programmes/bioenergy/ecosystem-land-use-modelling-elum

a 4-year £4 million undertaking funded by the Energy Technologies Institute (ETI) to better understand soil carbon and greenhouse gas fluxes associated with land use change.

The majority of research and energy crop innovation conducted in the UK currently focuses on increasing crop yields, in particular yields on lower quality lands, by producing new breeds – this will be discussed in detail below. Led by CEH, the UK also has expertise in land use management soil carbon implications and non-technical aspects of energy crops. Other programmes, such as the RELU programme, have studied the social, environmental and economic implications of land use changes.[226] The ETI is an industry and government-funded organisation which has carried out considerable amounts of work on the business model, policy and environmental implications of energy crops.

In addition to R&D capabilities, the UK has a relatively established but small energy crop industry. Coppice Resources is a grower and vertically integrated player who owns 1500 ha of SRC. Miscanthus Growers Limited is another player, comprising of a group of 80 local Miscanthus growers. In total the group owns around 4000 ha of Miscanthus fields – or about half of total planted area in the UK. Other players include Mere Plantation, Grange Farm, Strawson Energy and SEIL. SEIL provides services across the supply chain including rhizome planting, crop establishment, harvesting services and consultancy.

The UK also has a number of establishment contractors who grow rhizomes (Miscanthus roots) to sell to farmers who want to establish a Miscanthus crop. These actors also offer support services to new farmers who may otherwise lack the necessary knowledge. Players in this area are International Energy Crops and Miscanthus Nurseries.

Besides research organisations, growers and contractors, the UK has a presence of intermediaries that buy the energy crop, process it (normally to chips or pellets) before selling it on to the end user. Terravesta is one such company which buys the production from numerous farmers and then sells it to end-users in power and heat. Terravesta is also involved in R&D, focusing on growing Miscanthus from seeds in the GIANT Link and MUST project which has the potential to significantly scale production compared to using rhizomes (see innovation activities below)[227]. Other actors are South East Wood Fuels and Renewable Energy Growers.

UK support schemes

There is currently no public support to farmers to encourage growth of energy crops. The Energy Crop Support (ECS) scheme ran from 2000 – 2013, in two different phases, and although it supported the early growth of energy crops it fell short of its own deployment targets.[228] The Renewables Obligation (RO) provides support to plant operators using renewable fuel and is currently creating demand for energy crops from power plants such as Briggs

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[226] "Bioenergy" Research Councils UK Web. 24 May 2017 Available on: http://www.rcuk.ac.uk/research/xrcprogrammes/energy/EnergyResearch/Bioenergy/

[227] Cracroft-Eley, William "Growing Miscanthus from seed" (2015) 20 August 2015. Web 24 May 2017. Available on: http://www.terravesta.com/blog/post/08/2015/Growing-Miscanthus-from-seed-

[228] Mawhood, R., Slade, R and Nilay Shah (2016) "Policy option to promote perennial energy crops: the limitation of the English Energy Crop Support Scheme and the role for agent-based modelling in policy design". Available on: https://spiral.imperial.ac.uk/bitstream/10044/1/26656/2/Mawhood%202015%20AAB%20Policy%20options%20to%20promote%20perennial%20energy%20crops.pdf

and Snetterton (40-50 MW). The RO closed to new applications in March 2017 and will be replaced by the Contract for Difference (CfD). The Renewable Heat Incentive (RHI) is a feed-in-tariff scheme intended to stimulate demand for renewable fuels in heat generation and is open to new applications to 2021. Energy generated from energy crops can qualify for both CfD and RHI support.

The Research Council UK's Energy Programme (RCUK) has played an important role in supporting energy crop research. The programme has provided funds to initiatives such as the TSEC-BIOSYS Consortium[229] focusing on the technical, economic, environmental and social issues related to bioenergy in the UK. The Rural Economy and Land Use programme (RELU) is another RCUK funded programme. The Biotechnology and Biological Sciences Research Council's (BBSRC) Sustainable Bioenergy Centre (BSBEC) was launched in 2009 and is the largest single UK investment in bioenergy research at £24 million, also funded by the RCUK Energy Programme. These projects bring together leading universities and centres in UK bioenergy and energy crop research.

4.2 Innovation activities and their impacts

In this section we have identified key energy crop innovation activities under the categories of *1) breeding and crop R&D* and *2) growing and harvesting*. The activities are based on R&D priorities for development of lignocellulosic biomass as identified in the EU funded S2BIOM project[230], which ran over three years (2013-2016) and involved 31 research organisations from across the EU. The innovation activities were also validated by expert interviews and wider literature. The activities focus on SRC and Miscanthus due to the interest and capabilities in these feedstocks in the UK.

Innovation activities were identified across the value chain, although the interviewees considered that the most important innovation areas were in breeding and R&D. Commercialising new genotypes is important to both increase yields and planting rates and to improve sustainability performance. Breeding new varieties that can be grown from seed is a central part of the research agenda to increase yields and reduce costs for Miscanthus. Seed-based Miscanthus hybrids offer a breakthrough innovation opportunity to both increase planting rates and reduce establishment cost. This opportunity is not available to SRC. Overall, there is a significant amount of energy crop R&D in the UK and continued funding of these activities is important to making further progress. The UK could export this know-how in the form of selling seed and licensing IP on new breeds.

In addition to R&D and breeding, improving agronomic practices is considered an important innovation area, in particular in improving planting and fertiliser techniques and developing optimised harvesting and distribution systems. Some interviewees mentioned a potential to manufacture bespoke machinery domestically. The following sections elaborate on these innovation opportunities and their potential to improve energy crop economics and sustainability performance.

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[229] A whole-system approach to analysing bioenergy demand and supply: mobilising the long-term potential of bioenergy http://gtr.rcuk.ac.uk/projects?ref=NE%2FC516287%2F1

[230] Calliope Panoutsou et al. (2016) "R&D roadmap for lignocellulosic biomass in Europe". Available on: http://www.s2biom.eu/en/publications-reports/s2biom.html

4.2.1 Breeding and R&D: developing new energy crop varieties

Only a few varieties of energy crops are currently grown commercially and there is therefore significant potential in the breeding and R&D stage in developing new varieties of Miscanthus and SRC with the following possible benefits:

Increase Miscanthus planting rate while decreasing cost through seed-based hybrids

Miscanthus is traditionally grown through planting rhizomes. Rhizome planting is relatively labour intensive and is difficult to scale up due to slow propagation; 1 ha of rhizomes provides 10-30 ha of new Miscanthus. To overcome this shortcoming the GIANT-Link project (2012-2016) made 3500 breeding crosses to identify combinations capable of producing seed-based hybrids. It is estimated that 1 ha of Miscanthus seed could plant 2,000 ha of new crops.[231] Table 4 shows various estimated energy crop planting rates with different levels of supportive farming policy and a transition to seeds by 2019, which is the earliest time by which seed-based hybrids will be commercially available.[232], [233] While other energy grasses, such as switchgrass, can be grown from seed, these species can be more invasive than the currently developed seed-based Miscanthus hybrids.

Table 4 Planting rate scale up with seed-based hybrids

		2017	2018	2019	2020	2021	2022	2023	2024	2025
Planting rate (ha/yr)	Low	87	87	87	1000	1130	1277	1443	1630	1842
	Medium	132	152	175	1000	1160	1346	1561	1811	2100
	High	191	248	323	1000	1250	1563	1953	2441	3052

GIANT Link was followed by the £1.8 million on-going Miscanthus Upscaling Technology (MUST) project which is implementing commercial seed production experiments with a selected number of hybrids identified in GIANT Link. To facilitate seed establishment, this project is focusing on sowing seeds in modular plugs in glasshouses, preceded by strict germination tests and examinations of different composts, temperatures and fertiliser regimes.[234] Successful commercial deployment of seed-based hybrids could lead to a substantial increase in planting rates from the current ~100 ha/year to >1,000 ha/year, clearly contributing to a faster ramp up of Miscanthus production. There is currently no comparable effort to decrease establishment cost and increase planting rates for SRC, because SRC species do not produce or grow from seeds.

Seed-based hybrids also comprise less material than rhizomes. As planting material makes up the majority of establishment costs, results from the MUST project and other on-going field trials suggest that switching to seed based hybrids can reduce establishment costs by as much as 45% if applied via direct planting. However, the first seed-based hybrids are likely to be planted in seed plugs due to yield benefits for the final crop compared with directly planted seeds. Current methods for direct seed sowing have proven to waste seeds and produce unreliable

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[231] Cracroft-Eley, William (2015) *Growing Miscanthus from seed.* Available on: http://www.terravesta.com/blog/post/08/2015/Growing-Miscanthus-from-seed-

[232] Includes SRC. Source: Anthesis and E4tech (2017) Review of Bioenergy Potential: Technical Report for Progressive Energy and Cadent, to be published

[233] Farming (2016) *Terravesta: Miscanthus grown from seed available as soon as 2019.* Available on: http://www.wnif.co.uk/2016/07/terravesta-Miscanthus-grown-from-seed-available-as-soon-as-2019/

[234] Clifton-Brown, J et al. (2017) "Progress in upscaling Miscanthus biomass production for the European bio-economy with seed-based hybrids". Available on: http://onlinelibrary.wiley.com/doi/10.1111/gcbb.12357/full

results.[235] If seed plugs are used, a 20% reduction in establishment cost could be expected.[236] The same research also suggests that whilst the GHG impacts of seeds are considerably lower than that of rhizomes, the GHG impacts of seed plugs are about four times higher than that of rhizomes (kgCO_2 eq/ha/year) due to greenhouse space used for cultivation, assuming those greenhouses are run on fossil fuels.[237]

Develop new Miscanthus and SRC breeds with higher yields

The Miscanthus Breeding Team at the Institute of Biological, Environmental and Rural Sciences (IBERS) at Aberystwyth University currently maintains the UK's germplasm collection and aims to double the net energy yield of Miscanthus by 2030 via seed based hybrids.[238] Due to the novelty of these new breeds there is limited field data available to measure yields over the lifetime of the crop. However, recent results from early field trials indicate a higher yield for the new breeds from GIANT Link compared to the traditional *Miscanthus x giganteus* within the first two years of growing.[239] UK yield forecasts see a potential of 18 odt/ha average yield[240] for Miscanthus by 2050 based on these yield improvements compared to current average yields of around 11 odt/ha.[241] Note that it is important to distinguish between average yields over the whole plantation lifetime and peak yields within this lifetime, which are currently up to 15 odt/ha.[242] Average yields over the full 20+ years of the plantation (establishment, growth phase, peak and decline) can be up to 25% below peak yields.

Indicative production costs for Miscanthus at an average yield of 11 odt/ha are £67/odt[243]. With innovation and breeding resulting in an average yield of 18 odt/ha by 2050 a 33% reduction in costs (to £45/odt) could be achieved. Such a scale up in both planting rates and yield will therefore have significant knock on effects on establishment and production costs. In addition, developing Miscanthus breeds that, for example, flower earlier than the commercially grown Miscanthus can also lead to higher quality biomass by lowering moisture content and lowering the presence of potassium and chlorine leading to less corrosion in boilers or gasifiers.[244]

Alongside disease resistance and better water/nutrient use, higher yield is one of the key aims of current SRC breeding efforts. These efforts have successfully produced new willow varieties with yields of over 14 odt/ha/year and up to 20 odt/ha from ideal conditions on individual trial sites.[245] Indicative SRC production costs at a yield of

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[235] Hastings et al (2017) Economic and Environmental Assessment of Seed and Rhizome Propagated *Miscanthus* in the UK. Front Plant Sci. 2017; 8: 1058.

[236] E4tech Energy Crops Calculator from Taylor R, Ripken R, Montemurro F, Bauen A. Energy Crop Competitiveness and Uptake Report, version 5.4. Energy Technologies Institute, London, UK: 2013. combined with data from Hastings et al (2017) Economic and Environmental Assessment of Seed and Rhizome Propagated *Miscanthus* in the UK. Miscanthus establishment cost with rhizome (3351 £/ha) was compared to establishment cost with direct drill (£1875/ha) and with seed plugs (£2695/ha). Cost reductions are based on expected reductions in planting material costs from Hastings et al (2017) pg. 8 Figure 2.

[237] Hastings et al (2017) Economic and Environmental Assessment of Seed and Rhizome Propagated *Miscanthus* in the UK. Front Plant Sci. 2017; 8: 1058.

[238] http://www.Miscanthusbreeding.org/

[239] Hastings et al (2017) Economic and Environmental Assessment of Seed and Rhizome Propagated *Miscanthus* in the UK. Front Plant Sci. 2017; 8: 1058.

[240] Anthesis and E4tech (2017) *Review of Bioenergy Potential: Technical Report*

[241] E4tech Energy Crops Calculator from Taylor R, Ripken R, Montemurro F, Bauen A. Energy Crop Competitiveness and Uptake Report, version 5.4. Energy Technologies Institute, London, UK: 2013

[242] Hastings, A., Sunnenberg, G., Lovett, A., Finch, J., Wang, S., Hillier, J. and P. Smith (2012) "Spatial Mapping and Evaluation of Miscanthus Crop Distribution in Great Britain to 2050", presentation to Carbo-BioCrop and UKERC Spatial Mapping Research update and user feed-back meeting 25 January 2012. Available at: http://www.carbo-biocrop.ac.uk/uploads/Hastings_miscanthus%20yields_UKERC.pdf

[243] E4tech Energy Crops Calculator from Taylor R, Ripken R, Montemurro F, Bauen A. Energy Crop Competitiveness and Uptake Report, version 5.4. Energy Technologies Institute, London, UK: 2013. Including land rent at £200/ha/yr

[244] Jensen, E. et al (2016) Towards Miscanthus combustion quality improvement: the role of flowering and senescence. Available on: http://onlinelibrary.wiley.com/doi/10.1111/gcbb.12391/abstract

[245] Interview with SRC willow breeder 24/07/2017

8.5 odt/ha are currently £79/odt.[246] An average SRC yield of 14 odt/ha, achievable by 2050[247], could reduce production costs by 34% for SRC. Rothamsted Research has so far registered five varieties for conventional SRC biomass markets and continues to make selections from its willow breeding pipeline.

Higher yielding crops could also improve GHG performance on a per tonne basis. Improvement from a yield of 10.8 odt/ha to 18 odt/ha, and assuming no additional input needs, could reduce the CO_2 emissions associated with the cultivation of Miscanthus by 40% from 18.6 $kgCO_2e$/tonne to 11.2 $kgCO_2e$/tonne.[248] An average yield increase from 8.5 to 14 odt/ha for SRC could reduce GHG emissions from SRC cultivation by 39% from 9.26 $kgCO_2e$/tonne to 5.6 $kgCO_2e$/tonne.[249] In addition, increasing yields have been shown in the ELUM project[250] to have important soil carbon benefits.

Develop breeds with improved biodiversity impacts, nutrient efficiency and land-use impacts

GIANT Link focused on producing Miscanthus breeds with higher yields and planting rates with knock on effects on GHG performance. However, future breeds being developed can also be more drought resistant, and process water and nutrients more efficiently thereby improving overall sustainability performance including on-farm environmental benefits. The ongoing MISCOMAR[251] project funded by EU and UK partners is currently testing the ecological and environmental impact of the new seed-based hybrids on marginal lands and on heavy metal contaminated soils.[252] The project is expected to be completed in 2019. It should be noted that nutrient efficiency for Miscanthus is already one of the highest of all crops and there may therefore be limited additional benefits from increasing nutrient efficiency further.

Increasing water and nutrient efficiency and increasing SRC willow's ability to grow on marginal lands is one of the key aims of current SRC breeding efforts at Rothamsted Research. The BREDNET-SRC programme (2009-2012) identified a number of suitable genotypes to test for drought resistance and water and nutrient efficient genes. These have subsequently been established on field trials in UK and Sweden and follow up work through the ERA-NET programme is currently being pursued. Research efforts on SRC willow are also focusing on developing processes for extracting high-value renewable chemicals to sell to non-energy markets. This may have substantial sustainability benefits in that it could provide an alternative route to petroleum-derived chemicals (e.g. through extraction of high value chemicals from feedstock prior to feedstock use in energy sector; so-called 'cascading' use of biomass) and add value to the crop for growers. This technique is unlikely to be commercially available within the next 5-10 years.[253]

One study considered the impact of growing mixed grasses on a plot to increase biodiversity and other ecosystem services to a plot with a single grass. The study concluded that the negative yield effects of mixed grasses on

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[246] *Ibid.* Including land rent at £200/ha/yr

[247] Anthesis and E4tech (2017) Review of Bioenergy Potential: Technical Report for Progressive Energy and Cadent, to be published

[248] Assuming a fresh yield at 30% moisture content.

[249] B2C2 https://www.ofgem.gov.uk/publications-and-updates/uk-solid-and-gaseous-biomass-carbon-calculator

[250] ETI (2017) "Ecosystem Land-Use Modelling", Available from: http://www.eti.co.uk/programmes/bioenergy/ecosystem-land-use-modelling-elum

[251] MISCOMAR (Miscanthus Biomass Options For Contaminated And Marginal Land: Quality, Quantity And Soil Interactions) http://www.miscomar.eu/

[252] MISCOMAR (Miscanthus Biomass Options For Contaminated And Marginal Land: Quality, Quantity And Soil Interactions) http://www.miscomar.eu/

[253] Interview with SRC willow breeder 24/04/2017

average outweigh their biodiversity and ecological benefits. In general it could therefore be better to focus on maximising yield while protecting and restoring natural ecosystems.[254]

Summary of breeding and R&D innovation impacts

Table 5 summarises the innovation activities identified above in breeding and R&D. As shown from the cost breakdown above, yield is a key determining factor for crop cost, both for Miscanthus and SRC, and so developing improved and higher yielding breeds of energy crops is a priority in order to reduce costs. Increasing yield also has the benefit of increasing supply and improving sustainability performance. For Miscanthus, developing breeds that can be planted from seed would also reduce establishment costs, which are a major contributor to production costs, as well as enabling an increased planting rate. Developing breeds with improved biodiversity impact, nutrient efficiency and land-use impacts could have benefits through allowing a wider range of land types to be used. Although this activity has fewer near term benefits in terms of level of supply and cost, it is an important complement to breeding for yield increases, to ensure the long term sustainability of the sector.

Table 5: Breeding and R&D innovations and impacts. Dark blue = high impact, medium blue = medium impact, white = low impact

	Cost	Supply	Sustainability
Develop and commercialise seed-based Miscanthus hybrids	A move from rhizomes to seed plugs can reduce Miscanthus establishment cost by 20%, and a move to seeds could reduce this by 45%	Planting rates above 1,000 ha/year can be expected from seed plugs compared to ~100 ha/year for rhizomes. Seed plugs will also giver higher yields than rhizomes	GHG costs are higher for seed-based plugs compared to rhizomes. Gains in yield and scalability may outweigh higher carbon emissions on a per tonne basis.
Increase Miscanthus and SRC yields	Higher yielding breeds could lead to a 12% reduction in total production cost for Miscanthus and 25% reduction for SRC (£/odt).	Innovation can lead to increased average yields of 18 odt/ha for Miscanthus and 14 odt/ha for SRC by 2050 - an improvement of 42% and 70% respectively from 2017 yields.	Higher yielding energy crops could improve GHG performance by 40% for Miscanthus and 39% for SRC. Will also have soil carbon benefits.
Develop breeds with improved biodiversity impact, nutrient efficiency and land-use impacts	Low impact on cost	Low impact on supply although planting on low quality land may open up more land for planting	New breeds may be better suited for marginal lands

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[254] Anderson-Teixeira, Kristina et al. (2012) Biofuels on the landscape: Is “land sharing” preferable to “land sparing”?. Available on: http://onlinelibrary.wiley.com/doi/10.1890/12-0711.1/abstract

4.2.2 Growing and harvesting: improving agronomics

In addition to breeding and R&D to develop new crop varieties, there are a number of agronomic activities that can improve the economic and environmental performance of energy crops.

Accelerating early growth for Miscanthus

Accelerating early growth can be achieved by applying perforated biodegradable or plastic mulch films to the soil, which heat the soil to more optimal growing temperatures. Although this technique can be used for both seeds and rhizomes, it is particularly conducive to seed establishment by both raising the average soil surface temperature and by maintaining soil surface moisture which is a necessary precondition for seed establishment.[255] Researchers are currently targeting achieving 70% of the mature yield by the end of the second growing season based on mulch film application. Current research is also focusing on early growth of Miscanthus in glasshouse conditions prior to field growth under mulch films. This combination may lead to both accelerated growth and increased overall yield[256] which in turn may lead to GHG benefits from higher levels of carbon sequestration and lower emissions on a per tonne basis. Over the lifetime of the crop however, it is unlikely that accelerating early growth will have a material impact on the costs or availability of energy crops. For example, achieving 70% mature yield for Miscanthus one year early is likely to only increase overall farm output by 3.5% over the lifetime of the crop (20 years). The mulch film itself will also add £100/ha to establishment costs[257]. The benefit of accelerating growth may therefore be more in that it alleviates cash flow concerns and encourages more farmers to participate.

Improve planting, fertilising and weed control techniques

Planting material constitutes around 50% of the establishment cost of SRC (£/ha) and one interviewee identified cost reduction potential from changing the planting material used. UK companies have previously attempted to reduce planting material by planting smaller SRC cuttings (2 inches compared to 8 inches) although this initiative was abandoned due to lack of funding. Previous research has shown that the type of planting technique chosen for SRC has considerable impact on the amount of planting material required and hence cost.[258] Distinguishing features of different planting techniques are the size and direction (horizontal or vertical) of the planted cuttings or rods. Generally there is a direct relationship between the size of planting material used and the cost of that material. Reducing the material by 75% can therefore reduce planting cost by a similar amount and lead to a 25% reduction in total establishment cost.[259] For Miscanthus, the successful development of seed planting would significantly reduce planting costs per tonne of yield as shown in section 4.2.1.

For both SRC and Miscanthus, competition from weeds affects growth both in establishment and in subsequent years and research is needed to establish what weed control mechanisms are best suited to control for weeds without damaging the yield or quality of the crop. However, for SRC willow inappropriate weed control mechanisms

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[255] Clifton-Brown, J et al. (2017) "Progress in upscaling Miscanthus biomass production for the European bio-economy with seed-based hybrids". Available on: http://onlinelibrary.wiley.com/doi/10.1111/gcbb.12357/full

[256] Optimising development for improved yield quality in the perennial bioenergy crop Miscanthus http://gtr.rcuk.ac.uk/projects?ref=studentship-1674196

[257] Hastings et al (2017) Economic and Environmental Assessment of Seed and Rhizome Propagated *Miscanthus* in the UK. Front Plant Sci. 2017; 8: 1058.

[258] Larsen, S. et al (2014) "Long-term yield effects of establishment method and weed control in willow for short rotation coppice (SRC)" Biomass and Bioenergy Volume 71, December 2014, Pages 266-274

[259] *Ibid.*

can reduce yield by as much as 50-95% as it does not compete well with grasses or other weeds in the establishment phase. This has been compounded by the withdrawal of some useful herbicides recently. Appropriate agronomy and weed control is therefore crucial for willow to enable the yield benefits of new varieties to materialise in commercial operations. For Miscanthus the optimal weed control technique to apply depends on site specifics such as initial land use, type of vegetation, texture of the soil, ecology and climate.[260] The economic and GHG impacts of weed control are, however, the same regardless of the type of establishment technique chosen as weed control happens prior to establishment. [261]

There are currently also sustainability issues around fertilising which can be addressed by better application techniques – this is especially true for SRC as SRC requires more nitrogen fertiliser than commercial Miscanthus plots which currently do not require additional nitrogen application. Improved techniques include for example the use of direct drill for nitrogen application.

Optimise harvesting techniques and machinery to specific supply chains

Innovation in harvesting machinery and supply chain logistics is important in both SRC and Miscanthus. However, harvesting machinery for SRC must be customised whereas Miscanthus can take advantage of general machinery used for other crops in the summer and autumn. More bespoke SRC machinery could e.g. allow for more efficient harvesting, chipping and pelleting on-farm as well as machines with the potential to produce customised chip and/or pellet lengths depending on the intended market. Harvesting and chipping machines are expensive and fewer machines would therefore be required.[262] It would also be possible for farmers to save cost by sharing ownership of equipment within a cooperative although this may have other drawbacks –discussed further below under barriers. One interviewee commented that equipment manufacturers in the UK could play a significant role in developing bespoke SRC machinery.

Developing more effective harvesting and processing equipment for Miscanthus has significant potential for reducing transport and storage costs. For example, the adoption of large square high density balers has increased bale weights by 60% making both transport and storage more efficient.[263] Field trials have also shown that harvesting systems with low ground pressure tyres have the advantage of reducing the impact of the tyres on the soil and as such are less damaging to the crop.[264] Further field trials would also be necessary to test the most suitable equipment for each supply chain and end market. For example, baling is the economically optimal option if combined with an end-use of direct firing, while harvesting and chipping is preferred if pelleting is required. The impact of different harvesting techniques suggest that the costs vary from £28-£40 per tonne of harvested biomass.[265]

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[260] Hastings et al (2017) Economic and Environmental Assessment of Seed and Rhizome Propagated *Miscanthus* in the UK. Front Plant Sci. 2017; 8: 1058.

[261] *Ibid.*

[262] Interview with vertically integrated player 19/05/2017.

[263] Clifton-Brown, J et al. (2017) "Progress in upscaling Miscanthus biomass production for the European bio-economy with seed-based hybrids". Available on: http://onlinelibrary.wiley.com/doi/10.1111/gcbb.12357/full

[264] *Ibid.*

[265] Hastings et al (2017) Economic and Environmental Assessment of Seed and Rhizome Propagated *Miscanthus* in the UK. Front Plant Sci. 2017; 8: 1058.

Summary of growing and harvesting innovation impacts

Table 6 summarises the innovation activities identified above in growing and harvesting. These innovations all have benefits for the economic case for energy crops, either through reducing cost or improving cash flow for farmers, which should increase the speed of uptake. In particular, improving planting methods could lead to reductions in planting material and planting contractor costs for both SRC and Miscanthus, which in both cases is a significant contributor to production cost. The potential for optimised harvesting techniques will depend on the requirements of evolving UK biomass supply chains, and therefore is likely to develop as supply chains develop further.

Table 6: Agronomic innovations and impacts. Dark blue = high impact, medium blue = medium impact, white = low impact

	Cost	Supply	Sustainability
Accelerating early growth for Miscanthus	Will increase establishment cost. However, benefit would be to bring in revenue earlier for the farmer and alleviate cash flow concerns.	3.5% increase in supply over the lifetime of the crop. Main benefit is likely to be in alleviating cash flow concerns for farmers.	May be some sustainability benefits from sequestering carbon earlier on[266]. Increased yield may slightly decrease GHG emission per tonne
Improve planting, fertilising and weed control techniques	Reducing cuttings material by 75% can lead to a 25% cost reduction in establishment cost. Seed plug will reduce establishment costs significantly for Miscanthus	Significant improvement in Miscanthus establishment rate from seed plugs leading to more areas planted at a faster rate. Appropriate weed control can significantly improve SRC yields	Potential to reduce SRC fertiliser consumption by applying direct drill techniques. For Miscanthus no change from varying weed control but seed based plugs have higher GHG emissions than rhizomes
Optimise harvesting techniques and machinery to specific supply chains	Optimising machinery and techniques to fit specific end-uses can therefore improve energy crop costs. Potential for cost saving is likely larger for SRC due to requirement for specialised equipment	Improved economics (e.g. access to more markets, lower costs) may lead to more farmers converting	Understanding how to optimise harvesting and transport can improve the GHG performance of both Miscanthus and SRC.

4.3 Barriers and gaps

A number of barriers to the above innovation activities, and scaling energy crops in general, have been identified. These are discussed below under the categories of 1) cost competitiveness, 2) market conditions, 3) lack of funding 4) farmer attitudes and 5) harvesting machine availability.

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[266] Sequestration cannot be captured in GHG intensity calculations because of accounting rules (carbon sequestered by feedstock growth cancelled out by carbon emitted when feedstock is burned). However, carbon sequestered in underground root systems may be captured.

4.3.1 Cost competitiveness: difficult supply side economics

A fundamental barrier to energy crop deployment is that they currently only provide around half the annual net margins of conventional crops such as wheat.[267] The payback time on the initial investment is a risk, and the time between establishment and first payments lead to cash flow problems. Miscanthus takes a full three years to reach an economically viable yield for harvesting while SRC takes up to four years with subsequent harvesting every three years. An SRC producer commented that establishing the crop and the cost of the planting material is the most expensive part of growing SRC. A payback period of five or more years is unattractive for a farmer used to annual income.[268] Furthermore, energy crops face competition for farmer capital from other technologies such as on-farm AD or solar PV, which can provide higher profits.

The Energy Crop Support Scheme 2 (ECS 2) was designed to plant 40,000 ha of energy crops. At the end of the programme in 2013 a total of 4,000 ha of energy crops had been planted. Several flaws of the programme have been identified including[269]:

- the absence of annual payments to alleviate early stage cash flow concerns
- no compensation for the environmental on-farm benefits such as increased biodiversity and flood prevention
- bureaucratic and time consuming application process
- prescriptive demands to the farmer having an off-taker contract at the time of planting leading to the farmer entering sub-optimal contracts
- no support for machinery or supply chain capacity building

The scheme was therefore considered to have little impact in addressing the economic barriers associated with energy crops. In the absence of an improved follow-up scheme, or the commercial availability of cheaper seed-based planting, it is not clear how farmers can take on the risk of switching to energy crops.

4.3.2 Market conditions: uncertain demand side policy

Energy crops, and in particular SRC, will incur removal costs if the grower wishes to return to growing traditional crops. The long term commitment involved with moving away from a more traditional crop is daunting and is exacerbated by uncertain market conditions despite current market support under the RHI and RO. For example, Drax recently cancelled contracts with domestic SRC and Miscanthus producers due to the large transaction costs involved with purchasing from several small farmers. Prices are not considered sufficiently competitive to create a sustainable stand-alone market.[270] Markets for energy crops are generally too illiquid to offset counterparty risk or offer bargaining power to farmers. The SRC industry also depends on a few major players that have optimised their supply chains for specific type of planting and harvesting operations, which could potentially create inertia within the industry in particular in regards to adopting new innovations.

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[267] E4tech Energy Crop Calculator

[268] Taylor R, Ripken R, Montemurro F, Bauen A. Energy Crop Competitiveness and Uptake Report, version 5.4. Energy Technologies Institute, London, UK: 2013.

[269] Why We Need an Energy Crop Support Scheme 3 – Position paper (2013) Kevin Lindegaard http://www.crops4energy.co.uk/wp-content/uploads/2013/08/Critical-appraisal-of-the-ECS-final-version.pdf

[270] Mawhood et al (2015*) Policy options to promote perennial energy crops: the limitations of the English Energy Crops Scheme and the role for agent-based modelling in policy design https://spiral.imperial.ac.uk/handle/10044/1/26656*

Given the stage of UK market development, it is difficult for farmers to compete with large-scale imported biomass in the market place. Attempts by Government to address market failures have not resulted in a long-term expansion of the UK energy crop market. Demand policy uplifts were introduced in 2009 that provided an additional 0.5 ROC for power generators using energy crops, but these were removed in 2013. Alongside a number of other factors, the removal of the Climate Change Levy (CCL) exemption in 2015 also led to Drax cancelling its energy crop contracts in favour of imported woody feedstock.[271] In addition, the RHI is scheduled to run out to 2021 which does not provide the long-term certainty needed for energy crops.

4.3.3 Lack of research funding

A lack of funding for R&D and breeding programmes going forward was also raised as a major concern as there is currently insufficient funding to continue the world leading research going on in UK research centres. The BBSRC has decided to not fund more Miscanthus variety development. The GIANT Link project, while generously funded at first, has been reduced from 30 to 4 employees. Another consideration is that a number of key energy crops research programmes, such as MISCOMAR and OPTIMISC, are currently EU funded. Whilst Horizon2020 funding has been guaranteed by the Treasury, it is unclear whether UK researchers will be able to participate in future EU funded research. This is a concern for breeders not only because of a potential lack of access to funding but also because current research is considered an international and European effort. There is also a feeling in the SRC breeding community that a lack of funding is holding back progress on further yield increases. This is particularly true in the sense that more research is needed to bridge the gap between SRC yields observed in field trials under optimal conditions and those observed in commercial operation.[272]

4.3.4 Farmer attitudes to new crops

According to previous research by the ETI, many farmers have harvested the same way for around 40 years and are not interested in trying new crops at this stage. The low maintenance associated with the crop is in fact seen as a negative by some as it entails less work and is perceived as boring.[273] A study found that 30 out of 36 surveyed farmers did not consider planting energy crops citing the long-term commitment, land quality issues and time to payback as major concerns.[274] Energy crops represent a relatively new type of farming in the UK and as such there is limited experience both in the farming community and in the surrounding infrastructure and institutions. Another issue relates to the social environment in which farmers operate. Converting all of a farmer's land to energy crops may entail taking on a new role within the farming community, for example going to different events and social meet ups, which can act as an additional barrier to the economic considerations of a conversion.[275] Currently, the UK is facing a hiatus in energy crops with only a few 100 ha per year being planted and Defra statistics indicate that larger

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[271] FWI (2016) "Drax ends Miscanthus contracts and reviews straw supply", Available from: http://www.fwi.co.uk/arable/drax-ends-miscanthus-contracts-and-reviews-straw-supply.htm

[272] SRC willow breeder 24/04/2017

[273] Taylor R, Ripken R, Montemurro F, Bauen A. Energy Crop Competitiveness and Uptake Report, version 5.4. Energy Technologies Institute, London, UK: 2013.

[274] Wilson, P., Glithero, P. and S. Ramsden (2011) "Agricultural Economics and the LACE Programme: Farm Systems Assessment of Second Generation Biofuel Production". Presentation at UKERC workshop "The Economics of Land Use and Energy", 25-26 October 2011, Oxford, available at: www.ukerc.ac.uk/support/tiki-download_file.php?fileId=2064

[275] Mawhood et al (2015*) Policy options to promote perennial energy crops: the limitations of the English Energy Crops Scheme and the role for agent-based modelling in policy design https://spiral.imperial.ac.uk/handle/10044/1/26656*

areas are being pulled up every year, which may make other farmers reluctant to plant.[276] SRC particularly has also had regionally negative experiences in the past, such as the ARBRE willow gasifier project, the perception of which still has ripple effects in the local farming community 20 years on.[277] Outreach to SRC farmers was considered crucial to encourage correct preparation of the land including the appropriate weed control mechanisms.

4.3.5 Harvesting machinery availability

Energy crops, particularly SRC, require specialized equipment. While it is possible to access this equipment for single farmers, costs can be prohibitive as harvesters are expensive (around ~£200,000) and sharing equipment may mean it will be unavailable during crucial harvesting times. Most growers rent machines although as of 2015 there are only four of them in England, three of which are located in the Midlands and Yorkshire.[278] The lack of a large market was also reported to affect supply chain actors' willingness to produce additional specialized harvesting machinery.

4.4 Potential options to mitigate innovation barriers

4.4.1 Implement a Miscanthus seed production programme and a follow up GIANT Link project

Several of the benefits from developing new breeds of Miscanthus and SRC translate to a more compelling economic case for farmers. Seed-based Miscanthus could even avoid the need for upfront grants. Interviewees suggested that a follow up project to GIANT Link is needed to capitalise on the progress made to date and further improve yields. The GIANT Link project received a total of £6.4 million (2012-2016). This funding is considered sufficient to maintain the UK germplasm collections but not to further develop new breeds. This follow up project could focus on developing breeds optimised to end-use applications such as developing crops with less lignocellulose for anaerobic digestion, or less halides for thermochemical conversion in addition to higher yields and planting rates. The new breeds could also be tailored with additional environmental benefits such as improved water and nutrient use efficiency and resistance to climatic changes in addition to building on yield improvements in GIANT Link. These breeds could be considered the second generation of Miscanthus and will require extensive breeding and research programmes including the development of existing germplasm collections.

These breeding efforts could be followed up with commercial plot trials such as those in the UK, Germany, Ukraine and other European countries – similar to those in the current MUST project. These are important to test how breeds developed in the lab perform in real-world conditions. These trials are resource intensive and should only be attempted on few and highly promising novel varieties.[279] Interviewees stated that funding for projects would be needed over at least five years of planting, growing and harvesting to generate meaningful data. Field trials are also needed to optimise agronomic practices such as optimising machinery, weed control and crop management to reduce inputs and improve sustainability performance. These seed-based hybrids are expected to be commercially available at the earliest in 2019. The current hiatus in energy crop planting is therefore likely to continue until then in

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[276] Defra (2016) "Crops Grown for Bioenergy in England and the UK: 2015" https://www.gov.uk/government/statistics/area-of-crops-grown-for-bioenergy-in-england-and-the-uk-2008-2015

[277] Interview with SRC willow breeder 24/07/2017

[278] Mawhood et al (2015*) Policy options to promote perennial energy crops: the limitations of the English Energy Crops Scheme and the role for agent-based modelling in policy design https://spiral.imperial.ac.uk/handle/10044/1/26656*

[279] Kalinina, Olena et al. (2017) "Extending Miscanthus Cultivation with novel Germplasm at six Contrasting Sites" Front. Plant Sci., 19 April 2017

the absence of new policy. New breeds developed in a follow-up GIANT Link project are unlikely to be commercially available for a decade due to the long lead times involved with breeding and testing.

Interviewees considered that large-scale deployment of seed-based hybrids, and hence a rapid ramp up of Miscanthus planting, is unlikely to materialise without stronger public funding for seed production. Terravesta is the key commercial partner and investor in GIANT Link and MUST, but interviewees stated the need for a larger government supported dedicated project on seed production to scale to ~1000 ha/year by 2019. This project could also be supported by funding to develop infrastructure and farm equipment including optimised mowers, machinery for thin film laying and potentially mechanised weed control.

4.4.2 Develop targeted energy crop support as part of a wider heat strategy

In addition to funding R&D and breeding activities, a long term energy crop strategy is needed. Interviews clearly stated that the lack of certainty, both from government and the markets, needs to be addressed. Policy that supports lower GHG biomass (e.g. sustainability with knock-on effects on energy security) and that creates a supply push and market pull could be considered – these are discussed further below. However, interviewees noted that perhaps more important than financial support is a clear government statement and vision on the future importance of energy crops to UK decarbonisation. Market support is likely to be more important for SRC than Miscanthus in the absence of breakthrough innovations as SRC may be more expensive on a per tonne basis until yield improvements in trials materialise in commercial operations.

Supply push

If seed-based hybrids are delayed or do not ultimately save significant establishment cost then financial support to promote supply of energy crops, particularly for SRC, would be required to drive planting. In either case, government support for both SRC and Miscanthus would reduce the risk of a continuation of low planting rates, both in the short and long-term. One option would be to launch a scheme similar to the previous Energy Crop Scheme (e.g. ECS 3) including:

- Annual payments to farmers to alleviate cash flow problems for the first years of establishment
- Dedicated support to non-planting activities such as procurement of planting and harvesting equipment, storage facilities and transport. Previous estimates suggested £1.6 million total in funding towards this type of infrastructure from 2014-2020.[280]
- Support for crop removal at the end of a crop’s useful life.

One SRC interviewee stated that there is little need for innovation but a strong need for recognition of the environmental benefits and payments to attract farmers to plant the crop in appropriate regions. This resonated with an SRC willow breeder who stated that since certain willow breeds that have been developed (but not commercially deployed) can already yield 14 odt/ha in particular environments, supporting farmers to take up those new breeds is key to deploying SRC. This activity could be supported by a ‘recommended list’ of available SRC willow varieties which would allow farmers to make more informed choices about what varieties to plant. Alternative support for the environmental benefits of energy crops could for example be provided through scaling farmer support, to encourage planting in areas with the highest potential for positive biodiversity and flood prevention impacts. Brexit and the

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[280] Why We Need an Energy Crop Support Scheme 3 – Position paper (2013) Kevin Lindegaard http://www.crops4energy.co.uk/wp-content/uploads/2013/08/Critical-appraisal-of-the-ECS-final-version.pdf

current planned termination of CAP payments present an opportunity to restructure UK farming incentives towards these goals.

Demand pull

Continuation of market interventions for the energy vectors (heat, power, transport fuels) produced from biomass will be needed in order to enable continued production of energy crops, until innovations have enabled significant cost reduction. To stimulate significant expansion however, additional support for energy crops could be introduced that reflects their potential as a high resource UK feedstock at an early stage of commercialisation. This would encourage market growth for SRC and Miscanthus, and provide a driver for the commercialisation of seed-based Miscanthus hybrids.

The EU RED II, as proposed by the European Commission, would include biomass sustainability rules to 2030 including tightening the GHG thresholds for power and heat generation (from 60% to 80% required saving compared to fossil fuels) and removing subsidies for new dedicated power stations.[281] Combined, if these changes would be transposed to the UK they may favour smaller CHP plants using a higher proportion of energy crops. Other sustainability requirements could also be used such as encouraging demand for energy crops with positive biodiversity impacts or the use of marginal land, which may also provide an impetus to focus on these crop characteristics at the breeding stage.

4.4.3 Outreach to farmers

Farmers often do not have a good understanding of novel crops such as Miscanthus and SRC nor the energy markets to which their product would be sold. Farmer education has been mentioned in previous studies (Rokwood 2013; NNFCC 2012) as important to overcoming these barriers and can target both communities and individuals. Although covered in previous studies, studying evolving owner attitudes could be key to develop business models for biomass cooperatives targeting small land owners and fragmented resource situations. One interviewee mentioned the benefits of the recent development in knowledge and resource sharing between farmers, researchers and industry which is more common now than it used to be. Market intermediaries have fulfilled an important educational role and could be utilised to improve the dissemination of information. Other routes to reaching farmers could be through the changes in the CAP payments and accompanying information material that might be sent out with any large changes to farming support.

4.5 Indicative timeline

Figure 7 maps the potential actions discussed above on a timeline and suggests a prioritisation. The prioritisation is based firstly generating momentum to expand energy crop production and encourage the commercialisation of higher yielding seed-based hybrids by the early 2020s.

- In order to commercially deploy seed-based Miscanthus hybrids by 2019, a seed production programme could be initiated aimed at growing the required quantity for scale-up. If 1,000 ha/year is required, 1 ha of seed production could provide 2,000 ha of Miscanthus as well as sufficient margin of error for learning and testing. The

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[281] Proposal for a Directive Of The European Parliament And Of The Council on the promotion of the use of energy from renewable sources (recast) COM(2016) 767 final http://eur-lex.europa.eu/legal-content/EN/ALL/?uri=COM:2016:767:FIN. Negotiations on the proposal are ongoing at the time of writing.

programme could be open to producing seeds in the most ideal climates including non-UK locations such as Europe and North America. Without such a programme it is unlikely that seed-based hybrids will make a significant contribution to Miscanthus establishment in the early 2020s. This programme would directly capitalise on the progress made in GIANT Link and be a more extensive and industrial scale version of the current MUST, which currently plays an important part in the commercialisation of new Miscanthus breeds but is insufficient to make a significant contribution to planting rates by 2019 (e.g. by enabling ~1,000 ha/year).

- An improved grant scheme (e.g. ECS 3) could be implemented to mitigate the current low planting rates in the UK. This is especially important for SRC which does not have the same breakthrough innovation potential for increased planting rates and reduced costs as Miscanthus. Public support for SRC is therefore likely to be required until yield improvements are seen in commercial operations. Any grant scheme would need to recognise the issues farmers face along the supply chain particularly around procurement of establishment and harvesting machinery. Market demand could also be stimulated by transposing the RED II GHG threshold (80% saving compared to fossil fuels, as proposed by the EC) into UK sustainability requirements in 2020. This would create an impetus to contract local biomass if imported pellet fuel chains do not comply with the GHG threshold. Alongside a grant scheme and the realisation of the innovation potentials discussed above, a stricter GHG requirement could contribute to lower costs (due to local energy crops being cheaper than imported wood pellets) and a growing market demand for energy crops alongside wastes and residues.
- These two priorities could be implemented alongside a clear Government statement about the potential role of energy crops in long term decarbonisation of the energy system, and other potential bioenergy uses.
- Follow up funding to GIANT Link to develop new and improved Miscanthus breeds, in addition to the ones already identified and being trialled for commercialisation in 2019 could be used to capitalise on the UK's strong R&D capabilities. These breeds will also likely have improved characteristics over the ones produced in GIANT Link, including lower ash and halide content and therefore more optimised for specific end-use applications such as AD and direct combustion – which could have significant supply chain cost benefits. Continued breeding and yield improvement is also needed to reach the average 18 odt/ha by 2050. As with the current MUST project, a follow up commercial field trial would be needed to test the breeds in real world conditions and develop optimal agronomic practices. Due to the long-term nature of energy crop breeding, these are longer term investments compared to commercializing the first breeds developed in the GIANT Link project. New breeds from a follow up GIANT Link project would unlikely be commercially available before the next decade. The know-how produced through such a project however could be exported and potentially contribute to UK growth and job creation in the academic, rural and industrial sectors.

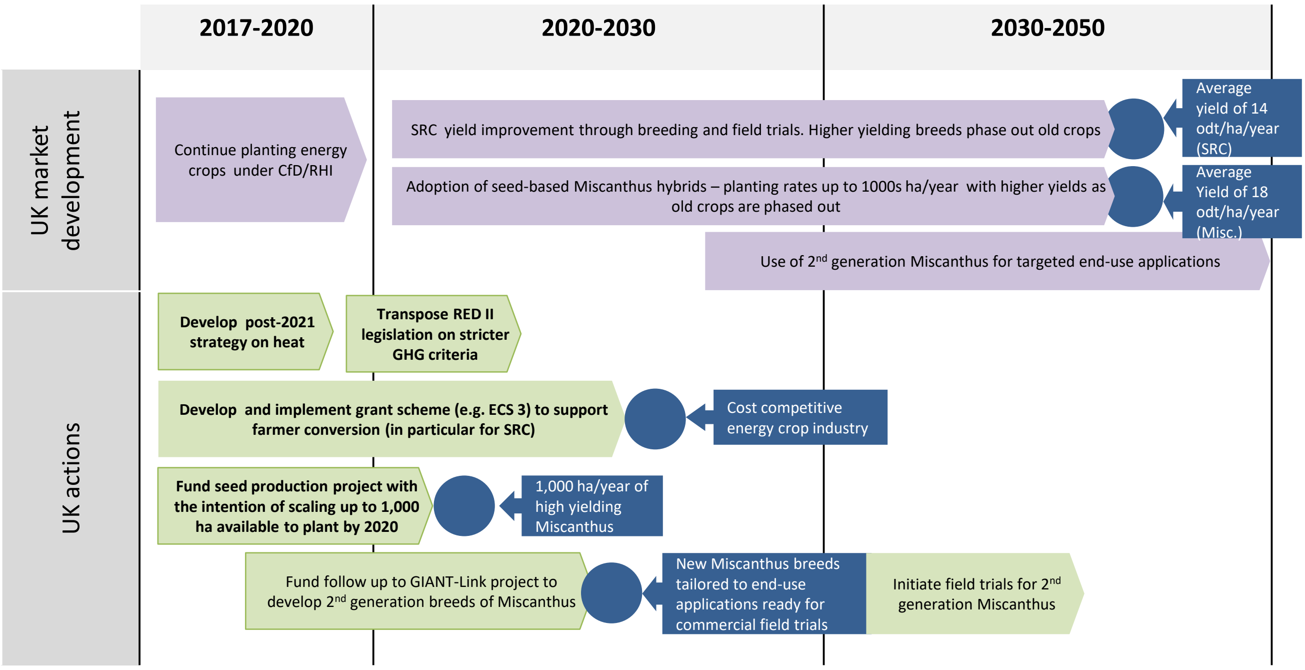
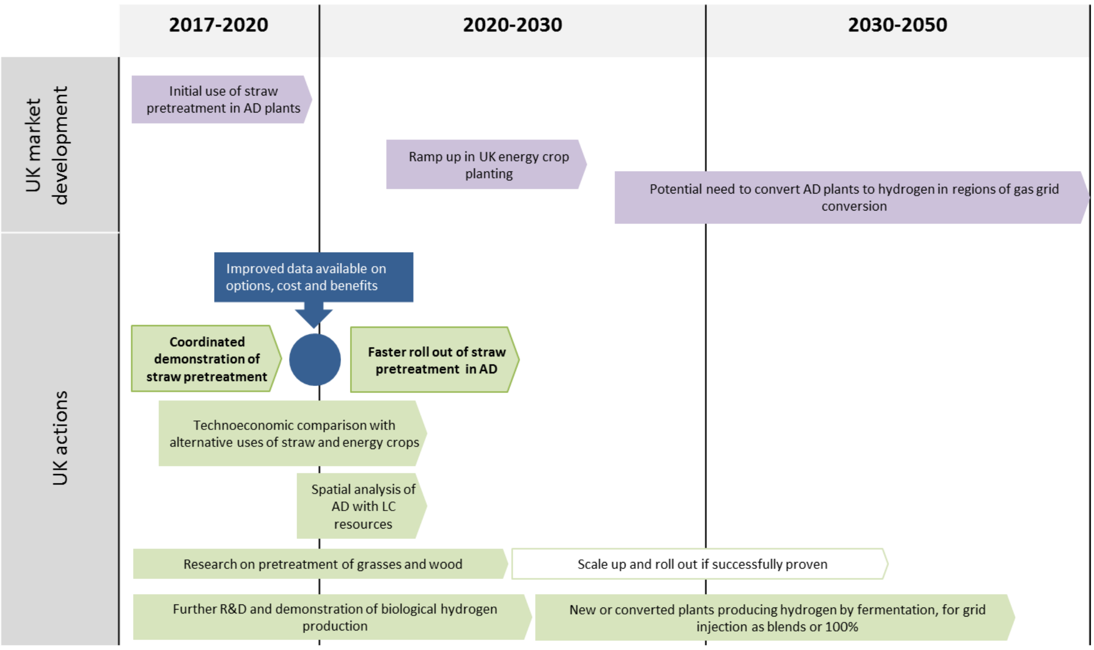


Figure 7: Innovation roadmap for energy crops. Green chevron = actions. Purple chevron = market developments. Blue boxes = milestones. Bold = prioritised actions

5 Pretreatment of lignocellulosic feedstock for anaerobic digestion or biological hydrogen production

Summary

- Anaerobic digestion (AD) is a commercially available and widely used biological process for converting biomass into biogas. Typical feedstocks are wet materials such as manures, sewage sludge, food wastes and some crops such as maize and agricultural residues such as grass silage.
- The potential for AD would be greatly increased by the ability to use lignocellulosic feedstocks with a higher supply potential in the UK and globally, such as grassy and woody energy crops, straw and wood. For example, adding the current UK straw resource to the existing wet feedstock resource would increase feedstock supply for AD from 22-52 PJ to 42-97 PJ. However, these feedstocks are not commonly used today, as they are very slow to break down in an AD reactor.
- A wide range of pretreatment technology options are under consideration by industry and academics. Use of straw in AD is at the early stages of commercialisation, with several technology options being commercialised in the UK and elsewhere. Pretreatment of energy grasses and wood is at the research stage.
- Adoption of straw pretreatment technologies could be accelerated by coordinated and monitored demonstrations of technologies which are currently available, to provide better information for potential adopters. In addition, further research could assess the potential impact of this technology for the UK, could enable better comparison with alternative routes to heat such as bioSNG, and could aim to widen AD pre-treatment to other feedstocks such as grassy energy crops and wood.
- Enabling these materials to be used in biological processes would increase the potential for biological routes to hydrogen by fermentation, an area where the UK has leading research.
- An indicative timeline for pretreatment for AD or biological hydrogen production in the UK:



5.1 Introduction

5.1.1 Technology description

Anaerobic digestion (AD) is a commercially available and widely used biological process for converting biomass into biogas, a mixture of methane, carbon dioxide and traces of other gases[282]. Typical feedstocks for anaerobic digestion are wet materials such as manures, sewage sludge, food processing wastes, food wastes, as well as some crops such as maize and agricultural residues such as grass silage. The feedstocks are broken down by bacteria to fatty acids and alcohols, with the products converted into methane and carbon dioxide, plus water and some remaining solid material (digestate). The biogas produced can be burnt to produce heat and power, or the methane separated for use as a transport fuel or for injection in to the gas grid. As discussed in Appendix B, improvements to AD in general are outside the scope of this project.

Whilst AD is used today in the UK, its potential contribution to gas grid decarbonisation is limited by the availability of feedstocks that can be easily digested using today's technology. The biogas potential would be greatly increased by the ability to use lignocellulosic feedstocks with a higher potential supply, such as grassy and woody energy crops, straw and wood. However, these feedstocks are not commonly used today, as they are very slow to break down, because their molecular structure is poorly accessible to microorganisms and their enzymes.[283]

A wide range of pretreatment technology options have been proposed, and in some cases used, in order to break down the feedstocks before use in an AD reactor. Development of the technologies has been driven in some cases by existing AD technology developers and operators, seeking to increase the rate of AD and improve biogas yield on existing feedstocks, and in some cases by the requirements of other industries, such as wastewater treatment and lignocellulosic ethanol production. Experience from lignocellulosic ethanol production, which is at early commercial stage, shows that pretreatment processes to break down lignocellulose to fermentable sugars are feasible at scale, but providing cost effective solutions at small scale may be a challenge. In addition, bacteria used for anaerobic digestion tend to be mixed cultures that are more robust to inhibitors produced in pretreatment than the enzymes and yeasts used in ethanol production, meaning that the pretreatment conditions may be less critical. However, systems are needed that work efficiently, reliably and economically at scales appropriate for AD plants, without producing species that inhibit the AD process. If large quantities of lignocellulosic materials are to be used in AD plants, different technologies may be needed from those suitable for increasing the rate and yield of biogas in plants where a small proportion of the feedstock is lignocellulosic such as straw mixed with farm waste.

The pretreatment technologies include physical, chemical and biological methods, and combinations of thermal and chemical processes. As summary of these methods is given below, predominantly based on information on each route available in a guide produced in 2014 by IEA Bioenergy Task 37 (Energy from Biogas)[283]. Whilst some advantages and disadvantages of the technologies are given in the table below, it is important to note that the best pretreatment technology depends heavily on the feedstock composition, including the dry matter content, lignin content, and presence or absence of other materials such as stones. The costs and energy balance will also be heavily influenced by the particular plant characteristics: notably the scale, and availability of waste heat.

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[282] For an introduction, see Anaerobic Digestion and Bioresources Association guide http://adbioresources.org/about-ad/what-is-ad/

[283] Montgomery L. and Bochmann G. 2014 'Pretreatment of feedstock for enhanced biogas production' IEA Bioenergy https://www.researchgate.net/profile/Lucy_Montgomery/publication/273632363_Pretreatment_of_Feedstock_for_Enhanced_Biogas_Production

This section focuses on technologies to allow the use of straw and high yielding energy grasses, rather than those that are used today to increase the biogas yield from feedstocks with a lignocellulosic component, such as MSW, manure mixed with straw and grass silage. Use of wood in AD is theoretically feasible given work that has been done to enable conversion of wood to lignocellulosic ethanol, but is less commonly mentioned. Several of these technologies have been tried with lower yielding grasses (hay) but this is not considered in scope here.

Table 7: Pretreatment options for lignocellulosic biomass for use in anaerobic digestion

Principle	Technique	Summary
Physical	Mechanical	• Reduces particle size to increase surface area and improve handling • Examples include knife mills (shredders), hammer mills • Already used in many biogas plants treating wastes • Can have high energy demand (hammer) and sensitivity to stones (knife) • Has been shown to improve biogas yields on some types of straw. More tests at full scale are needed to determine whether the electricity input for milling is justified by the electricity saved by improved mixing.
	Thermal	• Feedstock is heated (typically to 125 to 190 °C) under pressure for up to one hour, which can be done using waste heat. Microwave pretreatment has been proposed but not used at scale • Optimum temperature varies by feedstock type. Above this, products that can inhibit AD are formed • Overall less effective than combined processes below
	Others	• Ultrasound, electrochemical – typically used for sewage sludge
Chemical	Alkali	• Treatment with alkali, commonly lime or sodium hydroxide • Literature has shown good results in small scale batch tests, with challenges for continuous operation • Considered economically unattractive due to the high cost of alkalis, but may be useful for acidic and lignin-rich feedstocks • Previously commonly used in the UK for treating straw to improve digestibility for animal feed
	Acid	• Typically used with heat, in thermochemical pretreatment
	Oxidative	• Treatment with hydrogen peroxide or ozone to break down lignin • Lab tests only. Likely to have high costs at scale
Biological	Ensiling	• Silage making (ensiling) involves putting the feedstock in a silo • Little effect on AD yields seen in trials with Miscanthus at Rothamsted
	Anaerobic microbial	• Pre-acidification systems: Separation of the first steps of AD (hydrolysis and acid production) from methane production, to allow these steps to operate at a lower pH (4-6 rather than the 6.5-8 during methane production) at 30 to 50°C which is optimal for enzymes that can break down LC feedstocks. Also produces higher concentrations of methane in biogas • Currently offered by several biogas plant providers but not yet widely used
	Aerobic microbial	• Naturally occurring mixed cultures of aerobic organisms used in a leach bed reactor, where the percolate is collected for use in AD • An aerobic leach bed reactor has been used at large scale in an MSW treatment process[283]
	Fungal	• Use of white-rot fungi that degrade lignin • Early stage for both AD and lignocellulosic ethanol pretreatment
	Enzymatic	• Addition of cellulase and hemicellulose enzymes to the AD vessel (no effect seen), to a 2 stage system, or as a separate pretreatment step (both seen to have improvements in yield) • Enzyme products are offered by several companies

Principle	Technique	Summary
Combined processes	Steam explosion	• A combination of heating to 160 to 220 °C for 5 to 60 minutes then a sudden pressure drop, causing intracellular water to evaporate rapidly, rupturing cells and their surrounding fibre. • Used in several of the first commercial scale lignocellulosic ethanol plants (around 200ktpa feedstock input), TRL 6-8[284] • Early commercial stage for AD pretreatment. However, results from lab tests for AD have been reportedly inconclusive, with some showing improvement in yield, others only rate, and other no improvement. High temperatures and accumulation of inhibitors may decrease yield
	Extrusion	• Feedstock is subjected to high shear, temperature and pressure, e.g. by feeding it into a screw inside a tube • Has shown good results, particularly for straw • High electricity demands, and abrasion from stones severely reduces the screw lifetime, meaning they must be changed after a few months
	Thermo-chemical	• A combination of bases or acids and heating, with improvements in yield up to 160 °C • Dilute acid pretreatment (TRL 5-7)[284] used in several of the first commercial scale lignocellulosic ethanol plants (around 200ktpa feedstock input) • Tried at pilot scale several times for AD but currently no example of large-scale use

There has also been discussion of whether use of lignocellulosic feedstocks in new plants may be better done using a new type of AD reactor, rather than a pretreatment technology added to an existing AD reactor. The current widely used reactor type is a continuously stirred-tank reactor (CSTR), which is well-suited to traditional substrates like manure, sludge and easily digestible substrates, using small, fast moving impellers on wet substrates. Alternative potential reactor designs include dry digesters for feedstocks with high solids content, and for wetter lignocellulosic substrates, a leach bed reactor or a percolator could be used, combined with 'a high-rate reactor like an upflow anaerobic sludge blanket (UASB) reactor, an anaerobic filter or a hybrid reactor to digest the leachate'[283]. This suggests that further research will focus on the engineering of a combined process, where the pretreatment is integrated into the digester.

If these technologies were successful at breaking down lignocellulosic feedstocks, the pretreated material could also be used for hydrogen production by biological routes. This would change the Task 1 result for hydrogen production by biological routes, by increasing the resource base. As a result, hydrogen production by biological routes has been considered as a potential innovation activity in this chapter, which would become a higher priority if pretreatment for this route is successful.

5.1.2 Global status and activities

Use of straw in AD is at the early stages of commercialisation (aside from its use with manures), with most interest to date being in Germany and China. As well as research on the wide range of routes discussed above, there are a number of technologies on the market, and a few plants in operation using lignocellulosic feedstocks alone. These include:

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[284] E4tech (2015), From the Sugar Platform to Biofuels and Biochemicals, European Commission, available from http://www.e4tech.com/reports/from-the-sugar-platform-to-biofuels-and-biochemicals/

- Verbio has a 100% straw to biomethane plant in Schwedt, Germany, operating since 2015. It had a starting capacity of 8 MW, and by 2019 it is planned to have a capacity of 16.5 MW, with 40 ktpa straw input, generating 136 GWh/yr biomethane, to be fed into the gas grid.[285] The biomethane yield is around 300 m^3 CH_4/t straw[286]. The technology used includes shredding and thermal treatment with steam at 150-180°C for 10-30 minutes. The project was funded by the EU funding programme NER300 with €22.3 m funding between 2014 and 2019.
- Alkaline pretreatment of straw is in use at full scale in China using sodium hydroxide, at capacities of 10,000m^3 CH_4/day,286 for use in continuously stirred-tank reactors.
- There are a range of different reactor technologies (e.g. up-flow solids reactor, vertical plug flow reactor) that have been built in China at large scale for AD of straw, with multiple government funded demonstration plants.286,[287].
- MWK Bionik in Germany offers a combined biological, mechanical and thermocatalytic processes (BMT-System) which is claimed to operate on high lignin content materials like straw and wood residues.[288] The stage of development is not clear, but was reported in 2016 to be at pilot scale.286
- Biogas Systems in Austria have developed the Economizer steam explosion technology, which heats feedstock to 180°C (using recovered heat from CHP if available) at 10bar overpressure[289]. A pilot plant has been operating successfully in Austria since 2014 at a scale equivalent to 0.5MW_e output, using 50% straw. Future Biogas is using this technology at one plant the UK, with plans for further plants (see below). This technology did not work when tested on Miscanthus.[294]
- Lehmann has developed an extrusion technology[290] which is currently being used commercially with a range of feedstocks to improve biogas yields and enable a wider range of feedstocks, but reportedly not for lignocellulosic feedstocks alone.286 Electricity demand is 5-12 kWh/t feedstock.286
- Biobang is an Italian cavitation technology that has been tested on a range of feedstocks and is in use at plants in Italy, Germany and the UK.
- The ROTOCAV hydrodynamic cavitator[291] is a cavitation technology developed in Italy and marketed in Europe by Cavimax Ltd in the UK[292], which can be used for straw, grass and high lignin feedstocks.

As interest in use of straw is at an early stage in Europe, the potential for straw in AD is not generally considered assessments of the European potential for AD, such as Kampmann, 2016[293] which cited a lack of experience and information on economic viability.

Several of these technologies mention the potential for use with other lignocellulosic materials, but investigation of use of high yielding energy grasses such as Miscanthus and use of wood appears to be at the research stage. Academic research on pretreatment technologies in general is most prevalent in Germany, Denmark and China.

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[285] Schlimbach 2016 VERBIO Biomethane https://setis.ec.europa.eu/system/files/2016_bratislava_schlimbach.pdf.

[286] Clemens, 2016 'Straw Fermentation technology sharing' www.bngsummit.com/wp-content/uploads/2016/11/11.straw_clemens.pdf

[287] Li Biogas Production from Crop Straw through Anaerobic Digestion https://energypedia.info/images/b/bf/Biogas_Production_from_Crop_Straw_through_Anaerobic_Digestion.pdf.

[288] MWK Bionic BMT website accessed May 2017 http://www.mwk-bionik.de/en/systeme/bmt.html

[289] Biogas Systems website accessed May 2017 http://www.biogas-systems.com/en/economizer-se/

[290] Lehmann website accessed May 2017 Process of „Bioextrusion by LEHMANN®" http://www.lehmann-maschinenbau.de/en/biogas-technology/bio-extrusion.html

[291] ROTOCAV hydrodynamic cavitator https://www.epic-srl.com/en/

[292] http://www.cavimax.co.uk/

[293] Kampmann et al 2016 'Optimal use of biogas from waste streams. An assessment of the potential of biogas from digestion in the EU beyond 2020' https://ec.europa.eu/energy/en/studies/optimal-use-biogas-waste-streams-assessment-potential-biogas-digestion-eu-beyond-2020

5.1.3 UK status and activities

The UK has a large AD industry, which has increased significantly over the past few years as a result of support from the Renewable Heat Incentive for biomethane injection in to the gas grid. Use of straw in AD is at the early stages of commercialisation in the UK. UK activity includes:

- Future Biogas Systems[294] is the sole distributor of the Economizer technology and has installed the first Economizer SE in the UK at a Future Biogas plant, with an output of 2.5-2.8 t/h pretreated output (system sized for 1MWe biogas output). This system has been running for 2 months, and has been working to overcome initial problems resulting from low quality straw with a high content of stones. The output is used to feed 50% of the feedstock demands of the AD plant. A further 4 plants are planned at existing AD plants in the UK, including larger scale systems.
- Cavimax Ltd is the marketer of the Cavimax cavitation technology above
- UK academic research:
    - The Supergen Bioenergy Hub project 'Evaluation of synthetic natural gas' [295] including assessment of the impact of ensilage on AD yields from Miscanthus, and of the impact of green harvesting (see section 5.2.4) on Miscanthus yield at Rothamsted, and life cycle analysis and technoeconomic comparison of routes from biomass to biogas and bioSNG at the University of Bath
    - Bioenergy and Organic Resources Research Group at the University of Southampton has a wide range of work on AD including involvement in the EU FP6 CROPGEN - Renewable Energy from Crops and Agro-wastes project which included use of grasses[296]
    - Redesigning hydrolysis reactors to allow better digestion of agricultural residues, aimed at developing containerised AD and electricity production at the University of Oxford[297]
    - The Energy and Environment Research Institute (EERI) at the University of South Wales investigates novel biogas and anaerobic digestion systems, as well as biological routes to hydrogen (see below), including use of straw and energy crops, and is also considering potential uses of lignin-rich digestate

5.1.4 Enabling factors for innovation

The global and UK activities are covered above, and so this section focuses only on factors driving this innovation and on support mechanisms.

Global

Use of straw for AD in China has been driven by the very large amount of agricultural residue production in China, and the need to avoid impacts of burning straw in the field, such as air pollution and wildfires[287]. In Europe, the AD sector's success has been highly dependent on Member State level policies, which have changed considerably in recent years, affecting the business case for existing and new plants[298]. This has included decreasing feed in tariffs

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[294] Future biogas website and interview http://www.futurebiogas.com/the-economizer/

[295] Evaluation of synthetic natural gas, Supergen Bioenergy Hub, http://www.supergen-bioenergy.net/research-projects/evaluation-of-synthetic-natural-gas/

[296] Bioenergy and Organic Resources Research Group at the University of Southampton http://www.bioenergy.soton.ac.uk/index.htm and Cropgen http://www.bioenergy.soton.ac.uk/projects/Cropgen%20130823.pdf and http://cordis.europa.eu/result/rcn/47572_en.html

[297] BBSRC NIBB AD Network Proof of Concept Awards: Titles and Summaries http://www.anaerobicdigestionnet.com/index_htm_files/WINNING%20POCs-Title%20and%20Publishable%20Summaries%20v2.pdf and Final report http://www.anaerobicdigestionnet.com/index_htm_files/WINNING%20POCs-FINAL%20REPORT%20for%20web.pdf

[298] EurObserv'ER 2014 Biogas barometer https://www.eurobserv-er.org/biogas-barometer-2014/

in Germany and Italy and withdrawal of premia for use of crops (principally maize) in Germany. Interest in straw has been driven by existing AD operators looking for lower cost feedstock options, in particular instead of maize. In several countries, restrictions have also been placed upon the use of maize, as a result of concerns over land use, such as in Germany, Denmark and the UK. However, even without these restrictions there is a strong economic driver for lower cost feedstocks. This also results in little interest in using higher cost lignocellulosic feedstocks such as Miscanthus. Other influences in the EU include:

- A driver for use of waste and residue feedstocks and woody and grassy energy crops, rather than starch crops within EU biofuels policy (RED and proposed RED II[299])
- Sustainability criteria for crops used for biogas, and minimum 50-80% GHG savings for all biogas installations over 0.5 MWe (as EC proposed in RED II), depending on their start date

In both the EU and China, public funding has supported academic research (e.g. FP6,7), as well as demonstration of technologies at scale, such as the Verbio plant (NER300) and multiple plants in China described above.

UK

In the UK, interest in AD of lignocellulosic feedstocks is supported by a similar range of drivers, policy mechanisms and research funding as at EU level. This includes:

- An economic driver for lower cost feedstocks than maize given the current level and past variation in support for AD under the Feed in Tariff Scheme, Renewable Heat Incentive, Renewable Transport Fuel Obligation
- A requirement for UK AD plants to have GHG savings of 60% greenhouse gas saving against the EU fossil fuel average, currently 34.8g of CO_2 equivalent per megajoule of heat generated or gas injected into the grid
- A requirement for new AD plants producing biogas for combustion or injection to the gas grid as biomethane to produce at least 50% of the biogas or biomethane from waste or residues to receive RHI support for all heat generated or biomethane produced, and to qualify for FiTs for new plants
- A driver for larger AD plants, given the removal of FiT support for electricity, meaning more of a driver for biomethane production for grid injection. As grid injection has fixed costs for connection and calorific value monitoring, this implies a minimum plant scale
- Additional support for biomethane produced from wastes and residues under the Renewable Transport Fuel Obligation compared with biofuels produced from sugar, starch and oil crops
- Research funding through EPRSC (e.g. Supergen Bioenergy Hub), BBSRC, Innovate UK
- BBSRC Networks in Industrial Biotechnology and Bioenergy (NIBB) Anaerobic Digestion Network[300] has a working group on Feedstock enhancements, novel feedstocks and new markets working group. The Network has a fund of £200,000 for Business Interaction vouchers, up to £10,000 each, for industry partners to fund an academic's time to solve specific problems, available until June 2017. It also has a fund of £700,000 for Proof of Concept (PoC) research, which network members can apply for, with grants ranging from £10,000 to £60,000, as well as funding for researchers to travel to and attend workshops and seminars
- Green Investment Bank investment in Future Biogas' first pretreatment plant

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[299] Proposal for a Directive Of The European Parliament And Of The Council on the promotion of the use of energy from renewable sources (recast) COM(2016) 767 final http://eur-lex.europa.eu/legal-content/EN/ALL/?uri=COM:2016:767:FIN. Negotiations on the proposal are ongoing at the time of writing

[300] BBSRC Networks in Industrial Biotechnology and Bioenergy (NIBB) Anaerobic Digestion Network http://www.anaerobicdigestionnet.com/

5.2 Innovation activities and their impacts

5.2.1 Prove straw pretreatment for AD at scale

Although there are several technologies at the early stages of commercialisation for straw pretreatment, there is still a need for further development and learning to enable systems that can be widely used by existing and new AD plants. Even for the most developed systems, there are likely to be improvements possible in:

- biogas yield and rate of biogas production, through optimising the pretreatment conditions to give a greater degree of feedstock breakdown, and avoiding production of inhibitors
- improved reliability and reduced maintenance time and cost, for example with lower quality feedstocks
- reduction in electricity and heat use, and in water use
- cost reduction with scale increase, and learning from construction and operation of systems

It is not possible to state at this stage which of the pretreatment technologies has the greatest potential, given that there are no studies directly comparing different types of pretreatment operating at scale[301].

A key benefit of making these systems commercially available will be to increase the supply of biogas possible from AD routes, through allowing use of straw in AD plants. The UK straw resource given in the Evidence Review ranges from 34PJ to 75PJ of straw in 2015, compared with a total biogas potential of 22 to 52PJ for other feedstocks that can be anaerobically digested (maize, food waste, sewage sludge, wet manure and macroalgae), and so potentially represents significant increase in AD potential. For every PJ of straw used in AD, approximately 0.6 PJ of biomethane is produced[302], which means a biogas potential increase of 20-45 PJ. However, the extent to which this occurs will depend on physical constraints (proximity of straw resources to AD plants) and economic constraints (viability of adding pretreatment systems given equipment and straw costs).

It is also possible that the ability to digest straw could allow new AD plants to be built using a mixture of wet feedstocks and straw in areas where an AD plant at a scale suitable for biomethane grid injection would not be viable based on the local availability of wet wastes alone. This could increase the proportion of the UK wet wastes resource that could be used for energy. Currently even in the high scenario from the Ricardo model, 44% of the wet wastes resource is excluded from the available resource on this basis after 2020, and 72% before 2020. Detailed quantification of the extent to which this could be improved would require spatial modelling of wet wastes and straw availability and proximity to the gas grid.

There could also be other benefits if existing plants using maize switched to use of straw, although this is considered unlikely given that the restrictions on crop use under the RHI apply only to new plants, with grandfathering for existing plants:

- Cost reduction, if the feedstock cost reduction from switching from maize to straw outweighs the investment and operating costs of the new system. Straw costs are estimated to be £73/odt, compared with maize costs of £100/odt.

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[301] Several interviewees' views

[302] Estimate based on 19 GJ/odt straw, 600m^3 biogas/odt straw at 52% methane content, and 38 MJ/m^3 methane. Note that this figure does not account for energy use in conversion.

- Reduced lifecycle greenhouse gas emissions if plants switched from maize to straw, depending on the energy use in the pretreatment itself. Straw GHG emissions are estimated to be 61kgCO_2/odt, compared with maize GHG emissions of 397kgCO_2/odt. Data from two technology developers implies energy use (a varying combination of electricity and heat) which would lead to additional emissions of around 130kgCO_2/odt feedstock input[303] assuming use of grid electricity and natural gas for heating. However, this could be reduced if heat from CHP was used as an input, or electricity and heat were generated by biogas produced on site.

5.2.2 Develop pretreatment technologies for energy grasses and wood

Although many of the technologies discussed above have been tested on a range of feedstocks, there has been little focus on dedicated high yielding lignocellulosic energy crops like Miscanthus, or on wood. Given that lignocellulosic energy crops are at an early stage of commercialisation, and have higher costs than existing AD feedstocks, there is little driver for industry interest in this route. Woody feedstocks were also considered by interviewees to be more suitable for other bioenergy routes. Nevertheless, pretreatment of these feedstocks has been shown to be possible for lignocellulosic ethanol production, and systems capable of operating at smaller scale for AD could be developed. The principal benefits would be to increase the resource available for AD, with much larger resources available for Miscanthus, woody energy crops, forestry residues and imported woody biomass than for wet AD feedstocks.

There would also be the potential to improve lifecycle GHG emissions compared with maize AD[304]. It would be important to assess whether these benefits outweighed the investment costs and energy requirements of pretreatment for these feedstocks (no data available), and whether these routes had overall benefits compared with other uses of the same feedstock including conversion to bioSNG.

5.2.3 Develop new AD reactor types that can use lignocellulosic materials

As well as considering options that can be coupled with existing AD plants, there is the potential for improved biogas yield and rate through designing the pretreatment and AD together in a combined reactor. This could potentially have lower costs and higher yields than combining a pretreatment technology with a continuously stirred-tank reactor. However, it would be important to establish the market need for these systems, and the feedstock combinations likely to be used.

5.2.4 Optimise Miscanthus harvesting for AD

If techno economic and lifecycle analysis shows a potential benefit to Miscanthus to AD, compared with alternative bioenergy routes, then it would be worth considering Miscanthus harvesting options in combination with the pretreatment technology development.

Miscanthus is an energy grass, which is most commonly harvested in the spring, after senescence, when it is relatively dry. During senescence, Miscanthus loses a third of its dry matter content, for example due to leaf fall.

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[303] Assumes electricity and natural gas emissions factors from the UK Solid and Gaseous Biomass Carbon Calculator B2C2 calculator https://www.ofgem.gov.uk/publications-and-updates/uk-solid-and-gaseous-biomass-carbon-calculator. Assumes heat is provided by natural gas, with 85% conversion efficiency.

[304] GHG emissions of maize and Miscanthus for AD currently being assessed by Carly Whittaker at Rothamsted

Early harvesting of ‘green’, wet Miscanthus in September to November, when it is at the peak of its dry matter yield has been investigated for AD, as a way to boost crop yield[305]. However, this could have impacts on the longer term yield of the perennial Miscanthus crop: removal with the leaves could affect nitrogen requirements, and there could be an impact on the starch reserves in the Miscanthus rhizome (from which subsequent years’ crop regrows). One option could be green harvesting in some years and not others, but this is at an early stage of research, with yield trials having been done at Rothamsted. There may also be an impact on the soil carbon stock, depending on the fate of the leaf litter. The UK has world class research on soil carbon impacts of perennial crops, for example through the Carbo-Biocrop, ELUM and MAGLUE projects.

The GHG benefits of AD of Miscanthus compared with conventional crops such as maize will depend on their relative crop yield (t/ha) and biogas yield (m^3/t), and also on the GHG impacts of their cultivation. However, perennial crops like Miscanthus have been shown to increase soil carbon compared with cultivation of annual crops, which if maintained in the soil will contribute positively to the GHG savings. If Miscanthus is shown to have benefits for this route, the restriction on use of non-wastes and residues under the RHI may need to be revisited.

5.2.5 Couple pretreatment with hydrogen production by biological routes

If pretreatment of lignocellulosic material for AD is successfully commercialised, this will change the outlook for hydrogen production by biological routes, which has very similar feedstock requirements. Several research projects on hydrogen routes have used lignocellulosic materials such as lignocellulosic energy crops and straw, and so have included pretreatment steps.

Hydrogen production by biological routes is at the research stage. These routes to hydrogen start with fermentation to form hydrogen and acetate. This process has been successfully demonstrated in the lab (TRL 4), and releases one third of the hydrogen that could potentially be produced from the feedstock. There are then several options that have been investigated for use of the acetate produced. One option is anaerobic digestion, to produce methane (which can then be reformed to hydrogen), which is possible using today’s AD technology. Other more novel routes include:

- photofermentation (TRL 3-4)[361], which is considered by several researchers to be fundamentally limited by the difficulty of exposing the material to light in a cost effective manner
- microbial electrolysis, using bacteria that can convert acetate to CO_2, H_2 and H_2O when a small amount of electricity is supplied
- use of acetate in a biorefinery. Acetate can be used as a feedstock for a range of chemicals and plastics

Producing hydrogen as well as methane through the fermentation plus AD route has been shown to lead to a greater conversion efficiency from biomass to energy than AD alone. Work at the University of South Wales showed 20-40% better energy recovery than conventional AD, as a result of improved hydrolysis of biomass, more efficient gas producing organisms and removal of hydrogen from the system leading to improved energy efficiency compared with its usual conversion to methane. The first two of these factors are potential improvements to any AD process, whilst the last is specific to systems producing hydrogen as a first step. It is estimated that removing hydrogen as a first step in AD could increase the yield of energy (hydrogen plus methane) from AD by around 10%.

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[305] E.g. at Rothamsted, UK

5.2.6 Summary of innovation impacts

Table 8: Summary of impacts of biohydrogen innovations identified. Shading refers to impact of innovation in each category. Dark blue = strong impact, light blue = some impact, white = low impact

	Cost	Supply	Sustainability
Prove straw pretreatment for AD at scale	Feedstock cost reduction only if existing AD plants using maize convert to straw. Increased conversion cost compared with AD of wet feedstock	Increased potential biogas supply from 22-52 PJ to 42-97 PJ from addition of straw resource, plus additional potential increase in accessible wet wastes	GHG reduction only if existing AD plants using maize converted to straw
Develop pretreatment for Miscanthus and wood	Likely cost increase compared with use of wastes and straw	Large increased potential supply from Miscanthus and a range of woody feedstocks	Potential GHG reduction only if existing AD plants using maize converted to energy crops
Develop new AD reactors that can use lignocellulosic feedstocks directly	Likely cost reduction compared with separate pretreatment	No impact	Likely improved conversion and improved energy integration compared with separate pretreatment
Optimise Miscanthus harvesting for AD	Cost reduction compared with current Miscanthus harvesting	Yield improvement compared with current Miscanthus harvesting	GHG improvement related to increased yield
Link with hydrogen production	Not yet known	Yield improvement compared with AD alone	Not yet known

5.3 Barriers and gaps

5.3.1 Lack of comparable information on pretreatment technology options

Although a range of technologies are now being offered by different companies, there is no comparable information available on their:

- Performance - biogas yield, performance on different feedstocks, formation of species that are undesirable for the anaerobic digestion stage
- Economics – system costs, and likely economic benefits given local conditions such as feedstock costs, market support for biomethane production
- Reliability – plant lifetime, performance on feedstocks of variable quality and composition. One interviewee questioned the plant lifetimes of 10-15 years given by technology developers, as many AD plant components have been found in practice to only last 5-8 years
- Resource use – electricity and heat use (which affects GHG impacts), and water use. Interviewees noted that these figures vary widely between technologies

Lack of this type of information collected in one place (e.g. through academic work, industry guides) is not necessarily a barrier to technology deployment: there are many areas of technology where plant operators must assess the economics of systems offered by different vendors and make their own judgements. However, making this information available could potentially widen the range of AD operators with interest in the technology and encourage more of them to make a more detailed assessment, as well as informing how these technologies should be treated by policy. This could also speed deployment: an interviewee commented that adoption of new technologies in AD has been relatively slow in the past, with some innovations taking 20 years to progress from proof in the lab and dissemination of advice to the industry to adoption. In addition, it has often been difficult for potential technology adopters to determine whether a pretreatment technology has actually led to performance improvements, as distinct from increased yield resulting from more careful management of existing systems when pretreatment is installed. An expert also commented that in their experience the energy consumption of pretreatment technologies was considerably higher than claimed by technology developers, and that technologies often did not perform as expected if poorly operated.

5.3.2 Lack of widespread economic driver for use of large quantities of straw or other lignocellulosic materials for AD

In the UK, interviewees reported that interest in use of these technologies is driven both by improved economics compared with use of higher cost maize feedstocks, and by policy restricting the use of non-waste and residue feedstocks to 50%, which principally affects maize. Pretreatment technology providers are optimistic about the prospects for further deployment and for economic viability. However, other interviewees reported little interest in use of these technologies more generally in Europe, as a result of the benefits of increased methane yield in mixed feedstock plants not outweighing the costs of the new system, and no strong economic driver for use of large quantities of straw. They considered that although AD operators may be initially attracted by the idea of lower cost feedstocks, further investigation of local straw costs has led to a loss of interest.

Given that the economics of pretreatment will depend on the exact combination of local feedstock costs, technology costs, existing plant characteristics and national policy mechanisms, it is not possible to give an overview of the extent to which these systems will be viable enough to drive investment. The extent to which the technology is used globally will affect the range of systems available to the UK, and also the cost reduction and performance improvement of systems over time.

Use of energy grasses and wood face an additional economic barrier, as costs will be higher: through a combination of higher feedstock costs (energy grasses compared with wastes and residues) and likely higher processing costs due to less experience of development and higher lignocellulosic content (wood).

5.3.3 Some routes require combinations of multiple early stage feedstocks and technologies

Given the early stage of commercialisation of these pretreatment technologies, developers’ focus is on proof of technical and economic operation with readily available feedstocks such as existing AD feedstocks and in some cases, straw. There is little interest beyond academic research on use of energy grasses, or of coupling pretreatment with hydrogen production, as these options are also at an early stage, without widely established markets or supply chains. Conversely, green harvesting of Miscanthus is likely to receive little attention until there is more widespread proven deployment of lignocellulosic feedstock pretreatment technologies.

5.3.4 Lack of market demand for hydrogen, leading to diminished interest in biological hydrogen routes

There have been significant research efforts in universities in the EU and China on biological hydrogen production, including at the Harbin Institute of Technology's 50m^3 unit, and the EU HyTIME and HYVOLUTION projects[306], there has been a decline in the overall level of activity in the past ten years. Interviewees considered that this was as a result of demand for hydrogen not materialising as fast as expected in the 2000s, and the research councils funding the work not seeing the funded work being pulled through to production at scale after 5-10 years of funding. Work on fermentative hydrogen routes is ongoing in the UK, at the University of South Wales, with University of Birmingham also having capabilities in this area. However, taking forward this research into larger scale demonstration would rely on a demand for the hydrogen produced, and a project concept focused on maximising total energy output. Wider uptake in the AD industry is likely to be slow, given conservatism around technology changes and a focus on maximising gate fees (rather than maximising energy output), but is expected to require similar skills and equipment to conventional AD.

5.4 Potential options to mitigate innovation barriers

The actions proposed below are those that could to drive innovation in and uptake of pretreatment technologies and hydrogen production by fermentation. Interviewees also mentioned actions needed to support AD as a whole, including implementation of planned changes to the Renewable Heat Incentive (RHI), with tariffs at a level sufficient to drive deployment of grid-injected biomethane.

5.4.1 Coordinated and monitored demonstration of straw pretreatment technologies

Adoption of straw pretreatment technologies could be accelerated by coordinated and monitored demonstrations of the range of technologies currently available. This could be through installation of plants of each type on the same site, run by an independent body with testing on the same feedstocks. Capital costs of technologies reviewed here, at a range of scales, range between £350k-£1.8m, meaning that the capital cost of comparing, for example, five technologies would be around £4m. Alternatively, a lower cost option would be independent monitoring and verification of technologies installed at different sites, although in this case it would be more difficult to control for variation in the feedstock and between the operation of the pretreatment technology and AD plant itself. Making information about the technology's performance available to AD plant developers could then help to build understanding of the technology options, benefits and risks.

5.4.2 Technoeconomic comparison with alternative uses of straw and energy crops

Pretreatment of lignocellulosic material for AD and biohydrogen production has not been included in previous analysis and models of bioenergy routes, including the ETI Biomass Value Chain Model (BVCM), the UK TIMES and ESME energy system models, and has not been the subject of more detailed technoeconomic studies, to the level of detail similar to the ETI TEABPP project on pretreatment for thermal routes. The Supergen project "Evaluation of synthetic natural gas" includes a comparison of thermochemical and biological routes to gas, though does not include the range of pretreatment routes considered here. Inclusion in future studies from now would help to identify the potential role for this technology, albeit with uncertainty related to technology costs and performance. Once the

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[306] EU biohydrogen projects www.biohydrogen.nl/

demonstration and monitoring suggested above were completed, a fuller assessment would be possible of the role that these technologies could play, including optimising the costs, supply and GHG benefits from use of UK resources in a range of bioenergy conversion technologies.

5.4.3 Spatial analysis of anaerobic digestion with lignocellulosic resources

The ability to digest straw and energy crops could allow new AD plants to be built using a mixture of wet and dry feedstocks in areas where an AD plant at a scale suitable for biomethane grid injection would not be viable based on the local availability of wet wastes alone. Detailed quantification of the extent to which this could take place would require spatial modelling of wet wastes, straw and energy crops, including the interaction with AD/biohydrogen plant scale, and the gas grid. This could be similar to the approach taken in the ETI BVCM model, which did not include all wet feedstocks, or biological routes to hydrogen.

5.4.4 Research on pretreatment of grasses and wood

Whilst considerably bigger than the wet wastes resource alone, straw resources are also likely to be considerably smaller than potential resources of energy grasses, other energy crops and wood. Investigating use of these feedstocks further, beyond the relatively limited range of academic research and trials by technology developers would be useful to know whether this is an interesting route in terms of costs, yield and energy use. These projects could be coupled with those on improvements to energy crops for fermentative routes, such as green Miscanthus harvesting and crop breeding for improved ease of pretreatment. Given that both energy crop cultivation and lignocellulosic pretreatment are at an early stage of commercialisation, and the likely increased costs compared with current AD feedstocks, this would be unlikely to happen in industry without government support. As an indication of cost, the EU FP6 CROPGEN project was a 3 year project focusing on a range of (non-lignocellulosic) crops for AD, with EU funding of €2.5m over 3 years, including literature research, modelling and lab-scale trials – not including crop trials or demonstration at larger scale.

5.4.5 Further R&D and demonstration of biological hydrogen production

Given that there are potentially promising technologies for use of lignocellulosic feedstocks in fermentative routes, interest in gas grid blending and 100% conversion to hydrogen, and potential for increased energy yields from fermentation to hydrogen and methane, compared with methane alone, further R&D and demonstration of this route would be valuable. This could be done through continuation of research funding to UK universities through H2FC Supergen, potentially in combined projects with Supergen Bioenergy, together with support for demonstration at larger scale of hydrogen production combined with AD.

5.5 Indicative timeline

Figure 8 below shows the actions described above mapped onto a timeline, with near term actions which would have the most significant impact shown in bold. Further analysis of the benefits of this technology is needed, which can begin before better data is available, with progressive improvement as data is improved.

Other actions shown could also be important in enabling greater supply of feedstock to biological routes, and making hydrogen available, but are contingent on other actions within and beyond this area: successful proof of technology on energy grasses and wood, decisions around hydrogen blending in the gas grid, and ramp up of UK energy crop production.

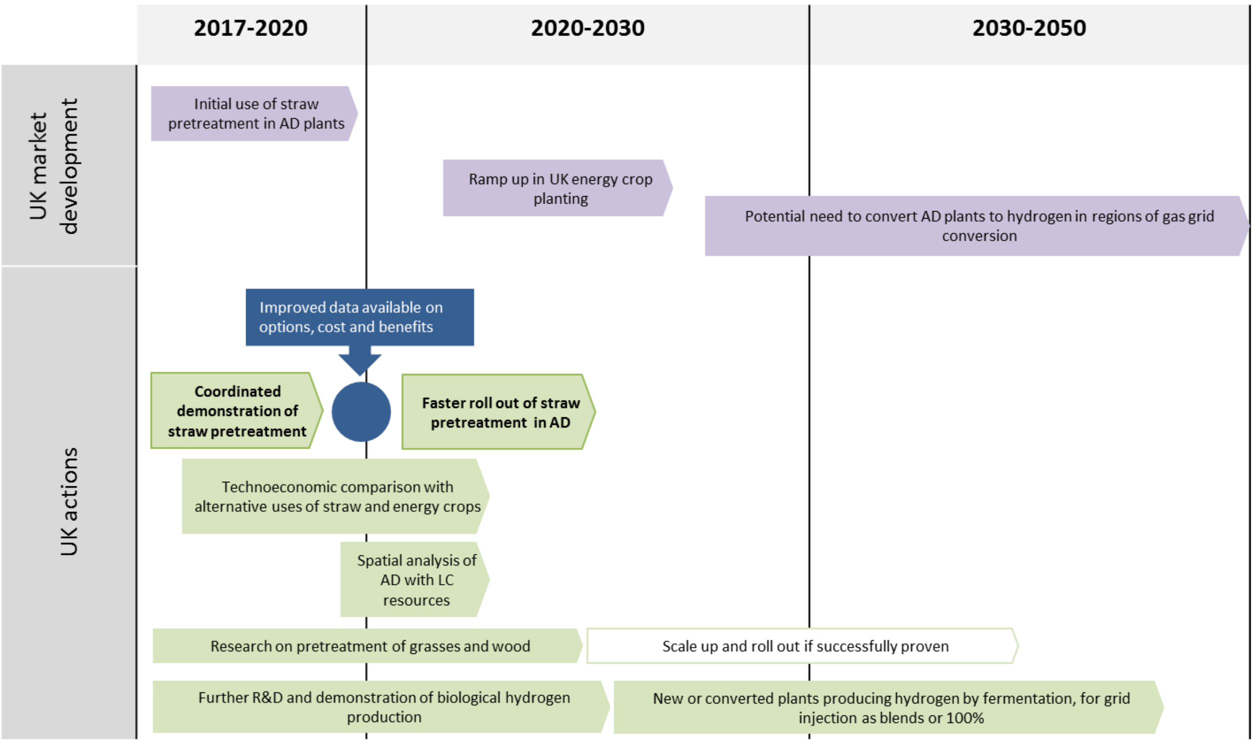
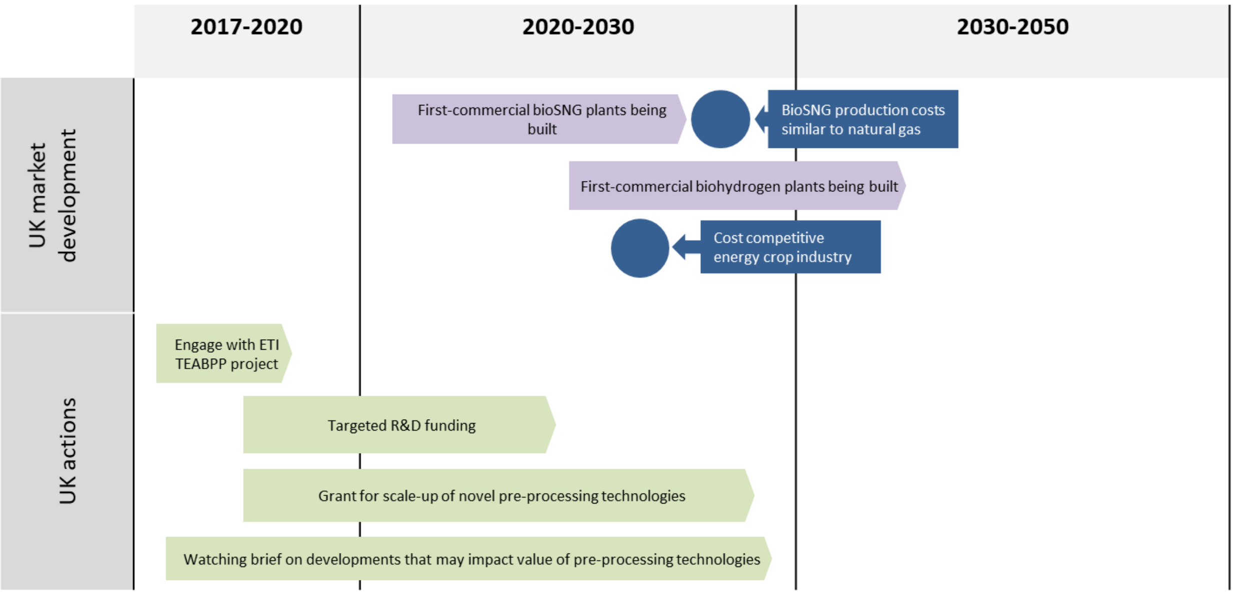


Figure 8: Actions to support innovation in pretreatment for AD and fermentation to hydrogen

6 Biomass pre-processing for thermo-chemical routes

Summary

- There is a wide range of biomass pre-processing technologies available today, used to clean up, dry and/or densify biomass prior to thermochemical conversion. Processes such as chipping and pelletising are commercially mature, but this chapter focuses on more novel processes: water washing, chemical washing, pyrolysis, torrefaction and steam explosion, which are at the demonstration to early commercial stage.
- Water washing and chemical washing of biomass are not widely deployed or researched today and require improved equipment design optimised for biomass. Pyrolysis and torrefaction are widely used today, but require further optimisation and increased deployment at large-scale in order to be used for a wide range of feedstocks. Steam explosion requires innovation for use as pre-treatment for thermo-chemical conversion, as to date it has largely been used as a pre-treatment for fermentation.
- However, none of these novel routes have yet been proven to have benefits to UK supply chains in terms of cost reductions in biomass transport or conversion that outweigh the costs and efficiency loss of the pre-processing itself. In particular, given the wide range of existing commercial pre-processing technologies, there is little commercial driver to develop novel routes.
- Research on the value of these routes is ongoing, and should be reviewed before determining the direction of future support for RD&D. Routes which could lead to supply-chain benefits will likely require both R&D and deployment support in order to reach commercialisation. The commercial driver for novel pretreatment routes will increase with the increasing scale of biomass supply chains.
- An indicative timeline for pre-processing for thermochemical routes in the UK:

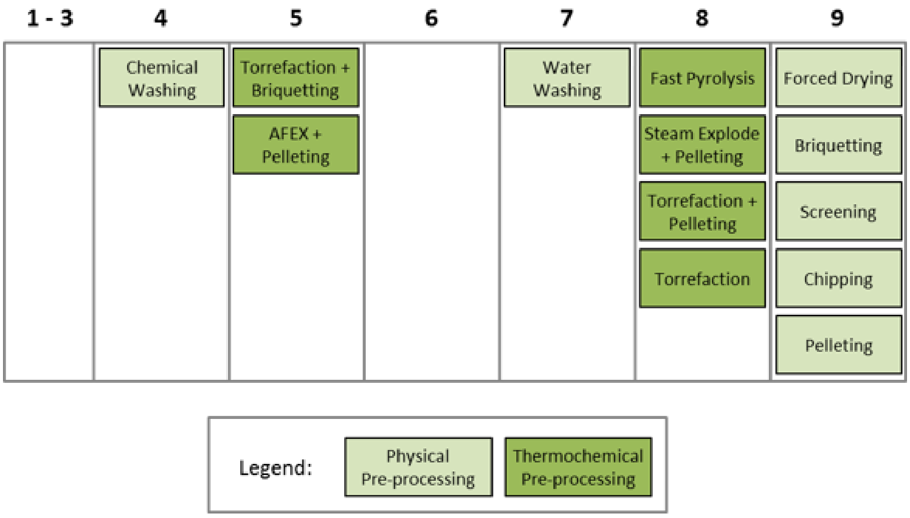


6.1 Introduction

There is a wide range of biomass pre-processing technologies available today, generally used to clean up, dry and/or densify biomass prior to thermochemical conversion. The value of pre-processing technologies to the provision of bioSNG or biohydrogen is highly dependent on the supply chain that is under consideration: the specific feedstock, feedstock location, logistics, gasifier type and gas clean-up technologies that are used.

It is possible to define general characteristics of biomass that must be met for it to be processed in a gasifier, but the specific biomass characteristics required for optimum operation are dictated by the exact gasifier type, and syngas clean-up steps that are employed. For example, fluidised bed gasifiers can tolerate particle sizes up to approximately 6 – 50 mm, while entrained flow gasifiers generally require particle sizes less than 0.15 – 1.0 mm in diameter, which requires pulverisation of the biomass prior to gasification. Most gasifiers are also designed to operate with biomass feedstock with a moisture content between 15 and 25% (wet weight), but some plasma and fluidised bed gasifier designs can operate at moisture contents of up to 55-60%[307,308].

In this project, given the focus on innovation activities, pre-processing technologies which are currently at TRL 9 (as given in Figure 9) are out of scope, due to their limited potential for innovation activities. In addition, ammonia fibre expansion (AFEX) has been scoped out, because when the primary developers of this technology (MBI) were contacted, they stated that development to-date has been focussed on AFEX as pre-treatment for biochemical processes, and they considered it highly unlikely that AFEX could be economically viable for gasification technology.



1 - 3	4	5	6	7	8	9
	Chemical Washing	Torrefaction + Briquetting		Water Washing	Fast Pyrolysis	Forced Drying
		AFEX + Pelleting			Steam Explode + Pelleting	Briquetting
					Torrefaction + Pelleting	Screening
					Torrefaction	Chipping
						Pelleting

Legend: Physical Pre-processing | Thermochemical Pre-processing

Figure 9 Current TRLs of biomass pre-processing technologies[309]

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[307] Sikarwar, V.S., Zhao, M., Clough, P., Yao, J., Zhong, X., Memon, M.Z., Shah, N., Anthony, E.J., Fennell, P.S. (2016) an overview of advances in biomass gasification, Energy Environ. Sci., 2016, 9, 2939-2977, http://pubs.rsc.org/en/content/articlehtml/2016/ee/c6ee00935b

[308] E4tech (2010) “Review of Technologies for Gasification of Biomass and Wastes”, report for DECC, via NNFCC. Available at: http://www.e4tech.com/reports/review-of-technologies-for-gasification-of-biomass-and-wastes/

[309] E4tech et al. (2016) "Review and benchmarking report", Deliverable 1 for the Energy Technologies Institute (ETI)'s Techno-Economic Assessment of Biomass Pre-Processing (TEABPP) project. Authored by E4tech, Black & Veatch, Imperial College Consultants, University of Sheffield and University of Leeds.

In the following section we summarise the current global and UK status and potential innovation activities for each pre-processing technology in scope. Each technology is then considered in turn, highlighting the current situation and innovations that are required.

6.2 Water washing

Current status

Water washing removes soil & stone contamination, along with a proportion of the biomass feedstock, ash, alkali metals, halides and other metal contaminants, therefore reducing problems of slagging and fouling downstream in the gasifier. Washing at higher temperatures (60 - 90°C) improves the efficiency of mineral removal.[310] Washing is most effective on ground, chopped or chipped biomass (i.e. particles with a large surface area), and an additional drying step is likely to be required after washing, along with a wastewater treatment plant (to deal with the metals and other contaminants). The greatest benefit from washing is experienced when the starting feedstock has a high alkali metal content, such as straw or Miscanthus.

Most commercial water washing plants are currently designed primarily for the agricultural sector, such as potato, or sugar beet sugar washing. There are some suppliers of washing machinery in the UK, such as Blue Machinery.[311]

While washing has been fairly well researched in the context of subsequent biomass combustion, the results have been highly variable, and there has been little research into the impacts of water washing for subsequent gasification of biomass. The ETI have just commissioned a £2.2m biomass washing demonstration project[312] in the UK (led by Forest Fuels, with Uniper Technologies, University of Sheffield and University of Leeds), with downstream combustion testing.

Innovations

Water washing technology needs to be developed and optimised for washing of a range of different biomass feedstocks and particle forms. Given that the technology is fairly simple, and is well-established for agricultural (food) products, achieving this change is not anticipated to be particularly challenging.[313]

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[310] Gudka, B., Jones, J.M., Lea-Langton, A.R., Williams, A., Saddawi, A. (2016) A review of the mitigation of deposition and emission problems during biomass combustion through washing pre-treatment, Journal of the Energy Institute, 89 (2) 159-171, http://www.sciencedirect.com/science/article/pii/S1743967114204089

[311] E4tech et al. (2016) "Review and benchmarking report", Deliverable 1 for the Energy Technologies Institute (ETI)'s Techno-Economic Assessment of Biomass Pre-Processing (TEABPP) project. Authored by E4tech, Black & Veatch, Imperial College Consultants, University of Sheffield and University of Leeds.

[312] ETI (2017) “Biomass Feedstock Improvement Process”, Available at: http://www.eti.co.uk/programmes/bioenergy/biomass-feedstock-improvement-process-project

[313] E4tech et al. (2016) "Review and benchmarking report", Deliverable 1 for the Energy Technologies Institute (ETI)'s Techno-Economic Assessment of Biomass Pre-Processing (TEABPP) project. Authored by E4tech, Black & Veatch, Imperial College Consultants, University of Sheffield and University of Leeds.

6.2.1 Equipment automation

Increased automation of water washing equipment is estimated to be able to reduce labour costs by up to 50%, from a baseline value of around £208,000/year for equipment processing 71,000 tonnes (wet) biomass/year.[314] This corresponds to a cost reduction for labour from £0.72/MWh biomass input to £0.36/MWh biomass input, and a total opex reduction of 14% from £2.90/MWh$_{output}$ to £2.49/MWh$_{output}$.

6.2.2 Improved design specific to biomass

An interviewee suggested that improvements to the design of the water washer could reduce current operating costs by around 10%. This could be achieved through better mixing of biomass and water resulting in reduced water input and therefore reduced waste water, and more efficient grinding and pumping reducing electricity input.[315] Based on a 10% reduction in total fixed and variable opex costs as reported in the ETI TEABPP project, this equates to a reduction in opex costs from £2.90/MWh$_{output}$ to £2.61/MWh$_{output}$.

6.2.3 Use of high-temperature water

An interviewee suggested that the use of higher temperature water would significantly improve the efficiency of water washing, by around 30-40%, as a higher level of alkali metal removal can be achieved while using less water.

If the amount of water used decreases by 35% then the costs of water input and waste water processing associated with biomass water washing would decrease from £0.23/MWh biomass input to £0.15/MWh biomass input,[316] corresponding to a 3% decrease in total opex costs from £2.90/MWh biomass output to £2.81/MWh biomass output. However, the cost of heating the water may outweigh this small cost reduction unless it can be provided by water heat, for example through thermal integration with downstream conversion processes.

6.2.4 Development of gasification technologies that can accept wet biomass

A key barrier to the uptake of water washing technologies is the high cost associated with it, particularly due to the subsequent biomass drying step (although this is improved if it could use waste heat from the methanation process). Whilst not an innovation in water washing technology itself, the development of supercritical water gasification or aqueous phase reforming, which can accept feedstocks with high moisture contents,[317] could improve the economic case for use of biomass water washing. Avoiding an energy-intensive drying step improves the GHG intensity of the water washing process, but whether the overall sustainability of bioSNG or biohydrogen provision is improved depends on the downstream technology, which for gasification of wet biomass is still at a very early stage, and could be significantly less efficient than conversion of dry biomass.

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[314] E4tech et al. (2016) "Initial techno-economic results", Deliverable 2 for the Energy Technologies Institute (ETI)'s Techno-Economic Assessment of Biomass Pre-Processing (TEABPP) project. Authored by E4tech, Black & Veatch, Imperial College Consultants, University of Sheffield and University of Leeds.

[315] E4tech et al. (2016) "Initial techno-economic results", Deliverable 2 for the Energy Technologies Institute (ETI)'s Techno-Economic Assessment of Biomass Pre-Processing (TEABPP) project. Authored by E4tech, Black & Veatch, Imperial College Consultants, University of Sheffield and University of Leeds.

[316] TEABPP D2

[317] Sikarwar, V.S., Zhao, M., Fennell, P.S., Shah, N., Anthony, E.J. (2017) Progress in biofuel production from gasification, Progress in Energy and Combustion Science (61) 189-248

6.3 Chemical washing

Current status

Chemical washing uses a similar plant set-up to water washing with the addition of chemicals such as acids and alkaline solutions in several staged reactors. It can remove a much higher percentage of ash, alkali metals and halides than basic water washing, but the wastewater produced is likely to be more difficult to treat. Chemical washing is a less mature technology than water washing and there are currently no known industrial-scale biomass chemical washing plants.

It is uncertain whether there will be sufficient drivers to develop chemical washing technology, given it could have a substantially higher cost for limited additional benefit compared to water washing.

Innovations

Chemical washing of biomass is at TRL 4. The technology needs to be scaled-up and commercialised, and more research could identify further areas of innovation, as the research into this technology is currently limited.

6.3.1 Equipment automation

As for water washing, increased automation of the chemical washing equipment could reduce the opex labour costs by up to 50%, from a baseline value of around £297,000/year for equipment processing 71,000 tonnes (wet) biomass/year. This corresponds to an 11% reduction in total opex costs from £5.65/MWh$_{output}$ to £5.06/MWh $_{output}$. These estimates are less certain than for water washing due to the earlier deployment stage of chemical washing technology and extra complexity of involving chemicals.[318]

6.3.2 Improved equipment design

Innovations in the design of chemical washing equipment could lead to greater efficiency and lower opex costs.

More efficient grinding and pumping can reduce the amount of electricity required by 40% (from 6.5 to 3.9 kWh/MWh$_{main\ output}$), better mixing of biomass and water can reduce the amount of water required by the process by 50% (from 0.28 to 0.14 tonnes/MWh$_{main\ output}$) therefore also reducing costs associated with waste water processing. Finally, technical innovations are also anticipated to reduce the chemical requirements by up to 40%.[319]

Overall the cost reductions associated with these improvements could reduce the opex costs by 19% from £5.65/MWh$_{output}$ to £4.61/MWh$_{output}$. Reducing power requirements also improves the sustainability of the process.

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[318] TEABPP D2

[319] TEABPP D2

6.3.3 Combination with water washing

An interviewee suggested that if the extremely high levels of alkali-removal achieved by chemical washing are required, then this technique could be combined with water washing so that the bulk of the impurities are removed first by water washing, and then a small amount of acid could be used to extract what remains. This could reduce the opex by reducing the amount of acid required, but is likely to have higher capex due to more stages in the process. This would likely result in lower GHG impacts due to a decreased use of acid, but this new process configuration is yet to be tested.

6.4 Pyrolysis

Current status

Pyrolysis is the controlled heating of biomass in the absence of oxygen to produce a mixture of liquid (bio-oil), gaseous and solid (bio-char) products. Fast pyrolysis technology, which maximises the liquid fraction, is used when pyrolysis is used for biomass pre-processing, as this high-density liquid fraction can then be cheaply transported, and be injected into the final conversion technology at low cost. The main reactor types used today for fast pyrolysis are bubbling fluidised bed, circulating fluidised bed reactors, and rotating cone reactors. Moisture content of the feedstock fed to the reactor must typically be between 10 and 15%[320] so a preliminary drying step may be required for certain feedstocks. Gassner and Maréchal (2009)[321] model the efficiency of an internally circulating fluidised bed gasifier both with and without pyrolysis as feedstock pre-treatment. They conclude that when pyrolysis is used as a pre-treatment the cold-gas energy efficiency of bioSNG production per unit of biomass input increases from 64.5% to 73.4%.

There are many demonstration and first commercial pyrolysis plants worldwide, producing liquid bio-oil for combustion heating applications, but the technology has not yet been fully commercialised and is at TRL 8. Although the pyrolysis pre-treatment technology would be very similar if the liquid bio-oil were gasified instead of combusted, this route is much less developed and is still largely at pilot-scale. Also, the Bioliq pilot plant at the Karlsruhe Institute of Technology (KIT) has a 2 MW fast pyrolysis plant followed by a 5 MW high pressure entrained flow gasifier, which processes the pyrolysis liquid fraction generated from straw. After gas cleaning and conditioning, fuel synthesis to Fischer-Tropsch products, methanol and DME is carried out at small-scale.[322] Pyrolysis was chosen as a pre-processing technology for the Bioliq process because it allowed a decentralised model with multiple small pyrolysis plants (collecting local straw) and one large central gasifier to be developed, and liquid bio-oil is much easier to inject into the high-pressure entrained flow gasifier than solid biomass.

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[320] E4tech et al. (2016) "Review and benchmarking report", Deliverable 1 for the Energy Technologies Institute (ETI)'s *Techno-Economic Assessment of Biomass Pre-Processing* (TEABPP) project. Authored by E4tech, Black & Veatch, Imperial College Consultants, University of Sheffield and University of Leeds.

[321] Gassner, M. and Maréchal, F. (2009) Thermodynamic comparison of the FICFB and Viking gasification concepts, Energy, 34, 1744–1753

[322] Bioliq (n.d.) The Bioliq Process, http://www.bioliq.de/english/55.php

There is UK activity in research and deployment of pyrolysis technologies, as summarised by the EBRI,[323] but little activity in developing plants which use pyrolysis as a pre-treatment for gasification.

Innovations

Although there remain some opportunities for improvement with the pyrolysis reactor itself, for example around achieving effective and efficient heat transfer inside the reactor,[324,326] interviews suggested that the pyrolysis reactor itself does not require significant innovation.

6.4.1 Understanding and tuning properties of bio-oil

There is opportunity to improve the properties of the bio-oil, which can be unstable and highly acidic.[325] This could be achieved for example through the use of catalysts to improve the efficiency of pyrolysis and remove the oxygen-containing functionalities in the bio-oil.[326] Further research may be needed to understand the changes to the properties of bio-oil over time if it is to be transported to alternative locations.[327] Techno-economic modelling carried out as part of the ETI's TEABPP project suggests that better control of the pyrolysis process or use of novel catalysts could reduce nitrogen, sulphur and chlorine composition of the bio-oil by up to 50%.[328] These improvements would increase the efficiency with which the bio-oil can be gasified, and likely reduce costs associated with downstream gasification as a result of lower impurity levels. However, the impact on capex or opex costs of the pyrolysis process itself is likely to be minimal. GHG emissions may decrease as a results of higher conversion efficiency, although there may be increased use of catalyst to offset this.

Ash and alkali metals in the biomass can also have a very significant impact on the relative yields of the bio-oil, gaseous and biochar fractions. Energy crop innovations that reduce alkali metal contents, or pyrolysis catalyst developments that can overcome alkali metal deselectivity, could therefore achieve large increases in bio-oil yields.

6.4.2 Increased deployment and scale-up

Scale-up and operational experience of commercial scale pyrolysis reactors, including in handling of the bio-oil, is also required to improve the reliability and reduce costs. The cost reductions anticipated with scale-up are illustrated in Figure 10 (approx. 130 wet tonnes / day). The figure shows there is scope for significant cost reductions on scale-up. However, there is a trade-off with cost and energy required to transport large volumes of biomass.

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[323] Aston University European Bioenergy Research Institute (2015) Biomass and Waste Pyrolysis A Guide to UK Capabilities, http://www.pyne.co.uk/Resources/user/UK%20Biomass%20and%20Waste%20Pyrolysis%20Guide%202015%20081015.pdf

[324] Dhyani, V., Bhaskar, T. (2017) A comprehensive review on the pyrolysis of lignocellulosic biomass, Renewable energy [In-press] http://www.sciencedirect.com/science/article/pii/S0960148117303427

[325] Venderbosch, R., Prins, W. (2010) Fast pyrolysis technology development, Biofuels Bioproducts and Biorefining 4(2):178-208, https://www.researchgate.net/publication/227509433_Fast_pyrolysis_technology_development

[326] Roy, P., Dias, G. (2017) Prospects for pyrolysis technologies in the bioenergy sector: A review, Renewable and sustainable energy reviews (77) 59-69, http://www.sciencedirect.com/science/article/pii/S1364032117304719

[327] Sikarwar, V.S., Zhao, M., Clough, P., Yao, J., Zhong, X., Memon, M.Z., Shah, N., Anthony, E.J., Fennell, P.S. (2016) an overview of advances in biomass gasification, Energy Environ. Sci., 2016, 9, 2939-2977, http://pubs.rsc.org/en/content/articlehtml/2016/ee/c6ee00935b#cit100

[328] TEABPP D2

More operational experience from deployment of additional plants would be likely to improve plant reliability, in terms of annual operational hours, therefore lowering opex and reducing risk associated with the technology.

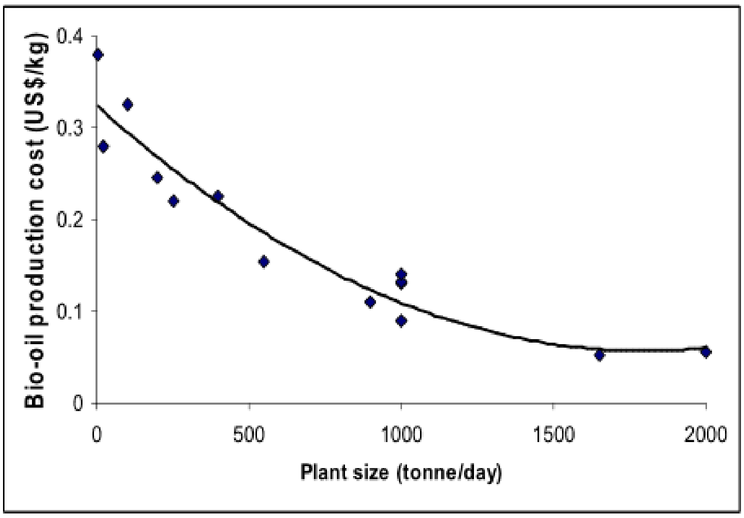

Figure 10 Correlation of bio-oil production cost with plant size (Jahirul and Rasul, 2012)[329]

6.4.3 Increase feedstock flexibility of pyrolysis process

An interviewee involved in research into a coupled pyrolysis-gasification plant stated that a key challenge is to increase the range of biomass that can be used in the system. Coupling pyrolysis with gasification when wood was used was not a problem, but ash-rich feedstocks create an ash-rich bio-oil which may cause problems in the gasifier. It was emphasised that it is not a single innovation that is required to tackle this, but a range of small improvements for example in the construction of the gasifier and the materials that are used. Because of the tuning that is required to optimise the plant for each feedstock, it may be more economically viable to process feedstocks separately rather than several types of feedstocks into one pyrolysis plant.

By enabling pyrolysis oil from a wider range of feedstocks to be used inside a gasifier, this innovation would increase the potential supply of pyrolysed material. In addition, widening the range of feedstocks that can be pyrolysed and processed by a gasifier would likely enable lower cost and more sustainable feedstocks to be accessed via this route.

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[329] Rahirul, M.I., Rasul, M. (2012) Recent Developments in Biomass Pyrolysis for Bio-Fuel Production, Its Potential for Commercial Applications, Recent Researches in Environmental and Geological Sciences, http://bit.ly/2uG4fs7

6.5 Torrefaction

Current status

Torrefaction is the heating of biomass (usually biomass chips) in limited oxygen to evaporate moisture and drive off volatile gases which have a low energy content. Torrefied biomass chips can be made straight into briquettes or can be more easily ground into powder before pelletisation. The key benefits of torrefaction are that the resulting biomass has higher energy density, lower moisture content, less oxygen, higher hydrophobicity, improved grindability (to facilitate production of pellets and improve handling), and more uniform properties.[330] Most research to-date focuses on the use of torrefied biomass in pulverised coal power plants or entrained flow gasifiers, which requires feedstocks to be finely ground before injection. Therefore the improved grindability of torrefied biomass is a significant advantage compared to conventional biomass, and allows easier co-processing with coal. Chen et al. (2015) report that in certain experiments, the use of torrefied biomass in a gasifier was shown to improve syngas quality and cold gas efficiency.[330] It should be noted however that whilst high lower heating value (LHV) and substantial logistics benefits from using torrefied pellets have been quoted in the literature, in reality the pellets have struggled to achieve high LHVs and durability.[331]

There are several companies who are operating commercial-scale torrefaction plants including TSI[332], Airex,[333] Vega Biofuels,[334] New Biomass Energy[335] and Earth Care Products[336]. Rotawave and CanBiocoal in the UK are both developing microwave reactors.[337] Work on torrefaction in the UK has been funded by the Supergen bioenergy hub in their Torrefaction integrated assessment project involving the Universities of Bath, Manchester, Aston and Leeds.[338]

Innovations

Innovations in torrefaction are identified and explained below.

6.5.1 Reduction in energy inputs to torrefaction process

It is estimated that the electricity input to the torrefaction process could reduce by as much as 20% as the technology becomes more established. Diesel use could reduce by 40% due to improved mechanical design and

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[330] Chen, W., Peng, J., Bi, X.T. (2015) A state-of-the-art review of biomass torrefaction, densification and applications, renewable and sustainable energy reviews (44) 847-866 http://www.sciencedirect.com/science/article/pii/S1364032114010910

[331] E4tech et al. (2016) "Review and benchmarking report", Deliverable 1 for the Energy Technologies Institute (ETI)'s Techno-Economic Assessment of Biomass Pre-Processing (TEABPP) project. Authored by E4tech, Black & Veatch, Imperial College Consultants, University of Sheffield and University of Leeds.

[332] TSI (2017) TSI, http://tsi-inc.net/biomasswood/products/torrefaction/ (Accessed 26th July 2017)

[333] Airex Energy (2016) Airex Energy, http://www.airex-energy.com/en/media-centre/21-a-flexible-biomass-torrefaction-plant-has-recently-been-unveiled-in-canada (Accessed 26th July 2017)

[334] Marketwired (2016) Vega Biofuels, Inc. Increases Production Capacity with Completion of Generation Four Torrefaction Machine, http://www.marketwired.com/press-release/vega-biofuels-inc-increases-production-capacity-with-completion-generation-four-torrefaction-otc-pink-vgpr-2174214.htm (Accessed 26th July 2017)

[335] Bioenergy International (2016) New Biomass Energy acquires Solvay's interest in torrefaction plant, https://bioenergyinternational.com/pellets-solid-fuels/new-biomass-energy-acquires-solvays-interest-in-torrefaction-plant (Accessed 26th July 2017)

[336] Earth Care Products, Inc. (n.d.) Earth Care Products Inc. http://ecpisystems.com/(Accessed 26th July 2017)

[337] Kumar, L., Koukoulas, A.A., Mani, S., Satyavolu, J. (2017) Integrating Torrefaction in the Wood Pellet Industry: A Critical Review, Energy and Fuels , 31 (1) 37-54, http://pubs.acs.org/doi/full/10.1021/acs.energyfuels.6b02803

[338] Torrefaction integrated assessment, http://www.supergen-bioenergy.net/research-projects/torrefaction-integrated-assessment/

more efficient engines, and a switch from diesel to electric motor for chipping and screening[339]. Reducing energy use for process would reduce opex costs, and switching to an electric motor instead of diesel could improve reliability. Based on process costs modelled in ETI TEABPP project, this could decrease the opex by 10% from £5.06/MWh$_{output}$ to £4.45/MWh$_{output}$.

Use of waste heat and combustion of the torrefaction gases could also improve the overall efficiency of the process,[340] contributing to lower energy use, therefore lower plant opex costs and GHG reduction.

6.5.2 Scale-up and further deployment

Further scale-up and commercialisation of torrefaction is required, particularly in the use of straw or Miscanthus, as torrefaction of these feedstocks is currently not well-developed. Most of the development of torrefaction to date has focused on clean wood feedstocks (currently at TRL 8).

Even scale-up of wood torrefaction could have significant advantages: in the FP7 SECTOR project a model is developed to compare the costs of a 72,800 tonne/annum plant with a 500,000 tonne/annum plant producing torrefied pellets. The project finds that the capital costs of the larger-scale plant are 44% lower on a levelised £/MW/year basis, reducing from around £80,000/MW/year to £45,000/MW/year. [341]

Therefore scale-up and further deployment of torrefaction of woody feedstocks is likely to reduce costs, whilst further deployment of torrefaction for straw or Miscanthus could result in access to a wider range of feedstocks, which could have lower costs and/or GHG emissions, therefore increasing supply of torrefied material.

6.5.3 Valorising torrefaction gas condensate

Mass yields of condensate (liquid collected from the process) in the torrefaction process vary from about 3 – 8%, and there is potential to improve the economics of the torrefaction process by finding productive and valuable uses for this by-product. The EU-funded SECTOR project suggests that they may have potential uses as biodegradable pesticides or in wood protection.[342] They found that the overall production cost of torrefied pellets, which in the base case plant (56MW$_{torrefied\ pellets}$) with no condensate recovery is 43 €/MWh, is lowered by 3 €/MWh with a condensate price of 100 €/tonne, and lowered by 11 €/MWh with a condensate price of 250€/tonne.[343]

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[339] [339] E4tech et al. (2016) "Initial techno-economic results", Deliverable 2 for the Energy Technologies Institute (ETI)'s Techno-Economic Assessment of Biomass Pre-Processing (TEABPP) project. Authored by E4tech, Black & Veatch, Imperial College Consultants, University of Sheffield and University of Leeds.

[340] Joshi, Y., de Vries, H. Woudstra, T., de Jong, W (2015) Torrefaction: Unit operation modelling and process simulation, Applied thermal engineering, 74, 83-88

[341] Arpiainen, V., Wilen, C.. (2015) Production of Solid Sustainable Energy Carriers from Biomass by Means of Torrefaction, Deliverable No. D3.2, Report on optimisation opportunities by integrating torrefaction into existing industries, SECTOR FP7 project, https://sector-project.eu/SECTOR-deliverables.16.0.html

[342] Koppejan, J., Schaubach, K., Witt, J., Thran, D. (2015) Production of Solid Sustainable Energy Carriers from Biomass by Means of Torrefaction, Deliverable No. D10.2, Torrefaction Technology and Strategy Report, SECTOR FP7 project, https://sector-project.eu/SECTOR-deliverables.16.0.html

[343] Fagernas, L., Kuoppala, E., Arpiainen, V. (2015) Composition, Utilization and Economic Assessment of Torrefaction Condensates, Energy and Fuels, 29, 3134-3142, DOI: 10.1021/acs.energyfuels.5b00004

6.6 Steam explosion

Current status

In steam explosion, biomass is held at high pressure and temperature for a given period of time, and then explosively released. This frees the lignin, which then acts as a glue-like substance on the surface of the biomass to form a tightly-bound pellet, often referred to as ‘black pellets’ due to their dark colour.[344] The advantages of steam exploded black pellets compared to conventional ‘white pellets’ is their energy density, grindability, durability, and safety (no self-heating and minimal off-gassing).[345] Gunarathne at al.[346] found that gasifying black pellets was likely to result in syngas with a higher LHV but lower hydrogen content compared to gasification of conventional white pellets.

Steam explosion is a commonly used pre-treatment technology, mainly for pre-treatment of lignocellulosic biomass prior to fermentation to ethanol.[347] However use of steam explosion for subsequent thermochemical processing, which operates under slightly different conditions and results in production of a pellet, is more limited. Zilkha is one of the most prominent developers of steam-explosion with pelleting, and have a 275,000 tonnes/yr production capacity plant in Alabama.

Innovations

Innovations in steam explosion are identified and explained below.

6.6.1 Develop steam explosion as a pre-treatment for gasification

There is potential to improve steam explosion as a pre-treatment for biomass gasification, as to-date the process has largely been optimised as a pre-treatment for fermentation or combustion processes. The process requires a large amount of steam (and hence energy) input, which needs reducing. There are also large volumes of waste-water that require treatment, which could be recycled more efficiently.[348] This would improve the efficiency of the process, contributing to lower costs and improved sustainability.

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[344] E4tech et al. (2016) "Review and benchmarking report", Deliverable 1 for the Energy Technologies Institute (ETI)'s Techno-Economic Assessment of Biomass Pre-Processing (TEABPP) project. Authored by E4tech, Black & Veatch, Imperial College Consultants, University of Sheffield and University of Leeds.

[345] Zilkha (2014) “Zilkha Black Pellets Handling, Storage and Grinding in Existing Coal Plants”. World Biomass Power Markets, Amsterdam, Netherlands. Available at:
http://zilkha.com/wp-content/uploads/2014/12/ZilkhaBiomass_Handling_Storage_Grinding_05Feb2014_v3.compressed.pdf

[346] Gunarathne, D.S., Mueller, A., Fleck, S., Kolb, T., Chmielewski, J.K., Yang, W., Blasiak, W (2014) Gasification characteristics of steam exploded biomass in an updraft pilot scale gasifier, Energy, 71, 496-506, http://www.sciencedirect.com/science/article/pii/S0360544214005313

[347] Maria, A., Galletti, R., Antonetti, C. (2011) Biomass pre-treatment: separation of cellulose, hemicellulose and lignin. Existing technologies and perspectives, www.eurobioref.org/Summer_School/Lectures_Slides/day2/Lectures/L04_AG%20Raspolli.pdf

[348] E4tech et al. (2016) "Review and benchmarking report", Deliverable 1 for the Energy Technologies Institute (ETI)'s Techno-Economic Assessment of Biomass Pre-Processing (TEABPP) project. Authored by E4tech, Black & Veatch, Imperial College Consultants, University of Sheffield and University of Leeds.

6.6.2 Reduce energy demand of process

A key limitation of the steam explosion process is the large additional energy input that is required (additional energy inputs can exceed 20%), making it a costly and energy-intensive process.[349] Therefore innovations that could reduce the energy demand of the process would improve the economic viability and sustainability benefit of this technology. This could come through optimisation of the process, and/or co-location with sources of waste heat.

As electricity and natural gas together comprise around 88% of the total opex costs for the plant,[350] reducing energy demand could significantly reduce opex costs. In addition, GHG emissions would fall if energy use was decreased.

6.7 Summary of innovation impacts

Table 9: Summary of impacts of pre-processing innovations identified. Shading refers to impact of innovation in each category. Dark blue = strong impact, light blue = some impact, white = low impact

	Cost	Supply	Sustainability	Other
Water washing: Equipment automation	Opex costs reduce by 14%			
Water washing: Improved design specific to biomass	Opex costs reduce by 10%			
Water washing: Use of high-temperature water		Lower level of contaminants in biomass		
Water washing: Development of gasification technologies that can accept wet biomass	Lower opex as no need for dying		Improved sustainability as no need for dying	
Chemical washing: Equipment automation	Opex costs fall 11%			
Chemical washing: Improved equipment design	Opex costs fall 19%		40% reduction in electricity consumption	
Chemical washing: Combination with water washing	May have lower opex		Less acid / alkali required.	
Pyrolysis: Understanding and		Increased supply of bio-oil that is	Increased efficiency	

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[349] E4tech et al. (2016) "Down-selection and workshop report", Deliverable 3 for the Energy Technologies Institute (ETI)'s Techno-Economic Assessment of Biomass Pre-Processing (TEABPP) project. Authored by E4tech, Black & Veatch, Imperial College Consultants, University of Sheffield and University of Leeds.

[350] E4tech et al. (2016) "Initial techno-economic results", Deliverable 2 for the Energy Technologies Institute (ETI)'s Techno-Economic Assessment of Biomass Pre-Processing (TEABPP) project. Authored by E4tech, Black & Veatch, Imperial College Consultants, University of Sheffield and University of Leeds.

tuning properties of bio-oil		suitable for downstream gasification		
Pyrolysis: Increased deployment	Lower capex and opex, improved reliability			Less risky
Pyrolysis: Increase feedstock flexibility of pyrolysis process	Use lower cost feedstocks	Increased supply by using wider range of feedstocks	Use more sustainable feedstocks	
Torrefaction: Reduction in energy inputs to torrefaction process	Reduce opex by 10%		Reduce electricity use by 20% and diesel use by 40%	
Torrefaction: Scale-up and further deployment	44% reduction in capex	Use wider range of feedstocks	Use more sustainable feedstocks	
Torrefaction: Valorising torrefaction gas condensate	Improve plant economics by valorising torrefaction gases			
Steam explosion: Develop steam explosion as a pre-treatment for gasification	Likely lower opex costs	Improved conversion efficiency	Improved conversion efficiency	
Steam explosion: Reduce energy demand of process	Significant fall in plant opex costs		Reduce energy demand	

6.8 Barriers and gaps

In this section, we outline the key barriers to the development of pre-processing technologies in general, and identify those which are specific to specific pre-processing technologies.

6.8.1 Lack of commercial drivers for developing pre-processing technologies

Currently there are few downstream users of steam exploded pellets or pyrolysis oil, and limited experience with torrefied pellets. Therefore, there is limited existing demand for biomass produced by these methods.

Moreover there is little demand from downstream users for the development of the early-TRL pre-processing technologies which are considered here. Most gasifier developers are not considering the use of low-density and/or high-impurity feedstocks (such as Miscanthus and straw) for which pre-processing technologies might be economic, and instead focus either on RDF, wood chips or wood pellets for which the relevant pre-processing technologies are already commercialised. Even for these more challenging feedstocks, it is not clear that pre-processing is economically viable or improves supply chain sustainability within the UK.

6.8.2 Many competing commercial pre-processing technologies

As outlined in Figure 9 there are many pre-processing technologies, with a significant number already at TRL 9. The wide range of existing commercial technologies present a barrier to the development of other pre-processing technologies because they already operate at large scale and in relatively optimised plants, so are likely to be lower-cost. In addition, investments to enable large-scale use of pellets or wood chips can lock in to these pre-processing technologies for many years, even if novel techniques such as torrefaction prove to be more beneficial.

6.8.3 Finance for developing and scaling up processes

For small companies with limited finances, obtaining finance for R&D and upscaling technology can be a severe barrier to its development, particularly if larger industrial partners are unwilling to participate in the scale-up of the technology. It is reported that several early torrefaction developers discontinued their efforts to commercialise the technology because they could not get long-term financing for R&D.[351] In particular, gasification plant owners are unlikely to have the funds to support other companies to bring new supply technologies into the market.

6.8.4 Washing: insufficient research to identify required areas of innovation

There is currently very little research ongoing into water washing or chemical washing technology. This limits the development of the technology because there is limited information on the downstream benefits of washing technologies, or the efficiency of different technologies. With limited understanding of areas of improvement or innovation, little development can occur.

6.8.5 Infrastructure compatibility for pyrolysis oil

Pyrolysis oil is highly acidic and there may be challenges associated with handling and storing it that represent a barrier to further development. In transportation of pyrolysis oil, specific equipment is required for loading, unloading and handling, and all surfaces in contact with the oil must be acid proof material.[352] Whilst highly acidic products are already transported widely, and suitable transportation does exist, availability of appropriate tankers, ships and rail cars may be limited.

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[351] Koppejan, J., Schaubach, K., Witt, J., Thran, D. (2015) Production of Solid Sustainable Energy Carriers from Biomass by Means of Torrefaction, Deliverable No. D10.2, Torrefaction Technology and Strategy Report, SECTOR FP7 project, https://sector-project.eu/SECTOR-deliverables.16.0.html

[352] Laihanen, M. for BE Sustainable (2014) Requirements for transportation of fast pyrolysis bio-oil, http://www.besustainablemagazine.com/cms2/requirements-for-transportation-of-fast-pyrolysis-bio-oil/

6.9 Potential options to mitigate innovation barriers

6.9.1 Research into the value of pre-processing technologies

The ETI is currently conducting the Techno-Economic Assessment of Biomass Pre-Processing (TEABPP)[353] project which aims to compare the costs, performance and emissions of biomass supply chain configurations with and without pre-processing. The outcomes of this research will provide indication of the economic value of pre-processing technologies for a range of conversion technologies (gasification and combustion) to provide either power or heat. The ETI is also funding a £2.2M project building a pilot plant to investigate water-washing that will run to late 2018, providing more detail on the cost and sustainability impacts of cleaning up various biomass feedstocks for combustion.[354]

Engagement with this research could help BEIS to target future support for pre-processing technologies, including through specific research into the impact of pre-processing technologies on bioSNG and biohydrogen production. As these projects are currently ongoing, this is a short-term action designed to focus longer-term research and development funding.

6.9.2 R&D funding

Several recent research projects have focussed on quantifying the benefit and impact of pre-processing in biomass supply chains, including the ETI TEABPP project and the Supergen Bioenergy Torrefaction integrated assessment project.[355] Therefore having identified the most promising pre-processing technologies for improving the economics or sustainability of biomass-to-heat value chains, funding for research and demonstration activities could be effectively targeted towards these technologies, focusing specifically on innovations that can improve their performance as outlined in sections 6.2 to 6.6. Research projects should involve pilot or demonstration-scale plants and should ideally involve an industrial partner so that developments can be quickly commercialised. For some earlier TRL technologies such as water washing and chemical washing, the first research step may be to identify required areas of innovation.

Research funding could be distributed through the Supergen Bioenergy hub, but should be specifically targeted towards pre-processing technologies. In addition, biomass pre-processing could be prioritised by Innovate UK when running competitions under the Infrastructure Systems sector. While some biomass pre-processing technologies have been funded by Innovate UK recently, for example a briquetting project run by Paperback Collection and

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[353] ETI (2017) Techno-economic assessment of biomass pre-processing, http://www.eti.co.uk/programmes/bioenergy/techno-economic-assessment-of-biomass-pre-processing (Accessed 26th July 2017)

[354] ETI (2017) ETI launches project to remove impurities from biomass to make bioenergy cheaper and more efficient, http://www.eti.co.uk/news/eti-launches-project-to-remove-impurities-from-biomass-to-make-bioenergy-cheaper-and-more-efficient (Accessed 25th July 2017)

[355] Supergen bioenergy hub (n.d.) Torrefaction integrated assessment, http://www.supergen-bioenergy.net/research-projects/torrefaction-integrated-assessment/

Recycling Ltd.[356], the importance of these technologies within the ‘energy systems’ sub-sector could be further emphasised.[357]

6.9.3 Support for technology development and scale-up

Support for technology development and scale-up could include capital allowances or grant funding. Support should be given to technology developers who can prove the supply-chain benefits of their technology to the UK, to scale-up and work with commercial downstream conversion plants to overcome the challenges of operating at larger scale and in a commercial environment.

The Bioenergy infrastructure scheme was cancelled in 2010,[358] but had been used to provide grants to farmers, foresters and businesses to develop the biomass supply chain, including for investment in pre-processing equipment such as dryers, chippers and pelletisers.[359] A similar grant scheme could be reinstated to support novel pre-processing technologies. It would work closely in parallel with schemes to support farmer conversion to energy crops, as many pre-processing technologies are not currently optimised for energy crops, but it is with these feedstocks, which may be low density or challenging in composition, where they may have the greatest value.

6.9.4 Monitor ongoing developments

BEIS could keep a watching brief on whether development of novel pre-processing technologies could enable significantly increased use of certain global bioenergy resources, in the way that development of pelleting technology significantly increased the UK’s ability to use North American forestry residues. For example, development of pyrolysis may increase potential straw availability to the UK, and all pre-processing technologies will be become more valuable if global demand and price of biomass increases.

If conversion plant emissions legislation tightens then there will likely be a greater need for pre-processing to remove contaminants from biomass. In addition, several pre-processing technologies (e.g. torrefaction and steam explosion) are likely to improve the storability of biomass, which might become more valuable in the future if degradation of biomass and methane emissions from biomass piles is found to be an issue.

Monitoring of wider developments in pre-processing technology and the bioenergy landscape could help BEIS to understand whether additional pre-processing technology types might be valuable to develop in the UK.

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[356] Gov.uk (2017) Innovate UK funded projects since 2004, https://www.gov.uk/government/publications/innovate-uk-funded-projects (Accessed 25th July 2017)

[357] Innovate UK (2016) Innovate UK Delivery Plan Financial Year 2016/17 https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/514962/CO300_Innovate_UK_Delivery_Plan_2016_2017_WEB.pdf

[358] Gov.UK (2010) Savings by DECC on low-carbon technology programmes, https://www.gov.uk/government/news/savings-by-decc-on-low-carbon-technology-programmes (Accessed 24th July 2017)

[359] DEFRA (2004) *adlib.everysite.co.uk/resources/000/025/632/infrastructure-detailed.pdf (Accessed 24th July 2017)*

6.10 Indicative timeline

Figure 11 outlines the actions identified for the development of pre-processing technologies.

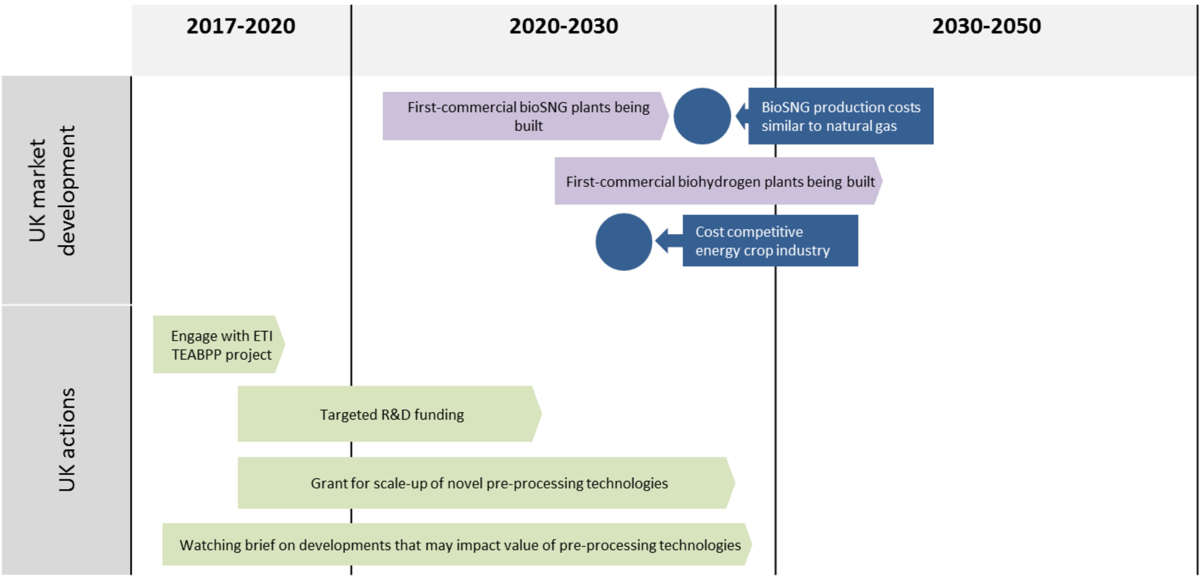

Figure 11 Actions for the support of pre-processing technologies, as required over time (green chevrons) in the context of wider UK market developments (purple chevrons)

Actions proposed in the short to medium term – targeted R&D funding and grants for technology scale-up – should aim to promote developments in those pre-processing technologies which can bring value to existing or under development biomass value chains. This is not likely to be determined until the ETI TEABPP project is finalised.

Pre-processing technologies are likely to become increasingly valuable as bioenergy use is scaled up, as they will allow the efficient use of low-density or remote biomass feedstocks. Therefore, a watching brief could inform BEIS if some novel pre-processing technologies are likely to be necessary to access such challenging feedstocks, in which case R&D funding and grant support could be extended to these technologies.

Appendix A Interviewees

The project team would like to thank the following people for providing their insights:

Waste pre-treatment	• Arturo Castillo Castillo, Imperial College, London • Matt Gibbon, Development Director at Kier Environmental • Peter Metcalfe, Wilson Steam
Forestry material	• Peter Coleman, BEIS
BioSNG and biohydrogen from gasification	• Christian Aichernig, Repotec • Prof Henrik Thunman, Chalmers University of Technology • Prof Christoph Pfeifer, Uni of Natural Resources & Life Sciences, Vienna • Andy Cornell, Advanced Plasma Power • Chris Manson-Whitton, Progressive Energy • Prof Nilay Shah, Imperial College London • Neville Hargreaves, Velocys • Dr Geraint Evans, Energy Technologies Institute • Prof Stefan Rönsch, Deutsches Biomasseforschungszentrum gemeinnützige GmbH (DBFZ) (via email) • Vann Bush, Gas Technology Institute • Gareth Fletcher, Materials Processing Institute
Biomass pre-processing	• Dr Paul Adams, University of Bath • Khalidah Al-Qayim, University of Sheffield • Dr Nicolaus Dahmen, Karlsruhe Institute of Technology (KIT)
Woody and grassy energy crops	• Jeanette Whitaker, Centre for Ecology and Hydrology • William Cracroft-Eley, Terravesta • Astley Hastings, University of Aberdeen • Mark Paulson, Coppice Resources Limited • John-Clifton Brown, University of Aberystwyth • William Macalpine, Rothamsted Research Centre
Anaerobic digestion of lignocellulosic materials	• Ollie More, ADBA • Carly Whittaker, Rothamsted Research • Lucy Montgomery, NNFCC (by email) • Paul Adams, University of Bath • John Scott-Kerr, Future Biogas • Gunther Bochmann, Institute for Environmental Biotechnology, BOKU University of Natural Resources and Life Sciences, Vienna • Richard Dinsdale, University of South Wales • Emma Greenwood, Cavimax Ltd • Marco Soldo, BioBANG

Appendix B Identification of key technologies, feedstocks and types of innovation

B 1 Approach to selection

This section gives the results of the selection of technologies, feedstocks and types of innovation to be included in this study.

The criteria for selection of technologies and feedstocks were agreed with BEIS at the start of the project. The selection of technologies and feedstocks below is based on the following two criteria **both** being met:

1. **Significant contribution to decarbonisation of GB heating by 2050** – assessed for technologies based on their maximum contribution to UK heating in scenarios from previous energy systems modelling such as UK TIMES and ESME, or bioenergy systems modelling in the ETI's Biomass Value Chain Model (BVCM), and for feedstocks based on UK and import availability of biomass. Note that this did not include new model runs. Where technologies or feedstocks are not represented adequately in models, assessment has been based on the project team's expertise, with assumptions clearly documented. Note that this is not based on any new information that may result from the Evidence Review project because the selection of technologies was conducted at the start of the project.
2. **Significant potential for innovation**, using the proxies of:
    - Technologies or feedstocks that are not yet commercially available (TRL 9); OR
    - Technologies or feedstocks that are not yet widely exploited in the biomass supply chains that are most likely to make a significant contribution to decarbonisation of GB heating; OR
    - Technologies or feedstocks where a potentially game-changing innovation is known to the project team, based on our understanding of bioenergy supply chains.

In order to conduct this assessment most efficiently, a first pass assessment was done to exclude technologies and feedstocks that do not pass one of the two selection criteria, to avoid spending time gathering evidence for the other criterion for technologies and feedstock that would be excluded in any case.

The technologies and feedstocks selected are generally a subset of those considered in the Evidence Review project. However, in some cases there are several alternative technology options, not all of which will be considered in the Evidence Review, but which could each have the potential for innovation. In these cases we have included multiple technology options.

The types of innovation considered when assessing these selection criteria are those that:

- **Increase supply** – e.g. efficiency and yield improvement, use of different feedstocks
- **Reduce costs** – e.g. scale up, new technology options, enhanced reliability or lifetime
- **Significantly increase sustainability performance**, such as through reducing GHG emissions, air quality emissions, land use requirements, reduce biodiversity impacts. Considering all potential sustainability improvements is not possible within the scope of this project, as they tend to be very site-specific, and so this is limited to significant and widely applicable improvements.

Innovation potential had to be identified in at least one (but not necessarily all three) of the above cost, supply or sustainability types to allow a technology or feedstock to pass the innovation selection criterion.

B 2 Feedstock and technology selection results

The results are presented below in Table 10.

It is important to note that a failure against one of the criteria in the table below **does not mean that the technology or feedstock is not an important contributor to UK decarbonisation**. Feedstocks that have not been taken forward in this project include:

- feedstocks and technologies that make too small a contribution to make a focus on innovation a priority
- feedstocks that are more suited for uses other than heat
- feedstocks and technologies that are already commercially mature.

Most of these feedstocks and technologies are nevertheless likely to be important in realising the full potential of bioenergy to contribute to decarbonisation. The bioenergy sector will need a diversity of feedstock and technology options in order to provide different energy services in the most cost and GHG efficient way.

TRL figures given in the table are E4tech estimates based on a range of previous E4tech reports including the bioenergy TINA[360], studies for the ETI and DfT.

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[360] E4tech analysis underpinning LCICG 2012 Bioenergy TINA for the Low Carbon Innovation Coordination Group (LCICG) https://www.carbontrust.com/our-clients/b/bioenergy-tina/

Table 10: Selection of feedstocks and technologies for further consideration in this project

Feedstock and technology	Significant contribution to decarbonisation of GB heating by 2050?	Potential for innovation?
BioSNG production with and without CO_2 capture	Has the potential to use a wide range of UK and imported biomass resources, and is important to the energy system transition.	Good potential for innovation – low TRL with CO_2 capture or using wastes (TRL 5-6). TRL 7 without CO_2 capture but only based on clean wood
Biohydrogen production via gasification with and without CO_2 capture	Has the potential to use a wide range of UK and imported biomass resources. Unlikely to be deployed without carbon capture	Good potential for innovation – low TRL (5 or less), despite similar components to BioSNG. Also potential for other thermochemical biomass to H_2 technologies to be developed
Direct biomass combustion (Domestic, commercial)	Has the potential to use a range of UK and imported biomass resources	TRL 9, little potential for long term innovation. Some near term requirements for reduced air quality emissions and improved installation
Direct biomass combustion (industry, large CHP, district heating)	Has the potential to use a range of UK and imported biomass resources	TRL 8-9, little potential for long term innovation. Some near term requirements for reduced air quality emissions, use of new feedstock types, improved lifetimes, and reduced thermal losses in water/steam distribution
Gasification to syngas for direct combustion, either on site or via a syngas grid	Transport of syngas via the gas grid is not considered feasible (ETI gas vectors project). Also this route has no CO_2 capture potential	Limited potential for innovation, as close-coupled gasification systems are TRL 8-9 and have limited benefits over direct biomass combustion
Pyrolysis to hydrogen	Not modelled in TIMES. Unlikely to be a more efficient approach than gasification, given that pyrolysis produces a mixture of oil, gas and char. To be considered only as a pre-treatment technology (below)	Low TRL (4-5) for hydrogen production given that this is not the focus of pyrolysis developers. Pyrolysis for producing bio-oil suitable for heating applications (a pre-treatment technology) is at TRL 8
Anaerobic digestion of wet wastes and food/feed crops	Limited potential from wet wastes. Sustainability concerns over food/feed crops	TRL 9 commercial technology with widespread UK uptake, limited innovation opportunities
Biological routes to hydrogen	Limited potential based on wet wastes, and biomass conversion efficiency needs to be improved. Not considered in any models. However, this would change if pretreatment of lignocellulosic materials is achieved, so considered within this chapter.	Dark fermentation is at TRL 4 and photofermentation at TRL 3-4[361]
Pretreatment of lignocellulosic materials for AD or biological hydrogen production	Potential to use a range of UK resources. Not considered in any models, but increasing interest from UK AD plants	Will require different feedstock practices or additional pre-treatment technologies, some of which have potential for innovation

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[361] LBST, 2015 'Study on Hydrogen from Renewable Resources in the EU' http://www.fch.europa.eu/sites/default/files/GHyP-Final-Report_2015-07-08_5%20%28ID%202849171%29.pdf

Feedstock and technology	Significant contribution to decarbonisation of GB heating by 2050?	Potential for innovation?
Woody and grassy energy crops, including SRF	Significant UK and global potential	Good potential for innovation – early stage of commercialisation compared with other more widely grown crops
Agricultural residues (straw, husks, dry litter)	Modest UK resource of around 20 TWh/yr of straw, with competing uses. Imports unlikely, even of pellets or via bioLNG imports	Straw and husks have commercially mature supply chains, but potential for improved sustainability of management
Forestry material (residues, sawmill co-products, small roundwood)	Significant global potential, but limited UK potential	Extraction and use of forestry material such as small roundwood and forestry residues, as well as co-products from sawmills, is an established and commercially mature industry, and does not have significant potential for innovation to reduce costs, increase supply or to improve sustainability of the extraction process itself (i.e. efficiency or emissions of harvesting machinery).
Macroalgae (seaweed) – feedstock production and conversion to CH_4 or H_2 e.g. AD	UK biomethane potential from macroalgae is limited to 22 TWh/yr in 2050 in the highest scenario of the DECC 2050 Calculator[362]. There is ongoing UK work in this area but no updated potential. Imports of the feedstock or gas derived from it are unlikely	Good potential for innovation in cultivation and harvesting and in AD of macroalgae, which presents additional challenges to AD of conventional feedstocks
Biomass pre-processing technologies (e.g. pelleting, torrefaction, pyrolysis)	Important enabler for imports, as densification reduced transport costs and GHG emissions. May not be deployed for UK feedstocks to a large extent	Good potential for innovation in many lower TRL technologies e.g. torrefaction, pyrolysis, water and chemical washing, but not in pelleting (which is already TRL 9)
MSW production and collection	Potentially important feedstock for early bioSNG or hydrogen plants as gate fees help plant economics, but there is competition from use in the power sector, often with long term contracts	Supply chains for MSW production and collection are commercially mature.
Waste pre-processing technologies (e.g. sorting, MBT, MHT)	Pre-processing can improve feedstock handling and plant operation, and enable long transport distance supply chains	Waste pre-processing technologies are commercially mature. Requirements of particular gasification technologies can be achieved with current technologies and practices. See section below.

B 3 Further detail on areas of initial uncertainty

B.3.1 Waste pre-processing technologies

Technologies to improve homogeneity

Thermal treatment processes such as gasification require feedstock consistency within reasonable tolerances for particle size, moisture content, density, chemical composition, and ash content in order to facilitate stable operations, regardless of the treatment technology used. However, household and commercial and industrial waste

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[362] DECC 2050 calculator (n.d.) Marine Algae one page summary http://old-interface.2050.org.uk/assets/onepage/18.pdf

is, by its nature, a variable and heterogeneous product. In order to reduce the variability of the feedstock it is necessary to pre-process the varying waste streams to homogenous refuse derived fuel (RDF) or higher quality solid recovered fuel (SRF) which is normally produced to a client's requirements[363] or EN15359 standards.

A typical waste analysis is shown in Table 11, arising from segregated household waste, commercial and industrial waste, household waste recycling centre residual waste and MRF residual waste.

Table 11: Typical waste composition[364]

Waste constituent	Approximate Percentage
Paper & cardboard	20
Plastic Film	9
Rigid plastic	9
Textiles	4
Combustibles	10.5
Non-combustibles	1.5
Glass	6
Ferrous & non-ferrous metal	3
Putrescibles (organic matter that can be decomposed by microorganisms)	30
WEEE	2
Hazardous materials	3
Fines	2

This heterogeneous material is converted to RDF and higher grade SRF by:

- Shredding - waste fuel is received at the MRF, which can be either a separate entity or part of the gasification plant. It is shredded in a low speed shredder into large particle sizes <300mm.
- Sizing separates waste into different sized fractions. Usually done either by vibrating screen, trommel or disk screen.
- Screening to remove metals and hard particles (grit, glass etc.) – magnetic separator, eddy current separator, hard particle separator.
- Secondary shredding at high speed to reduce the particle size.

Depending on the final use, additional drying may be required in a drum drier, belt drier or by bio-drying to meet moisture content requirements.

Interviews with an MRF operator, academic researchers and several gasification technology developers showed that all of the above process element technologies are mature and well established, at TRL 9 and that there is no

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[363] European association for recovered fuel from solid non-hazardous waste https://www.erfo.info/about-srf

[364] Confidential 2017 UK MRF specification document reviewed by Ecofys

significant potential for innovation. Some gasification technologies may require specific waste characteristics, such as drier feedstocks, higher biogenic content, or removal of particular components, but interviewees believed that these could all be achieved through combinations of existing technologies. On that basis we have not selected technologies to pre-treat wastes to homogenise the feedstock for further investigation.

Technologies to separate MSW to increase biogenic content

Processes have also been developed to separate MSW further so that a stream with higher biogenic content can be produced:

- DONG is developing a waste pre-treatment process called "REnescience"[365] which uses a combination of washing, heating and enzymes to separate municipal solid waste (MSW) into recyclates, RDF/SRF and a bioliquid which can then be fed into a digester to produce gas. This first plant is planned to open in the UK in 2017. This is a novel process, although many of the component parts are commercially available.
- Wilson Steam have also developed a process to increase the biogenic content of waste. The process autoclaves MSW to produce a biogenic fibrous material suitable for further processing into gas, heat and power or high value chemical products. The process is similar to the DONG process treatment of MSW to biogas: the Wilson System homogenises and sanitises all the biogenic content of the raw MSW through steam autoclaving and increases the surface area to mass ratio making it easier for the microbes to quickly digest the biomass content to produce methane through anaerobic digestion. Wilson claim that research carried out by a Swedish AD supplier indicates a 200-300% increase in methane potential on autoclaved biogenic fibre as opposed to untreated mixed waste. Wilson's autoclaved material is also suitable for combustion/gasification to heat and power on WID approved boilers and they have a number of other ongoing projects to explore alternative uses for the autoclaved material. The University of Nottingham is carrying out a study to investigate the possibility of dedicated ethanol production plants connected to the Wilson Autoclave system and Wilson Bio-Chemical have been awarded a grant in 2015 to build a facility situated at the Bio Renewables Development Centre in York to evaluate MSW derived autoclave fibre for the production of high value chemicals. In 2014 Wilson Bio-Chemical was awarded £1,900,000 European Union grant towards a £5,000,000 project to build a waste to butanol and hydrogen demonstrator plant at the Bio Renewables Development Centre in York. The system will process 1.5 tonnes of MSW per day and de-risk the whole integrated process to allow achievement of TRL 7-8 System Development. The demonstrator is in-build now and the project is due to be completed August 2018.

These novel processes have a role to play in increasing recycling rates and certainly may be interesting for companies to develop in in the context of a policy regime that incentivises purely bio-derived fuels for heat, power or transport fuel. However, using energy to increase the biogenic proportion of a material is unlikely to significantly reduce emissions in the context of overall decarbonisation of the economy, if the remaining fossil material is still incinerated or combusted for energy, which is likely to be the case once recyclable materials have been removed. On that basis we have not selected technologies to pre-treat wastes to increase the biogenic content of the waste stream for further investigation.

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[365] REnescience website http://www.renescience.com/en

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