Bioenergy and waste gasification in the UK
Barriers and research needs

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Key findings

1. The barriers that have faced biomass and waste gasification projects have typically involved a combination of:
   a) Availability of finance
   b) Technical challenges
   c) Non-technical considerations

   Crucially, these aspects exhibit significant interplay. With additional finance, it is likely that other challenges could be overcome. Conversely, the lack of proven experience at scale hinders the securing of finance. This consideration suggests that there is the potential for a virtuous circle in the development of this technology if these barriers can be overcome.

2. To resolve this, there is an immediate need to establish demonstration and reference plants at appropriate scale. These will build experience and increase confidence.

3. Points (1) and (2) do not negate the attractiveness of research to develop technologies at a lower TRL that may increase efficiency, improve feedstock flexibility, reduce costs or provide more effective cleaning and production of higher quality syngas. These research options include improved control of the processes, analysis of pre-treatment options and further development of plasma-gasification technologies.

4. The funding support for commercial gasification is inadequate. This relates to:
   a) The quantity of support (e.g. via Renewable Transport Fuel Obligation or Contracts for Difference (CfD)) is uncertain but potentially not significantly lower than the long-term cost support needed.
   b) Confidence in the support (i.e. being able to secure it, the quantity of it when secured)
   c) Barriers to applying for the support (notably CfD)
   d) Mismatching of support mechanisms to the level of technical confidence in gasification projects.

5. Non-technical barriers include supply-chain development, permitting delays, workforce development and stakeholder management.

6. Development of options to facilitate the integration of biomass gasification with CCS are needed at each stage of technical readiness. The potentially lengthy path from development to demonstration at sufficient scales means that some concurrency between the development of techniques and integration of more established CC routes is possible. Given the potential anticipated scale of biomass gasification with CCS, wider system-level modelling is also warranted – in particular there are trade-offs regarding plant scale, energy vector outputs, feedstock selection and handling (e.g. transport) of captured carbon.

Contents

1. Introduction

Biomass and waste gasification is potentially a key technology to facilitate the wider use of biomass and waste as energy sources. The resulting energy vectors are flexible and there is a wide range of potential feedstocks. There is also the possibility that it could be combined with carbon-capture technologies. This potential significance is broadly recognised (e.g. BEIS[1], Defra[2], ETI[3], IEA[4], REA[5]).

Despite this potential, and several successful examples, gasification is yet to fulfil its potential. Although some have identified gasification as the enabling technology for modern biomass use, whether it can live up to these expectations has been questioned[6]. In noting the opportunity presented by biomass gasification, the CCC suggest that the technologies need to be proven and deployed at larger scales over the coming years to remove uncertainty around their commercial viability[7]. Cadent Gas Ltd view gasification as the most promising technology for supply of renewable gas but in need of further support and development[8].

The aim of this Supergen Bioenergy Hub funded report is to outline key barriers to successful biomass gasification. In addition, the report outlines potential support required in order to realise a greater role in the future.

A range of approaches were adopted in order to gather information from a relatively wide set of sources and to provide perspectives on the issue that hopefully reflect the broad concerns of relevant stakeholders. The report begins with an overview of commercial gasification projects in the UK and then of academic research activity. Literature and reports of previous studies investigating similar issues are then summarised. The report continues to a synthesis of the views expressed by academics in individual interviews and conversations, a summary of outputs from a workshop session and views received from industry and other stakeholders. The various barriers and research needs are then drawn together, and conclusions presented.

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1 Department of Energy & Climate Change (DECC). (2012). UK Bioenergy Strategy. White Paper
2 Defra. (2014). Energy from Waste A guide to the debate.
3 ETI. (2017). Targeting new and cleaner uses for wastes and biomass using gasification.
4 IEA Bioenergy. (2018b). Hydrogen from biomass gasification. IEA Bioenergy.
5 REA. (2019). Bioenergy strategy. Phase 2: Bioenergy in the UK - A vision to 2032 and beyond. London, UK: REA
6 Kirkels, A. F., & Verbong, G. P. J. (2011). Biomass gasification: Still promising? A 30-year global overview. Renewable and Sustainable Energy Reviews, 15(1), 471–481. https://doi.org/10.1016/j.rser.2010.09.046
7 CCC. (2018). Biomass in a low-carbon economy. London: Committee on Climate Change.
8 Walsh, R. (2018). 2018 Bioenergy Review Call for Evidence. Coventry: Cadent Gas Ltd.

2. UK gasification commercial activity

Although gasification has not achieved the level of commercial success that had been expected there are still some reasons for cautious optimism. Some energy from waste gasification plants are now operational and various pilot-scale plants have delivered promising results. Some of the reasons for previous delays are understood and there are several ambitious projects currently in the pre-planning stage. While technical and other hurdles are significant and should not be underestimated, with appropriate support it is possible that several significant commercial-scale plants could be developed over the next five years.

There has been substantial interest in developing biomass and waste gasification facilities over the last 25 years. BEIS list around 130 "advanced thermal conversion" plant proposals that were or are at some stage of planning in the UK since 1995 (see Figure 1). In addition, there are some gasification sites (e.g. technology demonstrators) that they do not list, and some additional sites listed by other groups (e.g. UKWIN) that are at pre-planning or other stages.

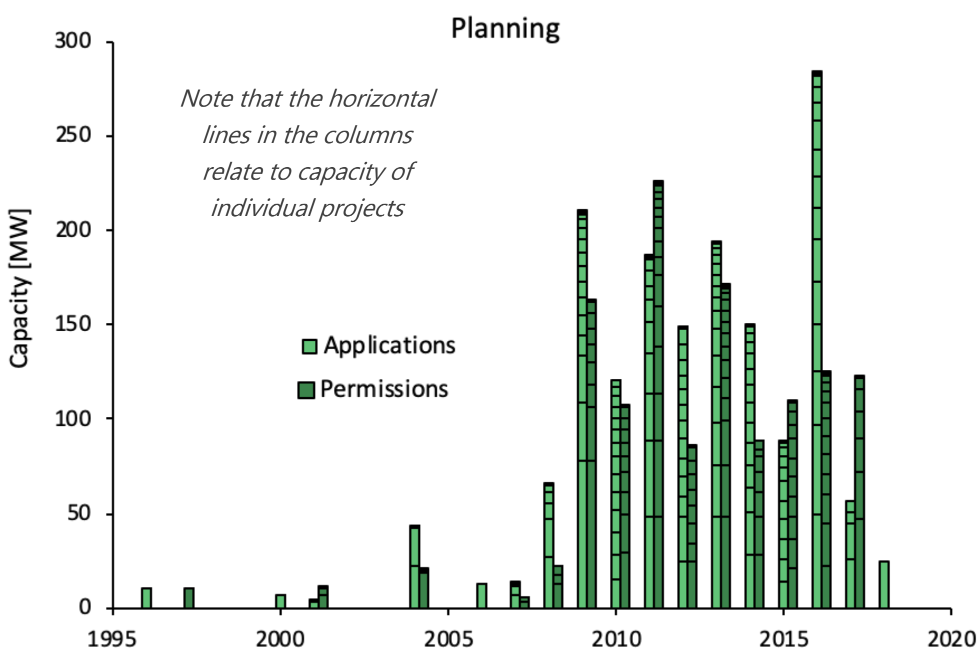

Figure 1: Planning permission for ATC plants in UK by capacity. Data source: BEIS[9].

9 Renewable Energy Planning Database, BEIS (2019) https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/816563/Public_Database-Q2_June_2019_excel.xlsx

Despite this interest, far fewer projects have successfully completed financial close, construction, commissioning and hand-over to achieve full operation. Figure 2 shows generation from gasification plants in the UK that qualified for ROCs.

The mean continuous generation during the first quarter of 2019 was less than 30MW and represented less than 1% of total bioenergy production receiving ROCs in 2018. However, on a proportional basis, this is still a dramatic increase since 2016.

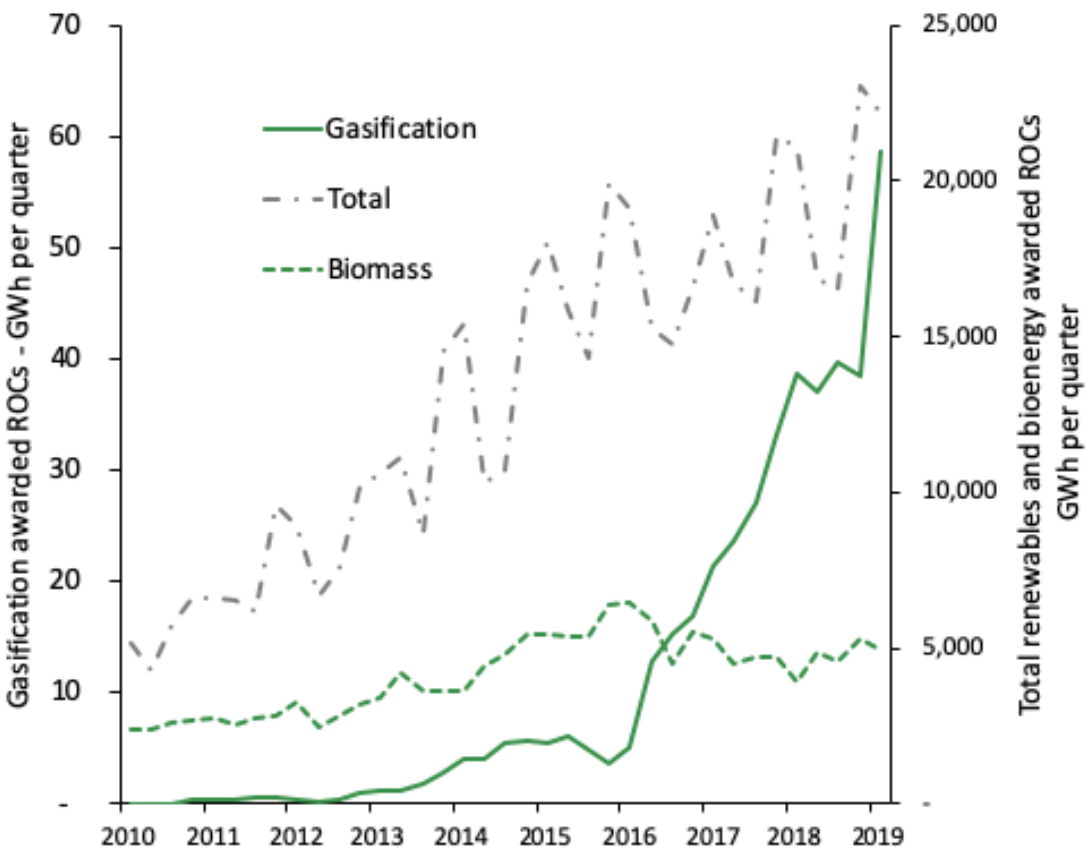

Figure 2: Gasification and other generation awarded ROCs. Source: BEIS[10].

10 https://www.gov.uk/government/statistics/energy-trends-section-6-renewables

Figure 3 maps out 24 sites of particular interest in the UK. These have been identified by further investigation into the sites listed in the Renewable Energy Planning Database through their websites, internet searches of news articles and discussion with representatives of the companies wherever possible. Of these sites, eight are operational, seven are at late stages of construction or commissioning, and nine are noteworthy either because their successful development would demonstrate other milestones (e.g. technology, use of producer gas, scale) or in two cases because their failure was notable.

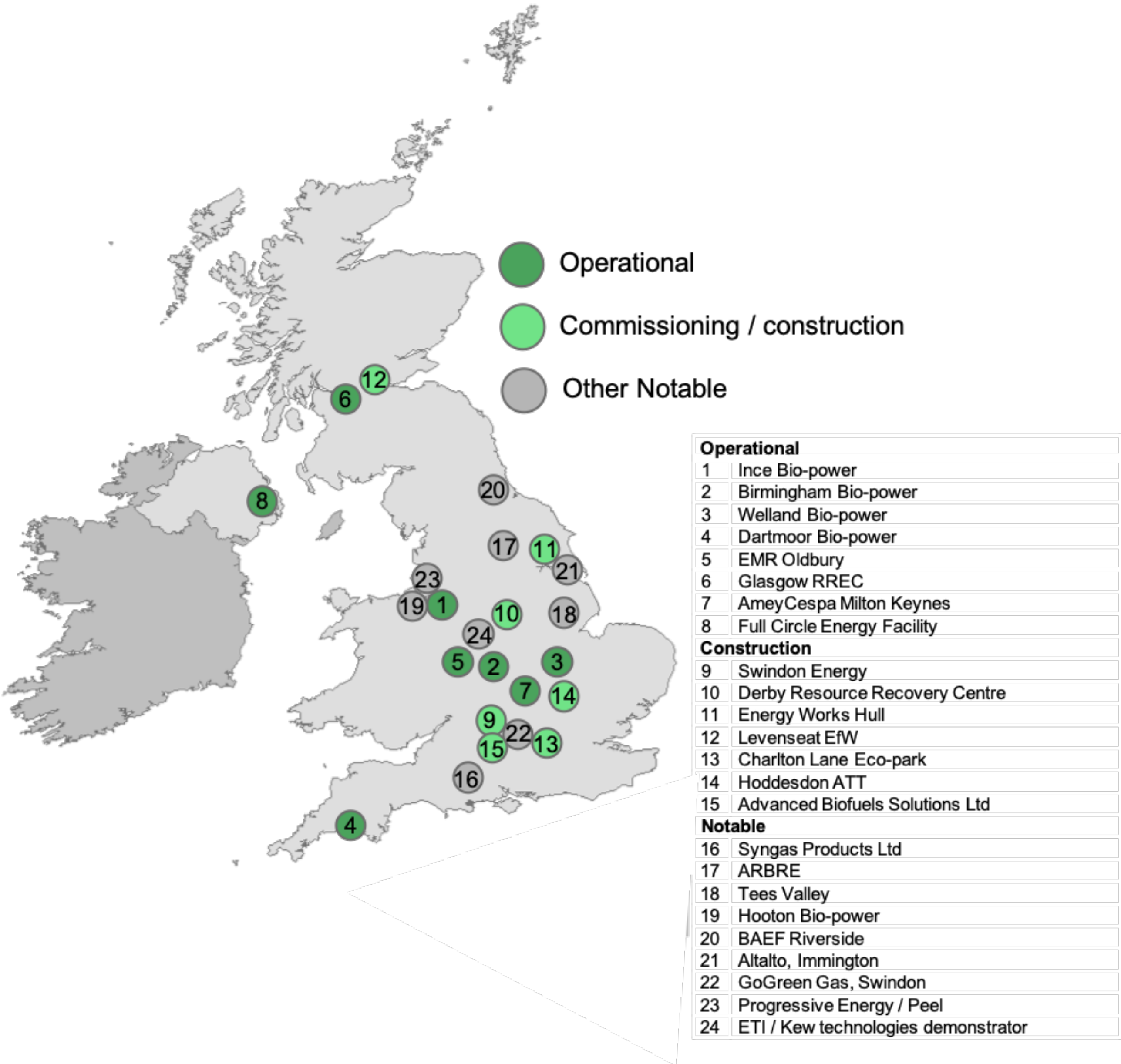

Figure 3: Gasification sites of particular interest to this report

Operational sites

1. Ince Bio Power

Ince Bio Power was made operational in March 2019. It is a 26.5 MWe gasifier plant that will use around 160 kt/year of class A to C waste wood. It was developed by CoGen with EPC by Black & Veatch and MWH treatment. BIG were involved in the financing and also control a collocated waste-wood processing site that may supply the waste wood[11,12]. It is on the Protos site owned by Peel Environmental in Cheshire. The project uses Outotec fluidised-bed technology in a close-coupled gasifier arrangement.

2. Birmingham Bio Power

Birmingham Bio Power is a 10.3MWe gasification facility. It was constructed and operated (as BBPL) by MWH treatment with development by CoGen[13]. The project was supported by £18.2M from the Green Investment Bank[14] and others including Balfour Beatty to investment of £47M. It uses four Nexterra gasifiers close-coupled to a boiler to produce steam for generation.

3. Welland Bio Power

Welland Bio Power is a similar 10.6MWe gasification facility processing around 70kt/yr of waste wood from the adjacent waste timber processing facility. It also uses four Nexterra gasifiers close-coupled to a high-pressure boiler. The project was developed by CoGen and is operated and managed by CoGen / Nexterra in conjuction with Welland Waste Management Ltd. The project received approval in 2014[15] and project cost has been reported as £51.6M[16].

4. Dartmoor Bio Power

This is an earlier plant that CoGen were involved in developing. It generates around 4.3MWe using waste wood as feedstock and a Nexterra gasifier.

5. EMR Oldbury

This gasifier is operated by European Metal Recycling to deal with Automobile Shredder waste. It uses Chinook Science's RODECS gasifier system to generate around 10MWe. This two-stage system has been suggested for other applications but at EMR the feedstock is automotive shredder waste - generally non-biogenic.

6. Viridor Glasgow Recycling and Renewable Energy Centre (RREC)

This project was constructed by Interserve and then Babcock and Wilcox from 2016. It was handed over in January 2019 and reported as operational from March 2019[17,18,19]. The site includes Anaerobic Digestion and other Mechanical Treatment facilities. An Energos gasifier is used in

11 https://www.endswasteandbioenergy.com/article/1580210/uks-largest-biomass-gasifier-fully-operational
12 https://www.bioenergy-news.com/display_news/14524/cheshire_biomass_plant_operational_largest_of_its_kind
13 https://www.cogenuk.com/projects
14 https://resource.co/sustainability/article/gib-invests-birmingham-biomass-gasification-plant
15 https://www.bbc.co.uk/news/uk-england-northamptonshire-29344205
16 https://premierconstructionnews.com/2016/04/12/welland-biomass
17 https://www.endswasteandbioenergy.com/article/1579246/delayed-glasgow-waste-gasification-plant-operational
18 https://www.insider.co.uk/news/recycling-renewable-energy-centre-opens-18971949
19 https://www.bioenergy-news.com/news/new-recycling-and-renewable-energy-centre-opens-in-glasgow-scotland

close-coupled configuration. The plant is designed to generate around 10MWe from 140kt/yr of waste.

7. AmeyCespa Milton Keynes
This site also combines several technologies (Mechanical Treatment and Anaerobic Digestion) and first accepted waste in November 2016 although reported as "fully operational" as of March 2018[20]. It uses Energos close-coupled gasification technology intended to supply 7MWe from around 90kt/year of RDF. It is on a council owned site, with the waste contract awarded by Central Bedfordshire Council.

8. Full Circle Energy Facility (Bombardier)
This plant near Belfast harbour estate is intended to supply 15MWe and additional heat to the nearby Bombardier Aerospace site from around 150kt/yr of commercial and industrial waste supplied by Riverridge[21]. Planning permission was granted in 2014 and financial close achieved in November 2015[22] (Green Investment Bank, Equitix, P3P partners). Construction was through Bouygues Energy and Services with Biomass Power supplying three 5MWe (via steam generation) step-grate gasifier units[23]. Commissioning was complete as of early 2018 but as of October 2018 it appears that there may be some delays to full operation[24].

Late stage construction or commissioning

9. Swindon Energy
This site uses six Refgas fixed-bed, air-blown downdraft gasifiers fed with waste wood to supply producer gas to three 2MWe Jenbacher engines[25]. This project is notable because the gas is cleaned before being fed to internal combustion engines for power generation (rather than the close-coupled system used in most other sites that are in or close to operation).

10. Derby Resource Recovery Centre
This facility was being developed by Resource Recovery Solutions – a collaboration between Renewi and Interserve on behalf of Derby County Council and Derby City Council as the Sinfin Integrated Waste Treatment Centre. It is intended to use an Energos gasifier, close-coupled to produce 7.5MWe from around 190kt/yr waste. It was originally due to cost £145M and commence operation in 2017 but as of August 2019 DCC were looking to find another company to complete construction[26]

20https://www.letsrecycle.com/news/latest-news/amey-overcomes-teething-problems-in-milton-keynes
https://www.mrw.co.uk/knowledge-centre/has-the-time-come-for-gasification-to-succeed/10027717
21 https://waste-management-world.com/a/202-contract-for-15mw-waste-to-energy-gasification-plant-in-northern-ireland
22 https://riverridge.co.uk/app/uploads/2017/03/FCG.pdf
23 http://www.biomasspower.co.uk/first-of-three-gasifier-units-complete/
24 http://www.bouygues.com/wp-content/uploads/2018/10/pr_bouygues_18_10_2018_en.pdf
25 https://www.refgas-uk.com/portfolio-item/swindon-energy-6mwe-1
26 https://www.bioenergy-news.com/news/derbyshire-councils-seek-firms-to-take-over-building-and-maintenance-of-waste-treatment-plant/

11. Energy Works Hull

This project uses an Outotec close-coupled Fluidised Bed Gasifier[27]. It is intended to generate around 24MWe from 240kt/yr C&I waste[28]. Black & Veatch replaced M&W as contractor for commissioning as of April 2019[29]. Around £20M of the £200M cost of this project was from the European regional development funding, with BIG also providing finance.

12. Levenseat EfW

The Levenseat plant will use an Outotec two-stage fluidised-bed close-coupled gasifier[30]. It is intended to generate 12.5MWe (11MWe net) from around 215kt/yr of commercial and industrial waste. The project has received funding through BIG[31] along with £28M from the Green Investment Bank. EPC was conducted by M&W group. The project was reported to be undergoing initial commissioning in February 2018 followed by hot commissioning in September 2018[32]. Supporting information for a permitting change application, prepared by Fichtner, provides additional details[33].

13. Charlton Lane Eco Park

The Charlton Lane Eco Park will also use an Outotec fluidised bed close-coupled gasifier. It is to be operated by Suez on behalf of Surrey County Council. Design and build are being done by M&W group. As of May 2019, waste was being processed on site (in the pretreatment facility) but not gasified[34].

14. Hoddesdon Advanced Thermal Treatment

This site uses a Biomass Power Step-Grate Gasifier and was in testing as of January 2018[35]. It is designed to generate 10MWe using 105kt/yr of commercial and industrial waste[36]. EPC through Bouygues Energies & Systems with involvement from BIG and AssetGen Partners Ltd. The project has received around £30M from the GIB.

15. Advanced Biofuels Solutions - Swindon

This commercial demonstration plant follows on from the GoGreenGas project (see #22, below). It is designed to produce approximately 22GWh/yr of bio-SNG (i.e. equivalent to 3-4MW) from 10kt/year RDF. It is being developed in order to gain experience and provide confidence to stakeholders to enable larger plants to be built. The project suffered some costs overruns in 2018 (from around £25M to around £30M) resulting in the GoGreenGas project going into administration. Advanced Biofuels

27 Eunomia. Investment in Advanced Conversion Technologies: Has the Time Finally Arrived? 2016.
28 https://bioenergyinfrastructure.co.uk/site/energy-works-hull/
29 https://www.endswasteandbioenergy.com/article/1581107/new-contractor-delayed-waste-gasification-plant
30 https://www.sepa.org.uk/media/162417/supporting-information.pdf
31 https://bioenergyinfrastructure.co.uk/site/levenseat-renewable-energy/
32 http://lrel.levenseat.co.uk/community-update-on-commissioning/
33 Sturman, James, and Stephen Othen. Levenseat Gasification Plant - Supporting Information. Fichtner Consulting Engineers Ltd, 2014, https://www.sepa.org.uk/media/162417/supporting-information.pdf.
34 https://www.ecoparksurrey.uk/news/site-progress
35 https://www.letsrecycle.com/news/latest-news/testing-starts-hoddesdon-gasification-plant/
36 https://bioenergyinfrastructure.co.uk/site/hoddesdon-energy/

Solutions Ltd has secured an additional £10M in order to complete its construction with support from DfT and Cadent. The plant is now expected to be completed late 2020[37].

Based on experience with the pilot plant, commercially competitive costs for bio-SNG production of £20/MWh were projected for commercial scale operation (NOAK, 665GWh/yr).

Other notable facilities

16. Syngas Products Ltd

Syngas Products Ltd have developed a 1MWe modular demonstration using RDF. One unit is currently being demonstrated and further developed at their site in Dorset (possibly since 2016) with plans to expand to around 10MWe (with similar modular design). The system uses a two-step process in which the feedstock is pyrolyzed before the resulting char is gasified to provide heat for the pyrolysis. The resulting gas is clean enough for an internal combustion engine generator with high calorific value (e.g. 28MJ/Nm^3) and contains other valuable co-products.

17. ARBRE bioenergy

The ARBRE project was an early biomass IGCC plant. It was intended to generate 9 to 10MWe from 42kt/yr wood (willow and waste). It had costs of around £30M-£40M (£10M public funding) but the project went into liquidation in 2003[38]. Piterou, Shackley and Upham[39] investigated the reasons for this and concluded that it was due to several reinforcing factors:

- Financing. The major backer had a strategic redirection away from renewables.
- Organisational. Changes in key players, notably the bankruptcy of the original turnkey contractor. Notably, the organisation with the greatest interest was perhaps least influential.
- Technical. Gas cooling and tar cleaning (atmospheric FBG rather than pressurised). To achieve acceptable tar cracking, the temperature was raised above the original specification, causing other problems.
- Fuel supply chain. The project required the concurrent establishment of a significant fuel supply chain as well as the development of the novel plant.

37 https://www.swindonadvertiser.co.uk/news/18035820.south-marston-energy-plant-will-put-swindon-heart-low-carbon-economy/
38 https://www.yorkshirepost.co.uk/news/arbre-energy-bought-by-mystery-buyer-but-willow-suppliers-fear-for-future-1-2515938
39 Piterou, A., Shackley, S., & Upham, P. (2008). Project ARBRE: Lessons for bio-energy developers and policy-makers. Energy Policy, 36(6), 2044–2050. https://doi.org/10.1016/j.enpol.2008.02.022

18. Air Products, Tees Valley Plants

Air Products were involved in the development of two ambitious gasification plants in Teeside. These were each to be 50MWe, using around 350kt/yr of waste. Unfortunately, they were both cancelled in 2016 with the first in commissioning (construction began 2012) and the second in construction[40,41], probably due to difficulties in commissioning of the first. They were going to use AlterNRG plasma gasification technology and it is possible that some challenges related to the scale at which these were to be employed[42].

19. Hooton Bio Power

The Hooton Bio Power facility reached financial close in October 2018 and is in construction. It is anticipated that the 24MWe plant will use around 270kt/yr of MSW. The project has been developed by CoGen and is being constructed by BWSC. It will use Kobelco Eco Systems Fluidised Bed Gasifiers. This project is notable as an unsubsidised large-scale site using RDF (rather than waste-wood) and as a reference for the Kobelco FBG system.

20. Boston Alternative Energy Facility (BAEF) / Riverside

In January 2019 a proposal was submitted by Alternative Use Boston Projects Ltd. for an expansion on this site to a 102MWe (80MWe net) facility using around 1000kt/yr of RDF – considerably larger than other sites and potentially delivered by ship[43]. As of June 2017 there was a 12MWe waste wood and RDF facility being constructed which would use around 80kt/yr[44]. The gasification technology supplier would potentially be Outotec. This proposal is also noteworthy for the proposal that some CO_2 would be captured for industrial use[45].

21. Altalto, Immingham

This is an ambitious collaboration between Velocys, BA and Shell. The scheme is notable as it would combine waste gasification with Velocys' Fischer-Tropsch reactors to produce jet fuel[46]. The scale of the proposed facility has possibly increased[47] and is currently stated to be around 70kt/yr of jet fuel and naphtha[48] from a feedstock of around 600kt/yr of waste[49]. Advanced Plasma Power (APP) were suggested as gasification technology supplier in earlier literature. Velocys are targeting financial close on the project by early 2021[50]. An initial, phase 1 part of this project was supported by the Department for Transport's F4C competition. Phase 2 F4C projects are due to be announced in the next few months.

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40 https://waste-management-world.com/a/air-products-to-ditch-plasma-gasification-waste-to-energy-plants-in-teesside
41 https://www.bbc.co.uk/news/uk-england-tees-35962958
42 https://www.letsrecycle.com/news/latest-news/is-large-scale-gasification-viable
43 https://www.mrw.co.uk/latest/gasification-plant-could-process-a-third-of-uks-rdf/10039368.article
44 https://www.endswasteandbioenergy.com/article/1435445/uk-biomass-plant-allowed-rdf
45 https://www.bostonaef.co.uk/document-library/
46 https://biomarketinsights.com/5-minutes-with-neville-hargreaves-from-velocys/
47 https://www.velocys.com/wp/wp-content/uploads/2018-World-Bio-Markets-Velocys-FINAL.pdf
48 https://www.velocys.com/projects/altalto/
49 https://www.endswasteandbioenergy.com/article/1594456/planning-application-600000t-yr-srf-to-jet-fuel-facility
50 https://www.velocys.com/projects/altalto/

22. GoGreen Gas, Swindon

This project was a collaboration between Progressive Energy, Advanced Plasma Power and Cadent Gas. A 50kW pilot plant was operated successfully from around 2016 to 2018, producing bio-SNG[51]. Plasma gasification was used to avoid problems with tar-fouling and to improve the quality of the resulting syngas. The project also demonstrated the use of small-scale methanation approaches using steam injection.

23. Project Bright

Progressive Energy are currently developing a larger (i.e. commercial scale - 175kt/yr RDF, 30-40MW) bio-SNG plant at Peel Environmental's Protos Energy Hub in Ellesmere Port[52,53]. Planning permission has been approved and it is hoped that this plant will be operation around 2023 at an estimated cost of £150M[54].

24. ETI / Kew Technology gasification demonstrator

The Energy Technologies Institute (ETI) has identified the importance of biomass gasification and need to expand UK commercial experience of it in order to capture its potential for the UK[55,56]. As part of a roadmap to achieve this, they ran a competition around 2014, with three design projects funded to produce project proposals for gasifiers capable of producing clean syngas. The projects were run by Advanced Plasma Power (6MWe)[57], Royal Dahlman (7MWe, MILENA-OLGA in conjunction with ECN) and Broadcrown Renewable Energy (3MWe).
The Broadcrown option was then selected to be taken forward by Kew Technology as a 1.5MWe plant that will be capable of running from RDF and producing syngas of sufficient quality to run a gas engine. There will also be option for slipstream to other testing or applications, potentially including F/T processing. Tar fouling was identified early on as a key challenge; this is being resolved with partial combustion cracking enabled by tight control of the process.
As of July 2019, the gasifier has been operated to produce syngas (~6MJ/Nm^3). The engine has been operated on syngas produced from bottled hydrogen and the tar clean-up is in commissioning / testing. The project team are aiming to have the system fully running in the next few months, followed by four 1000-hour tests with different feedstocks including waste wood and RDF.

51 https://gogreengas.com/pilot-plant/achievements/
52 https://www.insidermedia.com/insider/northwest/progress-made-on-150m
53 https://www.endswasteandbioenergy.com/article/1578231/uks-first-commercial-scale-biosng-plant-revealed
54 https://www.bioenergy-news.com/news/plans-for-150m-uk-bio-resources-to-fuel-facility-approved/
55 ETI. (2017). Targeting new and cleaner uses for wastes and biomass using gasification. Retrieved from http://www.eti.co.uk/insights/targeting-new-and-cleaner-uses-for-wastes-and-biomass-using-gasification
56 ETI. (2018). The role for bioenergy in decarbonising the UK energy system. Loughborough, UK: Energy Technologies Institute
57 https://www.advancedplasmapower.com/eti/

3. Academic research activities

Overview

Globally, biomass and waste gasification themes have attracted increased academic attention over the last 15 years. This is illustrated in Figure 4 which shows the results of keyword analysis of academic articles.

In total, over 22,000 papers relating to bioenergy and published since 2000 were analysed. Of these, 819 mention biomass gasification in their abstract or title (721 include gasification but exclude coal). The proportion of bioenergy papers relating to gasification has remained fairly consistent at around 3%, approximately three times as many as pyrolysis. Over half of the biomass gasification papers were published since 2014 and only 56 in 2000 - 2009. 258 of the papers mention tar in their abstract or title, a theme that has remained of consistent interest throughout the period. Gasification of waste has also maintained consistent interest (160 papers over the period) but significantly less than biomass gasification as a whole.

Of the various gasification technologies, fluidised bed gasifiers have received far more interest with 136 specific mentions, followed by 39 for downdraft gasifiers, 20 for entrained flow gasifiers, 18 for plasma gasifiers and 14 for updraft gasifiers. Microwave technologies received 10 mentions, all since 2010.

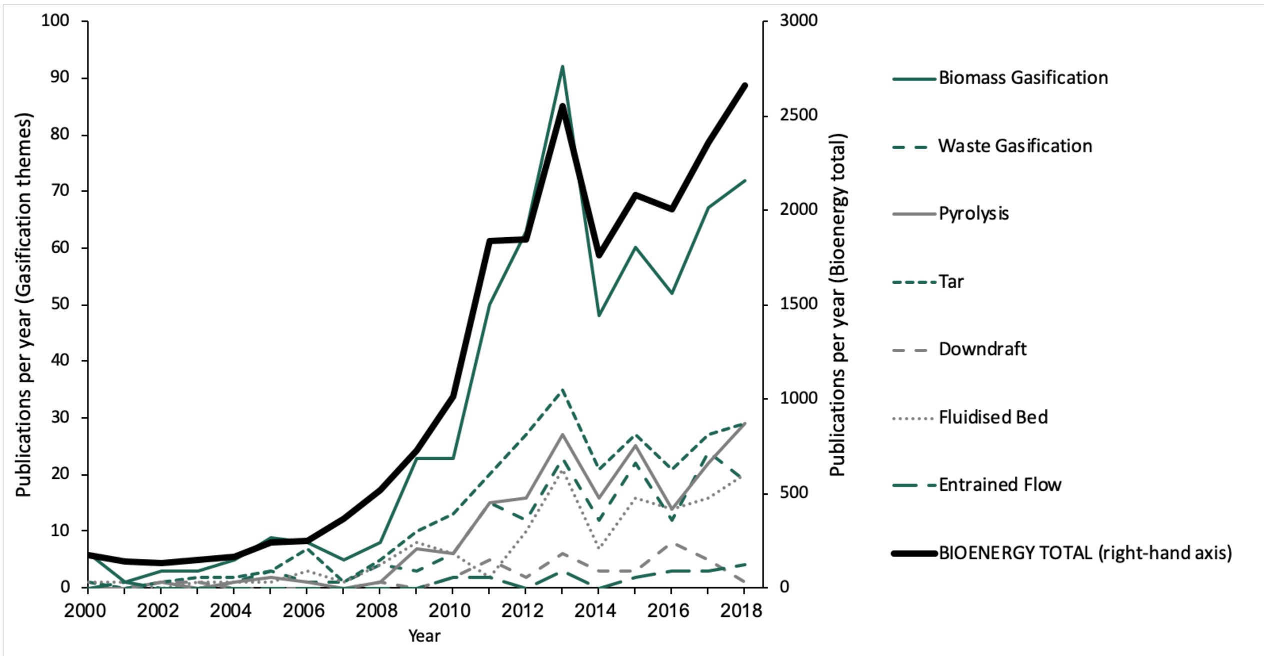

Figure 4: Keyword trends in published academic articles

In the UK, 81 projects that relate to gasification have been identified as funded by UKRI (or predecessors) since 2002[58]. These have a combined value of over £61M.

However, many of them are not specific to gasification:

- 13 projects (£20M) relate to the use of fuels and feedstocks that might be produced by gasification,
- 12 projects (£12M) relate to fundamental science or developments that may be relevant to gasification in the future,
- 9 projects (£5.6M) relate to feedstock developments that may be relevant to gasification,
- 14 projects (£7.3M) relate to novel Carbon Capture approaches that may be relevant to gasification
- 10 projects (£18M) relate to gasification within a broader context (e.g. Supergen Bioenergy Hub and projects relating to international development).
- 23 projects (£6.5M) relate directly to gasification technology. These cover a range of topics including gasification process control, investigation into factors affecting (produced) fuel quality, reaction kinetics, small-scale demonstration, ceramic filter and other gas cleaning approaches development, and plasma gasification investigation (including microwave induced plasma). These are covered in more detail below.

There are several research groups that are engaged in gasification research but not reflected in the UKRI grants list. However, we believe that these are reflected by the Bioenergy Research Mapping[59] and the list of researchers consulted for this study.

The UKRI list does not include the ETI activities that are noted earlier in this report under commercial activities.

58 https://gtr.ukri.org
59 Gomez-Marin, Natalia, and Tony Bridgwater. Mapping UK Bioenergy Research Stakeholders. Aston University, 2017.

Examples of specific research activities

A wide range of research activities that relate to aspects of gasification development are in process. Research activities listed on the UKRI grants on the web database and a recent UK bioenergy research stakeholder mapping[60] were examined before more information was gathered from the websites of relevant institutions and discussion with key individuals where possible. These examples are intended to cover the range of relevant research activities being undertaken but is not necessarily comprehensive of all gasification research in the UK. The space given to each institution reflects information available rather than level of activity.

Aston University / Energy and Bioproducts Research Institute (EBRI)
EBRI conducts a wide range of bioenergy research activities from techno-economic analysis of bioenergy systems through to experimental research. Dr. Clara Serrano is the plant manager. EBRI has a wide range of experimental facilities including a 1MW fluidised bed gasifier. These are supported by a range of analytical equipment including gas chromatography and thermo-gravimetric instruments. Dr. Paula Blanco-Sanchez is involved in a range of related research, focussing on the use of different feedstocks and improving syngas properties (e.g. tar cleaning).

University of Bath
Prof. Marcelle McManus researches the relative merits of a range of bioenergy technologies through techniques including Life Cycle Assessment and Techno-Economic Analysis.

Cardiff University
Dr. Agustin Valera Medina is using analysis from an experimental rig (1-2kW) with 1-D and 2-D CFD modelling to investigate reactor conditions and fuel characteristics. Cardiff University did have a 500kW to 1MW scale gasification setup but most interest from industry has been on results from the smaller scale modelling.

University of Chester
Prof. John Brammer is investigating the use of high-ash feedstocks and the scope to improve their characteristics with natural additives. They have two 25kW downdraft gasifiers and analytical equipment to measure the quality and tar content of the producer gas.

University of Glasgow
Prof. Ian Watson is leading research into real-time control of gasifiers. This is being developed with a downdraft gasifier using varieties of miscanthus. Work is ongoing to characterize syngas produced from paper, plastic, solid and liquid feedstocks. There is also interest to look at split-bed (e.g. pyrolysis / gasification) options. There is a bubbling fluidized bed gasifier that might be used for other work. Dr. Siming You is involved in optimizing bioenergy systems, including gasification, in terms of techno-economics and environmental criteria.

60 Gomez-Marin, Natalia, and Tony Bridgwater. Mapping UK Bioenergy Research Stakeholders. Aston University, 2017.

Herriot-Watt University
Dr. Aimaro Senna's group is investigating co-firing of biomass with coal, reaction kinetics and catalysts.

University of Hull
Dr. Vicky Skoulou is researching the effect of different biomass and waste pretreatment options, with particular regards to the design of biomass and waste processing reactors, and the needs of downstream processing / use of the syngas. They currently have two lab-scale (1-3g/s) gasifiers with extensive TGA and other analytical gas, liquids and char monitoring capability. Further interest relates to analysis of products from steam gasification and the use of catalysts. Previous work has included design, construction and optimization of larger scale biomass / waste gasifiers.

University of Leeds
Prof. Paul Williams has been investigating the role of plasma gasification in ensuring cleaner syngas. They have achieved promising results both with and without a combination with catalysts. This work used a fixed-bed gasifier but they have a fluidised bed gasifier in commissioning and hope to use it for experimental work soon. Other experimental facilities include a pilot-scale pyrolysis plasma reactor, a screw-fed pyrolysis reactor and six desktop-scale reactors.

Liverpool University
Dr. Xin Tu is working on application of plasma catalysis tar cracking and the application of catalytic processing to gasification products.

University of Manchester
Prof. Ali Turan has experience of large-scale gasifier design and is looking at improving the available design methodologies from fundamentals. Particularly relating to off-design operation at lower output levels.
Dr. Samira Garcia-Freites is researching gasification integration and assessment, with application to agricultural residues.

Newcastle University
Prof. Adam Harvey's group includes researchers investigating plasma catalysis as a means to treat syngas tar content. The group deals with process intensification and so also considers other technologies that are relevant to the further processing of gasification outputs.

University of Nottingham
Prof. Hao Liu is investigating innovative approaches to syngas cleaning with specific applications to waste gasification. Other work has involved process simulation, NOx reduction and development of absorbents for carbon capture. Some experimental work involves their 10kW prototype downdraft gasifier. Alison Mohr's research on biomass governance issues also touches on gasification.

Queen Mary University of London
Prof. Xi Jiang has conducted extensive physicochemical modelling of biogas combustion, with application to gasification. In particular, this has related to validation of models predicting reactor conditions and producer gas properties as operating parameters are varied.

Queen's University Belfast

Dr. Chunfei Wu is investigating a range of topics relating to the operation of gasifiers. These include the development of catalysts, the use of varied feedstocks and integration with carbon capture technologies.

University of Sheffield

Dr. Yajue Wu is director of Sheffield University Waste Incineration Centre (SUWIC). The centre has ongoing collaborations with companies such as Veolia (investigating technical aspects of plant operation) and previously with Biomass Power. Her research interests include the effect of reactor conditions and feedstocks (e.g. adding plastics or contaminants) on the characteristics of the gasifier outputs and syngas. There is a wide range of experimental facilities at SUWIC including a co-flow pyrolysis unit, FBG and fixed bed gasifiers, and a 2m entrained flow gasifier which they have used with superheated steam flame fuel injection (sludge mix) and can track particles through. They also work with numerical simulation based on kinetics and CFD and analyse how design changes might affect the flow of particles though the gasifiers. Others in the group are researching issues relating to H&S, risk management and feedstock storage.
Prof. Mohamed Pourkashanian's work covers a broader energy remit but also includes gasification, numerical modelling and carbon capture.

University of Strathclyde

Dr. Jun Li is working on models to predict reaction mechanics, for example modelling the effect of particle size on the gasification products and generation of ash. This has combined experimental work to characterize combustion products (e.g. in a large, high temperature dynamic gravimetric analyser). The results can be used to inform reactor design and process upgrading. In future, they would like to expand investigation to include the effect of different feedstocks and the inclusion of impurities).

University College London

Dr. Massimiliano Materazzi is looking at how variations in feedstock and gasifier conditions affect the properties of the gas and other co-products. A small-scale FBG rig (equipped with analytical facilities such as X-ray and thermal imaging) is being used to investigate the fundamentals of feedstock introduction at high temperature and subsequent reaction behaviour. Plasma-assisted gasification is also subject of interest. A benchtop facility is used to analyse the effect of temperature and plasma activated reactions on tar reforming and ashes stabilization. Results are directly related to experience with Advanced Plasma Power's pilot-scale facilities. Interest in use of plasma under different combinations of redox conditions, inputs, temperatures, plasma power and then investigating properties of resulting syngas and contaminants.
Prof. Paola Lettieri is part of the same research group, focusing on questions relating to the bigger picture of gasification use and on LCA studies.

4. Previous studies: challenges to gasification

Several studies have sought to explore the factors behind the failure of biomass gasification to fully consolidate its position relative to other bioenergy technologies. The literature relating to these studies and related perspectives takes a range of formats. This includes several review papers assessing whether biomass gasification might meet its potential[61], how it has advanced[62], and the technical and commercial barriers to it[63 64 65]. Two studies report on workshops exploring these issues from a range of stakeholder opinions[66 67] while views have also been sought within the REA[68]. Several responses to the CCC call for evidence supporting their 2018 Biomass Review are instructive[69 70 71 72]. Other reports and papers discuss the outcome and development of commercial projects[73 74 75 76] and the rationale behind the approach taken[77]. Consultancies have conducted projects exploring other aspects of biomass gasification uptake (e.g. reviewing the available technologies[78], assessing its future prospects[79], and considering

61 Kirkels, Arjan F., and Geert P. J. Verbong. "Biomass Gasification: Still Promising? A 30-Year Global Overview." Renewable and Sustainable Energy Reviews, vol. 15, no. 1, 2011, pp. 471–81, doi:10.1016/j.rser.2010.09.046.
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63 Ruiz, J. A. A., et al. "Biomass Gasification for Electricity Generation: Review of Current Technology Barriers." Renewable and Sustainable Energy Reviews, vol. 18, 2013, pp. 174–83, doi:10.1016/j.rser.2012.10.021.
64 Asadullah, Mohammad. "Barriers of Commercial Power Generation Using Biomass Gasification Gas: A Review." Renewable and Sustainable Energy Reviews, vol. 29, 2014, pp. 201–15, doi:10.1016/j.rser.2013.08.074.
65 Adams, P. W., et al. "Barriers to and Drivers for UK Bioenergy Development." Renewable and Sustainable Energy Reviews, vol. 15, no. 2, Elsevier Ltd, 2011, pp. 1217–27, doi:10.1016/j.rser.2010.09.039.
66 Bridgwater, Anthony V. The Future for Biomass Pyrolysis and Gasification: Status, Opportunities and Policies for Europe. 2002, https://ec.europa.eu/energy/sites/ener/files/documents/2002_report_p536.pdf.
67 Harvey, Adam, et al. Gasification Technologies Delivering the Potential. 2013.
68 Stone, Hilary. Gasification & Pyrolysis: Realising the UK Opportunity July 4. 2012, https://www.r-e-a.net/images/upload/events_90_1207REA_HoC_event_Hilary_Stone_address_final.pdf.
69 Energy Systems Catapult, and Energy Technologes Institute. Committee on Climate Change – Bioenergy Review (2018) Call for Evidence. 2018, https://www.theccc.org.uk/publication/bioenergy-call-for-evidence-report/.
70 Progressive Energy. Response to the CCC Bioenergy Call for Evidence. 2018, https://www.theccc.org.uk/publication/bioenergy-call-for-evidence-report/
71 Walsh, Richard. 2018 Bioenergy Review Call for Evidence. Cadent Gas Ltd, 2018, https://www.theccc.org.uk/publication/bioenergy-call-for-evidence-report/.
72 Advanced Plasma Power Ltd. Bioenergy Review 2018 Call for Evidence Response. 2018, https://www.theccc.org.uk/publication/bioenergy-call-for-evidence-report/.
73 GoGreenGas. BioSNG Demonstration Plant - Project Close-Down Report. 2017, http://www2.nationalgrid.com/UK/Our-company/Innovation/Gas-distribution-innovation/NIC-Projects/BioSNG/.
74 GoGreenGas. Commercial BioSNG Demonstration Plant, Third Project Progress Report. 2017, https://gogreengas.com/wp-content/uploads/2015/11/3rd-PPR-December-2017.pdf.
75 Piterou, Athena, et al. "Project ARBRE: Lessons for Bio-Energy Developers and Policy-Makers." Energy Policy, vol. 36, no. 6, 2008, pp. 2044–50, doi:10.1016/j.enpol.2008.02.022.
76 Larsson, Anton, et al. The GoBiGas Project. Demonstration of the Production of Biomethane from Biomass via Gasification. Goteborg Energi AB, 2018.
77 ETI. The Role for Bioenergy in Decarbonising the UK Energy System. Energy Technologies Institute, 2018.
78 E4Tech. Review of Technologies for Gasification of Biomass and Wastes Final Report. NNFCC, 2009, http://www.e4tech.com/wp-content/uploads/2016/01/gasification2009.pdf.
79 Eunomia. Investment in Advanced Conversion Technologies: Has the Time Finally Arrived? 2016.

application to waste treatment[80 81]). While there is a rich literature reporting research to develop gasification, the focus here is on factors affecting the uptake of the technology. Although the format and motivation for these studies varies somewhat, there are many repeating themes that can be drawn out. These are summarised and grouped below.

1. Project financing

Most reports noted poor availability of finance relative to the capital expenditure required for projects. This partially relates to the perceived level of technical and non-technical risk inherent in developing these projects. However, this also reflects the distribution of risk in the mechanisms by which these projects are currently supported; incentives based on the output from plants place considerable risk on the project developers and investors. Three reports noted that overly optimistic initial estimates of costs or lack of contingency have resulted in sufficient finance being unattainable for successful project completion. In other cases, backers have lost confidence or patience in projects and alternative backers have not been available, resulting in greater perceived risk to other projects. Improved mechanisms to attract financing have been recommended, notably the concept of making a form of loan guarantee available. Development of demonstration plants to increase stakeholder confidence is also suggested.

2. Financial viability and incentives

Related to theme #1 is the combination of the level of uncertainty over the future returns that biomass gasification plants might achieve and the possibility that any returns will be low. This is partly due to significant uncertainty over the level and availability of incentive and support mechanisms that might be secured. It also relates to uncertainty over future market conditions, feedstock availability and competition from conventional fuel sources. For example, concern is expressed that the development RTFC will not support a sufficiently sized market to effectively enable the development of fuel production technologies. The future of the Renewable Heat Incentive (RHI) is currently unknown and is potentially too low for plant sizes that would be needed for commercial operation (>40GWh/yr). In some cases, these concerns are exacerbated by barriers to access certain markets or uncertainty over their future status. It is interesting to note the key role of a local municipal energy company in securing finance and energy offtake agreements for the GoBi gas project.

3. Gasification objectives

Overall there seems to be a consensus that better definition of the market or the proposed role of gasification would be beneficial. This relates to both current application of the technology but also a clearer roadmap to future applications, ideally within an overarching decarbonisation strategy that sets out the

80 AEA. Energy from Waste Technology Landscape Review Advanced Thermal Technologies. 2011.
81 CARE Ltd. Pyrolysis and Gasification of Wastes: UK and Ireland Review. 2011.

role of gasification and its products. Several reports state the need to ensure that the most appropriate uses for gasification are the ones that are incentivized as it expands (for example, delivering maximum GHG emissions savings). Others related this to concerns in the consistency of financial support mechanisms, leading to a lack of investor confidence (as above). Directing development away from electricity towards other vectors was suggested. It was also observed that historically, confused policy support may have resulted in projects that focused on "chasing" the incentives, were driven to inappropriate timescales, or that do not make best use of the syngas produced.

4. Gasification scale

There are similar questions over the appropriate scale for gasification development. These relate to cost, technical risk and demonstration, and infrastructure development. Given a potential mismatch between the typical scale of fossil-fuel based alternatives and local availability of biomass, this may also reflect questions over the proposed role of biomass gasification (see theme #3).

A related but separate issue is the difficulty that several projects have faced in scaling up technologies. There is a possible tension between doing this too aggressively, against not achieving the economies that are potentially available.

5. Large-scale demonstration plants

The development of demonstration plants is widely suggested as a potential solution to help address some of these barriers. Construction risks are still significant despite the examples of the technologies that are currently at pilot and demonstration stages. This relates to the difficulty of scaling up technologies but also the sentiment that longer-term testing and demonstration has been lacking. As a result, financing of projects has been hindered by a lack of comparable reference plants (especially using waste feedstocks). The need for increased experience of plant operation is noted by several studies.

Several reports made related points about the dissemination of experience and knowledge gained – in demonstration plants but also other R&D activities. Any scheme to fund demonstration plants needs to be carefully created to ensure that lessons can be effectively shared and applied but also reassure technology developers that an appropriate level of IP protection can be maintained. Some feel that better use could be made of existing research and modelling in combination with pilot or demonstration plants. As examples, data that might validate models is often proprietary, or the potential benefits of other models are not exploited fully.

6. Gas cleaning

Dealing with the tar content of producer gas is widely recognised as a significant technical sticking point; arguably greater than gas conditioning. However, while the majority of studies highlighted this, several also present technical options and in some cases recommend a shift of focus towards process development rather than process innovation. There are technically viable methods to clean the producer gas (from tar and other contaminants); the apparent challenge is applying these without unacceptable cost, efficiency or other impacts on the process. However, others identify that there are still significant technical risks in producing high-quality syngas and relate this to difficulty in securing investment. In some cases, "knock-on" difficulties in projects were noted as a result of actions taken to achieve acceptable gas properties (e.g. raising reactor temperature to increase tar cracking led to other problems, or, altering the handling of the fluidised bed to ensure better catalyst activation).

7. Feedstock supply

Developing a feedstock supply chain is a complex problem that may have been underestimated in some projects. There are challenges relating to the availability and contract for feedstock, the cost of the feedstock and to the reliability of the supply chain. Where waste is used, there are additional considerations around the contractual commitments that need to be entered into regarding the quantity of waste to be handled and the future gate-fee that might be levied. There is a risk that expansion of conventional Energy from Waste (EfW) plants will limit the scope for waste gasification. For bioenergy feedstocks, corresponding considerations relate to the development of the co-dependent supply chains and the time and investment necessary to achieve this.

8. Feedstock properties

There are also practical challenges relating to the feedstock used. These include physical handling and storage of the feedstock, achieving consistency in any pre-processing steps, and achieving effective and reliable feeding into the gasifier. Practical engineering problems overcome have included ensuring air tightness at high pressure, and preventing pyrolysis from occurring in the feeding equipment.

Gasifier reactor operation is typically optimised for given feedstock properties so variability in the feedstock (both over time and in terms of its homogeneity) is a significant challenge to efficient gasifier operation, achieving good-quality clean producer gas and handling ash production. Options to mitigate this including multi-stage gasification and improved process-control have been suggested. Use of waste derived fuels typically exacerbates these challenges.

9. Organisational barriers

Difficulty in securing sufficiently experienced staff for plant operation is mentioned in three of the reports. Other reported experience highlights the need to ensure that projects have access to an appropriate project delivery team, including the development of the business case, project management and effectively managing all stakeholders. This relates to aspects of theme #1 (finance, above) but was specifically noted as a requirement for wider development of successful gasification plants.

10. Health and Safety considerations

The complexity of ensuring effective Health and Safety (H&S) practices in gasification plants is highlighted. There are several aspects to this including toxic producer gas (e.g. CO), fire, explosion and environmental contaminants (e.g. ashes and condensate).

11. Waste perceptions

Different aspects of perceptions to waste are discussed in the literature. Demonstrating that syngas is a useful product rather than a waste has caused difficulty for some operators. It is also noted that social perceptions for waste gasification are still often unfavourable – especially where misleading information is publicised and that permitting regulations are felt to be unclear in places.

12. Other research needs

In addition to research needs implicit in the barriers discussed above, several specific research needs are explicitly mentioned:

- Characterization of pyrolysis – i.e. the tar compounds formed at the pyrolysis stage of gasification
- Feedstock preparation
- Modelling – especially scaling up
- Identifying the best uses for syngas
- Developing control systems for gasification plants
- Materials for reactor – i.e. dealing with the corrosive nature of alkali compounds
- Monitoring feedstock quality in time to adjust gasifier operation before the feedstock enters it
- Ensuring the continuous supply of fuel
- Dissemination of practical experience in building gasifiers at scale.

5. Opinions raised by academics

Individual discussions

Several academics with research interests relating to gasification (see Acknowledgements section below) were asked about the barriers that they perceive are hindering the wider adoption of biomass gasification and the research that they feel is appropriate to enable these to be overcome. Typically, these were telephone conversations of 10 to 30 minutes. Despite the wide range of research activities that these academics are involved in, there was a good level of commonality in responses – often relating to aspects somewhat incidental to their own research. In almost all cases, their research groups are actively engaged with industrial partners at some level of TRL.

While several researchers pointed out specific areas of research to improve the performance of gasifiers and overcome technical hurdles, most noted that they believe the primary barriers to their widespread use are non-technical.

There was a general sense that the need for biomass gasification and related technologies is increasingly acknowledged by government and other stakeholders, but that the actual incentives and policies in place are not sufficient to achieve the necessary level of ambition. Government policy and public perception of gasifiers were identified as an area of challenge as these are likely to affect the level of actual support available (to industry but also to research efforts). One researcher opined that the unique advantages and potential of technologies such as gasifiers are obscured in the current narrative. The importance of a long-term and stable incentives and policy regime was emphasised several times.

Suggestions for areas of technical research included:

- Reactor designs that are suited to the variability of feedstocks that they may encounter.
- Improvements in understanding and subsequent modelling of the effects that different reactor designs and feedstocks may have. For example, on the quality of syngas, formation of co-products, and risk of tar fouling.
- Extension of this understanding to effective control of the gasification process(es).
- There were some differences in the detail of the suggested approaches for achieving this (probably reflecting the range of individual experience) but a general consensus that a combination of further experimental studies, monitoring of larger scale gasifiers under different conditions and modelling based on these results will be necessary. One leading researcher opined that current understanding of the processes inside gasifiers is somewhat overestimated.

- While research relating to tar removal and gas conditioning was mentioned by several researchers, one (with a significant research group) reflected that it is the costs, complexity and uncertainty of these systems that are most problematic. For them, a key challenge is in delivering performance within the constraints of what is commercially worthwhile. The need to regenerate catalysts was presented as a specific example.
- Technical optimisation of downstream integration of the syngas and co-products with other processes.
- Development of catalysts and other processes to make best use of the gas and other products generated.

The difficulty of dealing with variability in feedstocks was flagged as a concern by several researchers, but suggestions to deal with this varied from development of the gasifier technology to upstream options relating to the supply-chain. Several observed that biomass is typically easier than waste to successfully manage; it was suggested that the approaches to these options may need to be different to reflect the barriers and drivers that they face.

Most researchers who expressed an opinion on the uses for gasification suggested that the focus for this going forwards needs to be on demands that are less readily satisfied in other ways. For example, one recommended a focus on transport fuels rather than heat and power applications. Some felt that this is recognised but (as above) needs to be turned into more effective steps to incentivise these higher value products.

Some questions over the appropriate scale for gasifiers were raised; with others reflecting that this was highly dependent upon the primary drivers for their use. In particular, three researchers pointed out that there are many important questions relating to integration with carbon capture and storage / utilisation that will need to be addressed if this potential is to be realised. Other researchers were more interested in smaller scale gasifiers and the potential advantages such as flexibility, location and matching to feedstocks that they might present. One researcher noted difficulty in securing interest from industry in research relating to larger scale facilities and reflected that this may be due to past failures such as ARBRE and a current commercial environment in which long-term investments are harder to secure.

Points raised at Supergen Bioenergy Hub Researchers’ Day

The Supergen Bioenergy Hub Researchers’ day (Glasgow, 16th May 2019) was attended by around 40 bioenergy experts and researchers from industry and academic backgrounds. During the afternoon, a short workshop session was used to enable group discussions and feedback relating to gasification. Participants were asked for their perceptions of barriers that have limited commercial uptake of biomass gasification and for the research topics that they believe are most important in order to help address them. This was done in six groups of around five to seven individuals to facilitate some discussion and cross-fertilisation of ideas before participants were encouraged to feedback their thoughts orally and with written notes that were collected. The barriers that were raised ranged from technical issues through to aspects of financing and clarity over future requirements. These thoughts are summarised here.

Most tables mentioned aspects of the technical challenges associated with cleaning tars and other contaminants from the gas stream. In some cases, broader considerations around ensuring consistent gas quality were also raised. The potential compromise between the level of gas cleaning and conditioning and overall system energy efficiency was also raised.

Two related technical challenges are the consistency and handling of feedstocks. Some tables noted the need for consistent storage and conditioning of feedstocks while others mentioned reliable mechanical feeding solutions. Some frustration was expressed that a lack of information regarding the “ideal” characteristics of feedstocks may be hindering effective research into suitable pretreatment options.

In dealing with varied feedstocks, the continued development of suitable control systems was suggested as a research priority. Further research into other aspects of process control was also recommended by others.

Research to develop our ability to conduct effective thermochemical modelling and chemical process modelling was also proposed.

Ensuring the financial viability of gasification projects was raised by most tables but was expressed with several different emphases. In one case, it was the general competitiveness with fossil fuel alternatives that was of concern. Others noted the need for security and consistency in any financial support that is available. The perceived level of risk relating to investment in gasification was pointed out by some; with the suggestion that approaches to de-risk these investments are necessary (through a range of approaches possibly including government-backed loan guarantees but also support to increase the number of projects available as references). Frustration in the variability of experience that potential EPC contractors deliver was expressed.

Several tables commented on the need to ensure that gasification is used to produce the most appropriate products. This sentiment was expressed in different ways: that prioritisation should be given to speciality feedstocks and aviation fuels rather than heat or power, that there should be greater alignment of financial support to the higher value products (especially regarding CfD support for close-coupled gasification), that the RTFO incentives are promising but potentially lack the necessary volume and certainty (concern was expressed that one large plant could potentially crash the price of RTFCs). Some felt that research is still needed to ascertain the most appropriate uses for gasification and in optimising the extent to which various thermo-chemical conversion technologies might be used to produce complementary products.

Additional research into several "broader picture" topics was suggested. These topics were: social aspects of gasification, integration into current energy systems, and Life Cycle Assessment and integration with the downstream applications for syngas.

It was pointed out that in order for gasification to fulfil the role that is often proposed for it, significant research and development will be needed relating to effective scaling up to commercial scale and effectively integrating with CCS. Others suggested that there might be scope to better transfer knowledge and experience from related sectors and fuel processing. Concern was expressed that much of the potential learning from previous unsuccessful gasification projects has either not been effectively captured for future use, or not acted upon.

One table proposed that it might be necessary to transfer some development focus from medium-scale plants (up to 50MW) to large-scale (around 500MW, entrained flow) plants. This would probably require an increase in R&D for pretreatment options but might then enable effective transfer of experience with coal gasification to be applied along with the potential for more attractive finances.

6. Points raised by industry and other stakeholders

Around 15 industry and other non-academic stakeholders were approached for comments relating to the development of biomass gasification (see Acknowledgements, below). They represent a varied set of priorities and roles but the points raised were quite consistent. These are collated and summarised below, split between barriers and challenges, and research and development needs.

Barriers and challenges

Some pointed out that there are operational references for many of the technologies required to make use of biomass gasification. Opinions were more varied on the significance of differences in context but there was a consensus that while technical challenges might hinder projects, these can be overcome and that it is non-technical issues that are the key barriers hindering wider use. Some frustration with financiers taking an overly simplistic approach in appraising risk and therefore being overly dismissive of projects was expressed.

Financiers are weary of the level of risk, resulting in a high cost of capital. This has also resulted in projects being risk-averse to newer technologies or opting for "safer" technical options that do not necessarily take full advantage of what might be achieved. The initial 2-ROC subsidies available to gasification plants for a limited period probably resulted in projects that were rushed into when a more measured approach could have been more effective. Some of the practical engineering challenges relating to these projects were clearly underestimated. This may have been further exacerbated by a lack of experience with the feedstock supply chains that therefore needed to be developed concurrently.

Specific concerns were raised relating to each of the current support mechanisms and are summarised below. While there are schemes that are intended to support heat (including gas to grid), power and transport fuels, the lack of equivalents for chemicals or for carbon capture was raised as detrimental to gasification as these are considered key advantages. It was also suggested that some technologies / projects might be optimally operated to provide a mixture of these energy vectors, but that the support mechanisms effectively rule this out.

The Contracts for Difference (CfD) scheme was criticised by several groups. The barriers to entry (in terms of registration and application) are felt to be overly onerous relative to the size of typical gasification projects (around 30MW). Most notably, the projects need to be developed before they know whether they will receive CfDs and there is considerable uncertainty about the level of support (if any) that will be available to them. There are real examples of this occurring (e.g. APP's Tysely project in 2014). Competition with more established renewables technologies such as offshore wind is considered unrealistic and does not take account of additional benefits that gasification might offer or the level of maturity of the market. The "winner takes all" approach results in a high level of risk that most respondents feel is inappropriate and unnecessary. Concern was expressed that this will (or has) also result in wasted development and lost experience in projects that subsequently fail to secure support.

The Renewable Heat Incentive (RHI) has the potential to support heat or gas to grid applications that are seen by some as a more effective use for gasification. However, notwithstanding the recent extension[82], the closure of the scheme leaves a gap in support for this application and a significant lack of clarity about intentions for its replacement. Others also note that the decreased level of support for plants supplying more than 40GWh/yr is also problematic to the scale at which gasification would be commercially viable.

The Renewable Transport Fuels Obligation (RTFO, and development fuels sub-target of the RTFO) schemes are generally seen more favourably and are likely to drive proposals towards liquid fuels. There is a general sense that transport fuels are the area in which there is most future potential but also frustration that future intentions are vague. Some parties expressed concern that the level of ambition in the RTFO is insufficient to support adequate prices if production of fuels is increased to a reasonable level. This again leads to a level of uncertainty that may hinder investment. One expert noted that while a reasonable price for Renewable Transport Fuel Certificates (RTFCs) could, in principle, make a commercial scale fuel production plant viable, it would not be sufficient to fund demonstration scale plants nor to finance construction; these still represent barriers to development.

In addition to these concerns relating to support when plants are operating at commercial scale, there was a common theme that there is a gap in funding for pre-commercialisation projects. Without the necessary experience and demonstration at this scale, delivery of full-scale projects is far more challenging. Even if incentives are developed to make commercial-scale activities attractive, the route to get to these is problematic. Several noted that funding that is contingent on the successful output of projects is far more appropriate to mature technologies whereas lower risk options such as grant-funding are better suited to encourage development activities. Reflecting this common theme that support mechanisms do not adequately reward the risk inherent in these projects (both technical and commercial but also that support might not be available at sufficient level later), the suggestion of a loan guarantee scheme was put forward by several people. Others noted, however, that such a guarantee would help when

82 https://www.gov.uk/government/news/government-proceeds-with-extension-to-tariff-guarantees

financing commercial scale activities but might be less helpful for smaller scale demonstration plants that were unlikely to be financially viable without other support. The cash-negative design of Innovate UK funding (i.e. that funding is given after work has been done) was also cited as a barrier to smaller companies. It was further noted that while grant funding is a key opportunity, there is often concern (potentially due to lack of communication) about the type and detail of information / IP that will need to be published as a requirement of this grant process.

There is a general lack of confidence in the overall direction and availability of support mechanisms. Several companies are requiring that project proposals are viable without them, somewhat limiting the options that are possible and increasing the relative importance of the level of landfill tax. However, others also expressed uncertainty over this and the level it will be set at in future. It was suggested that it takes around ten years for companies to build confidence in a subsidy arrangement. In addition to problems with the delivery of support mechanisms, it is felt that the lack of clear government objectives or targets in this area make future prospects even more risky and further increase the cost of capital.

Most of the operational waste gasifiers in the UK use a close-coupled system in which the gasifier(s) feed minimally cleaned or uncleaned producer gas into a boiler to raise steam. This option carries less technical risk but results in what is considered to be a less useful application for the syngas. The newer (round 2) CfD regulations include conditions to exclude it. Most of those asked felt that the tighter requirements in this regard are sensible. Again, though, a key requirement for companies is consistency in what is being incentivised so that they can work towards that.

Several practical but non-technical barriers were identified. Environmental permitting was reported to often take around 12 months rather than the target of four months, leading to problems in development timelines. Connections to the electrical grid and gas network can also be challenging.

Attracting suitably qualified and experienced personnel and plant suppliers can be difficult in the UK. This was attributed to a vicious circle in which firms apparently do not invest because of a lack of skilled operators and people do not train because of a lack of plants and investment.

There has been some poor publicity regarding the social desirability of gasification that may act as a deterrent to their development and to effective support policies. While some of this is from groups specifically opposed to EfW and bioenergy, there is also some opposition from environmental advocacy groups. Some of this may stem from historic ineffective disambiguation from conventional EfW facilities. In other cases, concerns about the overall level of recycling do not appear to have been addressed (or communicated effectively).

Managing the complex set of stakeholders and parties involved in the development of gasification facilities is a challenge that is exacerbated by the diversity of their priorities and concerns. For example, these stakeholders can include technology suppliers (for the gasifier(s) and also post-treatment), EPC contractors, financers, local resident groups, local authorities, planning and environmental permitting, owners of land, feedstock or waste suppliers (typically with long-term contracts) and off-take agreements for the gasification products. Each of these relationships can present challenges that have the potential to disrupt the others. Specific examples provided were the barriers to entry for long-term waste management agreements with local authorities, and risks associated with supplying heat networks due to the limited number of suppliers and buyers involved. It was suggested that some previous projects have suffered from inadequate stakeholder analysis and engagement, especially relating to the investment community and identification of appropriate investors so that high levels of credibility can be maintained.

While waste (e.g. RDF) gasification is generally considered more technically challenging, it has received more attention because of the gate-fees that it attracts. Most of those consulted felt that it is difficult to envisage a project being viable in the current context without this additional revenue. Gasification also has the potential to work well at scales appropriate to waste, providing an efficient option at these scales that is modular and minimises transport distances. However, this does bring challenges. The variation in feedstock (e.g. particle size, moisture, metal content etc.) requires flexibility in material handling, reactor design and control. In principle, gasification is well suited to this but practically realising this potential while maintaining appropriate syngas quality is technically difficult. Some view this as an opportunity; in that if successful gasification with RDF can be demonstrated, this brings additional confidence that gasifiers using woody biomass could be successfully developed.

Other regulatory barriers were commented on. Waste and energy regulations can vary significantly and depend upon the feedstock. Demonstrating that the products are useful and should not be subject to waste regulations can be difficult. One respondent noted that this challenge also relates to development activities as current regulations limit R&D plant size to 50t/yr, which is too small to adequately demonstrate or test the technologies. Another group suggested that better incentives for treating plastics that are hard to separate / recycle would also be appropriate. Looking to the future, there is some uncertainty over future waste policy (e.g. relating to landfill tax and other EfW plants) and over how waste composition might change as recycling rates and separate food waste collections increase.

Various comments touched on aspects of the "bigger picture" relating to gasification. In some cases, these were expressed as a desire that there would be clearer direction about the development aspects to focus on, whereas one response opined that the full range of potential products (chemical feedstocks through to energy generation) was important and that there should be scope to expand the role of gasification across all of them. Two comments related to whether bigger plants (i.e. at the scale of entrained flow coal gasification) at coastal locations might be more appropriate for future biomass gasification than the "local scale" gasification employed for waste treatment. In this case, additional focus on pretreatment would be necessary. Similar suggestions were made about technology read-across from the successful gasification of coal and similar processes in other sectors (e.g. relating to mechanical handling). In the other direction (but potentially complementary), it was cautioned that small-scale gasification or pyrolysis might still have a role and should not be dismissed.

Research and Development needs

While a wide range of suggestions for useful research and development were made, these were often caveated with an opinion along the lines that developing several operational demonstration plants is the primary current need in order to enable biomass gasification to be employed at scale. That is, while there is plenty of scope for R&D to improve and refine processes, it is development of the practical engineering and management of projects along with the adequate funding that this would enable, that needs to be focussed on. Some specifically related the need for demonstration to liquid fuels production.

In emphasising the need for demonstration plants, it was also noted that (if done appropriately), a single project could unlock development of multiple products. For example, a demonstrated route to catalyst-quality syngas would enable production of hydrogen, methane and F/T-based fuels.

Several comments related to aspects of downstream integration between the gasification and further processing of the syngas to other products. This related to concerns over total efficiency of the process and ensuring that the necessary skills and expertise are effectively brought together. Conversely, it was also pointed out that most of what needs to be done (e.g. methanation) has already been demonstrated elsewhere at scale.

Practical research areas suggested were:

- Tar removal and cleaning to sufficient level. In particular, avoiding the energy penalty associated with options such as scrubbing or high temperature plasma cracking.
- Pretreatment of biomass for entrained gasification (relating to comments above). Questions over supply chain logistics as well as technical pretreatment options were mentioned.
- Investigation of large particle size (i.e. above 100μm diameter) in entrained flow gasifiers.
- Modelling of variation in syngas quality and constituents as feedstocks vary.
- Improved real-time control of gasifier operation.
- Alternative feed gases (i.e. gases fed into gasifier to enable oxidation and / or fluidisation of bed).

Some non-technical research topics were also suggested:

- How might policy effectively support the introduction and integration of CCS.
- How might different gasification options fit into the broader set of needs (e.g. are different technologies more or less suited to different energy vectors or overall objectives).
- What are the most appropriate roles for the outputs from gasification (e.g. hydrogen to peaking plants).
- What are the most appropriate feedstocks for gasification development to be focussed upon (i.e. where some of these feedstocks might otherwise be fed to complementary processes such as anaerobic digestion).
- How might value added co-products be best used. How could this be appropriately encouraged.
- How might gasification fit within a wider biorefineries strategy.
- How could other potential environmental benefits (e.g. concentration of metal contamination) be best realised.

7. Findings and Conclusions

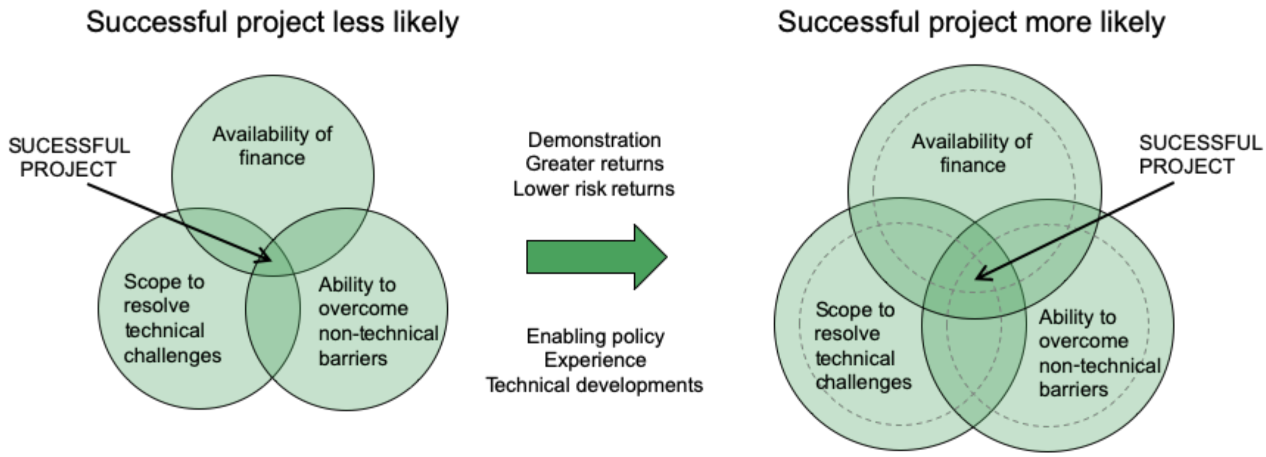

Figure 5: Elements of successful gasification projects

Delivering a successful project depends upon the intersection of three key elements (see Figure 5): technical challenges must be resolved, non-technical barriers must be overcome and sufficient finance must be secured. Increasing the solution space for each of these key elements increases the chance of a project succeeding; **unsuccessful projects have typically resulted from a combination of issues relating to each of these elements, where greater leeway in any one of them might have led to a better outcome**.

Crucially, there is significant interplay between them. If technical challenges can be resolved more readily (or with a better demonstrated path), then the project will be deemed less risky and it will be easier to secure affordable capital and overcome non-technical issues (e.g. planning constraints and development of personnel). If greater finance is made available (e.g. through greater eventual returns or, potentially more cost-effectively in the short-term by reducing risks to these returns) then there is greater scope to weather set-backs and to engineer the most effective integration of the technologies. Similarly, reducing the "grit" introduced by non-technical barriers (either by removing unnecessary barriers, or by increasing experience in overcoming necessary considerations) will reduce the technical compromises that need to be made and the extent of risks that discourage investment.

While biomass gasification has arguably underdelivered to date, these considerations suggest the potential for a virtuous cycle in which the technology might develop rapidly and achieve what is necessary. However, **there is an urgent need for effective demonstration plants to unlock this success** by demonstrating its potential and by building expertise in the route to achieving it. These plants could **unlock the route to several products** if reliable production of catalyst-quality syngas can be demonstrated. Effective and appropriate dissemination of this experience is vital.

Some specific aspects merit highlighting. **Funding support mechanisms are not adequate.** This relates not only to the level of funding support that is available but also to the barriers to obtaining it and the risks of either not obtaining it or it being at a significantly lower level than anticipated. There is a need for long-term stability and confidence in the support that will be offered. There is also a need for alternative, lower-risk funding or finance support options for demonstration and first-of-a-kind projects.

There are clearly some significant technical challenges still remaining. It seems that these are not the primary barrier to wider adoption of biomass gasification and that the **primary technology need is for evolution of practical engineering rather than radical technology innovation**. However, **improvements in technology are still important**. In the short-term they can help to resolve challenges more readily and in the long-term improve the overall economic, social and environmental case for the use of gasification. The most frequently mentioned areas were syngas cleaning (primarily from tar), real-time control, and feedstock handling and pretreatment. However, there are many other research areas (e.g. downstream integration, process modelling) that could deliver significant additional benefits and synergies while also supporting other developments (e.g. in terms of the fundamental understanding of underlying processes).

In order to underpin all of this, research needs regarding the most appropriate roles, applications and scale of biomass gasification persist. Clarification of these issues and effective policy to encourage development in a consistent direction will be needed.

Significant non-technical barriers remain. These include supply chain development (relating to consistency of feedstock but also reliability and confidence in it), delays caused by permitting and other factors, difficulty in employing experienced operators, and general project- and stakeholder-management. The importance of resolving these aspects may have been underestimated in traditionally technical or finance-orientated perspectives but is vital to actually achieving success.

There is an urgent need for appropriate plants to be successfully developed at commercial scale in order to improve confidence in the technologies along with experience in their operation and associated activities. Failure to deliver this is likely to result in societally sub-optimal options to deliver a low-carbon economy and appropriate action to address the identified barriers is recommended.

Appendix: Approaches taken to gather evidence

Several approaches were taken to collect the evidence supporting this report:

- Interviews and discussions with individuals including developers, technology suppliers, consultancies and trade association groups. The interviews primarily related to the perceived barriers and challenges, and suggestions for how these might be overcome.
- Interviews and discussions with academics. These primarily related to their perceptions of the commercial needs and ways in which academic research might support these.
- Review of academic articles and grey literature (including responses to relevant calls for evidence), focussing upon barriers to use of gasification and adoption at scale.
- Group discussions at the Supergen Bioenergy Hub Researchers' day (Glasgow, 16th May 2019). The Researchers' day was attended by a range of academic and industry representatives and so this session enabled some group discussion of these barriers and cross-fertilisation of ideas.
- Trend analysis of academic articles relating to gasification.
- Data collection on academic research activities in the UK. This was conducted by consulting UKRI's grants on the web[83] and a recent UK bioenergy research stakeholder mapping[84] and then reviewing data from the websites of relevant institutions.
- Follow-up discussions with academics from those institutions to clarify research activities and facilities.
- Data collection on commercial activities in the UK. Databases (the UK renewable energy planning database and others) were consulted to create an initial list of EfW sites. These sites were individually investigated through trade magazine and other news articles, along with the websites of the organisations involved (typically several organisations will be involved in each project – EPC, technology supplier, waste or feedstock operative, financing etc. – and report on it separately).
- Where possible, operational status of sites and plans relating to them were then confirmed by talking to representatives of those sites or organisations.
- In total, around 30 individuals were consulted (in addition to the group discussion at the Supergen Bioenergy Hub Researchers' day) and are listed in the Acknowledgements section below. These individual discussions formed the key part of this work.

83 https://gtr.ukri.org
84 Gomez-Marin, Natalia, and Tony Bridgwater. Mapping UK Bioenergy Research Stakeholders. Aston University, 2017.

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The Supergen Bioenergy Hub works with academia, industry, government and societal stakeholders to develop sustainable bioenergy systems that support the UK's transition to an affordable, resilient, low-carbon energy future.

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Front cover photo: Kew Technology / ETI gasification demonstrator (courtesy of ETI / Paul Winstanley)