Department for
Business, Energy
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Advanced Gasification Technologies – Review and Benchmarking

Opportunities and barriers for next generation AGTs

Task 4 Report

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Management Summary

This report presents the outcome of Task 4 of the Advanced Gasification Technologies (AGTs) benchmarking study being undertaken on behalf of the Department for Business, Energy and Industrial Strategy (BEIS) by AECOM / Fichtner. It identifies opportunities for, and barriers to, the scale-up and deployment of biomass and waste fired AGTs to produce low carbon hydrogen and hydrocarbon products. The report is intended to support the assessment of the feasibility of large-scale deployment of AGTs in the coming decades and understand what would be required to allow it to occur.

In this report the term AGT is used to refer to a thermal conversion technology (gasification or pyrolysis) used to convert biomass or waste into hydrogen or hydrocarbon products. AGTs do not include technologies used to produce electricity. The term Advanced Conversion Technology (ACT) is used to describe gasification or pyrolysis technologies used to produce electricity. ACT plants may, or may not, include equipment for cleaning or upgrading of syngas prior to use for the generation of electricity.

AGTs have the potential to produce low carbon hydrogen and hydrocarbon products, with the possibility to operate with a net negative release of CO_2.

This assessment has been based on a review of publicly available information, contributions from the Steering Board and AECOM / Fichtner in-house professional experience.

UK Gasification Experience

In the last 20 years, more than 30 gasification projects using waste or biomass have been developed in the UK, with assistance from a variety of government support mechanisms. All these projects were intended to produce electricity. However, many of these projects have never been successfully commissioned, did not perform in line with initial expectations, or only operated for a limited period of time. A list of UK commercially developed gasification plants is presented in Table 1 below.

Table 1. Commercial Scale Gasifiers

Plant	Fuel	Gasifier supplier	Indicative Status[1]
Acharn Biomass Gasification CHP Plant	Wood	LiAg	Commissioning
Advanced Biofuel Solutions Limited Swindon	RDF	RadGas	Commissioning

[1] The status of the projects shown is indicative. Plants shown as operational may not be operating with high availability and plants shown as in commissioning may have been in commissioning for an extended period.

Plant	Fuel	Gasifier supplier	Indicative Status[1]
ARBRE	Wood	TPS	Shut down
Biomass UK No. 1 (Hull)	Waste wood	Outotec Energy Products	Commissioning
Biomass UK No. 2 (Barry)	Waste wood	Outotec Energy Products	Commissioning
Biomass UK No. 3 (Boston)	Waste wood	Outotec Energy Products	Commissioning
Charlton Lane Eco Park	RDF	Outotec Energy Products	Commissioning
CliniPower	Clinical waste	Compact Power	Shut down
Dargavel, Dumfries	RDF	Planet	Shut down
Dartmoor Bio Power	Waste wood	Nexterra	Shut down
Derby Resource Recovery Centre	RDF	Energos	Mothballed
EMR Oldbury	Automotive shredder waste	Chinook Sciences Limited	Shut down
Energy Works Hull	RDF	Outotec Energy Products	Commissioning
Full Circle, Belfast	RDF	Biomass Power Limited	Operational
Glasgow Recycling and Renewable Energy Centre	RDF	Energos	Operational
Hoddesdon Energy	RDF	Biomass Power Limited	Operational
Hooton Park	RDF	Kobelco	In construction
Ince Bio Power	Waste wood	Outotec Energy Products	Operational
Kew Technologies	RDF	Broadcrown	Commissioning
Levenseat Renewable Energy Limited	RDF	Outotec Energy Products	Operational
Milton Keynes Waste Recovery Park	RDF	Energos	Operational
New Earth Solutions (multiple plants)	RDF	NEAT	Shut down
O-Gen, UK (multiple plants)	Waste wood	OGEN	Shut down
Swindon Energy	Waste wood	Refgas	Shut down
Tees Valley 1&2	RDF	Alterg-NRG	Shut down

Plant	Fuel	Gasifier supplier	Indicative Status[1]
Tyseley Bio Power	Waste wood	Nexterra	Operational
Welland Bio Power	Waste wood	Nexterra	Operational

While publicly available data on many of these plants is limited, it is noted that those identified as shut down have ceased operation for a range of reasons, including failure of the plant to meet initial operating expectations and / or commercial failure of the owner / operator. A number of those that are identified as 'operational' operate with limited availability, and some declared as being in commissioning have been commissioning for a number of years. More detail on some of these plants is included in a 2019 report from Supergen[2] and in Tolvik Consulting's Report *UK Energy from Waste Statistics 2019*[3]

While the specific circumstances of individual projects differ, a number of common themes have been identified that led to the difficulties experienced, including:

- Delivery of projects by contractors with limited experience in complex process plant
- Commercial pressures on projects leading to a lack of robustness in plant design and auxiliary systems
- Underestimating the impact of feedstock variability on reliable plants operation
- Underestimating the complexities of significant scale-up of existing technologies
- Development of projects based on support mechanisms that incentivised projects that may otherwise have not had a favourable business case

From a technical perspective, ACTs that produce electricity without syngas upgrading are simpler than AGTs because they do not require syngas cleaning, syngas upgrading and the addition of CCUS. The performance issues experienced by waste and biomass fired ACTs are a concern in relation to the development of more technically complex AGTs.

Gasification and similar thermal processes have been, and are, used commercially in industries other than power generation. The use of gasification and pyrolysis in other industries demonstrates that long-term commercial use of gasification and pyrolysis is possible if the right economic conditions are in place. It should be possible to transfer skills and technology developed in other industries to future biomass and waste gasification projects.

Demonstration projects have been constructed to produce hydrocarbon fuels from biomass or waste using gasification-based processes. Details of these projects are provided in Task 2.

[2] www.supergen-bioenergy.net/wp-content/uploads/2019/06/Bioenergy-and-waste-gasification-report-2019.pdf
[3] Tolvik-UK-EfW-Statistics-2019-Report-June-2020.pdf

Lessons Learned on Government Incentives

The historical UK approach to subsidise electricity generation from gasification as a first step in developing either higher efficiency electricity generation or to making chemical or fuel products has realised limited benefits. The majority of the gasifiers built are not suitable for either higher electrical generation efficiencies or to produce a syngas to make products. Future support will need to be more targeted to ensure projects can achieve the aims of the support.

Lessons in relation to government support for advanced conversion technologies (ACTs) in the electricity generation sector include:

1. Incentive schemes should be mindful of potential unintended consequences, such as supporting the development of technologies that lack clear and demonstratable advantage(s) over existing technologies.

2. There may be advantages in incentives that are outcome based rather than pathway based. For example, to support efficient electricity generation from biomass and waste rather than providing support for a specific class of technologies.

3. Development and implementation of robust incentive schemes for complex process plant that involve multiple inputs and outputs is a challenging process.

Lessons Learned on Project Delivery

A number of projects that have been constructed have not met initial expectations for a variety of economic, technical and non-technical reasons. However, there are common themes that emerge in underperforming projects. For future projects, lessons that could be learned include:

1. Realistic assessments of cost and performance risk (particularly availability) should be made by investors or third-party advisors.

2. Optimism bias should be managed, particularly in relation to performance claims made by organisations without exposure to financial risk in relation to plant performance. Realistic assessment by independent parties is essential.

3. If historical operational data is not available for process equipment there is considerable risk associated with assuming that high levels of performance will be achieved. This risk will always be present for new technologies, but needs to be understood and managed to deliver successful projects with an appropriate balance between risk and return.

4. The existence of reference facilities does not always indicate that a technology is ‘proven’, or that it would be reasonable to assume high operational availability in any

future project. Consideration needs to be given to the actual performance achieved, scale, configuration and feedstock used at any reference facility. Changing from operation on biomass to operation on waste is a significant step.

5. Financial contingencies and plant designs should make adequate allowances for process optimisation when new technologies are being developed.
6. Appropriate risk allocation is required during project development, ideally with risks being allocated to parties most able to control them.
7. The tension between the desire to build a large facility to benefit from economies of scale and avoiding excessive scale-up risk should be understood and assessed by stakeholders.
8. The capabilities of organisations involved in the design and construction of projects needs to be considered during project development. Suitably funded and experienced technical oversight is valuable during design, construction and testing.
9. Processes that are more complex are more likely to experience technical difficulties.
10. Building multiple similar units at the same time offers little opportunity for additional innovation, and increases the risk associated with the repetition of mistakes.
11. Commercial pressures on projects may lead to lack of robustness in plant design and auxiliary systems

Cognisance of these issues is required in future project development to promote more positive project outcomes and encourage valuable technology development.

Opportunities

The primary opportunity for AGTs is as a means of producing low carbon hydrogen and hydrocarbon products. Use of biomass or waste feedstocks give AGTs with CCUS the potential to be one of a limited number of technologies available for operating with a net negative release of CO_2.

AGTs will give a wide range of CO_2 emission reduction performance depending on the feedstock, the technology used and whether, and how, CCUS is applied. The ability to provide cost effective CO_2 emission reductions relative to other CO_2 emission reduction technologies is a key factor to consider when evaluating different AGT configurations.

There are opportunities for technical innovations and improvements across the full chain of equipment that comprises an AGT plant. These improvements could lead to cost reductions in the technology. However, it should be appreciated that, when new technologies are moving from the demonstration phase to commercial operation, capital cost requirements can increase as challenges, such as full chain integration, are met.

Barriers to Scale-up and Deployment

There are a variety of economic, technical and non-technical barriers to the scale-up and deployment of AGTs. Many of these barriers are complex in nature and this report provides only a high-level overview. Barriers have been summarised and categorised in Table 3 with explanations of the categorisations given in Table 2. The categorisation and quantification of risk is an inherently subjective process. Table 3 should be considered in relation to the additional information provided in the body of this report and the fact that the barriers being considered are complex and varied in nature.

Table 2. Barrier Classification

Barrier Description	Category
A potential barrier to the large-scale deployment of AGTs in the UK.	
A potential barrier to large scale deployment of some AGT configurations prior to 2035.	
In isolation, unlikely to prevent deployment of well-developed AGT configurations prior to 2035.	

Table 3 Barriers to AGT Deployment

Barrier	Comment	Category
Economic Barriers		
Government incentives	Level of support required, and time required to develop incentives for low carbon products and CO_2 capture.	
Competing technologies for CO_2 emissions reductions	The potential availability of simpler, lower cost CO_2 emission reduction options.	
Competing technologies for producing low carbon products	Competition from other technologies capable of producing low carbon hydrogen and other low carbon products.	
Competition for feedstock	Biomass and waste are limited resources with other uses. Many other uses of biomass and waste have their own positive environmental impacts.	
Product price volatility	Market prices of AGT products are volatile and unpredictable.	
Availability of finance	The perceived risk of gasification may influence the future cost and availability of finance for AGTs.	

Barrier	Comment	Category
Technical Barriers		
Plant availability	Achieving an acceptable balance between equipment cost and availability. Availability is dependent on many of the factors listed below.	
Reliable process unit operation	Development of reliable process units for all process stages.	
Scale-up	The cost, time and technical challenges associated with scale-up.	
Full chain integration	Demonstration of full chain operation from feedstock reception to product output and CO_2 capture (if applicable).	
Requirement for CCUS	Some AGTs may require CCUS to provide CO_2 emission reductions. CCUS infrastructure will take time to develop and adds additional cost and complexity to the project.	
Efficiency of conversion	Mass of product output per unit of feedstock is fundamental to the viability of AGTs.	
Feedstock flexibility	Achieving an acceptable balance between grade of feedstock that can be processed and cost of equipment.	
Product quality	The ability to reliably produce products of the required specification without incurring excessive equipment costs.	
Safety	Effective management of process safety in a process with varied hazards.	
Non-Technical Barriers		
Reputation of gasification	Poor reputation of gasification among stakeholders including, contractors, financiers and planning authorities. Potential for public perception issues due to underperforming projects.	
Planning and Permitting	Time required to develop large infrastructure projects, particularly an issue for waste processing plants.	
Dissemination of lessons learned	Openness in relation to sharing lessons learned from underperforming projects.	
Skills	Availability of suitably skilled and experienced staff, and organisations at all stages in project delivery.	

Development of AGTs

Many of the barriers to deployment faced by AGTs could be overcome with further time and financial investment. However, due to the number, nature and magnitude of barriers identified there is considerable uncertainty in relation to the achievability of successfully deploying multiple large scale AGTs in the UK by 2035, as discussed with BEIS during this assignment. Furthermore, some of the barriers identified have potentially fundamental implications to the long-term viability of some, or all, of the AGT configurations considered.

Ultimately, the development pathway for AGTs will depend on several factors including the cost of products, CO_2 savings achievable, technology risk of AGTs, competition from other technologies and support mechanisms available.

1 Introduction

This report presents the outcome of Task 4 of the Advanced Gasification Technologies (AGTs) benchmarking study being undertaken on behalf of the Department for Business, Energy and Industrial Strategy (BEIS) by AECOM / Fichtner. It identifies opportunities for, and barriers to, the scale-up and deployment of biomass and waste fired AGTs to produce low carbon hydrogen and hydrocarbon products. Where barriers have been identified, potential pathways for addressing them have been described as applicable.

AGTs have the potential to produce low carbon hydrogen and hydrocarbon products, with the possibility to operate with a net negative release of CO_2. However, the ability to achieve a commercially acceptable balance between costs (capital and operational) and plant performance has been, and is likely to continue to be, a key challenge in the development of gasification technologies.

Information on lessons learned and barriers to future development will inform the technical and economic requirements to move from the current level of technology development, as described in Task 2, to the large-scale deployment of commercial plants, as considered in Task 5. In turn this will provide an improved understanding of the feasibility of large-scale deployment of the next generation of AGTs in the coming decades and what would be required to allow it to occur.

One challenge when reviewing gasification technologies is the diversity of technological options available. There are many different options in relation to feedstock processed, types of gasifier, syngas upgrading, end products produced and scale of operations. This diversity of options represents both an opportunity and a challenge for gasification as a class of technologies. Different configurations and applications of the technology have different associated advantages and challenges.

When considering the future development of AGTs, it is important to consider the overall purpose of the technology being considered. This could be manufacturing products, treating residual waste or capturing carbon. Maintaining a focus on purpose promotes a fair assessment of the potential benefits of the technology for fulfilling that purpose. Critically, this allows comparisons to be made to other, non-gasification based, technology options for achieving the same outcomes.

Maintaining a focus on purpose and alternative technology options available will help to focus development efforts on applications for gasification-based technology where it is most likely to be of benefit in the medium to long term.

This assessment has been based on a review of publicly available information, contributions from the Steering Board and the collective professional experience of AECOM and Fichtner Consulting Engineers. Professional experience often includes knowledge and information gathered from working on live projects that cannot be directly referenced for reasons of confidentiality. If specific projects have been mentioned in this report it is based on publicly available information on that project and information sources have been referenced.

2 Lessons Learned

Constructing large scale processing plants that fail to operate successfully, or perform below expectations, can have negative consequences for local authorities, companies, individuals and the wider industry sector that the plant was part of.

In the last 20 years, more than 30 gasification and pyrolysis projects using waste or biomass have been developed in the UK, with assistance from a variety of government support mechanisms. A high proportion of these projects have experienced notable performance issues. This section seeks to identify lessons that can be learned from gasification project performance and related government incentive schemes. Many projects that have not met initial performance expectations have done so for similar reasons, the most significant of which are discussed below.

2.1 Incentives for Gasification

This section considers the gasification of waste or biomass for the purposes of electricity generation. Such projects have been supported by the UK Government through the Non-Fossil Fuel Obligation (NFFO), Renewable Obligation Certificate (ROC) and Contracts for Difference (CfD) schemes under the definition of Advanced Conversion Technology (ACT).

The intention of subsidising gasification was to develop processes which could either operate at higher electrical efficiency than conventional electricity generation plants or produce fuel products. It was recognised that developing such processes had higher risks and could be achieved in stages. However, by providing subsidies for electricity generation without ensuring that either the technology could be later developed to higher efficiencies or to produce fuels, there was no safeguard on what technologies were allowed subsidies.

Details of incentive schemes have evolved over time. When many of the gasification plants currently entering operation were built, eligibility for fiscal support as an ACT required the plant to demonstrate that syngas of a certain calorific value had been produced. No requirements were stated in relation to processing of the syngas, how it was used to generate electricity or overall plant electrical generation efficiency. This resulted, in many cases, in no syngas processing being included in the process and raw syngas being combusted shortly after it is generated, sometimes in the same vessel in which it is generated. Heat was then recovered from the flue gases generated and used to generate electricity using a water-based Rankine cycle.

These plants generally offer lower electrical generation efficiency compared to gasification plants that upgrade syngas for the use in a gas turbine or reciprocating engine, and they do not provide demonstration of syngas processing technologies. Furthermore, if gasification and combustion are conducted in the same vessel, there is no guarantee that the gasification part of the process would still work if the syngas was to be removed for further processing, rather than being combusted.

This definition of ACT resulted in technologies being supported that were technically similar to existing staged combustion technologies for generating electricity from waste or biomass, but were however not suitable for the longer-term goal of higher electrical efficiency or producing fuel products. Being classified as 'Advanced' may have been an advantage in relation public perception. However, many of the plants built presented few technical advantages over existing combustion-based technologies for the purposes of electricity generation and provided limited innovation as part of a pathway to using gasification for production of other end products or more efficient generation of electricity. In addition, many of the ACT plants built had a lower net efficiency than conventional energy from waste plants using combustion only.

A secondary impact of the subsidy regimes was that few of the more advanced suppliers in the Energy from Waste (EfW) sector took advantage of it. These suppliers already had conventional products with a strong track record that were sold commercially world-wide. They saw little purpose in developing new solutions suited to the UK subsidy regime which may have been viewed as short-term. The mainstream of the international biomass and waste supply industry continued to develop conventional combustion processes for electricity generation. Gasifier suppliers intending to produce fuels may also have seen little value in the UK subsidy regime which was based on electricity production.

Based on the above, a number of key points can be drawn out in relation to government support for gasification including:

- Incentive schemes should be mindful of potential unintended consequences, such as supporting the development of technologies that lack clear and demonstratable advantage(s) over existing technologies.
- There are advantages in incentives that are outcome based rather than pathway based. For example, to support efficient electricity generation from biomass and waste rather than providing support for a specific class of technologies.
- Development and implementation of robust incentive schemes for complex process plant that involve multiple inputs and outputs is a challenging process.

2.2 Biomass and Waste Projects in the UK

One of the first commercial attempts to use biomass gasification for power generation in the UK was the £30m ARBRE project constructed in 2001. The project intended to gasify biomass, clean the syngas and then use it to generate power in a gas turbine. However, the plant reportedly closed after around eight days of operation due to technical and financial difficulties[4]. In the nearly 20 years since, there have been other projects where the performance achieved was not in line with initial expectations. This includes projects that were built but never operated, or operated commercially, but only for a limited period. A full review of projects of this kind has not been conducted and publicly available information on

[4] www.biomassmagazine.com/articles/5149/biomass-gasification-in-the-ukundefinedwhere-are-we-now

many of them is limited. However, two recent published reports can be used to provide an indication of the type of issues experienced.

The first report, a 2019 report from Supergen[5], states that there are eight operational biomass of waste gasification plants in the UK at the time of publication. All eight of these plants were based on close coupled gasification technology (raw syngas being combusted in a boiler without being upgraded). The report does not include operational data to allow assessment of the performance achieved by the developments. Of the eight plants, four run on biomass (waste woodchip). Of these four plants, two went into administration in 2020, one uses the same technology and had the same owner as the two that went into administration, and no information is available on the operation of the fourth plant.

The second report is from Tolvik Consulting. For plants that use waste as a feedstock, certain performance information can be obtained through freedom of information requests and through the Environment Agency. Tolvik Consulting publishes annual performance data from UK based energy from waste plants. In Tolvik Consulting's Report *UK Energy from Waste Statistics 2019*[6] it states:

> *"ACT commissioning remains challenging – as highlighted by the effective "mothballing" of Sinfin Road ACT in Derby. After at least four years of construction the seven ACT facilities which combusted waste, collectively processed just 27% of their Headline Capacity."*

Given that an Energy from Waste (EfW) facility would typically take around two to three years to construct, these figures are an indication of poor performance across the UK fleet of waste fired ACT plants. Further analysis of the figures presented by Tolvik indicates that the best performing plant of the seven waste fired ACT facilities was the Energos plant in Milton Keynes, with an availability of around 62% based on waste processing capacity. This compares to the availability of a typical combustion based EfW plant of around 90%.

While availability of these ACT plants would be expected to improve over time if continued investment is made, there is a risk that some investors could stop funding the projects. The gasification equipment for five out of the seven plants identified in the Supergen report was supplied by companies that no longer exist and there have been legal disputes relating to the projects. There have been many biomass or waste fired ACT projects that have been built but not achieved long term commercial operation in the UK[7].

From a technical perspective gasifiers that produce electricity without syngas upgrading are simpler than those producing fuels because of the requirements for syngas cleaning and syngas upgrading. The potential addition of CCUS adds a further complexity. The current

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[5] www.supergen-bioenergy.net/wp-content/uploads/2019/06/Bioenergy-and-waste-gasification-report-2019.pdf
[6] Tolvik-UK-EfW-Statistics-2019-Report-June-2020.pdf
[7] UKWIN_Gasification_Failures_Briefing.pdf

performance of waste wood and waste fired ACTs is a concern in relation to the development of more technically complex AGTs to produce fuel products.

Project underperformance is often due to a combination of factors that may be economic, technical or non-technical in nature. The combination of factors responsible will vary between projects but often includes technical issues with the main process units, balance of plant issues, feedstock quality and supply issues and issues relating to project structure and contractual risk allocation.

An analysis of specific projects has not been conducted as part of this review. However, Section 2.4provides a list of key lessons that could be learned in relation to implementing gasification projects based on experience of underperforming projects. Section 4 outlines barriers to scale-up and deployment of AGTs. These barriers have contributed to historic project underperformance in gasification-based power generation projects, as well as applying to potential future projects.

2.2.1 Other Industries

Gasification and similar thermal processes have been, and are, used commercially in industries other than power generation. Coal gasification was used in the UK for the manufacture of towns gas prior to the conversion to natural gas. Coal gasification can also be used for the manufacture of hydrogen and this process is common in China. In South Africa there is a well-established industry for producing diesel and other liquid hydrocarbons from coal using gasification and syngas upgrading.

Pyrolysis processes also have long established commercial applications. These include manufacturing coke from coal, or heavy hydrocarbons, for use in steelmaking and the manufacture of charcoal from wood. As well as a solid product, these processes produce a syngas and other liquid products.

The use of gasification and pyrolysis in other industries demonstrates that long-term commercial use of gasification and pyrolysis is possible if the right economic conditions are in place. It should also be possible to transfer skills and technology developed in other industries to future biomass and waste gasification projects.

2.3 International Experience

Most of the thermal processing of biomass and waste internationally is conducted in combustion-based facilities.

Demonstration projects have been constructed that produce hydrocarbon fuels from biomass or waste using gasification-based processes. Details of these projects are provided in Task 2. Developing these technologies as demonstration projects, rather than in a commercial setting, will have had advantages in relation to certain aspects of the technology development process and in preventing unsuccessful projects in the commercial sector.

Japan is an exception in that it has many operational waste gasification plants. One of the drivers for the development of waste gasification in Japan is understood to be a desire to melt the ash produced. The melting of incinerator ash reduces its volume and changes its physical and chemical properties, which is seen as a worthwhile advantage in Japan.

Further details of international experience in gasification and pyrolysis technologies are detailed in Task 2.

2.4 Key Lessons Learned

Biomass and waste gasification projects often fall short of initial expectations for a combination of economic, technical and non-technical reasons. However, there are common themes that emerge in such projects. The list below sets out lessons that could be learned from gasification projects to promote better project performance in the future.

1. Cost and performance risk (particularly availability) should not be underestimated by investors or third-party advisors.
2. Optimism bias should be avoided, particularly in relation to performance claims made by organisations without significant exposure to financial risk in relation to plant performance. Realistic assessment by independent parties is essential.
3. If historical operational data is not available for process equipment there is considerable risk associated with assuming that high levels of performance will be achieved. This risk will always be present for new technologies, but it needs to be understood and managed to deliver successful projects with an appropriate balance between risk and return.
4. The existence of reference facilities does not necessarily indicate that a technology is ‘proven’, or that it would be reasonable to assume high operational availability in any future project. Consideration needs to be given to the actual performance achieved, scale, configuration and feedstock used at any reference facility. Changing from operation on biomass to operation on waste is a significant step.
5. Financial contingencies and plant designs should make adequate allowances for process optimisation when new technologies are being developed.
6. Appropriate risk allocation is required during project development, ideally with risks being allocated to parties most able to control them.
7. The tension between the desire to build a large facility to benefit from economies of scale and avoiding excessive scale-up risk should be better understood by industry stakeholders.

8. The capabilities of organisations involved in the design and construction of projects needs to be adequately considered during project development. Suitably funded and experienced technical oversight is valuable during design, construction and testing.
9. Processes that are more complex are more likely to experience technical difficulties. At all stages, simpler means of achieving the desired outcome should be considered.
10. Building multiple similar units at the same time offers little opportunity for additional innovation, and increases the risk associated with the repetition of mistakes.
11. Commercial pressures on projects leading to lack of robustness in plant design and auxiliary systems.

Biomass and waste gasification technologies in the UK have largely been developed in commercial settings supported by schemes such as Renewable Obligation Certificates (ROCs) and Contracts for Difference (CfD). While these incentive schemes have successfully promoted the development of other technologies, like wind and solar, the requirement to operate in a commercial setting may have exacerbated some of the issues listed above in relation to the development of gasification technologies. If an AGT project were to be built as a demonstration plant, rather than as a commercial project, this could have advantages in relation to many of the lessons detailed above. In addition, a demonstration project may provide a better platform for assessing different technical options relating to the design and operation of the facility.

However, a directly funded demonstration project would be unattractive to organisations investing for the purposes of making financial returns and are therefore unlikely to become involved. This may restrict the level of finance available and the speed of deployment of the technology. Also, funders of any demonstration projects would need to be convinced of the value of the investment relative to other technology development options available to them.

3 Opportunities

Gasification-based technologies can be used for many different applications, using different feedstock at different scales. This report, and the opportunities described in this section, relate to the use of biomass and waste fired gasifiers for producing low carbon hydrogen and hydrocarbon products at the scales considered in Task 5. Opportunities for other applications of the technology, such as electricity production, are outside the scope of this study.

Task 2 details the current status of different gasification and syngas upgrading technologies for producing different products. None of the AGTs investigated have demonstrated full commercial operation. If developments occur that allow the plants to operate commercially with a significant total installed capacity, then there are a range of potential benefits that could be realised, these are described below.

3.1 CO_2 Emission Reductions

AGTs have the potential to help decarbonise the economy by producing hydrocarbon products that result in a lower mass of fossil origin CO_2 emissions than the combustion of fossil-based hydrocarbons. As part of the AGT production process, CO_2 is generated. For some AGT configurations one of the streams containing CO_2 has a high concentration of CO_2 and this is a significant advantage for the addition of CCUS technology.

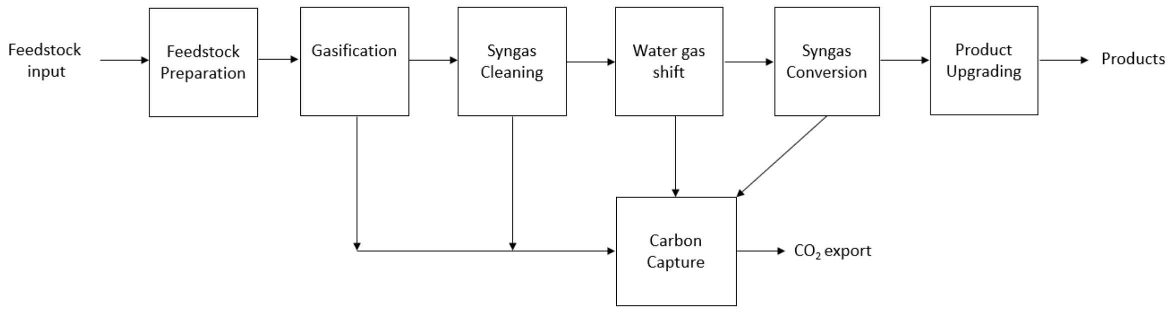
If biomass or waste feedstock are used, AGTs with CCUS have the potential to be one of a limited number of technologies that can operate with a net negative release of CO_2, helping to reach net zero carbon emissions by offsetting emissions from more difficult to decarbonise sectors.

AGTs offer a wide range of CO_2 emission reduction performance depending on the feedstock, the technology used and whether, and how, CCUS is applied to the process. There is a need to better understand the CO_2 emissions associated with selecting different options in the production process and using different feedstock. This would be a valuable area of further work. The ability to provide cost effective CO_2 emissions reductions relative to other CO_2 emissions reduction options is a key factor to considering when evaluating AGTs.

3.2 Technology Developments

Task 2 describes technologies that are being developed that could form all or part of an AGT plant. A generic block flow diagram for an AGT plant is presented in Figure 1 below.

Figure 1. Generic AGT Block Flow Diagram



There are areas for technology development in all the blocks represented above. Feedstock preparation and product upgrading are perhaps the most technologically developed due to their extensive use in other waste or biomass processes and hydrocarbon refining. Nevertheless, biomass and waste handling and hydrocarbon refining are both technically complex areas where refinements and improvements are expected to be possible.

In the other blocks, from gasification to syngas clean-up, conversion and carbon capture, there are many areas of potential research and opportunities for future innovation. Innovations could lead to benefits including improved process efficiency, reduced equipment costs, safer operation, reduced maintenance requirements and a wider range of end products. One important area of development relates to the demonstration of sustained operation with high availability under conditions experienced in a commercial environment. The extent to which this has been achieved is a key area for consideration when assessing technology readiness level. In some cases, such as Fischer-Tropsch upgrading, there is operating experience in other applications, but integration of this process with a biomass or waste fuelled gasifier presents unique conditions under which its operation has not been commercially demonstrated. Long term reliable operation of process units under relevant process conditions would encourage the development of full chain AGTs, and this in turn could lead to commercial projects, increases in scale and the associated benefits that that can bring. As described in Task 2 there are already technologies that have made progression along this pathway.

Improving product yield could help the viability of many AGT configurations. There will be a variety of measures that could be taken to improve product yield, including developments in syngas upgrading technology, heat integration or input of hydrogen produced off-site. The most beneficial development relating to increasing product yield, or improving any other aspect of plant performance, will be dependent on the AGT configuration under consideration. The wider impacts on factors like capital and operating costs, plant availability and net CO_2 savings would need to be considered in relation to any process developments that improve product yield.

3.3 Cost Reduction

AGTs, as discussed in Task 2, have been built for demonstration purposes but are yet to be proven in a commercial setting. Therefore, there will be a significant degree of risk and uncertainty associated with any cost estimate provided for a commercial plant.

For some technologies, as more units are built there is the potential for cost reductions to occur as lessons are learned and developments are made. However, it should also be appreciated that, when new complex process technologies are moving from demonstration to commercial operation, capital cost requirements often increase as challenges, such as scale-up and full chain integration, are met.

AGTs are a complex process technology so there is uncertainty as to whether cost reductions will occur if more plants are constructed. If cost reductions were to occur, the cost reduction pathway for AGTs will require some time, as the time from project inception, through development and construction to demonstration of reliable operation, is likely at be at least five years. This contrasts with, for example, wind and solar developments, which have seen dramatic cost reductions in recent years, in part due to the high number of similar units manufactured and the much shorter length of time between manufacture and performance assessment.

After commercial operation has been demonstrated, the principal areas of AGT plants that present opportunities for cost reduction are those areas where the technology is less developed such as:

- More reliable process units across the chain allowing reduced downtime and / or levels of redundancy.
- Gasifier design with improved feedstock flexibility, reduced maintenance requirements and improved syngas quality.
- Syngas cleaning with reduced energy requirements and improved methods for processing waste produced during syngas cleaning.
- Increased efficiency of the overall process leading to increases in yields.
- The development of catalysts with improved technical and economic characteristics.
- Advances in process control and unit integration.

3.4 Societal Benefits

3.4.1 Job Creation

The scale-up and deployment of AGTs has the potential to create new jobs, including high and medium skilled roles. This includes jobs in the feedstock supply chain as well as in the construction and operation of AGT facilities.

Comparing the job creation potential of AGTs in relation to other low carbon energy technologies, or projects that use biomass or agricultural products in other ways, could be an area for further work.

3.4.2 Fuel Security

There is value in having a diversity of sources for products that are relied upon by society. AGTs are another means by which hydrocarbon products can be produced, so can contribute towards fuel security if locally sourced feedstock is used.

A comparison of the energy security benefits compared to those brought about by other low carbon energy technologies could be an area for further work.

3.4.3 Technology Export

Any technology that is successfully developed in the UK has the potential to be exported to other parts of the world and this has the potential to be of benefit to the UK economy.

4 Barriers to Scale-up and Deployment

Barriers to the scale-up and deployment of gasification technologies may be economic, technical or non-technical in nature. These various interrelated factors would need to be addressed to allow AGTs to be deployed as a part of the overall transition to net-zero in the UK. A summary of the main economic, technical and non-technical barriers is provided in this section along with commentary on how they relate to each other and how they may be overcome.

It is technically challenging to reliably produce high quality and consistent products from feedstock materials that can be low quality and variable. The ability to achieve a commercially acceptable balance between costs (capital and operational) and plant performance has been, and is likely to continue to be, a key challenge in the development of successful projects using gasification technology.

Gasification plants, like many investments, are subject to a variety of risks of differing types and magnitudes. The sum of all the different risks that any one project is exposed to can be considered as the aggregate risk. Investment in new plants is a fundamental requirement of the deployment of any new technology. Fiscal incentives can be used to reduce risk and or increase the rate of return for investors. The ability to achieve a balance of risk and return that is good enough to attract investment without the need for excessive subsidies will determine whether there is increased deployment of AGTs.

The product costs determined in Task 5 must therefore be considered in relation to the risks associated with achieving that cost and the ability to successfully deploy the proposed configuration. The risks associated with these product costs will be dependent on the technical assumptions made. More, or less, ambitious assumptions relating to factors like plant availability or feedstock cost will mean more, or less, risk associated with the final product cost derived. It is important that the product cost figures in Task 5 are considered in conjunction with the assumptions made in Task 5, descriptions of technology track record from Task 2 and the risks and barriers described in this Task 4 report.

4.1 Economic

4.1.1 Government Incentives

4.1.2 Competing Technologies for CO_2 Emissions Reductions

All the products available from AGTs are readily available through the extraction and refinement of fossil fuels. One of the main issues that AGTs are seeking to address is that the extraction of fossil fuels leads to the release of fossil origin CO_2 into the atmosphere. Therefore, AGTs must be considered in the context of providing value for money in relation to other methods of preventing the release of fossil origin CO_2, or other technologies with the potential to operate with negative CO_2 emissions.

Biomass and waste fired AGTs have advantages over other CO_2 reduction technologies in that they have the potential to contribute to removal of CO_2 from the atmosphere, if CCUS is included, and they can contribute to CO_2 emission reductions in difficult to decarbonise sectors of the economy like aviation. However, there is a balance to be struck between spending money developing technologies with these advantages and spending money on simpler lower cost methods of reducing CO_2 emissions. A greater understanding of the barriers to the development of a technology can help inform decision makers in relation to striking an appropriate balance.

Having an appropriate balance between early development of CO_2 reduction technologies for the future, and implementing currently available CO_2 reduction measures now, should help reduce the average cost of CO_2 abatement. For example, deployment of direct air CO_2 capture plants is questionable when CO_2 is being emitted from ammonia production facilities, where the cost of capture would be far less.

There are a wide variety of technologies and strategies available for reducing CO_2 emissions in different industry sectors, including strategies like demand reduction and efficiency. Further work could be conducted into comparing AGTs with other options for achieving CO_2 reductions. The current availability of simpler, lower cost decarbonisation options is a potential barrier to the development and upscale of AGTs.

Further work could also be conducted in directly comparing AGTs with CCS, with other options for achieving negative CO_2 emissions. This could include options like land use change or post combustion carbon capture from biomass or waste fired power plants.

Mitigations

1. Determine whole life CO_2 emission reduction potential, and associated cost on a £/tonne of CO_2 basis, for different AGT configurations and feedstock.
2. Consider prioritising certain AGT configurations based on selected factors including cost of CO_2 reduction and barriers to development.
3. Use available information on costs and barriers for AGTs to inform national CO_2 emission reduction policies that consider a range of technologies and options for achieving CO_2 reduction.
4. Compare AGTs with CCS to other technology options for removal of CO_2 from the atmosphere.

4.1.3 Competing Technologies for Producing Low Carbon Products

CO_2 emissions from the combustion of hydrocarbons can be reduced by reducing demand, increasing efficiency or by using an alternative means of providing the required energy, such as electrification or combined heat and power from biomass or waste. Where available these options could have advantages over using products from AGTs.

Where options to reduce demand, or substitute the use of hydrocarbons, are not available at low cost, there are other competing technologies for producing similar low carbon hydrocarbon products. Some alternative existing and emerging technology options are listed below.

- Hydrogen production using electrolysis using excess renewable electricity.
- Hydrogen production by reforming natural gas with CCUS.
- Methane produced by anaerobic digestion.
- Liquid hydrocarbon production by biological means, for example plant oils or fermentation products.
- Methane or liquid hydrocarbon production based on technologies that combine low carbon hydrogen and CO_2.

Decarbonisation of industry sectors that rely on hydrocarbons can also be achieved through carbon offsetting schemes. In some cases, carbon offsetting may be the most cost-effective long-term way of reducing CO_2 emissions from a sector.

Comparison of different technologies with diverse advantages and disadvantages is not straightforward. Nevertheless, it remains important to question whether AGTs are, or have the potential to be, better than competing technology options for any given application. Further work could be conducted in this area. If the balance of cost, feedstock requirements, technological risk and CO_2 emission reductions of alternative production pathways is better than for AGTs, this is a potential barrier to their scale-up and deployment.

Mitigations

1. Compare AGTs with other technologies for producing the same products considering factors including cost, feedstock requirements, technological risk and CO_2 emission reductions.
2. Prioritise different AGT configurations based on risks and advantages.
3. Use available information on costs and barriers for AGTs to inform national policy in relation to the production of low carbon hydrogen and other hydrocarbon products.

4.1.4 Competition for Feedstock

Both biomass and waste are limited resources and there are existing and emerging competing uses for these materials. Competing uses for biomass and waste will impact both the price and availability of biomass or waste feedstock for any future AGT projects and this is a potential barrier to scale-up and increased deployment.

In some cases, supply chain improvements could improve the supply of biomass or waste to a given project. Supply chain development is encouraged most when projects can provide a constant and predictable demand for feedstock. Any unpredictability in feedstock demand, or unrealistic expectations in relation to quality or price, may make feedstock suppliers reluctant to invest in feedstock storage and handling equipment.

Both biomass and waste have a relatively low energy density compared to other fuels. This makes them more expensive to transport. Therefore, the availability of feedstock needs to be considered on a regional basis. If AGT plants have other site-specific requirements that may not be widely available, such as access to CCUS networks, then constraints on feedstock availability have a greater potential to reduce the number of potentially suitable sites.

For waste fired AGTs there is a risk that by the time the technology has developed to a commercial level much of the residual waste available in the UK will be used by other competing technologies such as combustion-based energy from waste plants. Much of this material will be supplied through long term contracts. To gain access to waste, AGTs may be required to offer to process it at a cost lower than existing facilities. In many areas this may be a barrier to the development of large waste fired AGTs.

In the future the economics of operating an EfW plant could change in relation to the cost of emitting CO_2 and the value of the electricity generated. This could make AGTs more, or less, competitive relative to EfW plants depending on a range of factors. One important factor will be the relative cost of CO_2 emission reductions using either an AGT with CCUS or an EfW with CCUS. If AGTs were able to reliably process waste at a lower cost that EfWs then it could be expected that over time waste would become available.

Many of the competing uses for biomass and waste have their own positive environmental impacts and will have an important role to play in relation to helping the UK to meet its net zero CO_2 emissions commitments. Assuming that both waste and biomass are finite resources, the environmental benefits of the competing uses for biomass and waste should be considered in relation to any potential future demand created by a new generation of AGT projects. If alternative uses of the material offer greater environmental benefits, or the same benefits at a lower cost or with lower technical risk, then this may be a barrier to the deployment of AGTs. Some existing and emerging competing uses for biomass and waste are listed below.

Competing uses for Biomass

- Bioenergy with carbon capture and storage (BECCS)
- The production of dispatchable low carbon electricity
- Contributing to the decarbonisation of domestic and industrial heat
- Manufacture of paper packaging as an alternative to single use plastic packaging
- A sustainable construction material
- Afforestation

- Alternative carbon negative processes such as the manufacture and storage of biochar

Competing uses for Waste

- Recycling (although in this study the waste being considered is the residual waste available after economic levels of recycling)
- Heat and power generation – with the potential to add CCUS
- Fuel for industrial processes such as cement manufacture - with the potential to add CCUS

Mitigations

1. Compare different uses for biomass and waste to inform national policy in relation to the use of these materials and the support for associated processing technologies.
2. Conduct, or review, market assessments of biomass and waste availability.
3. Consider feedstock availability and price in relation to the future development of AGTs.

4.1.5 Product Price Volatility

The market prices of products that can be produced by AGTs can be volatile and unpredictable as they relate to fossil fuel prices. This issue is discussed in Task 3 when benchmark costs for counterfactual products are considered. This product price volatility is a financial risk for future AGT projects and is a potential barrier for scale-up and deployment.

In addition to product price volatility, there is uncertainty relating to the cost and or revenue associated with the CO_2 generated. For AGT projects that include CCUS, there is uncertainty relating to the cost of exporting CO_2 to transport and storage infrastructure, and the cost of emitting CO_2 not captured by the CCUS system to atmosphere. For gasification projects not including CCUS, there is a higher potential cost associated with emitting CO_2 produced during the process to atmosphere. The ability of AGTs to operate as a process with net negative CO_2 emissions is a potential source of revenue. Economic uncertainty relating to the cost of CO_2 emissions is a potential barrier to the scale-up and deployment of AGTs.

Exposure to market risks relating to feedstock, product prices and CO_2, increases overall project risk and means that investors are likely to require higher returns compared to projects with less exposure to market risk. For example, a water electrolysis hydrogen project directly attached to a renewable energy generation asset would have little exposure to feedstock price risk.

Contracting strategies can be used to reduce a project's exposure to market risk. However, they are of limited value because, if a third party takes market risk by supplying a long-term fixed price contract, there is generally a cost associated with providing this service. In the electricity generation sector, the contracts for difference (CfD) scheme reduces asset owner's exposure to electricity market price risk. A similar mechanism could be used for the products and CO_2 generated by AGTs.

Mitigations

1. Acknowledge product and CO_2 price volatility risks relating to AGTs and consider it in relation to the rate of return required by investors.
2. Consider the possibility and impact of government adoption of product and CO_2 price risk through a contract for difference type arrangement.

4.1.6 Availability of Finance

Obtaining finance is a challenge for the demonstration of any new technology because of the increased levels of risk and uncertainty relative to existing technologies.

The availability of affordable finance and an overly conservative approach taken by finance institutions have been cited as barriers to the development of new gasification projects. However, new gasification-based power projects have continued to be financed under the current government incentive scheme, based on assessment of the project risks.

The reputation of gasification-based power generation projects, and the potential increasing size and complexity of AGTs in combination with the other risks and barriers described in this report, will influence the cost and availability of finance for AGTs in the future. However, 'low carbon energy technologies' are expected to remain of interest to financiers and, if a project can demonstrate an acceptable balance of risk and return, then sources of finance for AGTs are likely to be available.

Mitigations

1. Encourage lessons to be learned and adequate scrutiny of new projects to promote positive project outcomes.
2. Develop an appropriate deployment programme for development of AGTs to learn from experience and demonstrate performance of the individual process units, full chain integration and increasing scale of plants.
3. If project risk and rate of return are acceptable after other barriers have been addressed and considered, it should become possible to develop financeable projects.
4. Government grant support.

4.2 Technical

Risk relating to performing as anticipated is common to all emerging technologies. AGTs are complex process plants involving chemical reactions, heating, cooling, rotating machinery, complex material handling and control of multiple interconnected systems. This creates a different set of technical risks when compared to other renewable energy technologies such as wind and solar. For AGTs, performance risk primarily relates to the factors listed below. Issues in any of these areas will impact project economics.

- Availability
- Reliable process unit operation
- Scale-up
- Full chain integration
- Requirement for CCUS
- Efficiency of conversion
- Feedstock flexibility
- Product quality
- Safety

The technical risks and challenges associated with AGTs will depend on the application of the technology. For example, a project aiming to process waste into low carbon hydrogen may face challenges relating to waste processing but will not require a Fischer-Tropsch stage. The technical issues described below are common to waste and biomass gasification used in different applications.

4.2.1 Availability

The operational availability of a plant once constructed is fundamental to project economics. Realistic technical assumptions for plant availability were identified in Task 2 as being fundamental to the development of commercially viable financial models.

None of the AGTs for producing hydrogen or various hydrocarbon products considered in Task 2 have fully demonstrated commercial operation. A lack of technology that has demonstrated commercial operation with acceptable levels of availability is a barrier to the further deployment and scale-up of AGT projects. While technologies could be expected to improve over time if there is continued investment, it is difficult to predict the number of iterations, and length of time, required to develop technologies without a track record of achieving commercially viable levels of availability into commercially viable technologies.

For plants using waste as a feedstock, unplanned outages are particularly challenging because waste keeps being produced, it is difficult to store in large volumes, it is expensive to transport to other facilities and it can be challenging to find other facilities with enough unused capacity to accept additional waste at short notice. For this reason, local authorities who are responsible for waste disposal may be particularly reluctant to rely on technologies that are novel or perceived to have an increased availability risk. Similar supply chain challenges exist in relation to unreliable consumption of biomass, and unplanned outages could also be problematic in relation to the use of CO_2 transport and storage infrastructure.

Many factors can adversely affect plant availability including:

- Poorly performing main process units (for example the gasifier or gas clean-up equipment).
- Issues relating to scale-up.
- Poor quality construction and / or lack of resilience / redundancy in auxiliary systems.
- System integration issues.
- Feedstock that is incompatible with the equipment installed.

Improvements to availability can be achieved by improving the design of, or adding redundancy to, main process units and balance of plant, by sourcing feedstock that is compatible with the equipment installed and increased operational experience. However, in general these measures come at an increased cost. Achieving an acceptable balance of availability and cost is a key challenge for AGTs and a potential barrier to scale-up and deployment.

Mitigations

1. Consider appropriate evidence for, and sensitivity to, availability assumptions in project assessment.
2. Acknowledge availability risk in relation to financial model assumptions and the likely rates of return required by investors.

Refer also to Section 2.4 in relation to lessons learned.

4.2.2 Reliable Process Unit Operation

There are technical challenges associated with achieving long term reliable performance for the main process units in an AGT. The challenges experienced by different process units are multiple, varied and specific to the technology being considered. The summary below provides a high-level overview of some common challenges with AGT plant process units.

- **Feedstock Preparation and Handling** – The ability to reliably process the incoming feedstock to the quality required by the gasifier at an affordable cost.
- **Gasifier** – Availability, slagging (the melting of ash in unwanted places), coping with variations in the feedstock and producing syngas of consistent quality.

- **Syngas clean-up** – Effective control of tars, particulates and other contaminants. The ability to reliably produce a consistent syngas output, from a variable quality input, without incurring excessive equipment and operational costs.
- **Syngas upgrading** – Product yield, product quality, efficiency, catalyst life, ability to reliably process the syngas produced by the upstream equipment.
- **Product refinement –** reliably meeting quality requirements without excessive processing costs or product wastage.
- **Carbon Capture and Storage –** Availability of CO_2 transportation and storage infrastructure.

The development of reliable process units, of a suitable scale and cost, is a challenge associated with the upscale and deployment of AGTs. Further information on specific technologies is provided in Task 2.

Mitigations

1. Include suitable levels of redundancy in equipment designs.
2. Adequately assess reliable unit operation and redundancy during pre-financial close project reviews.
3. Ensure good quality equipment is sourced and the capital costs of the project are not unreasonably low.
4. Consider funding demonstration projects to promote the development of reliable process units.
5. Include demonstration of long-term reliable unit operation as a key research output from any funded demonstration or innovation project.

4.2.3 Scale-up

The optimum size for an AGT plant will be a balance between the benefits of economies of scale that can be gained by building larger plants and constraints that may occur in relation to factors such as scale-up risk, feedstock transportation, land available or investment requirements.

The scale-up of AGTs is a challenging process and issues have occurred in relation to previous attempts to benefit from economies of scale. Factors to consider in relation to controlling scale-up risk include:

- The extent to which the existing scale of plant has operated successfully.
- Realistic expectations of the time and risk involved in process scale-up. Several steps may be required before a commercially competitive scale is achieved.

- Recognition that some processes have fundamental technical limitations in relation to size and scale.
- An appropriate balance between the time required to achieve scale-up ambitions and the risk associated with large scale-up steps.

The number of scale-up steps required, the length of time required for each step, and a reasonable magnitude for each step is highly dependent on the technology being considered as well as other factors. Therefore, it is not possible to provide generic recommendations covering all technologies in relation to scale-up time and cost requirements. However, if large projects are desired, based on limited scale pilot plants, then several scale-up steps may be required, and each step may take several years.

Conducting scale-up processes too quickly increases the risk associated with the process and can lead to failed projects. If scale-up is conducted in smaller, incremental steps with more developmental work and experience gained at each step, then risks are reduced. However, this can be difficult to achieve in a commercial setting where there is pressure to operate at a sufficiently large scale to benefit from economies of scale.

A more controlled, lower risk scale-up process could be achieved through the construction of intermediate scale demonstration projects, where capital at risk and commercial pressures on performance are lower than for full scale commercial projects. However, this may require different sources of funding from commercial projects. Furthermore, a slow and methodical scale-up process does not guarantee that all desired or predicted economic and performance outcomes will be achieved when the equipment is scaled up. Lengthy scale-up periods also increase the likelihood that alternative technologies for achieving the same outcomes will be developed.

Scale-up issues can be successfully overcome, as has been demonstrated in other process industries that operate on a large scale. From a technical perspective it would be possible to scale-up any AGT process, either by increasing unit size or by using more units where units are limited in size for technical reasons. However, for any technology, there are challenges relating to the cost, risk and time required to progress through the scale-up process. Successful scale-up is a potential barrier to further deployment of many AGTs.

Existing large-scale commercial gasification technology that operates on other feedstocks, such as coal, has the potential to be modified to operate on biomass, or a mixture of coal and biomass. Additionally, many of the processes used in the syngas clean-up and conversion processes have already been demonstrated at scale in the oil and gas industry. Experience gained from such technology can be used to reduce the risks of scale-up. Several of the developers of biomass or waste to biofuels processes use designs converted from coal gasification processes to gasify the feedstock or convert the syngas into useful products.

Some suppliers have already developed and tested reasonable scale gasifiers and to scale-up plants the current intention is to supply two or more gasifiers. As long as the modular units or of a reasonable scale, this will not be a significant disadvantage in terms of costs or efficiency. In the waste industry it is commonplace to have multiple unit plants as this adds operating flexibility in managing waste streams.

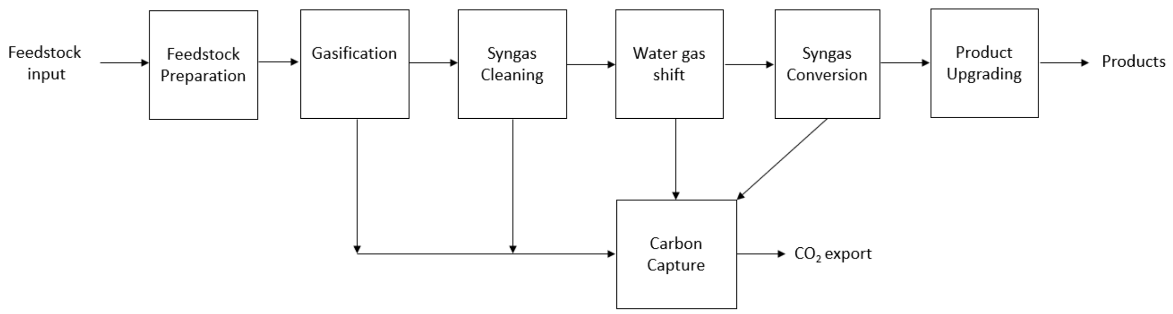
Mitigations

1. Consider the factors listed above in relation to scale-up on any new projects.
2. Highlight any scale-up risks during pre-financial close project reviews.
3. Consider funding of a medium scale demonstration project.

4.2.4 Full Chain Integration

AGTs involve multiple process units being integrated together, as seen in Figure 2, noting that each of the blocks in Figure 2 will contain multiple interconnected processes. For the whole chain to work as required, with acceptable levels of availability, all the process units are required to work together.

Figure 2. Generic AGT block flow diagram



Plant performance issues occur if any one of the process units fails to operate as intended. Due to the complex nature of the plant, there is a risk that a process unit that has functioned well on another site, performing a similar role, will fail to operate reliably due to differing operational conditions. An example of this could be a Fischer-Tropsch reactor that worked well when fed with syngas produced from natural gas or coal but may not operate well with syngas produced from biomass or waste. Interface conditions between the process units are also critical to the full chain integration, to ensure that outputs from each unit are consistently within the design parameters for the inputs to the following unit.

The issue of full chain integration is common in process industries and is generally addressed by a combination of:

- Using process units with a proven track record, if available.
- Ensuring each individual process unit can reliably process the full range of material that might be presented to it from upstream process units.
- Well designed, constructed and commissioned balance of plant.

- Adequate levels of equipment redundancy where required.
- Realistic assumptions on process unit availability.

Using the techniques above it would be possible to overcome the challenges associated with full chain integration. However, effective application of these techniques to control full chain integration risk will increase costs. The ability to demonstrate that that the whole process chain works reliably without incurring excessive costs is a potential barrier to the scale-up and deployment of AGTs.

Demonstrating reliable full chain integration has been an issue in the past when gasification has been used in electricity generation projects based on the combustion of unprocessed syngas and release of CO_2 to the atmosphere. Adding process steps for syngas cleaning, syngas upgrading, hydrocarbon refining, and CO_2 capture will increase the technical challenges associated with full chain integration for AGTs.

Mitigations

1. Consider the factors listed above in relation to full chain integration on any new projects.
2. Highlight any full chain integration risks during pre-financial close project reviews.
3. Consider shortening the chain by having elements such as feedstock preparation or product upgrading conducted by third parties.

4.2.5 Operation and Maintenance Costs

Like availability, operation and maintenance costs are a key economic parameter in relation to the financial viability of any new technology. AGTs will need to demonstrate acceptable operation and maintenance requirements in relation to several technically challenging areas including long term operation of the gasifier, removal of tars and particulates from syngas, treatment of process residues and catalyst life in relation to syngas upgrading processes. Lack of operating experience and an understanding of long-term operation and maintenance costs will be an issue for first-of-a kind plants. High, or uncertain, operation and maintenance cost requirements are a potential barrier to the scale-up and deployment of AGTs.

Rather than seeking to make first-of-a-kind plants overly complex by minimising consumable costs by producing oxygen and power on-site, it will be less risky to simplify initial projects and import consumables, knowing that improvements can be made in future projects, or systems added on later.

Mitigations

1. Highlight operation and maintenance cost risks during pre-financial close project reviews.

2. Research, demonstration projects and / or operational experience would reduce operation and maintenance cost uncertainty.
3. Use operating experience from similar process units to minimise uncertainties. For example, there is a reasonable amount of experience available on the operation of fuel processing and biomass/waste gasifier units.

4.2.6 Requirement for CCUS

AGTs are being considered in the context of aiding the UK in meeting its net zero CO_2 emissions targets by 2050. Therefore, the net CO_2 emissions associated with products from AGTs must be understood, to allow them to be compared with other means of producing the same products.

Calculation of net CO_2 emissions is a complex issue but is essential to demonstrating that government support to carbon reduction technologies across the whole energy system represents value for money.

When CO_2 emissions are being calculated to compare or evaluate different technology options it is important that the boundary conditions for the calculation are understood and are consistent between the options being compared. The use of different boundary conditions may give very different results to the CO_2 emissions calculations. For waste plants, if the boundary conditions are taken as the feedstock entering the plant (as is used when calculating the carbon intensity (gCO_2/kWh) of electricity generated at EfW plants) then products from waste fire AGTs without CCS may have higher associated fossil origin CO_2 emissions than the direct use of fossil fuels. This is because of the proportion of fossil origin carbon in the waste and the conversion efficiency of AGTs. If different boundary conditions are used, then the CO_2 emission calculations will provide different results.

If CCUS is added, either biomass or waste fired AGTs have the potential to provide negative CO_2 emissions. However, the addition of CCUS to an AGT presents a number of challenges. The required CO_2 transport and storage infrastructure does not currently exist, although there are plans to develop it at several locations in the UK. Including carbon capture technology adds additional process units, an additional project interface and increases the overall technical risk associated with the project.

CCUS itself is a developing technology and early stage CCUS deployments may choose to be associated with low risk, dependable sources of CO_2. The owners and operators of CO_2 transportation and storage infrastructure may consider dependability of supply when considering which CO_2 producers to provide capacity to (subject to the commercial basis on which they are developed). The requirement for, and complications associated with, the inclusion of CCUS in AGTs could be a barrier to scale-up and deployment.

Mitigations

1. Understand the whole life CO_2 emissions associated with different AGT configurations.
2. Identify AGT configurations that do not rely on CCUS to achieve carbon savings.
3. Make realistic development timeframe assumptions for AGT configurations that rely on CCUS to achieve meaningful carbon savings.
4. Consider the potential of the application of CCUS to create AGT configurations with net negative carbon emissions.

4.2.7 Efficiency of Conversion

Efficiency of conversion of feedstock to products is important for AGTs as it fundamentally influences project economics and CO_2 emission reduction potential and because biomass and waste are limited resources with competing uses. Conversion efficiency assumptions will be important in relation to estimating the cost of products from AGTs. Further information on typical conversion efficiencies will be provided in Task 5.

For processes that use waste or biomass feedstock it is important that any fiscal incentives promote the efficient use of the material. As waste has a gate fee (negative price) associated with it, particular care must be taken to avoid incentivising inefficient processes.

Mitigations

1. Determine overall conversion efficiency levels including all required auxiliary equipment, feedstock handling and CCUS if applicable. Reasonable allowances to be made for any external inputs such as support fuel, oxygen or electricity.
2. Use conversion efficiency figures to make fair comparisons with other technologies, such as combustion technology with electrolysis as a route to low carbon hydrogen.

4.2.8 Feedstock Flexibility

One of the challenges of waste gasification development has been that processes developed to process clean biomass has been adopted for waste wood or RDF, due to economic pressures. As waste wood is considerably cheaper than clean biomass and RDF attracts a gate fee, projects have been driven by economics to process more difficult fuels. Some technology suppliers have failed to appreciate the difficulties in using much harsher fuels and this has been a common cause of project difficulties. A technology which works reasonably on virgin wood will need significant modifications to work with waste wood or RDF. This was not well understood by some of the technology suppliers for the plants built recently in the UK.

Biomass and waste are complex materials to process, and there is a wide array of equipment available for handling this material. Generally, lower cost feedstock materials require more complex and expensive processing equipment. For example, wood pellets are typically easier to process than wood chips, which in turn are easier to process than refuse derived fuel (RDF) and raw municipal solid waste (MSW). On any waste or biomass fired project, whether using gasification or combustion, this creates a trade-off between the cost of the equipment and the cost of the feedstock that it can process. Achieving an acceptable balance between the grade of feedstock that can be reliably processed and the cost of equipment is a challenge for any biomass or waste processing plant.

We are not aware of any continuous gasification process that can process raw municipal solid waste (MSW) without some form of mechanical pre-processing. Waste processing equipment represents an additional capital and operating cost, uses energy, is a potential source of downtime and has associated hazards. EfW plants can operate on raw MSW with limited feedstock preparation. Being able to operate with limited feedstock preparation is an advantage for EfWs in relation to the treatment of waste, which is one of the services potentially provided by AGTs. However, mechanical pre-processing of waste to RDF is well understood and plants can be designed to have a marginal impact on overall AGT availability, albeit at a cost.

A further risk for waste fired gasifiers is the changing composition of waste. If consumer habits change such that the composition of waste will change, e.g. due to a reduction in use of single use plastics or increased recycling. Such a change has the potential to adversely impact any thermal waste processing technology, and technologies that are most sensitive to changes in the input composition of feedstock are at most risk to adverse impacts of such changes. This may be a barrier for the development of some AGTs, although it is probably a relatively minor risk.

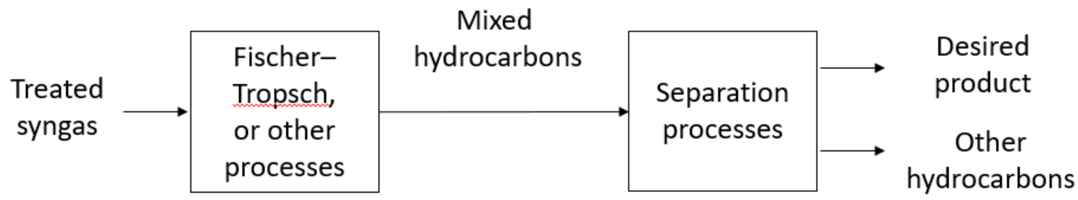
Mitigation

1. Ensure that there is a match between the quality of the feedstock available and the feedstock quality requirements of the installed equipment.
2. At government level the relative roles of waste and biomass need to be considered separately and support mechanisms tailored to achieve what is needed.

4.2.9 Product Quality

Upgrading of the treated syngas to produce longer chain hydrocarbons will be carried out using Fischer-Tropsch or other processes, Figure 3. Further refinement of the mixed hydrocarbons is then required to produce the desired end products such as aviation fuel, methanol or ethanol, as illustrated in Figure 3.

Figure 3. Product separation



The consistency of the treated syngas, and the ability of the upgrading and separation processes to produce consistent end products that meet the required quality standards is fundamental to the plant economics. By-products, or product that has not met required quality requirements could be sent to an existing oil refinery for further processing, but this will reduce its value. The ability of a full chain AGT plant to produce a high yield of compliant product remains to be proven in a commercial setting and therefore is a potential barrier to up-scaling and deployment of AGTs.

Mitigation

1. Develop an appropriate deployment programme for development of AGTs to demonstrate consistency and yield of end products.

2. Further product refinement could be conducted, with an associated cost.

4.2.10 Safety

Safety is a concern during the construction and operation of any biomass or waste processing facility regardless of whether gasification technology is used.

Fire is a particularly challenging hazard to control during the operation of waste management sites.

Examples of safety incidents at gasification plants include the major fire at the Scotgen facility in Dumfries in 2013 that took an estimated 70 firefighters two and a half days to extinguish[8] and in 2017 there was an explosion at a gasification plant in Oldbury that killed one worker.

AGTs have additional hazards in relation to the syngas created, the processing of syngas, the storage and handling of products and any CO_2 captured. The use of new technology and combinations of equipment means that safety is a critical consideration at all stages of design, build and operation to identify and eliminate, reduce or mitigate hazards as appropriate.

[8] https://www.letsrecycle.com/news/latest-news/scotgen-gasification-plant-gutted-by-fire/

Major safety incidents can have implications in relation to the lives and health of workers and nearby residents, the environment, compliance with the law, the reputation of a technology and the cost and ability to obtain insurance for other projects.

Established engineering practices for managing process safety at complex, high hazard installations are applicable to AGTs and, provided that appropriate practices are adopted throughout the development and operation of projects, process safety is not anticipated to be a fundamental barrier to the scale-up and deployment of AGTs.

In the UK the application of regulations such as Construction Design and Management (CDM) 2015 sets out what people involved in construction work need to do to protect themselves, and anyone the work affects, from harm.

Mitigation

1. Apply established engineering practices available for managing process safety at complex, high hazard installations at all stages of project development.
2. Ensure adequate fire detection and protection systems are installed.

4.3 Non-Technical

A brief summary of political, social and other non-technical issues relating to upscale and development of AGTs is provided below.

4.3.1 Reputation of Gasification

Commercial scale gasification-based projects are significant developments with respect to the money and time invested, and the number of different companies and diverse range of stakeholders involved. If a project significantly underperforms it can have financial and social implications for both the organisations and individuals involved. Under-performance may also impact the reputation of gasification-based projects, regardless of whether the gasification part of the process contributed to the performance issues experienced.

While it is difficult to quantify, a poor reputation could make many aspects of project development more difficult for future AGT projects. This could include obtaining feedstock contracts, obtaining finance, agreeing commercial terms with contractors, allocation of performance risk and obtaining the required permits and consents.

The poor reputation of gasification-based projects in the UK will make development of AGTs more challenging. This situation has the potential to be exacerbated if any of the current gasification-based power generation projects, that are in commissioning or early operation, fail to achieve long term commercial operation, resulting in further losses for investors, companies and individuals connected to the project.

Mitigations

1. Learn lessons from the past to encourage positive innovation and successful projects.
2. Consider marketing, brand management and public relations input.
3. AGTs being able to demonstrate benefits over other EfW technologies that are perceived as lower risk by investors.

4.3.2 Planning and Permitting

Obtaining the required planning and operating permits for large industrial developments is, by necessity, a complex and time-consuming process. Waste management processes face additional challenges due to several reasons including an often undeserved, poor reputation in relation to environmental performance. These challenges are not unique to AGTs. However, the length of time required to obtain the required permissions will influence timescales for the development and deployment of AGTs.

Reputational issues could be a challenge for AGTs in relation to obtain planning permission, particularly when they relate to the provision of a key service like waste management. Waste gasification plants that do not perform in line with initial expectations have the potential to result in increased costs and inconvenience for local authorities in relation to the provision of waste management services. Increased costs for local authorities in relation to the provision of essential services will have wider social implications for residents who rely on services provided by the local authority. Any authorities that have been directly impacted by technical challenges experienced at gasification projects may be reluctant to permit new gasification-based projects to form part of their waste management infrastructure in the future.

If any local authority area where CCUS infrastructure is accessible is reluctant to allow new gasification projects in its area, this could have a disproportionate impact on the ability to deploy larger scale AGT plant.

The challenges associated with obtaining the required planning consent will depend on the scale of the project being developed. If a project is large enough to be considered a Nationally Significant Infrastructure Project (NSIP) then a Development Consent Order (DCO) will be required rather than a local authority planning permission.

Obtaining operational permits for new industrial facilities, such as AGTs, requires technical information relating to the operation of the facility. However, permitting is generally considered as a less political process than obtaining planning consent, so is likely to be less of a barrier than obtaining planning consent.

Mitigations

1. Make realistic allowances for planning and permitting of projects in relation to deployment predictions.
2. Undertake potential site identification and selection assessment. Selecting the most appropriate sites is critical to a smoother planning process.

4.3.3 Dissemination of Lessons Learned

Organisations involved in the development of gasification-based projects will learn lessons by developing and commissioning projects. However, there are commercial sensitivities around project performance and sharing of innovations. This can slow down the overall development of the class of technologies by different organisations.

Increased openness in relation to the technical and economic aspects of developing successful gasification projects would help in relation to the dissemination of lessons learned from past projects.

Mitigations

1. Consider knowledge dissemination and sharing of performance data as a condition of government support to AGT projects.

4.3.4 Skills

A lack of suitably skilled and experienced staff, and organisations, at all stages in project delivery can be a barrier to the successful development of new projects. This issue is not unique to gasification-based projects. In general, the skills base for any technology will develop if successful projects are being deployed.

The availability of suitable skills to allow the future deployment and scale-up of AGTs could be impacted by the reputation of gasification-based technologies. Organisations and / or individuals with applicable skills, may choose to work with other technologies if they perceive them to be of lower risk and more likely to progress to a successful outcome. For the syngas handling and upgrading part of the AGT process there could be opportunities to use skills from the oil and gas industry. The UK oil and gas industry has seen declining job numbers in recent years, meaning that there may be a pool of suitably skilled staff for some parts of the AGT process.

Mitigations

1. Invest in education and training.
2. Learn lessons from the past to encourage positive project outcomes.

5 Development Pathway

5.1 AGT Development

Predictions relating to development timescales for emerging technologies to reach commercial operation and subsequent large-scale deployment are inherently uncertain. Some recently developed technologies such as wind and solar have surpassed many people's expectations, whereas other technologies, for example wave and tidal power, have shown slower progress in deployment.

The time required to deploy a new technology is dependent on the current state of development, the benefits that the technology can bring and the barriers to its development. For AGTs, the current state of development of specific technologies is described in Task 2 and opportunities and barriers are described in this report. Further details on the opportunities are being developed in Task 5 in relation to the anticipated cost of products.

In the last 25 years there has been ongoing investment in waste and biomass gasification-based projects and many advances have been made. However, there are barriers on the pathway to the large-scale deployment of AGTs to produce hydrogen and various hydrocarbons. Many of the barriers to deployment faced by AGTs could be overcome with further time and investment. However, due to the number, nature and magnitude of barriers identified there is considerable uncertainty in relation to the achievability of successfully deploying multiple large scale AGTs in the UK by 2035. Large scale deployment prior to 2035 will be particularly challenging if it is to be based on the development of new technology that is currently at a small scale. Some of the barriers identified have potentially fundamental implications to the long-term viability of the AGT configurations considered.

Notwithstanding the challenges associated with the development of AGTs, the positive aspects of the technology and opportunities that it could bring are significant. The potential to produce hydrocarbon products with negative associated CO_2 emissions is a key benefit.

5.2 Government Support Mechanisms

There are a variety of forms of government support that could potentially be provided to aid the development of the next generation of AGTs. The most appropriate form of support will be dependent on the specific AGT configuration being considered. Examples of potential support mechanisms are listed below:

1. Incentives based on the number of units of product made, for example the ROC scheme for electricity generators. This type of scheme may be most appropriate for more developed AGT configurations.
2. Grant funding for pilot or demonstrator type projects. This approach could mitigate some of the risks associated with development of complex process technology in a

commercial environment. However, it restricts the level of finance available and the speed and scale of deployment of the technology.

3. Targeted support aimed at developing a specific element of the process, such as catalyst development or syngas upgrading equipment. The most appropriate element to target will be dependent on the AGT configuration under consideration.

5.3 Next Steps

The most impact from any support provided to the development of AGTs will be achieved by focussing on the configurations with the most potential to be of value. To allow decisions to be made relating to the most appropriate form of support to provide, the following next steps are recommended to be taken alongside technology specific development actions relating to the development of AGTs. Data from Task 5 can be used in this assessment process.

1. Determine the cost of products from AGTs.
2. Compare the CO_2 emissions associated with AGT products, with the CO_2 emissions from alternative sources of these products.
3. Determine a specific cost of CO_2 saved (£/tonne) and consider the risks associated with the calculated cost. For example, assumed plant availability, access to feedstock and other factors detailed throughout this report.
4. Compare the cost and risk of CO_2 emission reductions using AGTs with other CO_2 emission reduction and removal options. This comparison will be sector specific as the alternative CO_2 emission reduction options available are dependent on the product being considered. Alternative CO_2 emission reduction options are available in all sectors and will include measures such as demand management.

The next steps above represent a structured approach to assessing the value of AGTs as a means of controlling CO_2 emissions in different sectors of the economy.

Due to the current level of development of AGTs and the assumptions required in the above analysis, there will be a degree of uncertainty associated with the results obtained. If AGTs are to be developed, then final selection of feedstocks and end products to pursue will also be influenced by BEIS policy within the overall strategy for achieving net zero carbon emissions.

Assuming one or more AGT configurations will be pursued, there are common issues to be addressed that will provide beneficial impact in deploying AGTs commercially at scale, such as:

1. Improving the reliability of operation and consistency of syngas produced by the gasifier. This is a technology-specific and feedstock dependent issue.

2. Developing and demonstrating existing technologies for use in AGT applications, e.g. water gas shift reactor, syngas upgrading technologies. Many of the process stages that form part of the AGT configurations assessed are demonstrated at a commercial scale in other applications, and fundamentally the processes are similar. However, their application in AGTs and the unique conditions that are derived from gasification of waste and biomass feedstocks will need to be demonstrated to support commercial deployment. For example, the impact of the specific gas conditions and composition, including trace contaminants, on the materials selection, process efficiency, operation and control, and maintenance requirements will need to be addressed. Again, these are configuration and technology-specific considerations.

3. Once the basic operation of the chosen configurations has been demonstrated, there are process improvements that may be considered to improve plant efficiency and yield, such as:

   a. Optimised heat integration to make best use of heat generated by the various process stages.

   b. Reduction in use of utilities and consumables, e.g. by producing oxygen and electrical power on site using power generated from surplus heat.

   c. Application of CCUS to reduce CO2 emissions

   d. Technology improvements, e.g. development of Fischer-Tropsch catalysts to reduce production of unwanted hydrocarbon fractions.

   However, it is emphasised that such improvements are secondary to the demonstration of reliable core process operation as an integrated chain.

5.4 Further Work

Potential further work relating to the development of AGTs are outlined below:

1. Conduct a more detailed feasibility study into a specific AGT configuration identified as promising through the exercise described in Section 5.3. This study would allow a more detailed assessment of the technology to be conducted and specific areas for development to be identified. This type of study could also be used to inform decisions relating to any potential demonstration project.

2. Compare the cost, risk and limitations of AGTs with other options for removal of CO_2 from the atmosphere. These other options could include land use change, post combustion carbon capture from biomass or waste fired power plants, direct air CO_2 capture or biochar projects.

3. Consider configurations of AGT that produce other products which have not been considered in this study. These other products could include raw syngas (for use in

heating), solid carbon products (such as a biological origin replacement for coke) or less refined hydrogen.

If further government support is to be provided to the development of AGTs, the barriers identified within this report should be continually reviewed. There is a complex technical and economic balance to be struck between supporting a wide range of technologies with the potential to be valuable at some point in the future, and more targeted support towards technologies that are likely to provide measurable benefits in the short to medium term. This report provides information in relation to achieving that balance.

This publication is available from: www.gov.uk/government/publications/advanced-gasification-technologies-review-and-benchmarking

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