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Advanced Gasification Technologies – Review and Benchmarking

Review of current status of advanced gasification technologies

Task 2 report

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Contents

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Management Summary

Globally, advanced gasification technologies (AGTs) have been identified as key technologies for the production of hydrogen (H_2), methane (CH_4) and drop-in fuels which can be used to substitute fossil derived fuels without any infrastructural or vehicle changes. In the UK, AGTs are considered to be potential low carbon routes for sectors which are known to be difficult or expensive to decarbonise. Consequently, AGTs are now thought to be integral to the UK achieving its net zero emissions target. However, commercial deployment of these technologies has been limited and many gasification and pyrolysis projects have failed due to technological and/or commercial reasons.

Given the importance of AGTs in the transition to net zero, the UK Government requires evidence-based assessment of the development status of AGTs to inform the development of policies and innovation spending initiatives to incentivise investment and promote wide scale deployment of these technologies by 2030.

The Department for Business, Energy & Industrial Strategy (BEIS) has commissioned AECOM and Fichtner Consulting Engineers Limited to assess the status of AGTs as part of the overall assessment of the capability and commercial competitiveness of these technologies to decarbonise the heating, industrial and transportation sectors.

AGTs

The AGTs under consideration in this study refer only to thermal processes for the conversion of biomass or waste and include both gasification and pyrolysis technologies. Generally, AGTs consist of a feedstock preparation plant, feedstock storage and transport systems, the gasifier/pyrolyser, syngas clean-up systems, a syngas reformer and syngas/pyrolysis oil upgrading system to convert the syngas/pyrolysis oil into the desired product and product clean-up systems.

Feedstock

Our review shows that AGTs can be fuelled by a wide variety of feedstocks including biomass, plastics, tyres and waste derived materials for the production of syngas or pyrolysis oil. Whilst, operation on most types of biomass is simple as these feedstocks are relatively homogeneous, operations on waste derived fuels are more challenging due to the high variability in chemical composition. However, waste derived fuels are the preferred feedstock for many systems as biomass is expensive and is a cost to a project whereas a gate fee can be earned for processing of waste derived feedstocks. For all of the technologies considered, pre-treatment of the feedstock is essential to meet the technical specifications of the process and for commercial viability.

Gasification technologies

Fundamentally, gasification of feedstock for the production of fuels is primarily carried out in fluidised bed systems which allow for rapid and efficient transfer of heat for the production of a good quality syngas.

Gasification for the production of fuels requires operation on steam or a mixture of steam and oxygen (O_2) to produce syngas with a high heating value and in which the ratio of H_2 to carbon monoxide (CO) is close to 1. This reduces the investment in downstream reforming of syngas as a H_2:CO ratio of 2 is the preferred syngas feed for the production of fuels. However, use of steam and steam/O_2 mixtures, face significant challenges, including the high energy requirements of the process and high tar content in the syngas. Consequently, advanced gasification systems must include waste heat boilers or other types of heat delivery systems to provide the energy required for gasification. In addition, these systems must be coupled with complex multireactor syngas clean-up systems to reduce the concentration of tars and other contaminants in the syngas to acceptable levels for commercial operation of syngas upgrading systems.

Pyrolysis technologies

Owing to key technical aspects of pyrolysis, many pyrolysis systems are small scale modular plants which have throughput capacities ranging from 7,000 – 10,000 tpa. Fundamentally, this means that these small-scale systems can be considered for the conversion of niche waste streams or the production of niche fuels rather than for large scale production.

Syngas cleaning

Removal of contaminants which can foul downstream systems, poison catalysts required for syngas upgrading and contaminate the fuels produce is an essential process in the production of fuels from syngas. Cleaning of the syngas is carried out using an integrated multisystem approach and all of these technologies are well established in the coal to liquids sector. Some of these technologies have been adopted without any adjustments whilst others have been modified for the treatment of syngas from biomass and waste.

Syngas upgrading

Upgrading of syngas and pyrolysis oil from biomass and waste derived feedstocks requires similar process technologies to those used in the conversion of petroleum feedstocks. Several new reactor systems and higher activity catalysts have been developed and are included in proprietary technologies for the conversion of biomass and waste derived feedstocks.

Overall, some of the technologies under development have developed their own complete solution from feedstock through to syngas upgrading whereas other technologies have coupled a proprietary syngas/pyrolysis oil production system to a proprietary syngas upgrading system.

Decarbonisation potential

Our review shows that these plants are primarily being developed for waste streams which bring a gate fee, whereas biomass is a relatively expensive fuel. However, to have a significant impact on net zero, biomass is a good feedstock as its carbon impact is low and its availability potentially high. Therefore, mechanisms will be needed to promote the use of biomass as a feedstock.

Generally, the production of syngas and the process for conversion of syngas to fuels produces CO_2. In addition, power is required to drive many of the key component systems. Consequently, whilst decarbonisation of the fuel production process is feasible if the whole chain from production of fuel through to products is taken into account, it will not be possible to achieve net zero using these technologies unless CO_2 is captured and low carbon electricity is used to power these systems.

Small scale modular systems for the production of H_2 can achieve decarbonisation in niche areas. However, due to the limitations in the gasifier design for some small scale systems, decarbonisation on a large scale using this type of technology is not likely to be commercially feasible. Where onsite power is generated using syngas engines, these systems will not be able to achieve net zero emissions unless the CO_2 produced during electricity generation is captured. Power consumed by the process would either have to be generated from renewables sources or by using the carbon present in the biomass or waste feedstock to generate power.

With the exception of tyre and plastic pyrolysis processing systems all of the technologies are capable of contributing to net zero emissions provided that CO_2 capture is integrated into the process.

Commercial issues

Assessment of the economics (capital and operating costs and revenue) must include realistic technical assumptions on plant output and availability. Additionally, equipment for syngas clean up, syngas upgrading and pyrolysis oil upgrading are significant costs to these projects and must be included in project financial models. The cost of CO_2 capture will also need to be considered in project financial models where the projects are required to contribute to net zero.

Development status

Overall, none of the gasification technologies reviewed are in commercial operation. The majority of these systems have been tested in other uses but need to be integrated at commercial scale to demonstrate the technologies. Where all of the operations have been integrated, these plants are being operated as commercial scale demonstrators to validate plant operations and predict plant performance. As none of the gasification technologies reviewed are in commercial operation the technology readiness level (TRL) of each has been assessed to determine the current status of the technology and the potential for deployment on a commercial scale. For the technologies reviewed the TRL values range from 6-8.

Several pyrolysis systems are in commercial operation but these are small modular plants which do not have the capacity for large scale production. Based on the information provided these technologies have TRL values of 9.

All of the AGTs in development for the production of liquid drop-in fuels can be operated at scale for the production of large volumes of fuel. Therefore, our initial assessment suggests that wide scale deployment of these technologies has the potential to produce fuels which can substitute conventional fuels without the need for infrastructural or vehicle changes. The technologies reviewed, feedstocks processed and TRL values assigned to these processes are listed in the table below.

Table 1: Advanced Gasification Technologies

Technology Supplier	**Technology**	**Feedstock**	**Product**	**TRL**
Advanced Biofuel Solutions Limited	Gasification	RDF	Synthetic natural gas	6
Enerkem Incorporated (Enerkem)	Gasification	RDF	Methanol and ethanol	8
GoBiGas	Gasification	Biomass	Biomethane	8
Kew Technology Limited	Gasification	Densified RDF	Electricity, H_2 and fuel	6
PowerHouse Energy Group	Gasification	RDF, SRF, and mixed plastics	Electricity and H2	6
Sumitomo Foster Wheeler	Gasification	Biomass	Renewable diesel	7
ThermoChem Recovery International Incorporated	Gasification	RDF	Syngas for aviation fuel and diesel	7
Alphaco	Pyrolysis	Tyres	Pyrolysis oil	9
Reoil Sp.	Pyrolysis	Tyres	Pyrolysis oil	9
Standard Gas	Pyrolysis	RDF	Electricity and methane	5/6
Velocys	Fischer Tropsch (FT)	Syngas	Renewable diesel and aviation fuel	8
LanzaTech	Microbial Fermentation	Syngas and waste gases	Ethanol	9

1 Introduction

1.1 Background

In the UK, advanced gasification technologies (AGTs) are recognised as key enabling technologies in the transition to a net zero carbon economy. These technologies can be used to produce a variety of energy products including methane, hydrogen and drop-in fuels which can be used to substitute diesel, gasoline and aviation fuel without infrastructural or vehicle changes. Consequently, these technologies are now considered to be significant low carbon routes for sectors that may otherwise be difficult or expensive to decarbonise. Whilst these technologies are integral to achieving the UK's net zero carbon emissions target, commercialisation of AGTs has been limited and many projects have failed due to technological and/or commercial reasons.

Given the importance of AGTs in the transition to net zero, the UK Government requires evidence-based assessment of the development status of AGTs to inform the development of policies and innovation spending initiatives to incentivise investment and promote wide scale deployment of these technologies by 2030.

The Department for Business, Energy & Industrial Strategy (BEIS) has commissioned AECOM and Fichtner Consulting Engineers Limited to assess the status of AGTs as part of the overall assessment of the capability and commercial competitiveness of these technologies to decarbonise the heating, industrial and transportation sectors.

For the purpose of this study AGTs are assumed to mean gasification (and pyrolysis) systems which are designed to create a quality syngas or pyrolysis oil which is suitable for further conversion to fuels. We have considered the better known gasification and pyrolysis systems (Sections 6 and 8) which have been installed in the UK for power generation purposes for completeness but only intend to consider further those systems which are capable of being developed for conversion of feedstock to fuels.

1.2 Objectives

The primary objective of this report is to assess the current status of AGTs by:

1. reviewing the types of feedstocks available for fuelling AGTs;
2. evaluating the availability, chemical composition and treatment requirements for feedstocks for operation of AGTs;
3. reviewing the development to date of AGT technologies which could be developed for the production of hydrogen, methane and transport fuels;
4. evaluating the decarbonisation potential of AGTs;

5. assessing the development status of each technology;
6. commenting on key technical considerations and process economics for commercialisation; and
7. developing a list of potential technologies for more detailed assessment based upon agreed selection criteria.

1.3 Basis of review

The information used in preparing this report has been provided by the technology providers referenced in the report or taken from publicly available sources. We have accepted factual information at face value and used it in good faith.

1.4 Selection criteria

This report is a first stage in assessing the viability of potential technologies. Further, more detailed work will then be carried out to review selected technologies in more detail. The criteria used to select potential technologies is as follows.

Supplier agreement

1. Technology suppliers must be willing to contribute to the report and provide the necessary information. Where technology suppliers are unwilling to contribute or do not provide adequate information, they will not be considered further as we will be unable to assess their solutions to the level expected for the overall review.

Ability to process non-fossil fuel feedstocks

2. Solutions must be developed to process non-fossil fuels. To decarbonise, this is a critical factor. Technologies must be capable of processing biomass or waste and their contribution to decarbonisation will be assessed. It is noted that some technologies are currently focussing on refuse derived fuels rather than biomass for economic reasons but may have the potential to process either feedstock. Technologies which are aimed solely at processing waste plastics may make less of an overall carbon reduction impact than purely biogenic based fuels. Nevertheless, the study will also cover potential fuels such as plastic waste and tyres, noting the potential for integration of carbon capture utilisation and storage (CCUS) in decarbonisation of the technology. The initial selection criteria will be: a. demonstrated ability to process biomass or waste fuels; and

b. ability to operate without using fossil fuels for support firing (except for start-up and shutdown).

Production of fuels and syngas of a specified quality

3. Technologies must be able to produce fuels which meet the technical requirements of the standards governing use of these substances in commercial operations. The fuels identified are H2, CH4 or some marketable liquid hydrocarbon such as diesel, methanol, ethanol or aviation fuel. It is recognised that some technologies may be capable of producing a syngas which can then be used in other conversion technologies to produce viable products. Therefore, technologies which can produce syngas of the required quality will be considered, along with technologies capable of converting syngas to useful products. The initial selection criteria will be: a. demonstrated ability to produce product quality hydrogen, methane, methanol, ethanol, diesel or aviation fuel; or

b. demonstrated ability to produce a clean syngas suitable for conversion to the above products (recognising that most syngas could be converted to produce some product but yields would be low and costs high, so we will focus on “good quality” syngas likely to produce viable products).

Thermal processes

4. The study is focussed solely on AGTs, so only thermal processes for the front-end treatment of biomass or waste will be considered. Biological processes such as anaerobic digestion or fermentation will not be included, although fermentation may be considered as part of the chemical conversion process following front-end gasification.

Scale of technology

5. The scale of a technology is potentially very subjective, as scalability of a process once demonstrated will vary with the type of technology. Also, some suppliers develop modular systems, so theoretically they can achieve any scale criteria by adopting multiple units. However, one of the aims of the study is to limit the assessment to technologies that can be commercialised within 10 years, and hence small-scale pilot plant operations are to be excluded from consideration. The initial selection criterion will therefore be:

a. a unit of at least 10 MW thermal currently in operation processing biomass or waste.

– However, the review will set out the current status of the technologies for which we have publicly available information, and these criteria may be adjusted, particularly with regards to considerations of modularity or niche markets.

b. where applicable, a process that could scale to 200-300 MW thermal.

Technology readiness level

6. The development status of the technology must be demonstrated at some reasonable scale or at commercial scale. It will be necessary to evaluate the size of the plant and the duration of continuous operation. This is again potentially subjective, but an assessment of the ability to meet the objective for commercialisation within 10 years based on the length of successful operation of a technology will also be applied. Rather than applying strict criteria at this stage,

we propose to identify technologies which fit the above criteria and then assess the stage of technology readiness for each of these. This will assess “Technology Readiness Levels” for each technology and identify any steps not yet achieved.

This report assesses and ranks technologies against these six criteria and identifies potential technologies suitable for detailed engineering assessment.

The ability to fully decarbonise or contribute to a low carbon economy is considered as part of the study, together with applicability of CCUS, but is not an initial selection criterion.

A factor which must be considered is that many of the key suppliers in the industry will develop their solutions to match economics and regulations. They have limited R&D budgets and focus these on short term markets. This means several viable technology suppliers may not currently be focussing on the gaseous/liquid fuels markets but could easily do so if this becomes a large-scale opportunity. As an example, there are several successful fluidised bed suppliers for biomass or waste, but these systems are largely focussing on power generation. These could be readily developed to provide commercial solution to produce syngas of suitable quality for conversion by demonstrated means to liquid fuels, as others are currently doing. Some technology suppliers may therefore not qualify for further review, but in the future could modify their processes. We consider this to be consistent with the objective of the study to enhance the evidence base for AGT technologies that can produce gaseous and/or liquid fuels. Consequently, this report focuses on the suppliers who are already developing these systems, but acknowledge that as the market becomes more attractive, other suppliers are likely to become available.

1.5 Nomenclature

Table 2: Table of Abbreviations

Abbreviation	Meaning
AGT	advanced gasification technologies
APCr	air pollution control residue
ASR	automotive shredder residue
ASU	air separation unit
BFB	bubbling fluidised bed
CCGT	combined cycle gas turbine
CCUS	carbon capture, use and storage
CFB	circulating fluidised bed
CH4	methane
CO	carbon monoxide
CO2	carbon dioxide
C&I	commercial and industrial
C&D	construction and demolition
CTC	carbon trim cell
DMG	Distributed Modular Gasification technology
dtpd	dry tonnes per day
EPC	Engineering, procurement and construction
FT	Fischer-Tropsch
GCV	gross calorific value
H2	hydrogen
MSW	municipal solid waste
Mtpa	million tonnes per annum
NCV	net calorific value
Nm3	Normal cubic metre
O2	oxygen
O&M	operating and maintenance
PC	pulse combustion
PSA	pressure swing adsorption
PVC	poly vinyl chloride

rCB	recovered carbon black
RDF	refuse derived fuel
SNG	synthetic natural gas
tpa	tonnes per annum
tpd	tonnes per day
TCC	thermal conversion chamber
TRI	ThermoChem Recovery International
TRL	technology readiness level
WGS	water gas shift

2 Conclusions

2.1 Feedstock

1. A wide range of feedstocks including biomass, residual MSW, plastics, RDF and tyres are used to fuel AGTs.

2. The main feedstocks which are likely to have a significant impact on the transition to net zero will be biomass and residual MSW/C&I waste. This is because both of these feedstocks are generated in significant quantities.

3. Biomass, sourced from virgin wood or energy crops such as short rotation coppice (SRC) or miscanthus, are considered to be carbon neutral if grown sustainably, as the amount of carbon released when the biomass is used is the same as was absorbed from the atmosphere in growing the biomass. However, biomass is a relatively expensive fuel due to the costs of growing, harvesting, preparing and transporting it.

4. Residual MSW or C&I waste currently contains approximately 50% biogenic matter by energy content, with the remainder coming from fossil fuels. The biogenic matter, for example food waste, is also considered carbon neutral if used to generate power, heat or fuels, in a similar way to biomass. MSW and C&I waste costs money to dispose of, therefore economically it is a more attractive fuel. It is also important to divert these waste streams away from landfill to avoid release of the carbon to atmosphere.

5. To convert residual MSW or C&I waste to fuels using the technologies described in this report will normally mean the waste has to be processed to create a more refined product, generally referred to as RDF.

6. Other biomass streams, such as agricultural, or wood waste, will also be suitable feedstocks and are cheaper than virgin biomass. However, only limited amounts of these materials are available and the majority of these waste streams are already recycled or used for energy recovery.

7. Niche waste streams such as plastic waste or end of use tyres may be suitable for conversion to fuels using specialist solutions. However, plastic waste is almost completely fossil fuel based and tyres are mainly derived from fossil fuel. There is also likely to be relatively small quantities of these waste streams as recycling or re-use will be the preferred disposal route where viable. These waste streams may have a role in the transition to net zero.

8. Clinical waste and hazardous waste are considered too difficult feedstocks and in too small quantities to be considered further.

9. We have developed a feedstock suitability matrix (see Section 4.8) to describe the suitability of various feedstocks.

2.2 Feedstock pretreatment

1. Biomass will require shredding and screening to a size suitable for each process considered. In most cases biomass will also require drying to deliver higher yields of products.

2. Biomass may also be densified. Whilst this is a costly process requiring drying, grinding and pelletising, this is already commonplace in large scale biomass power plants. Pelletising wood means the fuel is dry, consistent and a higher density reducing transport costs.

3. Waste streams will require mechanical treatment to meet the specifications set by the technology suppliers. In most case this will mean creating a good quality RDF and is a relatively costly process, reducing the gate fee paid for the disposal of the raw waste stream. This uses conventional equipment to shred the waste and separate out the undesirable elements such as glass, metal and stones. The RDF is also likely to require drying to increase product yields.

4. For some technologies densification of the waste is also required. Like the preparation of RDF this is a costly process and reduces the gate fee paid for disposal of the waste stream.

2.3 Gasification technologies for power generation

Most of the gasification systems used In the UK to date for power generation are not suitable for conversion of feedstock to fuels. These plants use air as the gasifying agent to produce a low grade syngas with a H2:CO ratio (approximately 0.25 - 0.5) requiring significant investment for commercial operation of syngas upgrading systems.

2.4 Status of advanced gasification technologies

2.4.1 Gasification

Globally, several AGTs for the conversion of syngas to grid quality methane, hydrogen or drop-in fuels are in various stages of development. Currently, none of the systems reviewed are in commercial operation. However, several AGTs are being operated as commercial scale demonstrators to validate plant operations and predicted plant performance. Our key observations across the range of technologies are as follows:

1. AGTs are being developed for operation mainly on biomass or RDF.

2. Steam and steam/O2 mixtures are the required gasifying agents for the production of a raw syngas with a H2:CO ratio which can meet the technical specifications for commercial operation of syngas upgrading systems.

3. Syngas clean-up systems for the removal of alkali metals, particulates, tars, sulphur compounds and several other contaminants must be coupled with a gasification systems to

ensure that the syngas delivered to the upgrading system meets the technical specification for commercial operation.

4. Fluidised bed gasifiers are the preferred type of reactor as these require small feedstock particle sizes which allow for rapid heat and mass transfer and good conversion of feedstock to syngas.

5. Most projects in development are focussed more on waste streams than biomass for economic reasons. However, most of the fluidised bed systems are able to process biomass which is likely to be an easier feedstock to process than waste.

6. The commercial scale systems for all of the technologies reviewed have been sized for a feedstock throughputs ranging from 75,000 – 100,000 tpa for a single fluidised bed gasifier. Economics dictate that larger systems will be cheaper based on a cost per unit of product. Once technologies are demonstrated, it is likely that fluidised bed based systems can be scaled up to larger units, well in excess of 100,000 tpa.

7. Plant configurations will typically consist of a fuel preparation plant, fuel storage and transport systems, a fluidised bed gasifier, syngas clean-up systems, a reformer to improve the syngas, conversion systems to convert the syngas into the desired product and product clean-up systems. The majority of these systems have been tested in other uses but need to be integrated at commercial scale to demonstrate the technologies.

8. The leading technology providers under development are as follows:

    a. Advanced Biofuel Solutions Limited;

    b. Enerkem Incorporated;

    c. GoBiGas;

    d. Kew Technology Limited;

    e. PowerHouse Energy Group;

    f. Sumitomo Foster Wheeler;

    g. ThermoChem Recovery International Incorporated; and

    h. Thyssenkrupp Gasification Technologies

9. Auxiliary systems for handling process residues and other auxiliary plant are the same type of systems used in power generation gasification and conventional combustion systems.

2.4.2 Pyrolysis

Overall, pyrolysis technologies for the production of fuels are primarily small-scale modular plant, each module having a throughput capacity of 7,000 – 10,000 tpa. Fundamentally, this means that these small-scale systems can be considered for the conversion of niche waste streams or the production of niche fuels rather than large scale production of replacement fuels. Our review of these technologies showed that:

1. Pyrolysis systems are being operated at scale and are fuelled by a range of feedstocks. The main feedstocks of interest are tyres, waste plastics and RDF.
2. Pyrolysis oil which is the primary product from conversion of the feedstock is being sold without further processing for substitution of heating oil and low-grade diesel.
3. Pyrolysis systems with integrated refining and upgrading systems for the production of fuels for blending are currently in operation.
4. Systems for the production of grid quality methane from methanation of pyrolysis oil are in development.
5. Pyrolysis technologies for the conversion of tyres to fuels are in operation at scale. Two of these technologies are:
    a. Alphaco; and
    b. Reoil Sp.
6. From our review a single pyrolysis technology is in development for the production of grid quality methane. The technology is being offered by Standard Gas and is fuelled by RDF.

2.4.3 Syngas clean up

1. Biomass and waste feedstocks contain a wide variety of substances which can foul process systems, poison downstream catalysts in the syngas reforming and upgrading systems and contaminate fuels. Consequently, treatment of the syngas prior to delivery to the reforming and upgrading systems is essential. Some of the key contaminants which need to be removed are as follows:

    a. alkali metals;
    b. hydrogen sulphide;
    c. particulates;
    d. tars; and
    e. volatile metals.

2. Syngas treatment technologies are well established and have been in use in coal gasification for more than 30 years.

3. An integrated multisystem approach for removal of various contaminants is essential for effective syngas cleaning.

4. These technologies are widely available from many suppliers.

2.4.4 Syngas upgrading

1. Some technology suppliers are developing systems to make a clean syngas which then requires an add-on upgrading system as highlighted below. Other suppliers are developing the full system, from the gasifier through to making a refined product using their own upgrading technology.

2. The production of hydrogen and synthetic natural gas (SNG) from syngas are technologies which have been widely used in the coal gasification industry for many decades. These technologies are now been adopted for the upgrading of syngas from the gasification of biomass and wastes.

3. Syngas upgrading using Fischer-Tropsch (FT) followed by hydroprocessing systems are established technologies for the conversion of petroleum feedstocks. New catalysts with higher activity for conversion of syngas from biomass and wastes have been developed and are in operation and have been validated for use in the production of fuels from these systems.

4. From the information provided the proprietary syngas upgrading technology developed by Velocys has demonstrated a TRL of 8 as the actual system has been completed, tested and validated.

5. The proprietary fermentation technology developed by LanzaTech has achieved TRL 9 as the actual system has been proven in an operational environment. Furthermore, publicly available information suggests that commercial operation of the technology has been ongoing since 2018.

2.5 Gasification and pyrolysis for net zero

1. For all of the AGTs reviewed, the production of syngas and the process for conversion of syngas to fuels produce CO2. In addition, power is required to drive many of the plant component systems. Consequently, whilst decarbonisation of the fuel production process is feasible if the whole chain from production of fuel through to products is taken into account, it will not be possible to achieve net zero using these technologies unless CO2 is captured and used and low carbon electricity is used to power these systems.

2. With the exception of small-scale modular pyrolysis technologies, all of the AGTs in development for the production of liquid drop-in fuels can be operated at scale for the production of large volumes of fuel. Therefore, our high-level initial assessment suggests that wide scale deployment of these technologies has the potential to substitute conventional fuels without the need for infrastructural or vehicle changes.

3. Modular systems for the production of H2 can achieve decarbonisation in niche areas where there are deployed. However, due to the scale of the system, large scale decarbonisation is not commercially feasible. Where onsite power is generated using syngas engines, these

systems will not be able to achieve net zero emissions unless the CO2 produced during electricity generation in the syngas engines is captured.

4. Small scale pyrolysis plants fuelled by tyres or waste plastics, or other plants operated on this feedstock, offer a low carbon route in the transition to net zero but will not be able to achieve net zero emissions as tyres and plastics are made primarily from fossil fuels.

2.6 Technology readiness levels

None of the technologies reviewed are in commercial operation. Technology readiness levels (TRL) were assigned on the basis of the following:

1. current scale of system (actual system or system prototype) in operation;
2. plant operating conditions (model operating environment or actual operating environment);
3. number of hours in operation;
4. longest continuous run;

Our assessment found that overall, the TRL values were in the range 6-8. This indicates that for some AGTs some key component systems have been demonstrated in a similar operating environment to the proposed commercial operation. For other AGTs, the actual system which will be deployed in commercial operations has been completed, tested and validated. Consequently, these systems have been proven to perform under actual operating conditions and long-term operation in a commercial environment is now required to demonstrate that the system is proven.

2.7 Key technical considerations for commercialisation

1. Realistic technical assumptions for plant output and availability are fundamental to the development of commercially viable financial models.

2. Investment in syngas clean up systems for the removal of particulates, sulphur compounds, tars and certain metals is essential for commercially feasible conversion of syngas to fuels.

3. The type of syngas upgrading system and the selection of catalyst are key factors which must be included in the technical assumptions in financial models for development of these systems.

4. Current focus is more on waste streams as these typically bring a gate fee, whereas biomass is a relatively expensive fuel. However, biomass is a good feedstock for contributing to net zero emissions as its carbon impact is low. Therefore, mechanisms will be needed to promote the use of biomass as a feedstock.

5. To meet net zero emissions targets, CCUS will be required for all processes. This will incur additional costs.

3 Recommendations

Based on the findings of the assessment of the current status of AGT technologies, the main focus of the detailed techno-economic study will be AGTs which are fuelled by biomass (virgin wood or energy crops) or MSW/C&I waste converted to RDF. However, for some of the niche technologies, waste streams such as tyres or plastics should also be considered.

To ensure that the plant models developed for the techno-economic study are based on realistic design and performance data for a similar scale and fuel output we recommend that the following systems are assessed in greater detail in Task 5.

Table 3: Recommended Advanced Gasification Technologies for Detailed Assessment

Technology Supplier	Technology	Feedstock	Product	TRL
Advanced Biofuel Solutions Limited	Gasification	RDF	Methane	6
Enerkem	Gasification	RDF	Methanol and ethanol	8
GoBiGas	Gasification	Biomass	Methane	8
Kew Technology	Gasification	Densified RDF	Electricity, H2 and fuel	6
PowerHouse Energy	Gasification	RDF, SRF, and mixed plastics	Electricity and H2	6
Sumitomo Foster Wheeler	Gasification	Biomass	Renewable diesel	7
Alphaco	Pyrolysis	Tyres	Pyrolysis oil	9
Reoil	Pyrolysis	Tyres	Pyrolysis oil	9
Velocys	Fischer Tropsch (FT)	Syngas	Renewable diesel and aviation fuel	8
LanzaTech	Microbial Fermentation	Syngas and waste gases	Ethanol	9

4 Feedstock

4.1 Biomass

4.1.1 Virgin wood

Virgin wood is wood which has not been used for other purposes. This means it is “clean” of any contaminants. In solid fuel terms, clean wood is one of the easiest feedstocks to burn, meaning projects generally have a lower technical risk.

Virgin wood can be sourced from logs, off-cuts from the manufacture of wood products such as planks, tree trimmings or forestry residues (brash). The presence of more bark or green leaves reduces the quality of the wood fuel due to an increase in ash content, moisture, chlorine, sodium, and potassium. Virgin wood comes in various forms, typically: roundwood which then requires shredding; woodchips; or pellets. Pellets cost money to produce but are drier and have a higher energy density so are normally preferred for large plants using imported biomass. Imported biomass is required to meet certain phytosanitary requirements, which pelletising will typically achieve. Virgin wood is a relatively expensive feedstock so it is important that the quality of the wood is high to allow the plant to operate at high steam temperatures to deliver a high efficiency.

Virgin wood has a typical net calorific value (NCV) of 6-9 MJ/kg as received. Its calorific value is strongly affected by its moisture content which can vary from about 40% to over 60%, or it can be dried to further increase its NCV. The cost of virgin wood is very variable, depending on quality and quantity sourced. It can be purchased as round wood in the forest, or it can be processed to dry, chip or pelletise it. Wood has a very variable cost dependent on quality and quantity, together with the amount of processing it has received. Clearly small amounts of round wood delivered locally will be far cheaper than large amounts of wood pellets sourced from the USA. Therefore, the cost of wood[1] could vary from £25/t up to £75/t for round wood or woodchips. Pellets are far more expensive as the wood is dried, with a typical NCV of 17-18 MJ/kg. They are likely to cost about £140/t delivered. Forestry residues, which are the left-over parts of harvested trees such as small branches can be collected and purchased at a lower cost (typically £15-30/t), although this material is wetter and contains more chlorine.

Whilst virgin wood is expensive, it has the following advantages:

1. it is considered a benign fuel bringing fewer technical challenges;
2. it is available in large quantities as it can be sourced internationally;
3. it has a low ash content limiting residue disposal costs;

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[1] The cost of feedstocks provided in this section are typical 2019 market values which we have seen on various projects or in reliable reference documents. As there is such a large variation in the market, together with quality and quantity, we have expressed these as ranges. Prices are given as delivered to the processing site as received. Prices take no account of Covid 19 impacts.

4. it is not regulated as a waste, so emission limits are more relaxed and flue gas treatment is limited; and
5. quality control, whilst necessary to avoid suppliers taking advantage, is quite straightforward due to the limited potential for contamination unless the supplier deliberately sources other material.

Harvesting, transport and chipping/drying/pelletising all use energy. Therefore, whilst virgin wood is considered to be carbon neutral (it releases the same amount of CO2 on combustion as is absorbed to grow the tree), systems fuelled by virgin wood will require installation of CCUS systems for net zero emissions to be achieved. The type of land used to grow the biomass also affects the carbon balance. If biomass plants are fitted with carbon capture, the overall impact of the process is likely to be carbon negative. Biomass is therefore recognised as a very important fuel to meet overall net zero targets as it is one of the few technologies which is capable of reducing the amount of carbon dioxide in the atmosphere.

4.1.1.1 Technical challenges

The main issues are regarding the moisture content of the wood, the particle size and levels of ash, chlorine, sodium and potassium in the fuel, but these are relatively straightforward to control and monitor. They are also relatively consistent as long as the virgin wood is from controlled sources.

4.1.1.2 Behaviour in AGTs

Moisture is an issue as the yield of product will be affected by the moisture content of the fuel. Wetter fuels will require more of their inherent energy to evaporate the moisture. For this reason, dried fuel or pellets are more likely to be required. Chlorine, sodium and potassium may cause increased corrosion and slagging, with high levels of sodium and potassium lowering ash melting points and potentially causing issues in fluidised bed based systems.

Ash is the inert material left after processing and needs to be removed and disposed of. Virgin wood should contain very low amounts of ash, less than 1%, but if the wood contains a lot of bark, or if soil or stones have been entrained during harvesting and transport, ash levels can be higher.

All solid feedstock process plants need to be designed to the feedstock which is to be used. Virgin wood is one of the easier feedstocks to process, especially if the moisture content is controlled by drying the fuel and therefore virgin wood should be suited to most AGT designs. The main issue is the high cost of virgin wood.

4.1.1.3 Availability

The UK burnt about 6.6 million tonnes of virgin wood in 2018/19[2], mostly imported, to generate electricity. This included 5 million tonnes of pellets, largely sourced from the United States and Canada. Clean wood is readily available from international sources and processing plant to

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[2] Biomass Sustainability Dataset 2018-19, OFGEM

pelletise the wood can be expanded to match demand. Clearly, international demand for wood will grow if it is seen as one of the best ways to meet net zero carbon requirements.

Virgin wood has to meet sustainability criteria meaning it meets standards for sustainable forestry and for greenhouse gases used in producing the fuel.

The Committee for Climate Change assessed that bioenergy available to the UK could provide up to 10% of the UK's total energy in 2050[3]. The Renewables Energy Association (REA) 's report on Bioenergy strategy[4] considered that by 2032 16% of the UK's final energy consumption could be from bioenergy.

4.1.2 Energy crops

Energy crops are biomass grown for the purpose of providing energy. These are usually in the form of fast-growing species of trees such as poplar or willow, commonly known as short rotation coppice (SRC) or grasses such as miscanthus. Energy crops are harvested on a short-term cycle of typically 3-5 years and managed sustainably to provide a continuous supply to match demand.

Energy crops have typical net calorific values of 12-16 MJ/kg as received. Their calorific value is strongly affected by its moisture content which can vary from 15% to over 30%. The cost of energy crops are high, as they are grown deliberately for a market and, unlike much wood based material not as a by-product. Miscanthus has a typical cost of £80-100/t.

Energy crops are expensive, but have the following advantages:

1. it could be available in large quantities if growers have confidence in the price and demand from the market;
2. it has a low ash content limiting residue disposal costs;
3. it is not regulated as a waste, so emission limits are more relaxed and flue gas treatment is limited; and
4. quality control, whilst necessary to avoid suppliers taking advantage, is quite straightforward due to the limited potential for contamination unless the supplier deliberately sources other material.

4.1.2.1 Technical challenges

The main issues are regarding the moisture content of the energy crop, the particle size and levels of ash, chlorine, sodium and potassium in the fuel. As the material is fast growing, it will have higher concentrations of chlorine, sodium and potassium, which are the main contaminants which enhance corrosion and fouling. As such, energy crops are seen as more problematic fuels than virgin biomass.

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[3] Net Zero The UK's contribution to stopping climate change. Committee for Climate Change, May 2019

[4] REA Bioenergy Strategy: Phase 3 Delivering the UK's Bioenergy Potential

SRC is easier to process as it can be chipped and it is more similar to forestry residue or clean wood than grasses. Sodium and potassium is not as elevated and most combustion systems will take SRC as a fuel, although, like forestry reside, as a percentage of the fuel mix rather than 100%.

On the other hand, grasses like miscanthus are considered to be much harder to process and harder to handle as the grasses can wind around equipment. More significantly this material has a lower melting point and behaves similarly to straw, slagging easily. Fluidised bed suppliers have typically excluded straw based material as a significant feedstock due to the low ash melting temperatures which may cause the fluidised bed to sinter.

4.1.2.2 Behaviour in AGTs

Moisture is an issue as the yield of product will be affected by the moisture content of the fuel. Wetter fuels will require more of their inherent energy to evaporate the moisture. For this reason, dried fuel or pellets are more likely to be required.

Chlorine, sodium and potassium may cause increased corrosion and slagging with SRC, with high levels of sodium and potassium lowering ash melting points and potentially causing issues in fluidised bed based systems.

Grasses such as miscanthus are likely to require specialist equipment and designs to process and, like straw, are not well suited to fluidised beds as the low melting points lead to the fluidised bed sintering and defluidising. Combustion processes which have been developed to burn straw are specially designed to manage the low melting points and tend to be grate based solutions, with boiler designs which include slagging superheaters. The current AGTs under development are designed to process virgin wood or RDF and we are unaware of any systems which have been designed for energy crops such as SRC or miscanthus. It is possible that if these were considered the main feedstocks that suppliers would be able to modify designs to cater for these fuels, but currently as well as being harder to process they also tend to be more expensive.

Ash is the inert material left after processing and needs to be removed and disposed of. Energy crops should contain very low amounts of inherent ash, like wood, but due to the harvesting and transport process entraining more soil and stones, ash levels are likely to be significantly higher.

Grasses like miscanthus may have niche designs which are capable of processing them, but on the whole are unlikely to be well suited to AGT designs. SRC is more likely to be the preferred fuel, although probably only as a proportion of the overall fuel mix. However, it is outside the scope of this report to assess whether a particular technology could be adapted to process SRC or miscanthus. The increased challenges need to be considered, but energy crops in some form are considered a viable form of feedstock. The increased cost of energy crops compared with virgin wood will disadvantage them when compared with locally grown round wood or wood chip.

4.1.2.3 Availability

Due to their cost and the lack of demand, there is not a large amount of energy crops available. As growers will only grow energy crops if there is a market, availability will be matched to demand. On the other hand, if economics make this viable, large amounts of energy crops could be planted and grown during the construction phase of a facility. To increase the amount of energy crops available, greater certainty in markets will be required. Farmers aren't able to invest in growing energy crops until there is a firm and mature market with options for the 25 year life of the product. Developers cannot fund projects using energy crops unless there are robust contracts in place and energy crops are demonstrably available for the life of the project. There are also regulatory/policy barriers to growing energy crops.

In 2015/16, 35 kt of miscanthus and 9 kt of SRC were grown for use in UK power stations[5]. The amount of energy crop grown in the UK is much larger than this as much of this material, including wheat, oil seed rape, barley and maize, is used to produce biofuels.

4.1.3 Waste wood

Waste wood is wood based material which has already been used for another purpose. It is frequently called recycled wood, although strictly speaking recycled wood should be used for another purpose than energy recovery. Waste wood can vary from wood which has been used for packaging which is untreated, through to construction timber with preservatives or paint, through to heavily contaminated waste wood such as railway sleepers. Waste wood is generally categorised into four main types.

1. Grade A waste wood is untreated wood and therefore has looser emission limits under the Industrial Emissions Directive.
2. Grades B is material sourced from construction and demolition (C&D) waste.
3. Grade C is sourced from municipal waste and household waste recycling centres.
4. Grade D, the most contaminated wood, is hazardous material which is normally avoided and is landfilled or treated in special plants.

Waste wood used for energy recovery is largely Grade B and C. As it is relatively dry, waste wood is likely to have a NCV between 12-15 MJ/kg.

Waste wood is generally handled by wood recyclers who separate the wood into various grades. The best quality waste wood is recycled for other uses, such as re-use, manufacture of board material or animal bedding. The remaining wood is then used for energy recovery. Materials containing preservatives, paint, attached PVC for example from window frames and metal such as hinges and nails are commonplace. In particular, the fines fraction of the

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[5] Crops Grown For Bioenergy in England and the UK: 2016 DEFRA Dec 2016 https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/664991/nonfood-statsnotice2016-6dec17b.pdf

recycled wood has few uses other than energy recovery and can contain increased amounts of heavy metals.

Whilst the wood component of waste wood has similar benign qualities to clean wood, the presence of contaminations can significantly increase technical risk. It is important that the type of waste wood is specified clearly and that the technical solution selected matches the waste wood. If waste wood is burnt in a clean wood designed plant with high steam conditions, significant corrosion and fouling are likely to occur. There are a number of examples of failed waste wood projects where the fuel quality did not match the technical design adequately and this is a key concern when reviewing projects. In particular, the design of the boiler and the steam temperatures need to be selected to match the waste wood quality. A strong preference is for the fuel supply specification to match, or be more stringent than, the EPC and O&M contract fuel specifications. Even if this is the case, there remains the risk that the fuel supplier is unable to supply fuel of the required quality. Therefore, the level of financial security provided by the fuel supplier is also a key factor.

The main advantage of waste wood is that it is cheaper than clean wood. Waste wood is typically available from £5/t up to £40/t, but at the cheaper end quality will be low. As the quality reduces, the cost of the wood should reduce. However, there is normally a continuous pressure on the plant owner to source cheaper, lower quality wood and on the fuel supplier to put as much low grade wood into the wood mixture as possible, to avoid landfill costs. Therefore, in our view assessments of amounts of waste wood available should be treated with caution. It is essential to quantify amounts of available wood with the correct quality, not just total amounts of waste wood. It is also essential to maintain a strong fuel management system and to monitor fuel quality closely through the life of the project.

4.1.3.1 Technical challenges

The main issues are regarding the particle size and levels of ash, chlorine, sodium and potassium in the fuel. The metal content of waste wood can be significant, largely ferrous but also other elements such as aluminium, zinc and lead. Waste wood can also contain significant amounts of heavy metals. Unlike virgin wood contaminants in waste wood are far less predictable and waste wood can behave more like municipal waste than virgin wood. This is because waste wood available for energy use is normally the fraction of waste wood for which there is no recycling market. The material can be contaminated by wood treatment chemicals, such as fire retardants, glue, varnish and paint. These all increase the levels of contaminants such as heavy metals, nitrogen and chlorine. Waste wood commonly has PVC based material attached to it from window and door frames. These chemicals increase the risks of slagging, corrosion and fouling and also increase the amount of flue gas treatment required.

4.1.3.2 Behaviour in AGTs

Moisture is less of an issue than for virgin wood as waste wood tends to have a much lower and less variable moisture content. Chlorine, sodium and potassium in the waste may cause increased corrosion and slagging, with high levels of sodium and potassium lowering ash melting points and potentially causing issues in fluidised bed based systems. Levels of chlorine can be elevated over virgin wood due to the presence of some plastics, particularly PVC type, due to the inclusion of window frames and other demolition wastes.

Waste wood can contain significant amounts of heavy metals from additives in the wood. These contaminants can lead to reduced ash melting temperatures and increased corrosion and fouling.

Ash is the inert material left after processing and needs to be removed and disposed of. Waste wood will contain larger amounts of ash than virgin wood, often around 5% and sometimes more due to the inclusion of tramp material such as metals and stones. The metal content of waste wood can be high due to metal fixings such as door handles and hinges.

4.1.3.3 Availability

The UK burnt about 2.6 Mtpa of recycled (waste) wood[6] in 2019 with a number of new plants coming on line during the year. It is estimated by Tolvik that there is about 5 Mtpa of recycled wood available in the UK, with much of the difference being used in the recycling industry. A number of additional waste wood plants came on stream in 2019/20 increasing the amount of waste wood going for energy recovery. Availability of waste wood for new plants in the UK is therefore a concern.

Covid 19 has had a significant impact on the amount of waste wood available. Closure of household waste recovery centres combined with suspension of much of the construction industry led to a large shortfall in waste wood. This led to most of the UK’s waste wood power plants running at reduced output. This should be a temporary interruption but the potential for similar occurrences does need to be considered.

4.1.4 Agricultural residues

In the UK, significant amounts of agricultural waste are burnt. These are mainly straw, meat and bone meal and poultry litter. This is largely processed in combustion plants. Straw typically has NCV around 13-16 MJ/kg and costs between £60-80/t including storage (it is seasonal) and transport. Poultry litter can vary in quality due to moisture, but has a typical NCV of 6-11 MJ/kg and is likely to cost £15-30/t.

4.1.4.1 Technical challenges

Straw contains significant amounts of chlorine, sodium and potassium which can be problematic. Moisture is typically relatively constant if harvest time is controlled to avoid bad weather and the straw is properly stored. Straw may contain variable amounts of ash if stones and soil are captured during harvesting and baling.

Poultry litter is largely made up of straw or wood chip which absorbs the urine and droppings from the poultry. Its quality is determined by the farmers and how frequently they replace the bedding. Poor quality poultry litter can be very wet. Its main contaminants are therefore similar

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[66] UK Dedicated Biomass Statistics -2019, Tolvik Consulting

to straw, with the addition of urine. Poultry litter will contain significant amounts of ammonia and this can lead to very strong odours.

Meat and bone meal is the material left over from rendering animal carcasses. It contains significant amounts of sodium and potassium. Moisture and ash contents should be reasonably consistent.

All agricultural waste can contain large metal objects or stones from the collection and storage operation and these need to be taken into account in ensuring robust equipment is used.

4.1.4.2 Behaviour in AGTs

There has been very limited development of AGTs to process agricultural wastes.

Straw has a relatively low melting point which means it is not commonly used in fluidised bed systems. Any technology used to thermally process straw needs to carefully consider the slagging tendencies of the fuel. Poultry litter which uses straw as bedding material will have the same considerations, although poultry litter based on wood chip will be more flexible.

Agricultural residues contain significant amounts of chlorine and this must be accounted for in design due to corrosion and fouling risks.

Ash is the inert material left after thermal treatment and needs to be removed and disposed of. Agricultural residues tend to have significant amounts of ash which may also be elevated due to the inclusion of tramp material such as stones. Much of the ash is likely to be entrained in syngas and cleaning systems will need to be designed to remove and dispose of this material.

Poultry litter in particular is very odorous and, whilst not an issue for the thermal process, storage and handling of the material needs to take this into account.

Agricultural residues therefore tend to be quite specific and plants need to be designed with specific measures to counteract the contaminants in the various fuels. Most plants are purpose built to process specific waste streams and this is likely to be the case for AGTs.

4.1.4.3 Availability

The UK burnt about 0.62 Mtpa of straw, 0.25 Mtpa of meat and bone meal and 0.57 Mtpa of poultry litter in 2018/19[7] for power generation. About 1.2 Mtpa of poultry litter is sent to the fertiliser market. The market is reasonably well balanced to match fuel availability and unless new AGTs displace combustion plants for these fuels, we do not foresee UK agricultural wastes being a significant source of fuel in the future.

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[7] UK Dedicated Biomass Statistics -2019, Tolvik Consulting

4.2 Municipal, Commercial & Industrial and Demolition waste

4.2.1 Municipal Solid Waste

Energy recovery from municipal and commercial waste has become an attractive concept in the UK. Due to landfill tax, this material has a high disposal cost of the order of £100/tonne. Therefore, many plants have been constructed which receive a gate fee for the waste disposed of, and in addition receive revenue from electricity and sometimes heat exports. MSW, or the residual part of municipal waste remaining after kerbside recycling, will have a NCV between 7-11 MJ/kg. Gate fees can vary widely from £40/t for longstanding local authority contracts up to £120/t.

Within this report we refer to MSW extensively. For the purposes of energy recovery or gasification, the likely source of feedstock is more specifically the residual MSW stream which is what is left over from the original MSW stream after recyclates have been removed.

4.2.1.1 Technical challenges

The problem with municipal solid waste (MSW) is that it can contain virtually anything. It has varying physical and chemical properties and inconsistent energy content. Combinations of materials can make the resulting flue gases unpredictable and corrosive. For this reason, very robust designs for energy from waste plants have been developed, largely in Europe, which can give high and relatively predictable performance.

MSW may contain anything householders seek to dispose of. Items such as engine blocks, gas canisters, bleach or paint are not uncommon.

MSW is likely to contain significant amounts of chlorine and sulphur and have a variable ash and moisture content. It will also contain loose metal, both ferrous and non-ferrous, together with heavy metals forming metallic salt compounds which are likely to be released.

Special consideration needs to be given to difficult waste types which may be included in small amounts. For example, gas canisters from camping stoves and aerosols may be present which can lead to explosion risks. Batteries can cause local hot spots in stored waste and lead to fires.

4.2.1.2 Behaviour in AGTs

The particle size of MSW is a key concern, as untreated MSW can contain large objects which householders can fit in their waste bins or dispose of at household waste recycling centres. Most AGTs are likely to require some screening and shredding of the input MSW. Loose metals may also cause fuel handling issues.

MSW also exhibits strong slagging properties and creates corrosive gases which requires any thermal process to be designed to cater for this. The syngas clean-up systems will need to be designed to allow for significant amounts of chlorine, sulphur, heavy metals and ash which will be released by thermal treatment.

Fluidised bed based systems are unlikely to be suitable for untreated MSW as the large amount of dense, non-fluidisable material such as glass, stones and metals may cause the bed to defluidise.

Variable moisture contents will affect the yield of any product and needs to be allowed for in the design.

4.2.1.3 Availability

26.4 Mtpa of household waste was produced in the UK in 2018[8]. Of this, about 45% was recycled leaving 14.5 Mtpa of residual MSW.

It has been estimated that there was about 27.5 Mtpa of residual MSW and similar C&I waste in 2017[9]. This includes the residual waste available from households and waste from other sources (largely C&I) which is similar in nature and composition to household waste. It is the waste left over following recycling. Tolvik estimates that about 10 Mtpa of what it classifies as "residual municipal waste" is C&I waste. Tolvik considered how this might change by 2030[10] based on a number of growth and recycling scenarios and predicted the amount of residual municipal waste in 2030 could vary between 17.3 to 29.5 Mt. In 2017 about 10.9 Mtpa of this material was processed in UK energy from waste plants. Some additional material was diverted via mechanical biological treatment plants and cement kilns. By 2022, Fichtner estimates there will be about 19.3 Mtpa of operational capacity in UK energy from waste plants, including plants processing RDF, with more facilities planned.

Depending on how recycling levels increase, the amount of residual MSW available could vary from small to significant amounts. If AGT systems producing chemicals or fuels are seen as viable technology for the future to achieve zero carbon, they will have to compete with energy from waste plants for waste. As energy from waste plants age they may be replaced by the new AGTs.

4.2.2 Commercial & Industrial wastes

There remain considerable amounts of commercial and industrial (C&I) waste suitable for energy recovery. Much C&I waste is similar in character to MSW, being sourced from similar sources such as catering, shops, restaurants and hotels. However, some industrial waste will vary significantly in composition, depending on the type of industrial process. For example, factories using significant amounts of plastics and PVC are likely to produce waste streams with high calorific values and high amounts of chlorine. Typical C&I waste similar in character to MSW waste streams is likely to have an NCV of 7-14 MJ/kg. Gate fees typically range from £50/t up to £105/t.

4.2.2.1 Technical challenges

Commercial waste is likely to contain similar contaminants to MSW, namely: chlorine; sulphur; ash; loose metals; and heavy metals. Industrial waste is far more variable and dependent on

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[8] UK statistics on waste – March 2020 update, https://www.gov.uk/government/statistics/uk-waste-data

[9] Filling the Gap: The Future for Residual Waste in the UK February 2019, Tolvik

[10] UK Residual Waste: 2030 Market Review November 2017, Tolvik Consulting

the processes used on the industrial site. Industrial waste streams may need to be separately assessed to check that they do not contain undesirable materials, e.g. large amounts of PVC or chemicals.

4.2.2.2 Behaviour in AGTs

Commercial waste is likely to behave similarly to MSW in AGTs as its composition is similar. Waste sourced from industrial sources needs to be treated with more caution as it may contain more contaminants of a particular type, for example chlorine if there is a lot of plastic in the industrial waste.

4.2.2.3 Availability

41.1 Mtpa of C&I waste was produced in the UK in 2016[11]. Much of is unlikely to be suitable for producing chemicals or fuels. As described in section 4.3.1.3 there is estimated to be about 10 Mtpa of C&I waste similar in character to residual MSW. In addition to this, some of the separate industrial waste produced may also be suitable for conversion to chemicals or fuels. However, many of these streams may also be suitable for recycling purposes.

4.2.3 Construction & Demolition wastes

C&D waste is largely inert, containing large amounts of rubble or bricks. However, some of the waste will contain non-inert material such as wood or plastics for example from window frames. Such material is likely to be separated out for separate processing with the inert material used as aggregate of for other purposes. C&D waste suitable for energy recovery is therefore contains significant amounts of wood waste. The majority of the energy-rich part of this waste stream will included with C&I waste or with waste wood.

4.2.3.1 Technical challenges

The portion of C&D waste likely to be used for AGTs is the separated waste wood and plastic portion. As such it will have similar contaminates to waste wood or plastic streams, particularly chlorine, heavy metals, loose metal and ash.

4.2.3.2 Behaviour in AGTs

The behaviour in AGTs will be similar to waste wood, with potential for increased corrosion and fouling, see section 4.1.3.2. There may be some additional C&D waste available suitable to conversion to chemicals or fuels, but the bulk of the material is already accounted for as waste wood.

4.2.3.3 Availability

About 66.2 Mtpa of C&D waste was generated in 2016 in the UK. 91% of this material was recovered, with the remainder sent to landfill. Much of this is rubble or bricks, and so inert in nature. The non-inert materials, such as plastics and wood tend to be separated and recycled

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[11] UK statistics on waste – March 2020 update, https://www.gov.uk/government/statistics/uk-waste-data

or used for energy recovery, making up some of the waste wood described in section 4.1.3.3 or included in C&I waste numbers in section 4.2.2.3.

4.3 Refuse derived fuel

An alternative strategy for technologies requiring treated fuel is to process the municipal and commercial waste first to generate refuse derived fuel (RDF). This can mean that the fuel can be produced to meet the specific requirements of the technical solution. RDF is a term which spans a very wide range of treatment. Some RDF is produced by just shredding MSW and removing some metal. As such it is very similar to untreated municipal waste in character other than particle size. Other treatment processes are more intense and can generate a more homogeneous fuel with lower moisture and ash contents, or less non-combustible material. It is therefore very important to consider the RDF specification and whether this matches the individual requirements of the technology. The NCV of RDF can vary from 10 MJ/kg up to 17 MJ/kg.

Whilst pre-treatment can adjust the physical elements of the waste and remove some contaminants, there are limitations on the extent to which it can impact on the chemical composition. Therefore, plants designed to process RDF should follow similar design rules to plants processing untreated MSW.

As RDF involves some form of pre-treatment of municipal or commercial waste, the gate fees which are offered from specialist RDF facilities are normally lower than for untreated MSW and are usually such that the overall cost is competitive with alternative options for unprocessed MSW or C&I waste. Typical gate fees can vary from £50/t to £105/t. Better quality, or more processed material tends to have a lower gate fee.

Some projects include the pre-treatment process to produce the RDF as part of an integrated offering, whereas others rely on fuel suppliers to produce the required RDF. In the latter case, strict quality control will be required to ensure that the fuel supplier maintains the quality at all times.

4.3.1 Technical challenges

Contaminants are likely to be very similar to MSW as the RDF production process does typically not remove many of the contaminants, other than some inert materials and metals. RDF will typically contain more chlorine per kilogram than MSW as moisture and ash is removed.

4.3.2 Behaviour in AGTs

RDF is likely to behave quite similarly to MSW (see section 4.3.2.2) although as RDF is shredded and screened the particle size of the RDF can be controlled to reduce issues with particle size. RDF will contain more chlorine and less ash than untreated MSW. RDF is more suited to fluidised bed processes than MSW as there is some control over particle size and non-fluidisable material. As RDF should be more homogeneous and some material has been separated, it should provide a more suitable fuel and a more consistent feedstock for more complex chemical processes.

4.3.3 Availability

RDF is produced based on market availability. As it costs money to produce RDF, if there is no offtake market, waste will normally be landfilled with minimal treatment. The main outlets for RDF are UK energy from waste plants, export to Europe and cement kilns. Currently we estimate that there is about 2.6 Mtpa of energy from waste capacity built in the UK which is supplied with RDF, with a further 0.4 Mtpa capacity in cement kilns.

The UK exported about 2.9M tonnes of processed solid waste (that is RDF) to Europe for energy recovery in 2018[12]. The amount of RDF exported is now starting to fall, driven partially by higher disposal costs in Europe, including a new tax on the material in Holland.

Most AGT processes will require RDF in some form rather than untreated waste. The RDF will be sourced either from existing plants which are currently supplying UK energy from waste plants or exporting the RDF, or by building additional pre-treatment plants to treat the residual MSW and C&I waste streams described in sections 4.3.1 and 4.3.2.

4.4 Plastic wastes

Plastic waste arises either from industrial processes as C&I waste (see section 4.3.2) or from source separation of MSW. The purpose of separating plastic from MSW is normally to increase recycling by reusing the plastics but it is possible in the future that more plastic waste could be used to produce liquid fuels or chemicals.

As the purpose of this report is to consider the role of AGTs in contributing to net zero emissions, it has to be noted that plastics are currently produced from fossil fuel sources. As such using plastics to produce liquid fuels or chemicals will not contribute to achieving net zero emissions. However, , if plastic waste can be used to minimise/eliminate the use of fossil fuels, this material may still have a significant contribution to achieving net zero in the long term. If the plastics collected have such a low quality (high contamination) that there is no suitable recycling path, this waste stream could have a modest role as a waste stream for waste to fuel processes.

The cost of plastics is difficult to estimate as it depends entirely on the quality of the material and how the material it is collected. Bales of single type plastics or high quality mixed plastics will attract a gate fee but will go for recycling. Lower quality mixed plastics unsuitable for recycling may have significant disposal costs.

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[12] https://www.letsrecycle.com/news/latest-news/rdf-exports-decline-in-2018/

4.4.1 Technical challenges

Plastic wastes consist largely of complex hydrocarbon chains which are well suited to convert to liquid fuels or chemical feedstocks. However, unless the plastic waste is sourced from a clean industrial process, in which case it is likely to be more suitable for recycling, it will be contaminated with other wastes. Plastic waste is therefore likely to contain some paper, food waste, liquid and other residues.

4.4.2 Behaviour in AGTs

Plastic waste has a low melting point and a high energy content. These characteristics, plus the general composition are well known and therefore can be designed for. Chlorine may be high depending on the type of plastic.

AGTs need to ensure they have robust design suited to the type of plastic waste available. A design which is only suited to clean, uncontaminated plastic waste may not work well if the plastic waste has significant contamination and higher ash, food or liquid contamination.

4.4.3 Availability

In 2017, 2. 6 Mtpa of plastic packaging waste was produced in the UK[13], of which 46% was recycled, leaving 1.2 Mtpa. Plastic packaging waste separated from MSW or commercial waste tends to be contaminated and from mixed polymer sources, so is more difficult to recycle. Plastic waste collected from industrial sources is more likely to be from identifiable polymer streams and so can be recycled more easily.

There is a great deal of focus on plastic waste due to environmental concerns and reducing and avoiding plastic waste is likely to affect the amount of plastic waste currently produced. Significant effort will be expended on developing more recyclable plastics so the amount of plastic waste available may reduce significantly. Historically much of the UK's plastic waste was exported to China, but when China stopped the import, the UK recycling industry had to find alternatives. Whilst much is still exported, plastic recycling plants are being built in the UK[14] to separate more of the plastic waste into re-saleable polymer streams. Therefore, development of processes which are limited to plastic waste risks competing with other developments also seeking to achieve net zero.

4.5 Other wastes

4.5.1 End of life tyres

Tyres have always been considered a problem for waste disposal and since 2003 the disposal of whole tyres in landfills has been banned[15]. They have been used as a fuel for use in cement

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[13] UK Statistics on waste data - Mar 2020 update https://www.gov.uk/government/statistical-data-sets/env23-uk-waste-data-and-management

[14] https://www.viridor.co.uk/who-we-are/latest-news/2019-news/avonmouth-plastic-recycling-announcement/

[15] Landfill (England and Wales) Regulations 2002

kilns, small power plants or for conversion to liquid fuels. More recently, much of the UK's waste tyres have been exported to India for conversion to pyrolysis oil.

As the purpose of this report is to consider the role of AGTs in leading to net zero emissions, it has to be noted that tyres are produced largely from fossil fuel sources. The natural rubber content of tyres is between 14% - 28% of the rubber,[16] with passenger cars having a natural rubber content at the lower end and lorries and trucks at the higher end of the range. Using tyres to produce liquid fuels or chemicals cannot be considered to be truly net zero, but if waste tyres can be used to avoid the use of fossil fuels, it may have a contribution to achieving net zero in the long term.

Tyres are largely made up of rubber compounds with steel wires reinforcing these. Tyres are therefore either processed by removing the steel and chipping the tyres, or in some processes as individual tyres. The composition of tyres is well known, with the main contaminant being sulphur. The NCV of tyres can vary from 26 MJ/kg up to 33 MJ/kg.

There is about 0.5 Mtpa of end of use tyres produced in the UK annually. Of these, the large majority are reused, recycled, exported or burnt in cement kilns. The amount of waste tyres available for AGTs to convert to liquid fuels is therefore very small and this is a niche market, unlikely to significantly affect the UK's drive to net zero, especially when the majority of the tyres are produced from synthetic rubber from fossil fuel. Typical gate fees for whole tyres are £200/t to £220/t.

4.5.2 Clinical waste

Clinical waste is a specialist waste which is separately regulated from other waste streams due to greater risks with its handling. Low grade clinical waste may be processed together with MSW, but higher risk grades need separate treatment. There are relatively small amounts of the hazardous material (about 0.1 Mtpa) which is typically treated by incineration in small, local facilities. As such, it is not an appropriate waste stream to consider in this study.

4.5.3 Hazardous waste

Hazardous waste covers a wide variety of difficult waste streams and is closely monitored and regulated in the UK. The majority of hazardous waste is processed in specialist hazardous waste incinerators. Hazardous waste can contain a variety of toxic materials and tends to have high levels of potential contaminants. As such, it is not an appropriate waste stream to consider in this study.

4.5.4 Sewage sludge

Very limited tonnages of sewage sludge is processed in thermal incinerators after drying and the majority of sewage sludge is treated by anaerobic digestion which captures the methane produced. Whilst there is some potential that sewage sludge could be mixed with other waste streams and processed in AGTs, it is not considered separately in this report.

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[16] WRAP (2006) 'The Composition of a Tyre: Typical Components.

4.6 Feedstock pre-treatment

Each feedstock is likely to require slightly different pre-treatment processes. In addition, the pre-treatment required needs to match closely with the technology selected. Each of the technical solutions will limit the fuels which can be used successfully to those in the fuel specification. As the intention is to convert the fuels into a good quality, consistent syngas and then to convert this into high quality products, preparation of feedstocks to the required specification for the technology is essential.

One of the most common failings in recent projects is to take a technology which is proven on one fuel and then to use it to process more difficult fuels. Alternatively, plants have been built expecting to receive a certain fuel specification and then the fuel has not been available.

As part of this study, we will consider the type of fuel to be used and any pre-treatment required to convert the fuel into a suitable feedstock. This is an essential part of assessing the capital and operating costs of any process. In addition, feedstock processing uses energy so will also impact the carbon footprint of the process.

In principle, biomass fuels will generally require the least preparation, although wood will need to be chipped or pelletised. This will require shredding and screening equipment. Pelletising is a more expensive process requiring grinding and normally drying, but it provides a more homogeneous feedstock and reduces transport and storage costs due to the relative high energy density.

For some processes drying, normally thermal, will be needed. Most fuels, even clean biomass, are likely to need some sort of metal separation as pieces of metal can be included in the waste during harvesting and transportation.

For waste, more advanced processing is normally required. Whilst grate based systems can process untreated waste successfully, few of the AGT processes will utilise robust grate systems. The majority of the systems will require a reasonable quality RDF to be prepared. RDF is more homogeneous, includes less ash and non-fluidisable material and is better suited to producing a more consistent syngas. RDF preparation will require pre-shredding of the incoming waste, then separation of unwanted material such as metal, stones and glass using screens, magnets, eddy current separators and density separators. The RDF may be dried and will then be shredded to the desired particle size.

4.7 Feedstock storage, handling and delivery

Facilities must also include suitable reception and storage facilities. These are also likely to be costly. Biomass and waste must be unloaded safely and then stored in adequate quantities, normally indoors. For biomass, this tends to mean large silos fed and unloaded by conveyors. For waste or RDF, silos may be used but halls or large storage bunkers are more normal, using overhead cranes. Sufficient storage capacity must be provided to accept deliveries as they arrive without delaying unloading, but also to cater for periods where deliveries are not planned or are disrupted.

Such facilities are normally large and expensive. They must be managed to avoid dust or odours escaping. Noise must be attenuated if the sites are close to residences. Fire is also a significant risk and fire detection and protection systems will be required, as agreed with insurers.

4.8 Feedstock suitability matrix

Based on the assessments above, we have developed a feedstock suitability matrix using key criteria:

1. Availability of the feedstock. Some feedstocks which are likely to be available in smaller quantities may still be suitable for niche markets or processes. In particular, developers are targeting plastic waste and tyres as potential feedstocks which are relatively homogeneous.

2. Suitability for AGT technologies in technical terms. It is recognised that generic comments on this may be contradicted by designs which have been developed with particular feedstocks in mind. Therefore, when considering individual technologies, suitability to different feedstocks will be considered. The intention is to indicate where feedstocks may see widespread application across different AGTs, or where they are better suited to niche designs.

3. Difficulty grade. This is intended to indicate whether the feedstock is likely to be more or less difficult to process, although it is noted that this will also depend on the technology selected.

4. Feedstock pre-treatment requirements indicates the likely pre-treatment equipment which will be needed. Again, this may be technology specific.

5. Feedstock pre-treatment costs. This is provided to give a simple view on the likely costs of pre-treatment. This will be considered in more detail for the technologies selected in later tasks as costs will depend both on the feedstock and on the technology.

6. Net zero impact is included to highlight which feedstocks may be able to achieve net zero emissions, or negative carbon emissions and which ones will only make a partial contribution.

7. Feedstock costs indicate whether the cost of the feedstock is high, or whether it will attract a gate fee.

The Overall Suitability rating in the table provides our initial assessment of the suitability of each feedstock for achieving net zero taking into account each of the criteria listed in the table.

It is noted that the comments in the matrix are subjective. At this stage of the study they will not be used to exclude specific feedstocks. However, the feedstocks marked as “good” will receive more focus. Some of the feedstocks marked as “poor” may still have potential in specialist solutions or may assist in the transition to net zero. Feedstocks considered “very poor” will not be considered further.

Table 4: Feedstock suitability matrix

Fuel Type	Potential UK availability	Suitability for Gasification/ Pyrolysis Technologies	Difficulty grade	Feedstock Pre-treatment Requirements	Feedstock Pre-treatment Costs	Net Zero impact	Feedstock Cost	Overall Suitability
Clean Wood chip	Significant availability imported, limited UK availability	Generally good, suited to fluidised bed solutions	Low	Chipping and screening, drying	Low	Neutral, negative with CCUS	High	Good
Wood pellets	Imported, Significant availability	Generally good, most technologies	Low	Pelletising	Medium	Neutral, negative with CCUS	Very high	Good
Energy crops SRC	Grown to demand	Generally good, most technologies	Low	Chipping and screening, drying	Low	Neutral, negative with CCUS	Very high	Good
Energy crops miscanthus	Grown to demand	Poor, requiring specialist equipment	High	Chopping and metal separation	Low	Neutral, negative with CCUS	Very high	Poor
Waste wood	Limited, current market close to saturation	Generally good, suited to fluidised bed solutions	Medium	Chipping and screening, density and metal separation	Medium	Neutral, negative with CCUS	Medium	Medium
Straw	Limited, current market close to saturation	Specialist equipment due to low melting point	High	Chopping and metal separation	Low	Neutral, negative with CCUS	Medium	Poor

Poultry litter	Limited, current market close to saturation	Poor due to variable moisture and straw content	High	Screening, metal separation, drying	Medium	Neutral, negative with CCUS	Low	Poor
Meat and bone meal	Limited, current market close to saturation	Most likely to be suited added to other feedstocks	Medium	Screening, metal separation	Low	Neutral, negative with CCUS	Medium	Poor
MSW	Significant availability	Likely to require pre-treatment as RDF for most AGT processes	High	Pre-sorting, screening, density and metal separation, drying	Typically converted to RDF	Low carbon, negative with CCUS	Gate fee	Good
RDF	Significant availability	Generally good, suited to fluidised bed solutions	High	Pre-treated	High	Low carbon, negative with CCUS	Gate fee	Good
C&I waste	Significant availability	Likely to require pre-treatment for most AGT processes	High	Pre-sorting, screening, density and metal separation, drying	Typically converted to RDF	Low carbon, negative with CCUS	Gate fee	Good
C&D waste	Limited availability, forms part of waste wood stream	Waste wood portion suited as above	High	Pre-sorting, screening, density and metal separation, drying	Low	Low carbon, negative with CCUS	Gate fee	Good

Plastic waste	Limited availability	Specialist equipment due to low melting point	High	Shredding and screening	Low	Carbon reduction, improved with CCUS	Gate fee	Poor
End-of-life tyres	Limited availability	Specialist equipment due to tyre characteristics	Medium	Shredding and metal separation	Medium	Carbon reduction, improved with CCUS	Low gate fee	Poor
Clinical waste	Limited availability	Poor due to high plastic/chlorine content	High	Pre-sorting, screening, density and metal separation, drying	High	Carbon reduction, improved with CCUS	High gate fee	Very poor
Hazardous waste	Limited availability	Poor due to widespread waste variability	High	Pre-sorting, screening, density and metal separation, drying	Very high	Carbon reduction, improved with CCUS	High gate fee	Very poor
Sewage sludge	Limited availability	Most likely to be suited dried and added to other feedstocks	Medium	Screening, drying	High	Neutral, negative with CCUS	Low gate fee	Medium

5 Gasification and Pyrolysis

5.1 Gasification

Gasification is the thermochemical conversion of any carbon containing materials at temperatures ≥ 600°C using less oxygen than is required for stoichiometric combustion. The process produces a gas known as syngas which is suitable for heating, power generation, industrial applications and liquid fuels production.

Oxygen is essential for gasification to occur and it is supplied primarily by air and/or steam. Carbon dioxide (CO2) can also be used as a source of oxygen but gasification systems using CO2 as the gasifying agent are rare. Air is the most widely used gasifying agent and gasification with air produces a syngas with a gross calorific value (GCV) of up to 7 MJ/Nm3. Syngas from gasification with air consists primarily of carbon monoxide (CO) (20-30%), hydrogen (H2) (10-20%), CO2 (6-14%) and methane (CH4) (3-8%). Small concentrations of high energy content gases such as ethane, ethene and acetylene are also produced. Where a syngas with a higher GCV is required, steam or a mixture of steam and oxygen is used as the gasifying agent. Steam/steam-oxygen gasification produces a syngas with a GCV of up to 18 MJ/Nm3 and consisting primarily of H2, CO and CO2.

Where air or O2 is the gasifying agent, the combustion reactions provide enough energy to support pyrolysis and the reduction processes between char and steam, all of which are endothermic. These gasifier systems are described as autothermal gasifiers and do not need any additional thermal input. Gasification with steam or CO2 does not produce the energy required to support the endothermic reactions and an external supply of energy is required to sustain these gasification systems. These gasifiers are known as allothermal gasifiers.

Entrained in the syngas are a range of contaminants including particles of ash and char, gaseous metals, sulphur and chlorine compounds as well as a range of volatile and long chain hydrocarbons known as tars. Ultimately, the percentage composition of the main components as well as the types of contaminants in the syngas depend primarily on the gasification process, the gasifying agent and the feedstock composition. Contaminants in the syngas are produced during gasification and must be removed using either wet or hot gas clean up systems to ensure that the syngas is acceptable for operation in the downstream power generation or syngas upgrading systems. Syngas can also be burnt directly and flue gases then used to generate steam in a boiler, in a process similar to straightforward combustion.

Typically, in efficient gasification systems 65-75% of the energy contained in the fuel is converted to chemical energy in the syngas. The remaining energy is lost as heat, unconverted carbon in the residual char and as chemical energy in long chain hydrocarbon compounds.

5.2 Gasification for power generation

The syngas produced can be burnt in conventional boilers and the heat produced is then used to raise steam for the generation of power using steam turbines or it can be supplied directly to syngas engines or gas turbines.

Large scale generation of syngas for combustion in boilers is generally carried out in fluidised bed or entrained flow gasifiers. Fluidised bed gasifiers are categorised into bubbling fluidised bed (BFB) and circulating fluidised beds (CFB). Generally, BFB and CFB gasifiers are operated between 700 – 1000°C at atmospheric pressure although some pressurised CFB systems for gasification of coal are in operation. Entrained flow gasifiers are categorised according to whether they are up flow or down flow and require feedstock to be < 75 μm. Typically, entrained flow systems are operated around 1400°C and between 20-70 bar. The estimated range in thermal input for fluidised bed gasifiers is 5 – 100 MWth and for entrained flow gasifiers 50 – 1000 MWth[17].

Syngas from gasifiers coupled directly to syngas engines and gas turbines must undergo extensive cleaning to ensure good operating efficiency and availability. Generally small scale (≤ 1 MWe) modular gasification systems are directly coupled to syngas engines whereas large scale systems are "close coupled" with a secondary combustion system so that the syngas produced in the gasifier section immediately undergoes combustion.

Close coupled systems are required to show that the formation of dioxins is prevented through combustion of the syngas at 850°C or higher and that the temperature can be maintained for at least 2 seconds. These plants must also show that in the event that the NCV of the syngas decreases, an auxiliary firing system is triggered and that a temperature of 850°C continues to be maintained for 2 seconds. For directly coupled gasification systems, combustion of the syngas occurs in the syngas engines and these systems are required to demonstrate that dioxin formation is prevented at the higher temperatures generated in the engine although the residence time in the engine is shorter than 2 seconds. The residual material remaining after gasification consists of a mixture of ash and char although some gasification processes produce a vitrified slag. Typically, the carbon content of the char/ash is less than 3% by weight of the ash.

5.3 Gasification for the production of fuels

To date large scale gasification of biomass and wastes unlike coal gasification has been developed with the primary goal of power generation. As such the focus has been on the conversion of biomass and wastes to produce syngas which can be combusted at atmospheric and low pressures in conventional boilers, gas turbines and syngas engines. However, syngas for the production of fuels must be of an extremely high quality which requires treatment for the removal of a wide range of contaminants. In addition, the refined syngas must be compressed

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[17] Basu, P. (2010) Biomass gasification and Pyrolysis. Oxford: Elsevier

to deliver the syngas at the high pressures required by the syngas upgrading/fuel synthesis equipment.

The following are key parameters/processes which must be considered in the production of fuels from syngas:

1. the ratio of H2:CO;
2. syngas clean up; and
3. syngas upgrading

Ratio of H2:CO

For the production of fuels the ratio of H2:CO in the syngas is a critical parameter which must be controlled depending on the fuel required. For example, the production of gasoline may require a H2:CO ratio of 0.5-1.0 whilst the production of methanol may require a H2:CO ratio of 2. Consequently, syngas from steam/steam-oxygen gasification is the preferred feedstock for fuels production rather than syngas from air gasification due to the higher concentration of H2 compared to CO. Moreover, the steam/steam oxygen mixture can be used for further shifting of the H2:CO ratio to produce the relative concentrations required. Whilst syngas produced from air blown gasification can theoretically be converted to fuels, the yield achieved will be low making it economically unattractive and also unlikely to be suitable for the ultimate goal of achieving net zero.

Syngas clean up

Control of the contaminants in syngas is critical to the efficient and cost effective production of fuels. Syngas clean-up is the general term for removal of contaminants from syngas prior to upgrading of the syngas. Generally, syngas clean-up is an integrated multistep process in which the component systems are determined by the type and quality of the fuel to be produced i.e. the offtaker specification. Due to the variable composition of biomass and waste feedstocks syngas clean-up is a significant capital and operating cost.

Syngas upgrading

Following syngas clean-up, H2, CH4 (substitute or synthetic natural gas) or liquid fuels can be produced using a variety of syngas upgrading processes. These include methanation, water gas shift (WGS), pressure swing adsorption (PSA), membrane separation, Fischer-Tropsch (FT), catalytic upgrading and gas fermentation.

A simplified overview of key process stages in the gasification of feedstock for the production of syngas is illustrated in Figure 1.

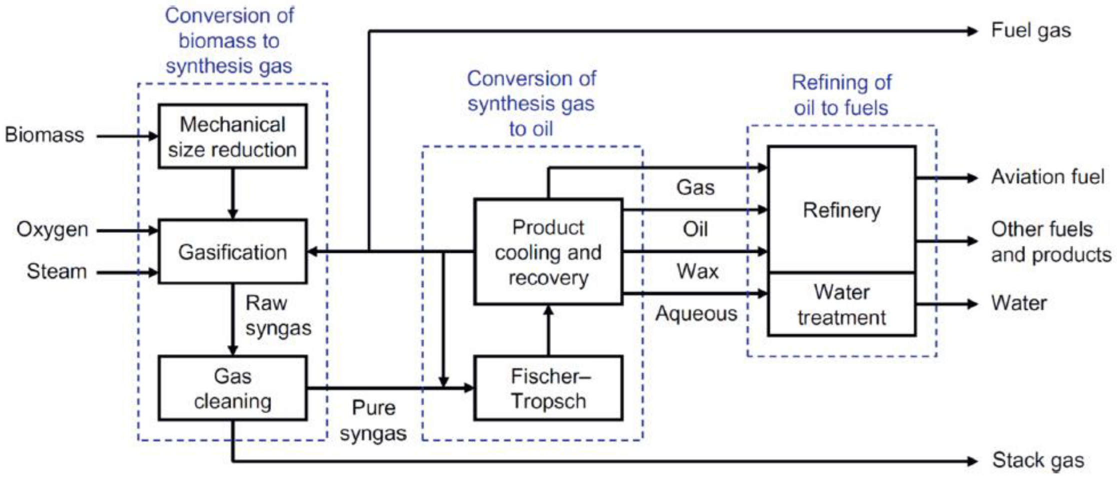

Figure 1: Generic block flow diagram showing the key component systems in the gasification of biomass for the production of aviation fuel

Source: Shahabuddin et al, 2020[18]

5.4 Pyrolysis

Pyrolysis, like gasification occurs when carbon containing materials are heated to temperatures ≥ 600°C. However, unlike gasification, pyrolysis is carried out either in the absence of air or with the use of less than 5% of the air required for stoichiometric combustion. Generally, the process is carried out at atmospheric pressure.

Depending on the rate of heating, use of a catalyst and the residence time in the pyrolyser, the conversion of the feedstock produces a mixture of syngas, tars, pyrolytic oil and char. The net calorific value of the syngas produced is dependent on the type of feedstock but is significantly higher than is produced during gasification. Typically, the net calorific value of the syngas produced can be as high as 25 MJ/Nm3 and the syngas consists primarily of H2 (30-37%), CH4 (25-28%) and CO (20-25%). Small concentrations of high energy content gases such as ethane, ethene and acetylene are also produced. Also contained in the syngas are particles of ash and char as well as gaseous metals and a range of volatile and long chain hydrocarbons.

Pyrolysis can be used for the conversion of a wide variety of feedstocks. However, biomass, plastics, tyres and waste derived fuels are the primary feedstocks of interest for production of liquid fuels. The pyrolysis oil produced from conversion of these feedstocks is a complex mixture of hydrocarbons and the composition varies depending on the type of feedstock. Pyrolysis oil like syngas can be upgraded to produce transportation fuels. However, extensive clean-up is required before final conversion to a useful fuel. A schematic of the process for pyrolysis of feedstocks followed by upgrading to liquid fuels is outlined in Figure 2 below.

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[18] Shahabuddin, M., Alam, M et al (2020) ‘A review on the production of renewable aviation fuels from the gasification of biomass and residual wastes’. Bioresource Technology 312.

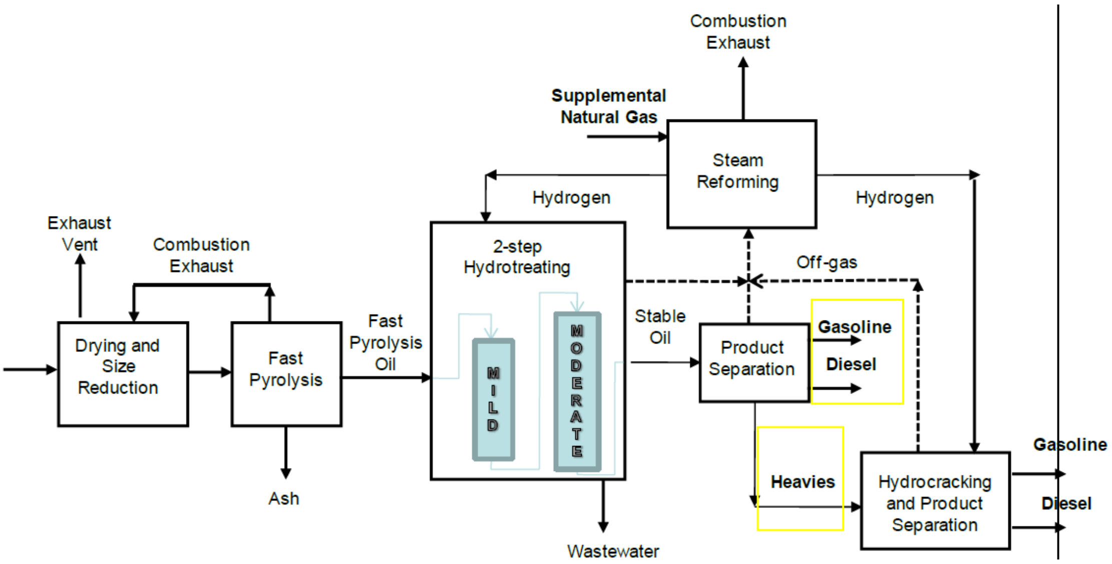

Figure 2: Schematic of a pyrolysis to liquids process

Source: US Department of Energy (2012) Production of Gasoline and Diesel from Biomass

Pyrolysis has now gained recognition as an integral process in the transformation of materials of low energy density into fuels of high energy density whilst also recovering high value chemicals. However, although pyrolysis is now recognised as a key process for the production of gaseous and liquid fuels pyrolysis systems are restricted in size because pyrolysis is an endothermic process requiring the transfer of large amounts of heat across the reactor wall for degradation of the feedstocks. Consequently, systems which are currently in commercial operation are primarily modular and large scale production is dependent on the operation of large numbers of modules. Fundamentally, this means that whilst modular scale pyrolysers can be considered for the conversion of niche waste streams or the production of niche fuels, reliance on pyrolysis for large scale decarbonisation of the marine and road transport sectors is unlikely to be technically and commercially feasible.

6 Gasification Technologies for Power Generation

This section of the report provides a synopsis of a variety of gasification technologies which have been demonstrated and/or commercialised for the production of syngas for power generation. It has been included to explain why many of the better known systems with a UK track record are not suitable, or are not being developed, to produce fuel or chemical products. This section will also be used in Task 4 of the study to assess lessons learnt from failures of gasification processes. For, various reasons including plant configuration and process economics these technologies are not currently being considered for the production of fuels.

The information presented is not intended to provide a comprehensive description of all gasifiers installed worldwide. It is focussed on technologies well known in the UK market as the purpose of the review is to understand technical solutions which may be applicable in the UK. The table below lists the technologies evaluated. A description of each technology and the current status of development are provided in Appendix A.

Table 5: Gasification technologies for power generation

Technology supplier	Gasification technology	Feedstock	Thermal input (MWth)	Output (Electricity/Heat)
A.H.T Syngas Technology	Downdraft/ updraft	Clean woodchip, hydrochar, black coal	1	200 kWe[19]
Alter NRG/ Westinghouse Plasma Corporation	Plasma	MSW, ASR, sewage sludge, biomass	2-250	1-50 MWe
Babcock & Wilcox Volund	Updraft	Clean woodchip	3.5-12	1-2.5 MWe, 1.9 MWth
Biomass Engineering Limited	Downdraft	Clean wood	Unknown	1-3 MWe
Biomass Power Limited	Moving grate	RDF	46-69	9-15 MWe

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[19] Output for single module system.

Technology supplier	Gasification technology	Feedstock	Thermal input (MWth)	Output (Electricity/Heat)
British Gas/Lurgi	Updraft	Hard coal, lignite, bituminous coal	200-1,500	500-1000 kt/y ammonia, 800-1750 kt/y urea
Chinook Sciences	RODECS™	ASR, MSW, industrial	Unknown	11 MWe
Concord Blue	Staged reformer	MSW, sewage sludge, woodchip	2-10	1-3 MWe, 3 MWth
Energos	Moving grate	MSW, C&I, RDF	15-50	4-10 MWe
Enerbee[20]	Moving grate	Virgin biomass, waste wood, RDF, sludge	13-22	3-5 MWe
Europlasma	Moving grate / Plasma	Woodchips, biomass, C&I	25	10 MWe, 18 MWth
Future Energy Resources Corporation	CFB	Biomass	40	7 MWe
Kobelco Eco Solutions	BFB	MSW, sewage sludge	5-40	0.9-10 MWe,
Lurgi	Updraft	Lignite, bituminous coal	Unknown	Various chemicals
New Earth Advanced Thermal	Staged pyrolysis and gasification	Biomass, waste	4.2[21]	Unknown
Nexterra	Updraft	Waste wood	9.2-40.8	3.5-9 MWe,
Outotec Energy Products	BFB	Biomass, waste wood	50-100	5-37.5 MWe
Plasco Conversion Technologies Inc.	Moving grate	MSW	Unknown	5 MWe

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[20] No direct reference plants, references are based on KIV technology.

[21] Modular.

Technology supplier	Gasification technology	Feedstock	Thermal input (MWth)	Output (Electricity/Heat)
Thermoselect	Plasma	MSW, industrial waste	12-75	10 MWe, 50 MWth
Valmet	CFB	Biomass, RDF, SRF	50-220	50-230 MWe, 90-170 MWth

7 Advanced Gasification Technologies for Fuel Production

7.1 Gasification for the production of fuels

This section reviews the more promising gasification processes which may be developed to generate fuels or chemical products. All of the technologies reviewed in this section are currently developing technologies for the production of gaseous and liquid fuels.

7.2 Advanced Biofuel Solutions Limited

Advanced Biofuel Solutions Limited (ABSL) was established in 2019 to commercialise the conversion of RDF into a synthetic natural gas which can be injected into the grid directly. The company is developing a technology known as RadGas which is based on the bio-substitute natural gas (BioSNG) technology developed by Advanced Plasma Power (APP) and Go Green Fuels (GGF) between 2006 -2018.

ABSL is currently developing a demonstration plant in Swindon, UK which has the capacity to convert 8,500 t per year of RDF into 22 GWh of SNG. The plant is scheduled to start continuous operations early in 2021.

7.2.1 Technology description

A process flow diagram outlining the RadGas technology is shown in the figure below.

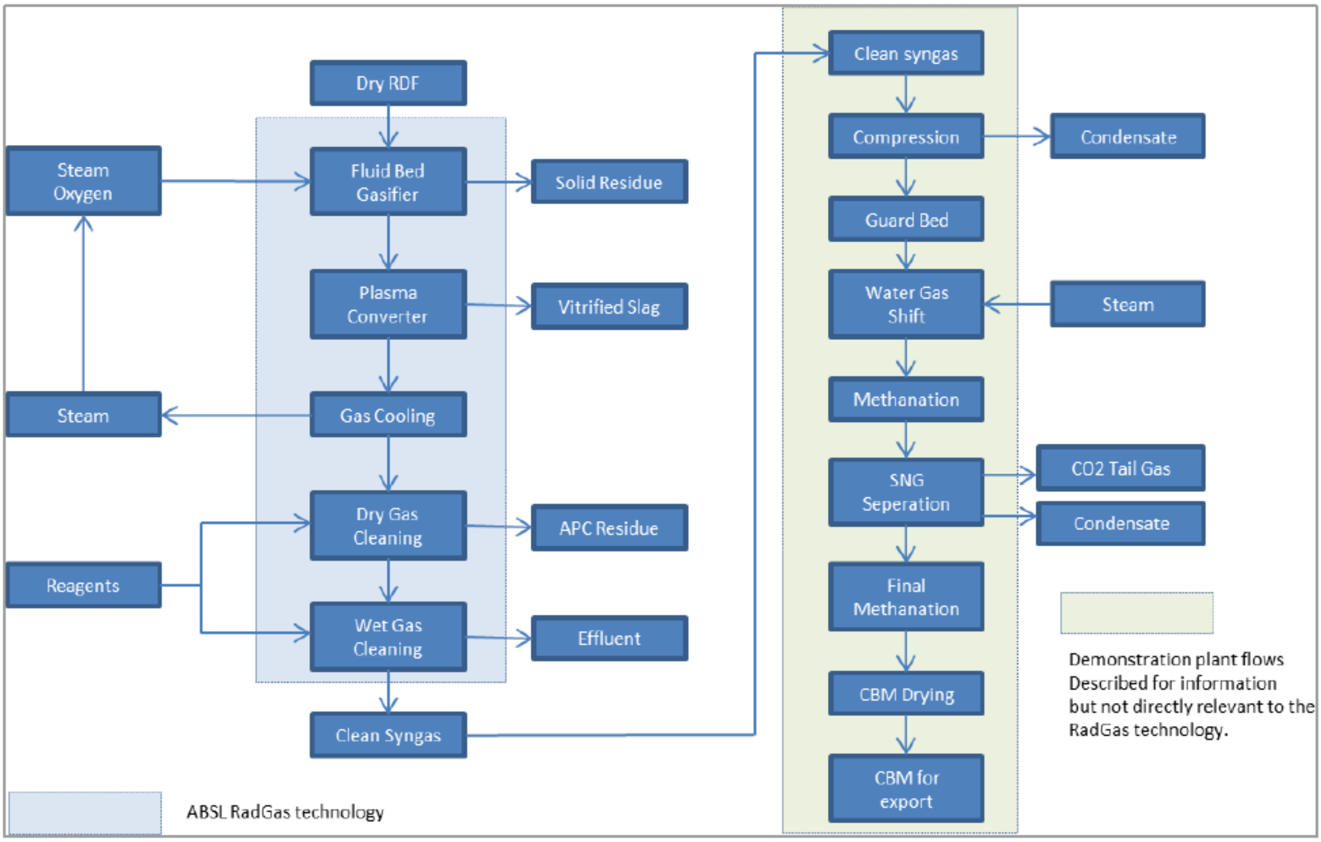


Figure 3: RadGas process flow diagram
Source: ABSL

In the RadGas process, dried RDF is heated in a conventional bubbling fluidised bed (BFB) gasifier at pressures between -2 to -10 mbar using a mixture of steam and oxygen as the bed fluidising and gasifying agents. CO2 is used as a blanketing gas to reduce air ingress into the gasifier and to minimise the nitrogen content of the syngas. Gasification in this process is autothermal and stable process operating conditions are maintained by controlling the feed rate of O2, steam and feedstock into the gasifier. Steam for the process is generated by a waste heat boiler using heat recovered from the syngas and high purity O2 is supplied to the process. Residual ash and char generated during gasification are continuously discharged from the fuel bed and sent for disposal offsite. The syngas produced is treated in a series of clean-up systems and the treated syngas is then compressed, and the H2:CO ratio shifted before methanation to produce RadGas.

7.2.2 Feedstock specification

RDF for the ABSL plant will be processed from MSW and C&I waste. Like other BFB gasifiers the feedstock has to be treated to ensure fluidisation. In the ABSL process this includes shredding and removal of ferrous and non-ferrous metals. Limits on the sulphur and chlorine content of the waste are also necessary. Consequently, feedstock supplied to the process will need to comply with a detailed list of requirements.

7.2.3 Feedstock handling and delivery

Pre-treatment of the feedstock for the ABSL process will include standard mechanical pre-treatment plant such as shredders, screens, metal separation and density separators to provide fuel of the desired particle size and quality. In addition, metal (ferrous and non-ferrous), large objects and dense, non-combustible material such as glass and stones will be removed. In the ABSL process a drier will also be required.

According to ABSL the feedstock can be prepared at the site or offsite to the agreed specification by fuel suppliers under contract. Prepared RDF will be stored at the site in bunkers and will be delivered to the gasifier on demand. All equipment used will be conventional, proven in other facilities to produce prepared fuel or RDF.

7.2.4 Plant description

The ABSL process consists of the following key process stages:

1. Feedstock pre-treatment system;
2. conventional BFB gasifier;
3. plasma converter;
4. waste heat and auxiliary boilers;
5. dry syngas cleaning system;
6. wet syngas cleaning system;
7. acid gas and volatile metals treatment system;
8. syngas compressor;
9. syngas polisher;
10. WGS reactor;
11. methanation unit;
12. ash and char collection and conveying system;
13. enclosed flare; and
14. stack

7.2.5 Syngas clean-up and conversion

Gasification of RDF in the ABSL process produces a syngas containing a mixture of particulate and significant quantities of long chain and cyclic hydrocarbons (tars). Removal of the contaminants entrained in the syngas is carried out in an integrated syngas clean-up process consisting of four main component systems.

Plasma converter

On leaving the gasifier, the syngas is transferred to a plasma converter where it is exposed to elevated temperatures and intense ultraviolet light. Under these conditions particulates entrained in the syngas become molten and are discharged periodically from the converter as a molten slag.

Gas cooling

The treated syngas is then cooled and heat is recovered by the waste heat boiler.

Dry gas cleaning

The cooled gas is the treated for the removal of acid gases and volatile metals and air pollution control residues (APCr).

Wet gas cleaning

Following removal of entrained contaminants, the syngas is quenched before final scrubbing for the removal of ammonia, hydrogen sulphide and any residual acid gases.

On completion of the wet gas cleaning the syngas is then compressed and the H2:CO ratio adjusted in the shift reaction. This is followed by methanation using a proprietary catalyst to produce a synthetic natural gas known as RadGas. Additional cleaning of the gas also occurs prior to compression and shifting to minimise the potential of contamination of the methanation catalyst. CO2 produced during methanation will be captured and moisture removed. Injection of RadGas into the grid is continuously monitored to ensure compliance with grid quality natural gas.

7.2.6 Process outputs

Synthetic natural gas and CO2 for use in the food industry will be produced from the process. ABSL has also indicated that the process is capable of producing syngas for upgrading to liquid fuels and hydrogen.

According to ABSL commercial scale plants will have the capacity to process approximately 100 ktpa of RDF to produce 320 GWh per year of synthetic natural gas (based on 7,446 hours of operation per year).

7.2.7 Process residue handling and disposal

The ABSL process produces the following main residual streams:

1. Large incombustible material is discharged from the bottom of the fluidised bed. This material should be inert and can either be used as secondary aggregate or landfilled.
2. Ash entrained in the syngas is heated in the plasma converter to produce a molten slag which should be suitable for re-use as secondary aggregate or landfilled.
3. Fine ash which is captured in the syngas clean-up system is treated and is sent to a hazardous waste landfill for disposal.

4. Flue gas produced by the waste heat boiler will contain some CO2.

7.2.8 Operation and maintenance requirements

ABSL has reported that the process has been designed for continuous operation for 11 months with a single annual outage for 28 days. No detailed breakdown of operational and maintenance requirements is available publicly. The fuel pre-treatment plant is conventional and straightforward to assess. The fluidised bed gasifier is similar to several other similar operational plants and is likely to require similar staffing and maintenance levels. The syngas clean-up and conversion equipment is operated continuously and automatically controlled so should require limited manual input. Operating and maintenance costs will need to be assessed based on data provided by ABSL.

7.2.9 Decarbonisation potential

In the ABSL process RDF is converted to synthetic natural gas. Therefore, much of the carbon in the biomass or waste is retained in the products. We understand that the process requires some fossil fuels on start up and during process disturbances. However, when the plant is running, no support fuel should be required.

CO2 will be released from the auxiliary boiler and from combustion of syngas during start up, unplanned outages and in normal operation. The process will also consume significant amounts of electricity to drive fans, compressors and pumps. The process requires O2 for fluidisation and gasification and the production of oxygen requires energy.

The process is therefore likely to be a low carbon technology for the production of natural gas if the whole chain, from production of the fuel through to the products is taken into account. It will not be fully net zero unless low carbon electricity is used to power the process and generate O2, and the CO2 released is captured.

7.2.10 Technology readiness level

Whilst the ABSL RadGas process includes several systems that have been demonstrated at scale, the commissioning and long term operation of the demonstration plant to evaluate and assess the overall process is yet to be done. As such, it is considered to have a TRL of 6.

7.2.11 Projects

ABSL has reported that the following projects are being considered:

1. Progressive Energy/Peel Environmental BioSNG plant in Cheshire;
2. The Helen gasification project, Helsinki; and
3. Two confidential projects

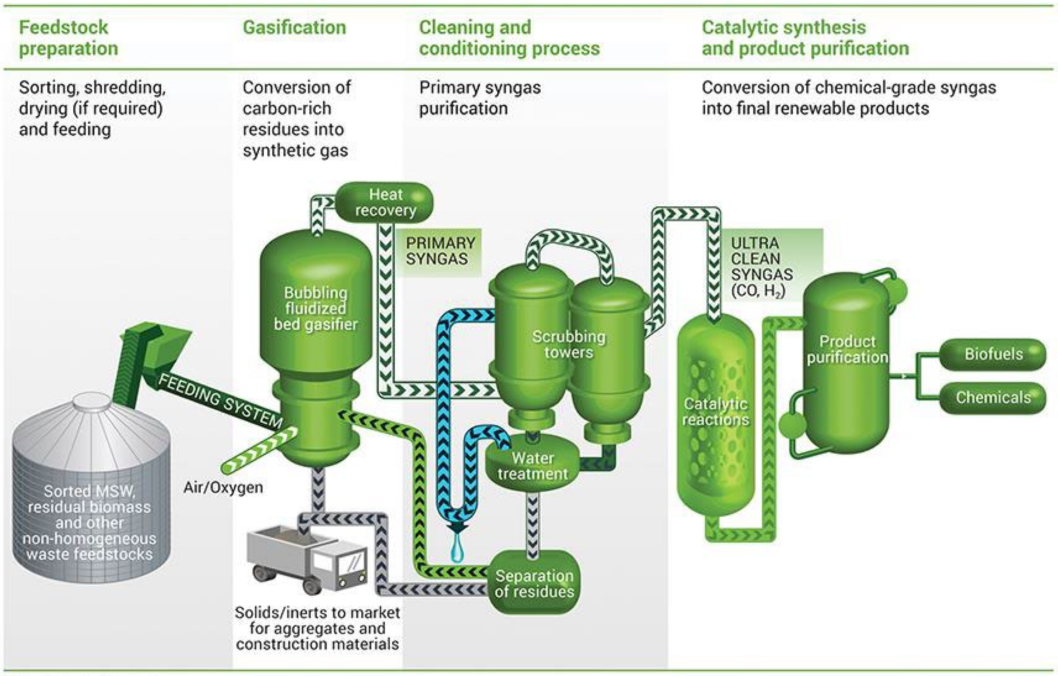
7.3 Enerkem

Enerkem is a mid-sized Canadian developer specialising in the conversion of waste feedstocks into chemicals, in particular methanol and ethanol. The company has been developing its process since 2000 and now operates the Enerkem Alberta Biofuels Facility which is the first full scale waste-to-biofuels plant in North America. The Alberta Biofuels plant is operated in campaigns and has been in operation since 2016. The ethanol produced can be used as a transportation fuel and in the production of a range of everyday products.

Information in this section has been taken from Enerkem's website and from a presentation made to the 2015 European Methanol Policy Forum, Brussels on 14th October 2015.

7.3.1 Technology description

Enerkem provided the following diagram which shows a simple overview of its process.



* *Municipal solid waste*

Figure 4: Schematic of the Enerkem process

The technology typically uses pre-treated wood, municipal or commercial waste. The fuel can either be supplied pre-treated to the requirements of the technology or pre-treatment equipment can be provided on site. The fuel is fed from the on-site store to the pressurised gasifier via a lockhopper system. The fuel is then converted to syngas in a pressurised bubbling fluidised bed (BFB) gasifier using O2 and steam as the fluidising medium. Syngas passes from the fluidised bed into a thermal refiner where O2 is added to heat the syngas and to crack any long chain hydrocarbons and tars. The syngas is then quenched in a venturi scrubber and this is followed by compression.

Further cleaning of the gas is carried out before catalytic conversion of the syngas to methanol. The product is then distilled and converted to ethanol. The syngas conversion uses relatively conventional chemical processes adapted to match the syngas produced from waste or biomass. Coarse material exits from the bottom of the gasifier and is cooled and depressurised. Solids entrained in the syngas melt in the thermal refiner and flows to the bottom of this vessel where it is cooled to form a hard slag.

7.3.2 Feedstock specification

Enerkem originally built a demonstration plant at Westbury which processed chipped waste wood sourced from telegraph poles or railway sleepers. For economic reasons commercial plants are likely to process MSW or C&I waste for which a gate fee is received.

The Enerkem gasifier is a pressurised bubbling bed gasifier. Therefore, fuel has to be prepared to ensure fluidisation and rapid conversion in the BFB. This means there will be limitations on particle size and on the amount of non-fluidisable material. Material with low melting points should also be avoided to prevent problems with the bed. A fluidised bed can normally cope with variable moisture. However, the yield of methanol or ethanol will be linked to the moisture content of the fuel and therefore this is also an important parameter.

Enerkem will therefore need to provide a relatively detailed feedstock specification to ensure the plant is reliable and the yield achievable. Feedstock for the Enerkem plant can either be prepared on site, or the fuel prepared elsewhere and delivered to the gasification site.

7.3.3 Feedstock handling and delivery

Like most fluidised beds, whilst they are flexible for gasification/combustion purposes, it is essential to prepare the fuel to ensure it fluidises. Therefore, wood, municipal or commercial waste streams require pre-treatment. This is achieved in a standard mechanical pre-treatment plant which will include conventional equipment such as shredders, screens, metal separation and density separators to provide fuel of the desired particle size and quality. A drier may also be required. The material rejected in the pre-treatment plant will consist of metal (ferrous and non-ferrous), large objects and dense, non-combustible material such as glass and stones.

Figure 5: Feedstock pre-treatment plant and the Enerkem Alberta Biofuels Plant

The waste pre-treatment plant operated by the City of Edmonton located alongside Enerkem's Alberta Biofuels Plant is shown in the photograph above. The prepared RDF is transported by conveyor to the storage facility for the gasifier.

The pre-treatment plant can either be located on site, as at Edmonton, or the prepared fuel or RDF can be transported to the gasifier site. The material will be stored normally either in silos or enclosed halls from where it is mechanically reclaimed by conveyors and transported to the gasifier. All equipment used will be conventional, proven in other facilities to produce prepared fuel or RDF.

7.3.4 Plant description

The Enerkem process consists of 4 main processes which can be categorised as follows:

1. feedstock preparation and handling;
2. gasification;
3. cleaning and conditioning of the syngas; and
4. catalytic synthesis

7.3.5 Syngas conversion

The syngas passes to a gas clean-up system to remove trace contaminants and is pressurised using gas compressors. It is then further cleaned and converted to methanol using a catalyst. Carbon dioxide is separated and used to pressurise the feeding system lockhoppers. Methanol can then either by purified by distillation to produce a product, or further converted to ethanol if economics determine that ethanol is a more valuable product.

7.3.6 Process outputs

The Enerkem process is designed to produce either methanol, or to further convert this to ethanol. The Alberta biofuels project referred to below has produced both methanol and ethanol.

Publicly available information from Enerkem (2015) indicates that it will provide plants to process between 100-400 ktpa of municipal or similar waste and produce either 38-152 million litres of ethanol per year or 50-200 million litres of methanol per year.

7.3.7 Process residue handling and disposal

The Enerkem process produces the following main residual streams:

1. Coarse ash which leaves the bottom of the fluidised bed. This material should be inert and can either be used as secondary aggregate or landfilled.
2. Char which is collected in the thermal refiner to produce a hard slag which should be suitable for re-use as secondary aggregate or landfilled.

3. Fine ash which is captured in the syngas clean-up scrubbers and separated. This material is likely to require landfilling if it contains unburnt carbon and tars.
4. Effluent from the syngas clean-up system. This is an aqueous stream which comes from the syngas scrubbers. It undergoes water treatment on site and can then be discharged off-site for additional treatment.
5. Flue gas exits from the stack after clean-up, flaring and thermal recovery. This gas stream consists of the various waste gas streams from the syngas conversion process. It will contain some carbon dioxide from the process and the thermal recovery unit.

7.3.8 Operation and maintenance requirements

No detailed breakdown of operational and maintenance requirements is available publicly. The fuel pre-treatment plant is conventional and straightforward to assess. The fluidised bed gasifier is similar to several other similar operational plants and is likely to require similar staffing and maintenance levels. The syngas clean-up and conversion equipment is operated continuously and automatically controlled so should require limited manual input. Operating and maintenance costs will need to be assessed based on data provided by Enerkem as there is no operating facility other than the one it runs in Edmonton.

7.3.9 Decarbonisation potential

The Enerkem process converts biomass or waste to methanol or ethanol. Therefore, much of the carbon in the biomass or waste is retained in the products. We understand that the process requires some fossil fuels to start it up and maintain operations during disturbances. However, when the plant is running, no support fuel should be required. Some CO2 is released from the process via the stack where trace gases and unconverted syngas is combusted. The process will also consume significant amounts of electricity to drive fans, compressors and pumps. The process uses oxygen to fluidise the bed and producing oxygen will also require energy.

The process is therefore likely to be low carbon if the whole chain, from production of the feedstock through to the products is taken into account. It will not be fully net zero unless low carbon electricity is used to power the process and generate O2, and the CO2 released is captured.

7.3.10 Technology readiness level

Enerkem has built a commercial scale plant in Edmonton which has been in operation for more than 4 years. It is also progressing with a number of projects worldwide with very credible partners. As such, it is considered to have a TRL of 8 with the critical parts of the process largely demonstrated. Data provided by Enerkem showing how Edmonton has operated will be needed to indicate likely availability, performance and operating and maintenance costs.

7.3.11 Projects

Enerkem's website indicates the following projects:

Figure 6: Enerkem's project pipeline

Enerkem initially operated a demonstration scale project at Westfield, Quebec, Canada (see below). This was sized to process up to 2 t/h of wood-based fuel, for example railway sleepers. This plant operated from 2009 and we understand that other fuels were also tested at the facility.

Figure 7: Enerkem's Westfield plant

Enerkem built a commercial scale plant at Edmonton, Alberta, Canada known as Enerkem Alberta Biofuels Facility. This plant started operation in 2016 and produced 5 million litres of methanol before the plant was extended to include equipment to produce ethanol. The first ethanol was produced in 2017. The facility is a single stream of Enerkem's modular design, sized to process about 100,000 tpa of dry waste and to produce 38 million litres of ethanol per annum.

Figure 8: Enerkem's Alberta Biofuels Facility

Enerkem is planning to build a plant in Rotterdam, Holland, with a consortium including Nouryon, Air Liquide, the Port of Rotterdam, Enerkem and Shell. This will be a two stream facility, processing 360,000 tonnes of waste per annum and producing 270 million litres of methanol per annum. Enerkem is also working with Suez intending to build a similar sized facility in Tarragona, Spain. A further project is under development in Varrennes, Canada.

7.4 GoBiGas

The Gothenburg Biomass Gasification Project (GoBiGas) was developed for the conversion of woodchip, forest residues and bark to biomethane for injection into the natural gas grid in Gothenburg, Sweden. The plant had a throughput capacity of 32 MWth and a maximum output of 20 MWth (NCV) of biomethane. The plant is a dual fluidised bed gasifier which is made up of a CFB combustor for heat generation and a BFB boiler which functions as a gasifier. The gasification technology was licenced from Repotec GmbH (now Aichernig Engineering) by Valmet. Valmet also supplied the CFB boiler. Construction of the plant started in 2013 and the test on completion was carried out in September, 2015. The plant was mothballed in March, 2018 after 4,000 h of operation (12,000 h gasifier only operation)[22]. According to GoBiGas the longest continuous operating period for the gasifier was 1,840 h. During operation a biomass to biomethane efficiency of up to 70% was achieved.

7.4.1 Technology description

In the GoBiGas process, feedstock with a moisture content ≤ 20 wt% is delivered to the BFB gasifier where it is heated at atmospheric pressure to 700-800°C by superheated steam and the hot fuel bed material from the CFB boiler. The steam is supplied by the CFB boiler and is also used as the fluidising medium. Char discharged from the gasifier is conveyed along with a flow of bed material which circulates between the two reactors. The char and some of the

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[22] The GoBiGas Project – Demonstration of the Production of Biomethane from Biomass via gasification, Goteborg Energi AB, 2019

syngas generated are burnt in the post combustion chamber and the heat produced is used to heat the bed material.

The syngas produced during gasification is discharged to a multistage gas clean-up system. The treated gas is then compressed followed by conversion in a methanator before being fed into the natural gas grid. A schematic overview of the process showing the major steps is shown in Figure 9.

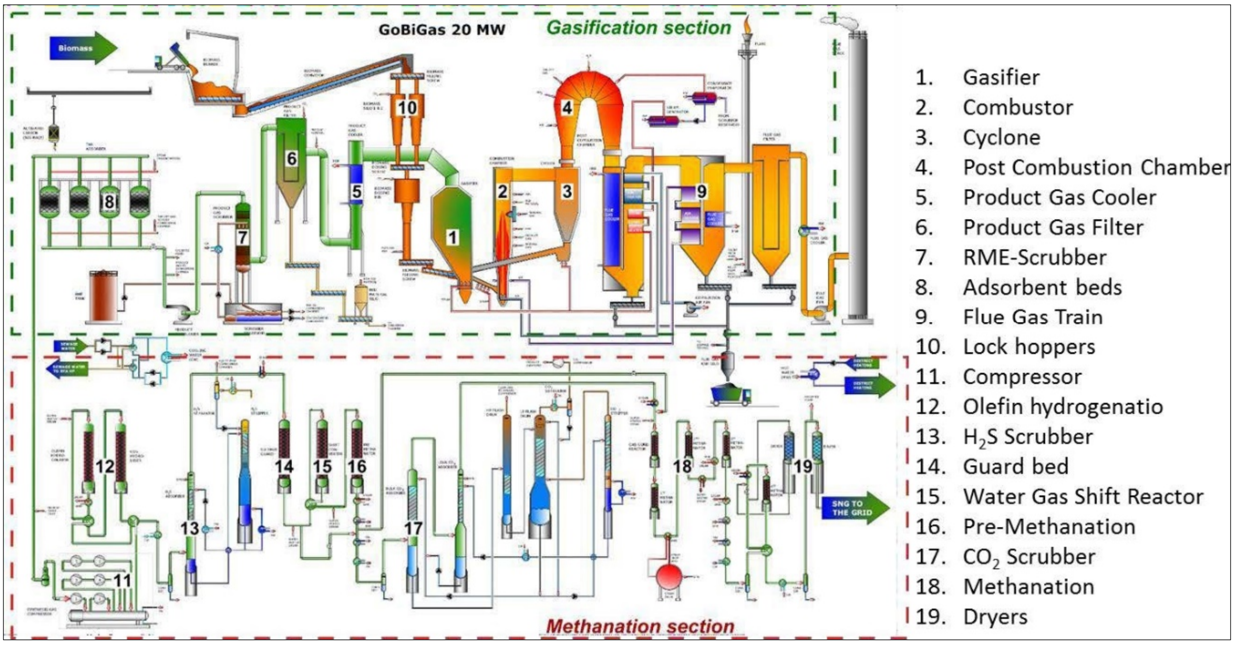


Figure 9: Schematic overview of the GoBiGas plant showing the key component systems

Source: Goteborg Energi AB

7.4.2 Feedstock specification

Feedstock processed in the GoBiGas system must be dried to ≤ 20 wt% moisture. In addition, like other fluidised bed gasifiers the feedstock particle size must be controlled to ensure fluidisation. Feedstocks with low melting points should be avoided to minimise ash fusion and agglomeration in the fuel bed. Limits on the S and Cl content of the waste are also necessary. Depending on the bulk density of the biomass, densification of the feedstock may also be necessary. Drying and shredding of the feedstock can be done onsite or the feedstock can be prepared offsite to an agreed specification by fuel suppliers. Consequently, feedstock supplied to the process will need to comply with a detailed list of requirements.

7.4.3 Feedstock handling and delivery

Feedstock for the GoBiGas system was prepared as follows: Like other fluidised bed gasifiers , pre-treatment of feedstock for the gasifier requires removal of the following items:

1. removal of ferrous and non-ferrous metals;
2. removal of glass and stones;
3. shredding/ pelletising;

4. screening; and
5. drying of the feedstock.

The feedstock is pre-treated to produce a high quality RDF. In the GoBiGas plant layout, the feedstock is stored onsite in a silo and is conveyed to intermediate storage hoppers for delivery to the gasifier when required.

7.4.4 Plant description

The GoBiGas process consists of the following key system components:

1. feedstock storage and delivery system;
2. BFB gasifier;
3. CFB boiler;
4. Syngas cooler;
5. multistage syngas clean up system;
6. methanator;
7. CO2 scrubbing and compression;
8. cyclone;
9. ash handling system;
10. flare; and
11. stack

7.4.5 Syngas clean-up and conversion

In the GoBiGas process the syngas produced is cleaned in several stages as follows:

1. the gas is cooled in a syngas cooler from between 700-800°C to 160-230°C;
2. particulates are removed in a bag filter known as the product gas filter;
3. the syngas is then scrubbed with rape-methyl-ester (RME) to remove tars; and
4. aromatic compounds are then removed by a series of activated carbon adsorption beds.

On leaving the carbon adsorption system, the syngas is then compressed and further gas cleaning is done to:

1. hydrogenate any unsaturated hydrocarbons;

2. convert organic sulphur compounds to hydrogen sulphide (H2S) and remove trace chlorides (Cl);
3. absorb H2S and CO2 using an amine; and
4. adsorb any remaining trace amounts of S using a guard bed.

From the guard bed, the H2:CO ratio in the treated syngas is then adjusted, the remaining CO2 in the gas is absorbed and the syngas is supplied to the methanator for conversion to biomethane. The biomethane is dried before delivery to the natural gas grid.

7.4.6 Process outputs

Methanation of syngas from the gasification of biomass in the GoBiGas process produces biomethane which is compliant with EN 16723-1:2016, the European Standard for injection into the natural gas grid.

7.4.7 Process residue handling and disposal

The main residual streams from the GoBiGas process are as follows:

1. Coarse ash is discharged from the CFB combustor. This material should be inert and can either be used as secondary aggregate or landfilled.
2. Flue gas exits from the stack after syngas clean-up, flaring and thermal recovery. This gas stream consists of the various waste gas streams from the syngas clean-up and conversion process.

7.4.8 Operation and maintenance requirements

No detailed breakdown of O&M requirements is available publicly. However, based on the information provided on the key component systems, we note the following points.

1. The feedstock pre-treatment plant and handling system is conventional and straightforward to assess.
2. The BFB gasifier and CFB combustor are more complex than other fluidised bed systems and are likely to require increased staffing and maintenance levels.
3. The syngas clean-up and conversion equipment are operated continuously and are automatically controlled so should require limited manual input. However, the syngas clean up is extensive and will require specialist maintenance skills.
4. The methanator is complex and will require specialist staffing and maintenance personnel.

Detailed assessment of the O&M costs will need to be carried out on the GoBiGas process. Like other first-of-a-kind demonstrator plants some of the costs are unlikely to be representative of the true costs during stable long term operation.

7.4.9 Decarbonisation potential

Like other gasifiers the GoBiGas process converts waste feedstocks to syngas. Generally, the carbon conversion efficiency in steam-blown gasifiers has been shown to be between 65-75%. Consequently, most of the carbon in the feedstock is likely to be retained in the products. Carbon losses will be primarily as CO2.

From the information provided the process will require fossil fuels on start up and during process disturbances. CO2 will also be released during these periods. The process will also consume significant amounts of electricity to drive fans, compressors and pumps.

Overall, the process will be a low carbon technology for the production of biomethane as renewable biomass is used as the feedstock. However, it will not be fully net zero unless low carbon electricity is used to power the process.

7.4.10 Technology readiness level

The GoBiGas process has been demonstrated at the actual scale in its configuration under actual operating conditions. On this basis the technology is considered to have a TRL of 8.

7.4.11 Project pipeline

Currently, we are not aware of any further projects which are based on the GoBiGas technology.

7.5 Kew Technology

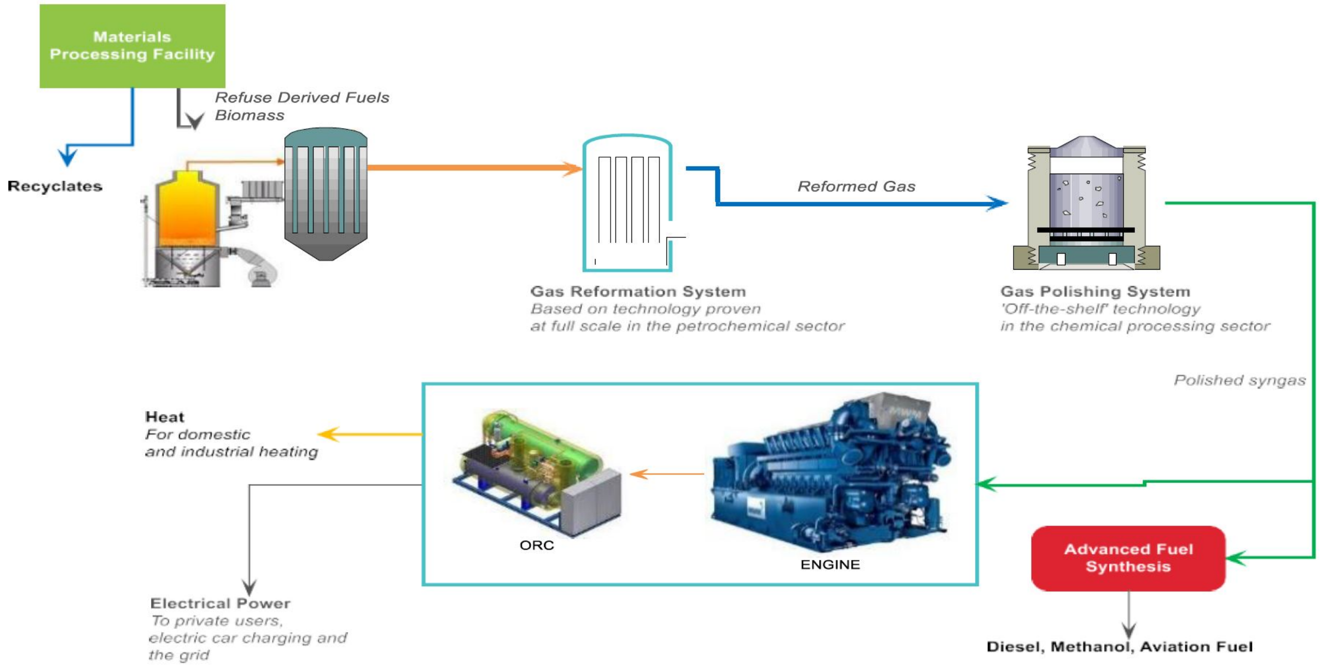
Kew Technology (Kew) was set up in 2015 to develop small-scale modular gasification plants for the conversion of waste feedstocks including RDF, biomass, clinical and hazardous wastes into a H2 rich syngas for the production of H2 and liquid fuels. The company is currently developing a demonstration plant in the Midlands with a throughput capacity to convert 12,000 – 15,000 tpaof biomass or wastes. The thermal capacity of the plant is 7 MWth. To date the demonstration plant has been operated on densified RDF and is scheduled to start continuous operations in Q4, 2020 to produce syngas for power generation. Operations for the production of fuels are scheduled to begin in Q1 2021. The recommended plant configuration is a minimum of 3 modules in parallel. In the longer term the company would like to consider development of larger modules with the capacity to convert 75,000 tpa of feedstock.

7.5.1 Technology description

A process schematic showing the key components of the Kew Technology modular gasification system are shown in the figure below.

Figure 10: Kew Technologies process schematic

Source: Kew Technologies



The Kew process converts densified feedstock in a pressurised BFB gasifier at approximately 7 barg and 800°C using a mixture of O2 and steam or air depending on the application for which the syngas will be used. The process is operated at temperatures below the feedstock ash fusion temperature to minimise agglomeration of the fuel bed. Syngas from the gasifier is then filtered before combustion in a syngas engine or delivery to a syngas upgrading system for liquid fuels production.

7.5.2 Feedstock specification

Feedstock for the plant is delivered to the site as a loose RDF which is then densified into cubes on site. Kew has also indicated that shredded demolition wood is blended on site with RDF to improve the biogenic content where necessary. The RDF is treated for the removal of ferrous and non-ferrous metals before delivery to the site. Limits on the S and Cl content of the waste are also necessary. Consequently, feedstock supplied to the process will need to comply with a detailed list of requirements.

7.5.3 Feedstock handling and delivery

Pre-treatment of the feedstock for the Kew process will include standard mechanical pre-treatment plant such as shredders, screens and metal separation for reduction in particle size and removal of oversize particles, non-combustible materials and ferrous and non-ferrous metals. The feedstock must also be dried. This feedstock can be prepared at the site or offsite to the agreed specification by fuel suppliers under contract. However, unlike many fluidised bed systems, feedstock for the Kew process must also be densified into cubes.

Prepared RDF will be stored at the site in bunkers and will be delivered to the gasifier on demand. All equipment used will be conventional and has been proven in other facilities.

7.5.4 Plant description

The Kew process consists of the following key process stages:

1. materials recovery facility;
2. conventional BFB gasifier;
3. equilibrium reactor;
4. syngas polisher;
5. WGS reactor;
6. ash and char collection and conveying system;
7. syngas engine;
8. flue gas treatment system;
9. flare; and
10. stack

7.5.5 Syngas clean-up and conversion

Following gasification in the BFB, the syngas produced is treated in an equilibrium reactor followed by a syngas polishing unit. According to Kew, three grades of syngas which are defined as Grade A, B or C are produced.

Grade C

This is the untreated syngas which is produced during gasification. This syngas contains a combined mixture of H2 and CO of approximately 30%, 30% CO2 and a mixture of hydrocarbons and N2.

Grade B

This syngas is reformed in the syngas conversion system (equilibrium reactor, syngas polisher and WGS reactor) to increase the combined mixture of H2 and CO to approximately 70%. CO2 and nitrogen make up the remaining 30%.

Grade A

Further reforming of the syngas is carried out in the syngas conversion system to increase the H2 content to >98%.

7.5.6 Process outputs

According to Kew the process can produce three types of syngas of varying concentrations of H2 and CO depending on the end use application of the syngas. Grade C syngas can be used for power generation whilst the Grade B syngas can be supplied to an FT process for synthesis of diesel and other liquid fuels. The Grade A syngas can be used for the supply of H2.

The Kew process is being demonstrated at scale with each module having the capacity to produce approximately 5 MWth of polished syngas.

7.5.7 Process residue handling and disposal

The Kew process produces the following main residual streams:

1. A mixture of bottom ash and fluidising sand is discharged from the bottom of the fluidised bed. This mixture is sieved to recover the fluidising sand and the incombustible material is collected for disposal offsite. This material should be inert and can either be used as secondary aggregate or landfilled.

2. Ash entrained in the syngas is collected in the syngas filtration system for disposal offsite.

3. Flue gas process residues from treatment of the exhaust gases from the syngas engine, or if the facility is used to produce H2 or fuels, from waste gases.

7.5.8 Operation and maintenance requirements

Kew has reported that the process has been designed for continuous operation for 8,000 h (333 days). Information on the number and duration of planned outages per year have not been provided. However, Kew has advised that a major outage every 6 years will be required.

No detailed breakdown of operational and maintenance requirements is available publicly. The fuel pre-treatment plant is conventional and straightforward to assess. Operation of the blending process and densification plant will require additional personnel. The fluidised bed gasifier is similar to several other similar operational plants and is likely to require similar staffing and maintenance levels. The syngas clean-up and conversion equipment is operated continuously and automatically controlled so should require limited manual input. Operating and maintenance costs will need to be assessed based on data provided by Kew.

7.5.9 Decarbonisation potential

In the Kew process the feedstock is converted to syngas. Therefore, much of the carbon in the feedstock is retained in the process. However, use of the syngas for the generation of electricity and production of H2 and fuels will produce CO2. Combustion of syngas in the auxiliary boiler will also produce CO2. Additionally, CO2 will be produced during start up and unplanned outages when syngas is flared.

We understand that the process requires some fossil fuels on start up and during process disturbances. However, when the plant is running, no support fuel should be required. The process will also consume some of the electricity produced to drive fans, compressors and pumps. The process requires O2 for fluidisation and gasification and the production of oxygen requires energy.

The process is therefore likely to be a low carbon technology for the production of syngas for liquid fuels and H2 production if the whole chain, from production of the fuel through to the products is taken into account. It will not be fully net zero unless the CO2 produced during electricity generation in the syngas engines is captured.

7.5.10 Technology readiness level

To date the Kew Technology demonstration plant has been operated for approximately 720 h with the longest continuous run of 160 h. Commissioning is still underway and process operations have not yet been demonstrated in an operational environment. On this basis the plant is considered to have a TRL of 6.

7.5.11 Projects

Kew has reported that the following projects are being considered:

1. Vale Clydach Nickel Refinery, South Wales; and
2. Several confidential projects

7.6 PowerHouse Energy

PowerHouse Energy (PowerHouse) in partnership with Peel L&P Environmental is developing a modular gasification technology for the conversion of mixed plastics to H2 and power. The process is known as the Distributed Modular Gasification technology (DMG®) and is not limited to operation on specific types of plastic. To date the company has been operating a research demonstrator with a capacity of 750 kg/day to carry out process modelling based on the data collected from on-site testing.

The first PowerHouse commercial scale plant will be built on the Protos development site in Cheshire and construction is scheduled to start in Q1 2021. Commercial operation of the plant is targeted for Q4 2021. Each plant will have the capacity for the production of 2 t/day of 99.99% pure, water free H2 and up to 3.8 MWe will be generated. A single plant will occupy approximately 1 ha. The commercial plants will be fuelled primarily by tyre crumb and residual plastic waste.

7.6.1 Technology description

In the DMG process, mixed plastic waste is converted at temperatures > 850°C in a pressurised rotary kiln using superheated steam. The rotary kiln is known as the Thermal Conversion Chamber (TCC). The steam is supplied by a package boiler which can be fired on natural gas, syngas or a mixture of natural gas and syngas. As the process is endothermic, a continuous supply of steam must be provided. The syngas produced consists primarily of H2, CO, and CH4 with small concentrations of CO2 and O2.

Syngas discharged from the DMG is first compressed and then treated in a multistep syngas clean up system followed by a gas polishing unit for removal of entrained contaminants. The treated syngas is then sent to syngas engines for power generation or to a pressure swing absorption unit (PSA) for separation of H2.

Ash and char produced during the gasification process will be continuously removed from the TCC by an ash collection and conveying system.

A process flow diagram illustrating the PowerHouse Energy technology is shown overleaf.

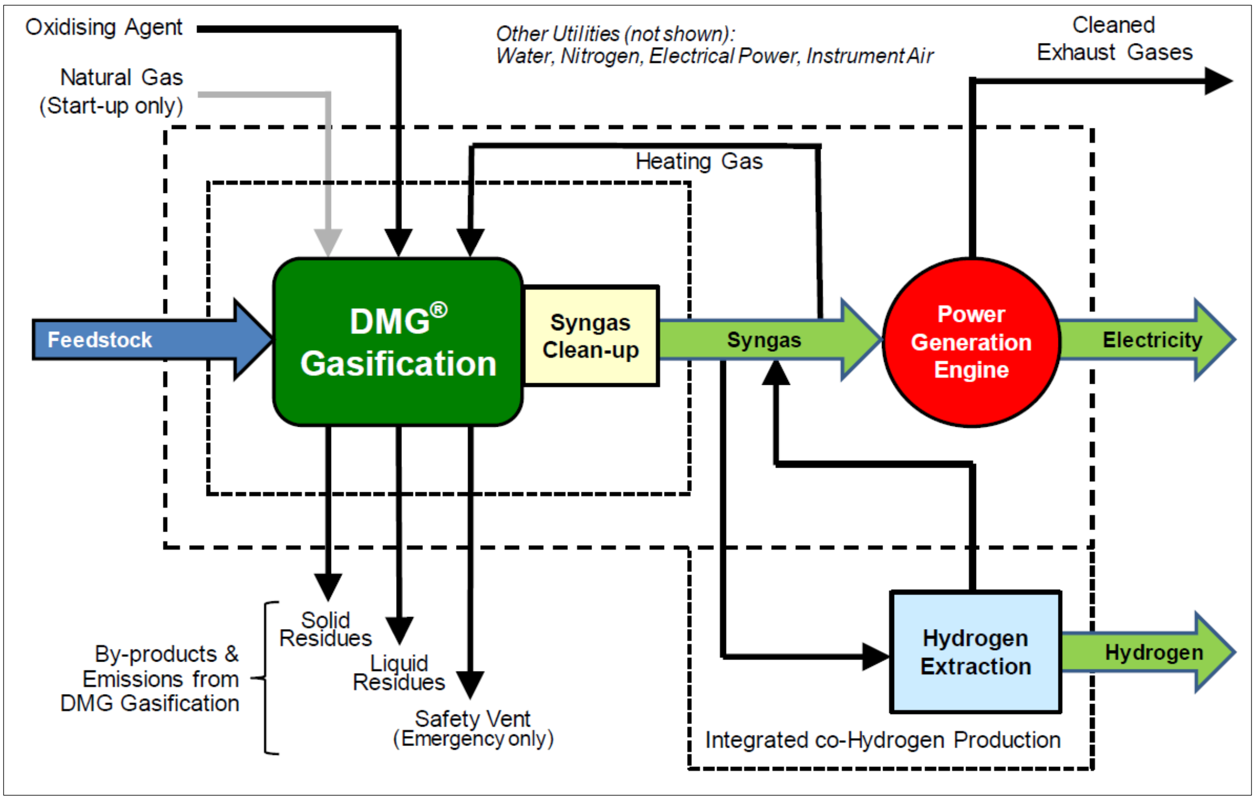


Figure 11: Schematic of the PowerHouse DMG gasification process

Source: PowerHouse Energy.

7.6.2 Feedstock specification

The DMG system can process mixed plastics, RDF and SRF. Although not stated by PowerHouse we would expect that limits on the S and Cl content as well as the ash melting point of the waste would be required. Feedstock for the process will be prepared on site to the required specification.

7.6.3 Feedstock handling and delivery

Pre-treatment of feedstock for the DMG process will require the following:

1. de-baling;
2. removal of ferrous and non-ferrous metals;
3. removal of glass and stones;
4. shredding;
5. screening; and
6. drying

Prepared feedstock will be stored at the site in silos and will be delivered to the feed hopper of the TCC by conveyor on demand.

7.6.4 Plant description

The DMG system consists of the following key process stages:

1. feedstock handling and delivery;
2. DMG® module;
3. Solid residue collection system;
4. syngas clean-up and waste water treatment system;
5. syngas compression system;
6. combined heat and power system;
7. a hydrogen production system;
8. ash and char collection and conveying system;
9. enclosed flare; and
10. 10. stack.

7.6.5 Syngas clean-up

Syngas leaving the TCC is treated in a multistep gas clean up system consisting of the following key components:

1. a quench system which the syngas temperature is rapidly reduced below the tar dewpoint;
2. a scrubber system for the removal of acid gases and particulates; and
3. a series of activated carbon beds to remove entrained hydrocarbons and other contaminants.

On leaving the syngas clean up system, the syngas is then stored in tanks from which it is supplied to the syngas engines or to the PSA system for separation of H2.

7.6.6 Process outputs

The DMG process produces the following:

1. syngas which can be used for firing syngas engines; and
2. H2 which can be used directly without the need for further treatment.

7.6.7 Process residue handling and disposal

The DMG process produces the following main residual streams:

1. Ash and char which are discharged from the TCC. This material should be inert and can either be used as secondary aggregate or landfilled.
2. Flue gas residues from the treatment of acid gases.
3. Wastewater contaminated with process hydrocarbons.
4. CO2 will be contained in the flue gas produced by the waste heat boiler and the syngas engines.

7.6.8 Operation and maintenance requirements

No detailed breakdown of operational and maintenance requirements is available publicly. The fuel pre-treatment process is conventional and can be assessed based on the operations at conventional mechanical treatment plants.

Whilst the TCC unit will have some characteristics which are similar to conventional rotary kilns. There are several aspects of this system which will be more complex and are likely to be unique to the DMG system. On this basis, this plant is likely to require increased staffing and maintenance levels. The syngas clean-up and conversion equipment are operated continuously and automatically controlled so should require limited manual input. Operating and maintenance costs will need to be assessed based on data provided by PowerHouse.

7.6.9 Decarbonisation potential

The DMG system converts plastics to syngas. Therefore, although much of the carbon in the feedstock is retained in the syngas, combustion of syngas results in the conversion of that carbon to CO2. The process requires a supply of fossil fuels on start up and during process disturbances. The waste heat boiler requires a constant supply of natural gas, syngas or a mixture of the two fuels. According to PowerHouse the waste heat boiler will typically be fired on syngas.

CO2 will also be released from the waste heat boiler and from combustion of syngas during start up and unplanned outages. The process will also consume some of the electricity produced to drive fans, compressors, pumps and the pressure swing adsorption system.

Where syngas is used to fire the waste heat boiler, the process is likely to be a low carbon technology for the production of H2 if the whole chain, from production of the fuel through to the products is taken into account. It will not be fully net zero unless the CO2 produced during electricity generation in the syngas engines is captured.

7.6.10 Technology readiness level

The DMG process includes several component systems that have been demonstrated at scale. However, the TCC unit has not been demonstrated at commercial scale and long term operation of a fully integrated process plant to evaluate and assess the overall process is yet to be done. As such, it is considered to have a TRL of 6.

7.6.11 Project pipeline

PowerHouse and Peel have indicated opportunities for the construction of several plants in England and Scotland over the next decade.

7.7 Sumitomo Foster Wheeler

Sumitomo Foster Wheeler Gasifier Technologies (SHI FW) supplies CFB air-blown gasifiers for the production of syngas from biomass and waste derived fuels. From 2004-2011 the company was part of a research and development programme which focussed on the production of syngas from biomass for the synthesis of renewable diesel. In 2009 based on the results of initial pilot scale studies SHI FW built a 12 MWth pressurised steam-O2 CFB gasifier, syngas clean-up and FT system for NSE Biofuels Oy Limited in Varkaus, Finland. The plant was set up as a joint venture between Neste Oil and Stora Enso and was operated on bark, wood chip, forestry residues and sawdust to produce syngas for upgrading to a biowax suitable for refining into renewable diesel. The plant produced approximately 656 t/year of renewable diesel.

7.7.1 Technology description

In the SHI FW system biomass is first dried to approximately 15 wt% moisture before it is supplied to the CFB gasifier where it is heated to between 830-940°C using a mixture of steam and O2 (30-50 vol% O2).The steam/O2 mixture is also used as the fluidising medium. The steam is supplied by a waste heat boiler and O2 by an air separation unit (ASU).

Syngas leaving the gasifier is first treated in a syngas clean-up system followed by conversion to a FT wax. A photograph of the demonstration plant is shown below.

Figure 12: NSE Biofuels Oy 12 MWth gasifier and 5 MWth slip stream gas clean up and FT synthesis plant, Varkus, Finland

Source: Sumitomo Foster Wheeler

7.7.2 Feedstock specification

The SHI FW system can process a variety of biomass wastes. Like other BFB gasifiers the feedstock has to be treated to ensure fluidisation. In addition, feedstock with low melting points should be avoided to minimise ash fusion and agglomeration in the fuel bed. Limits on the S and Cl content of the waste are also necessary. The feedstock can be prepared onsite in a mechanical treatment plant or offsite to an agreed specification by fuel suppliers. Consequently, feedstock supplied to the process will need to comply with a detailed list of requirements.

7.7.3 Feedstock handling and delivery

Like other fluidised bed gasifiers , pre-treatment of feedstock for the SHI FW gasifier requires removal of the following items:

1. ferrous and non-ferrous metals;
2. glass, stones and dense plastics;
3. shredding to 50 - 80 mm;
4. screening; and
5. drying of the feedstock.

The pre-treatment required is conventional mechanical treatment equipment used to produce RDF. Prepared feedstock will be stored at the site in silos or in a bunker before being delivered to intermediate storage hoppers for delivery to the gasifier when required.

7.7.4 Plant description

The SHI FW process consists of the following key system components:

1. feedstock delivery system;
2. CFB gasifier;
3. multistage syngas clean up system;
4. FT synthesis reactor;
5. external cyclones;
6. tramp metal collection system;
7. ash and char collection and conveying system;
8. flare; and
9. stack

7.7.5 Syngas clean-up and conversion

The SHI FW process produces syngas which requires treatment in a multistage syngas clean-up system prior to upgrading in a proprietary FT system. The syngas is first treated in a series of gas clean-up process units including:

1. a gas cooling system where the gas is cooled to around 600°C;
2. two syngas filtration systems where particulates, alkali and heavy metals are separated from the syngas using ceramic filters; and
3. a syngas scrubber.

From the scrubber the syngas is then stored and is supplied as required to a proprietary FT process.

7.7.6 Process outputs

Syngas produced by the SHI FW process is treated and converted into a primary FT wax for refining to renewable diesel.

7.7.7 Process residue handling and disposal

The SHI FW process produces the following main residual streams:

1. Tramp material which is discharged from the bottom of the fluidised bed. This material should be inert and can either be used as secondary aggregate or landfilled.
2. A mixture of ash and char is discharged periodically from the external cyclone. This should be inert and can be landfilled.
3. Flue gas exits from the stack after syngas clean-up, flaring and thermal recovery. This gas stream consists of the various waste gas streams from the syngas conversion process.
4. APCr from the treatment of the flue gas produced by the auxiliary boiler.

7.7.8 Operation and maintenance requirements

SHI FW has said that a commercial scale system will be designed for continuous operation for 8000 hours. Information on the planned outage period has not been provided.

No detailed breakdown of operational and maintenance requirements is available publicly. However, based on the information provided on the key component systems, we note the following points.

1. The fuel pre-treatment plant is conventional and straightforward to assess.
2. The fluidised bed gasifier is more complex that other fluidised bed systems and is likely to require increased staffing and maintenance levels.
3. The syngas clean-up and conversion equipment are operated continuously and are automatically controlled so should require limited manual input.
4. The FT synthesis is complex and will require specialist staffing and maintenance personnel.

Ultimately, operating and maintenance costs will need to be assessed based on data provided by SHI FW. However, we would caution that, as the process is yet to be operated at commercial scale, some costs will be first-of-a-kind costs and are unlikely to be representative of the true costs during stable long term operation.

7.7.9 Decarbonisation potential

Like other gasifiers the SHI FW process converts waste feedstocks to syngas. Generally, the carbon conversion efficiency in steam-blown gasifiers has been shown to be between 65-75%. Consequently, most of the carbon in the feedstock is likely to be retained in the products. Carbon losses will be primarily as CO2.

The information provided suggests that enough O2 is supplied to allow the process to be autothermal. On this basis, the process will require fossil fuels on start up and during process disturbances. In addition, CO2 will be released from the waste heat boiler and from combustion of syngas during start up and unplanned outages. The process will also consume significant amounts of electricity to drive fans, compressors and pumps. The process requires O2 for fluidisation and gasification and the production of oxygen requires energy. Overall, the process is likely to be a low carbon technology for the production of fuels if the whole chain, from production of the renewable diesel through to the products is taken into account. It will not be fully net zero unless low carbon electricity is used to power the process and generate O2, and the CO2 released is captured.

7.7.10 Technology readiness level

Gasification of several different types of biomass, syngas cooling, cleaning and tar reforming have been demonstrated over 9,000 h on a 12 MWth system. Conversion of the syngas to a primary biowax for refining into a renewable diesel was demonstrated for approximately 5,500 h on a 5 MWth slipstream of syngas. Overall, the SFW process has not yet been demonstrated at the scale at which it will be deployed. As such, it is considered to have a TRL of 7.

7.7.11 Project pipeline

Whilst operation of the demonstration plant at NSE Biofuels Oy Limited in Varkaus was considered to be a success, construction of the proposed 500 MWth commercial plant was shelved by Neste Oil and Stora Enso the joint owners of the demonstration plant as the investment required was considered to be prohibitive even with the assistance of public funding.

No further information on potential projects based on the SHI FW technology has been made available.

7.8 ThermoChem Recovery International

ThermoChem Recovery International (TRI) was founded in 1996 and has developed a patented indirectly heated fluidised bed steam reforming system. According to TRI, the process can be used for processing a wide range of feedstocks including woody biomass, MSW, RDF and sludges. The company has built and operated several bench, pilot and demonstration scale facilities.

The first TRI commercial scale plant for the production of syngas for use in the production of diesel and synthetic paraffinic kerosene (SPK) (synthetic aviation fuel) is currently under construction as part of the Fulcrum Sierra Biorefinery. The plant will have the capacity for the production of approximately 40,000,000 L/year of SPK from 175,000 t/year of MSW.

7.8.1 Technology description

The TRI gasification system has a throughput capacity of 500 – 2,000 dtpd per single steam reformer and is based on a two-stage steam reforming thermochemical process. A process flow diagram outlining the TRI technology is shown overleaf.

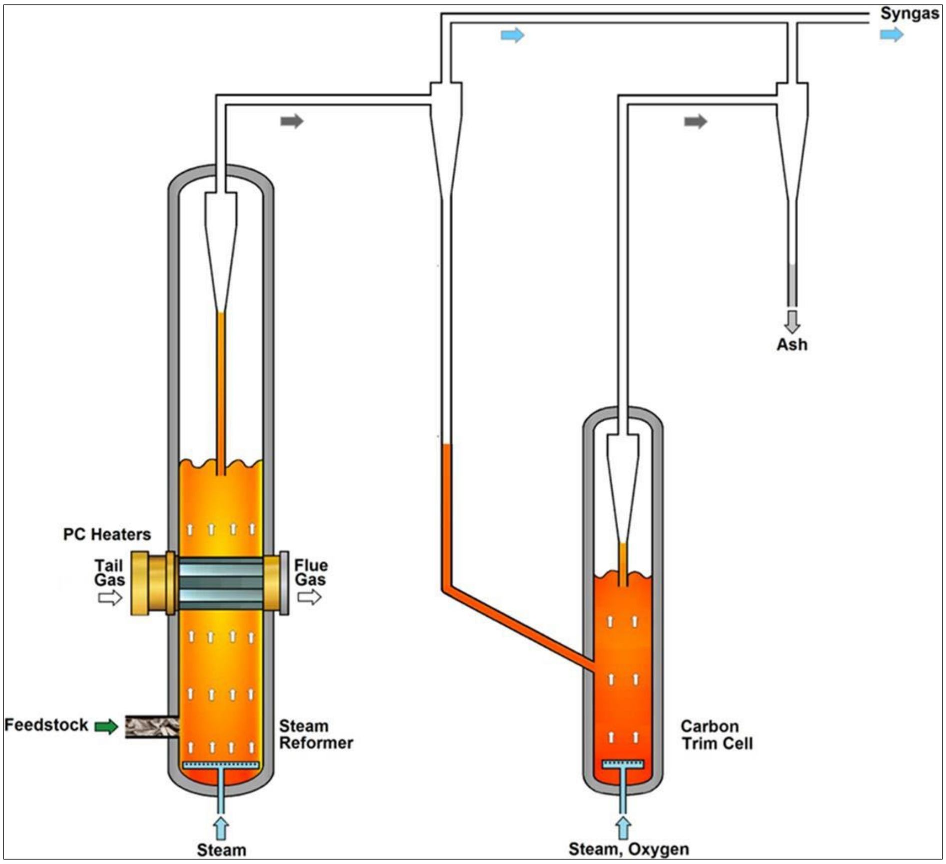


Figure 13: Schematic of the two-stage TRI gasification process

Source: ThermoChem Recovery International

Stage 1

In the first stage the feedstock is heated in a BFB steam reformer in which superheated steam is used to fluidise the fuel bed and gasify the feedstock. This process converts the feedstock to a syngas with a high H2 and CO content. Since steam is the gasifying agent the process is endothermic, and heat must be supplied to the steam reformer to sustain conversion of the feedstock. The steam reformer is heated by pulse combustion (PC) heaters which are submerged in the fuel bed and are fired on natural gas, tail gas or syngas. Heat from the PC heaters is transferred into the fuel bed by conduction. The PC heaters are cooled by feedwater from the waste heat boiler. The superheated steam generated by cooling the PC heaters is supplied to the steam reformer. According to TRI, O2 is also added to the steam where necessary to supplement the heat required for the reforming reactions.

Syngas generated in the steam reformer is discharged through internal cyclones which are used to return entrained bed material and any large ash and char particles in the syngas to the top of the steam reformer. After leaving the internal cyclone, the syngas is then discharged to an external cyclone where the remaining ash and char are separated from the syngas.

Stage 2

In the second stage, syngas along with ash and char entrained in the syngas from the steam reformer are heated in a BFB gasifier known as the carbon trim cell (CTC). No feedstock is fed to the CTC and only gasification of char and any unconverted carbon carried over to the CTC from the steam reformer occurs. In the CTC, a mixture of steam and O2 are used as the fluidising media and gasifying agents. Consequently, a higher concentration of CO is produced in the CTC than in the steam reformer. Indirect heating of the CTC using heaters is also required.

Like the steam reformer, syngas from the CTC is discharged via an internal cyclone and then onto an external cyclone where ash and any remaining char are recovered and sent to the ash handling system.

The syngas from the first and second stages are then combined for delivery to the syngas clean-up and conversion system.

7.8.2 Feedstock specification

The TRI system can process biomass and RDF produced from MSW and C&I waste. Like other BFB gasifiers the feedstock has to be treated to ensure fluidisation. In addition, feedstock with low melting points should be avoided to minimise ash fusion and agglomeration in the fuel bed. Limits on the S and Cl content of the waste are also necessary.

According to TRI the feedstock can be prepared at the site or offsite to the agreed specification by fuel suppliers. Consequently, feedstock supplied to the process will need to comply with a detailed list of requirements.

7.8.3 Feedstock handling and delivery

Pre-treatment of feedstock for the TRI gasifier requires removal of the following items:

1. ferrous and non-ferrous metals;
2. glass, stones and dense plastics;
3. shredding to 50 - 80 mm;
4. screening; and
5. drying to approximately 10 wt% moisture.

The pre-treatment required is conventional mechanical treatment equipment used to produce RDF. Prepared feedstock will be stored at the site in silos or in a bunker before being delivered to the steam reformer by the TRI proprietary plug feeder system.

7.8.4 Plant description

The TRI process consists of the following key system components:

1. feedstock delivery system;
2. steam reformer;
3. carbon trim cell (CTC);

4. CTC heaters;
5. internal and external cyclones;
6. tramp metal collection system;
7. ash and char collection and conveying system;
8. enclosed flare; and
9. stack

7.8.5 Syngas clean-up and conversion

The TRI process produces syngas which contains several compounds which can poison the downstream syngas upgrading system. Consequently, syngas from the TRI system must first be treated in a series of gas clean-up process units including:

1. a partial oxidation unit (POx) for the cracking of hydrocarbons in the syngas;
2. an acid gas removal system;
3. syngas polishing bed for the removal of S, arsine and mercury which will poison the catalysts used in FT systems.

Following clean-up the syngas is compressed and may then undergo further treatment in a WGS reactor to improve the H2:CO ratio prior to upgrading in an FT reactor.

7.8.6 Process outputs

The TRI process produces a syngas which is suitable for upgrading to diesel and SPK. Each TRI steam reformer has a minimum throughput capacity of 500 dry tpd for the production of 42,000 – 43,500 kg/h of syngas.

7.8.7 Process residue handling and disposal

The TRI process produces the following main residual streams:

1. Tramp material which is discharged from the bottom of the fluidised bed. This material should be inert and can either be used as secondary aggregate or landfilled.
2. A mixture of ash and char is recovered from the external cyclones. This should be inert and can be landfilled.
3. Flue gas produced by the auxiliary boiler during start-up and system trips will contain some CO2.

7.8.8 Operation and maintenance requirements

TRI has indicated that the gasifier system is designed for continuous operation at the design throughput for 7,884 hours annually (90% of the available hours per year). Planned maintenance is scheduled for 10-14 days (approximately 4% of the available hours per year).

No detailed breakdown of operational and maintenance requirements is available publicly. The fuel pre-treatment plant is conventional and straightforward to assess. The fluidised bed gasifier is more complex than other fluidised bed systems and is likely to require increased staffing and maintenance levels. The syngas clean-up and conversion equipment are operated continuously and automatically controlled so should require limited manual input. Operating and maintenance costs will need to be assessed based on data provided by TRI.

7.8.9 Decarbonisation potential

The TRI process converts biomass or waste to a syngas. Therefore, much of the carbon in the feedstock is retained in the products. The process requires some fossil fuels on start up and during process disturbances. The PC heaters require a constant supply of fuel. TRI has not provided any information on whether syngas is the primary fuel used to fire the PC heaters.

CO2 will be released from the waste heat boiler and from combustion of syngas during start up and unplanned outages. The process will also consume significant amounts of electricity to drive fans, compressors and pumps. The process requires O2 for fluidisation and gasification and the production of oxygen requires energy.

Where syngas is used to fire the PC heaters, the process is likely to be a low carbon technology for the production of fuels if the whole chain, from production of the feedstock through to the products is taken into account. It will not be fully net zero unless low carbon electricity is used to power the process and generate O2, and the CO2 released is captured.

7.8.10 Technology readiness level

The TRI process includes several component systems that have been demonstrated at scale. However, long term operation of a fully integrated process plant to evaluate and assess the overall process is yet to be done. As such, it is considered to have a TRL of 7.

7.8.11 Project pipeline

A TRI process plant is currently under construction as part of the Fulcrum Sierra Biorefinery project. In addition, the process is also being considered for the Altalto, Immingham (Velocys) waste to synthetic aviation fuel project. A process flow diagram of the Fulcrum Sierra Biorefinery project showing the TRI and associated key component systems is illustrated in Figure 14.

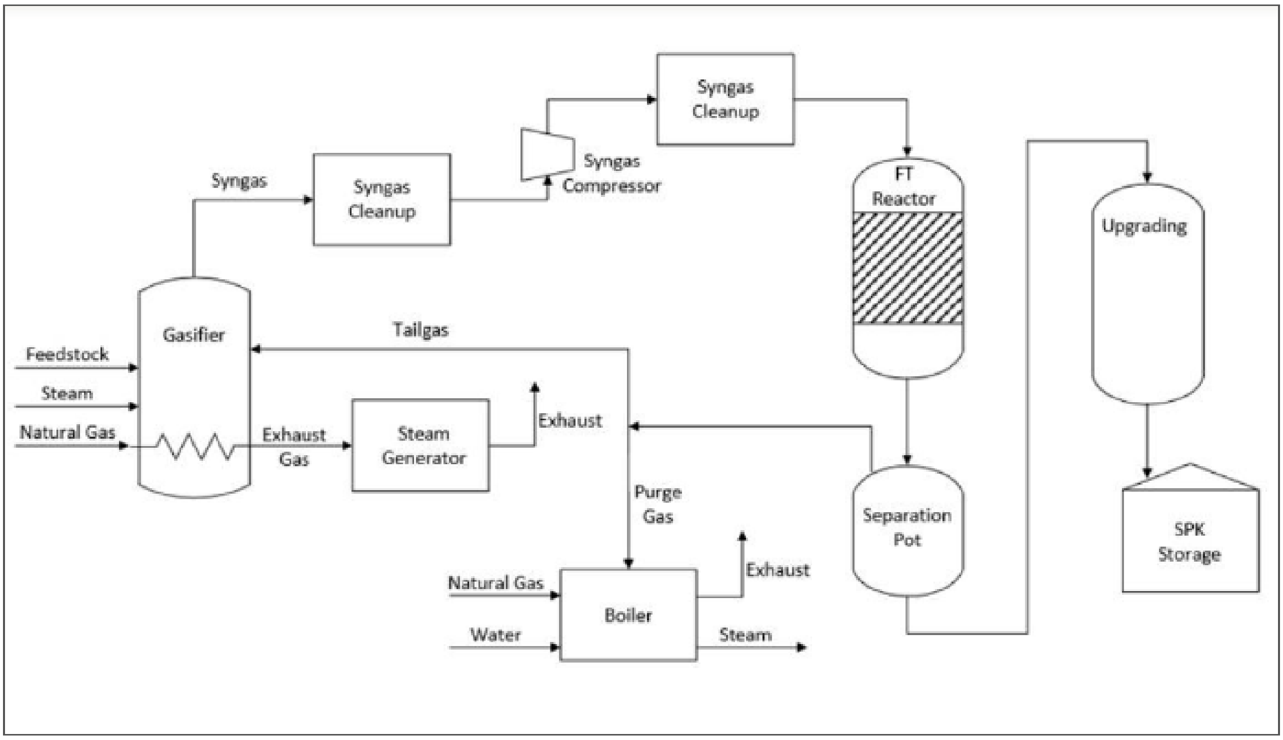


Figure 14: Process flow diagram of the key process components in the Fulcrum Sierra Biorefinery

Source: Fulcrum Sierra

8 Pyrolysis technologies for Energy Production

This section of the report outlines a variety of pyrolysis technologies which have been demonstrated and/or commercialised for the production of syngas for power generation. However, due to various reasons including plant configuration and process economics these technologies are not currently being considered for the production of fuels.

This section is not intended to review all pyrolysers installed globally, instead it focusses on technologies known to the UK market as the purpose of the review is to understand technical solutions which may be applicable in the UK. Included in the next stage of review will be an assessment of the causes of failure of some of the recent UK pyrolysis projects and therefore the main suppliers of these are included.

The table below lists the technologies evaluated. A description of each technology and the current status of development is provided in Appendix B.

Table 6: Pyrolysis technologies for heat and power

Technology supplier	Pyrolysis technology	Feedstock	Output
American Renewable Technologies Inc.	Horizontal rotary kiln	Tyres, manure, MSW, coal, biomass	Syngas, 136 m3/year diesel [23]
Graveson Energy Management Limited	Vertical rotary kiln	MSW, rubber crumb	Syngas for electricity and heat
Prestige Thermal Energy	Gravity column	MSW	Syngas for electricity and heat
TechTrade	Horizontal rotary kiln	Waste tyres	Syngas for the production of heat

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[23] Unverified.

9 Pyrolysis Technologies for Fuels Production

This section reviews pyrolysis systems which are focussed on fuel production and which are worth further consideration.

9.1 Alphaco

Alphaco is a UK company which has developed a modular pyrolysis system for the conversion of tyres to pyrolysis oil, recovered carbon black (rCB) and pyrolysis gas. The company has been developing its pyrolysis technology since 2015 and currently operates a two-module tyre pyrolysis plant with a throughput capacity of 15,000 t/year in Szczecin, Poland.

9.1.1 Technology description

Tyres supplied to the Alphaco process are heated in the absence of air in each pyrolyser to produce pyrolysis oil, pyrolytic carbon, pyrolysis gas and residual steel and textiles. The pyrolysis oil is treated onsite and is shipped to offtakers for use a low grade diesel. The pyrolytic carbon produced is transported offsite for upgrading. The pyrolysis gas is burnt in a combustion unit and the hot flue gases produced are used to provide the heat required to pyrolyse the tyre crumb. Steel and textiles removed from the tyres are also supplied to various offtakers. Alphaco has not provided a process flow diagram.

9.1.2 Tyre specification

The Alphaco process is not limited to a specific type of tyre and a variety of types of tyres are used in its process. Tyre crumb must be supplied to a specified size.

9.1.3 Tyre handling and delivery

Pre-treatment of tyres for the Alphaco process includes the following processes:

1. shredding; and
2. removal of steel wires.

Preparation of the tyres can be carried out at the site or the tyre crumb can be prepared offsite for delivery to the plant. The crumb is stored onsite according to the local environmental and fire safety regulations.

9.1.4 Plant description

The Alphaco process consists of the following key system components:

1. tyre handling and preparation system;

2. pyrolyser module;
3. pyrolysis oil collection and handling system;
4. pyrolytic carbon collection system;
5. syngas collection and combustion system;
6. residual waste handling system;
7. effluent collection and treatment system; and
8. stack

9.1.5 Pyrolysis oil processing

The pyrolysis oil is processed to a low grade diesel before delivery to offtakers. Alphaco has advised that processing of the pyrolysis oil is confidential.

9.1.6 Process outputs

Tyre pyrolysis in the Alphaco process produces the following process outputs:

1. pyrolysis oil which is upgraded to a renewable diesel.
2. pyrolytic carbon; and
3. pyrolysis gas which is used for onsite heating.

9.1.7 Process residue handling and disposal

The primary residues produced from the Alphaco process are as follows:

1. An oily sludge which must be disposed of as a hazardous waste.
2. Wastewater from the wet scrubber system which is treated onsite or sent for disposal offsite.
3. Flue gas from the pyrolysis gas combustor which is discharged to the atmosphere.

9.1.8 Operation and maintenance requirements

The Alphaco process is designed for operation in campaigns. The number of hours of operation annually, planned maintenance period and the number of outages have not been provided.

No detailed breakdown of operational and maintenance requirements is available publicly. However, based on the information provided on the key component systems, we note the following points.

1. The feedstock pre-treatment plant is conventional and straightforward to assess.

2. The pyrolyser is likely to be similar to other pyrolysers of comparable size so staffing and maintenance levels can be assessed.
3. The pyrolysis oil upgrading process may include proprietary systems which will require specialist O&M and operating personnel.

Overall, based on the information supplied by Alphaco the plant in Poland has been in operation at scale for 5 years. On that basis Alphaco should have developed realistic plant operating costs.

9.1.9 Decarbonisation potential

In tyre pyrolysis approximately 50% of carbon in the feedstock is converted to carbon in the pyrolysis oil. Around 30% of the carbon remains in the pyrolytic carbon for production of recovered carbon black (rCB). The pyrolysis gas used for heating the process contains approximately 15% of the carbon in the feedstock. However, tyres are largely fossil fuel based with the majority of the carbon derived from fossil fuels.

Fossil fuels will be required on start-up and during process disturbances for firing the combustor. CO2 will be released from the furnace and the burners which burn the pyrolysis gas or fossil fuel. The process will also consume significant amounts of electricity to drive fans, compressors and pumps

Overall, the process can be considered a low carbon technology for the production of fuels. The process will not be fully net zero even if low carbon electricity is used to power the process and the CO2 is captured.

9.1.10 Technology readiness level

The Alphaco technology has been demonstrated at scale and has been in commercial operation in Szczecin, Poland since 2015. As such the technology is considered to have a TRL of 9. Evidence to support commercial operation can be provided on a confidential basis.

9.1.11 Project pipeline

Alphaco has advised that it has several projects nearing financial close in Europe for construction of 8 or more modules per site. These projects are confidential.

9.2 Reoil

Reoil is a Polish company which has developed a modular pyrolysis system for the conversion of tyres to pyrolysis oil, recovered carbon black (rCB) and pyrolysis gas. The company has been developing its pyrolysis technology since 2015 and currently operates a four-module tyre pyrolysis plant with a throughput capacity of 20,000 t/year in Bukowno, Poland. According to Reoil the plant has been operated for more than 28,000 h and the longest continuous run has been for 3,264 hours.

9.2.1 Technology description

Tyres supplied to the Reoil process are heated in in the absence of air in each pyrolyser to produce pyrolysis oil, pyrolytic carbon, pyrolysis gas and residual steel and textiles. The pyrolysis oil is treated to remove contaminants and water using conventional industrial processes. The pyrolysis oil is then supplied without further processing to offtakers for use as a heating oil. The pyrolytic carbon produced is upgraded to produce a rCB which is sold as a substitute for virgin carbon black. The pyrolysis gas (referred to as syngas by Reoil) is burnt in a combustion unit and the hot flue gases produced are used to provide the heat required to pyrolyse the tyre crumb. Steel and textiles removed from the tyres are also supplied to various offtakers. A schematic illustrating the process is shown overleaf.

9.2.2 Tyre specification

The carbon content of tyres varies, depending on the type of vehicle. For the Reoil process tyres from specific vehicle types are used. In addition, the tyre crumb must be provided to a specified size.

9.2.3 Tyre handling and delivery

Pre-treatment of tyres for the Reoil process includes the following processes:

1. shredding; and
2. removal of steel wires.

Preparation of the tyres can be carried out at the site or the tyre crumb can be prepared offsite for delivery to the plant. The crumb is stored onsite according to the local environmental and fire safety regulations.

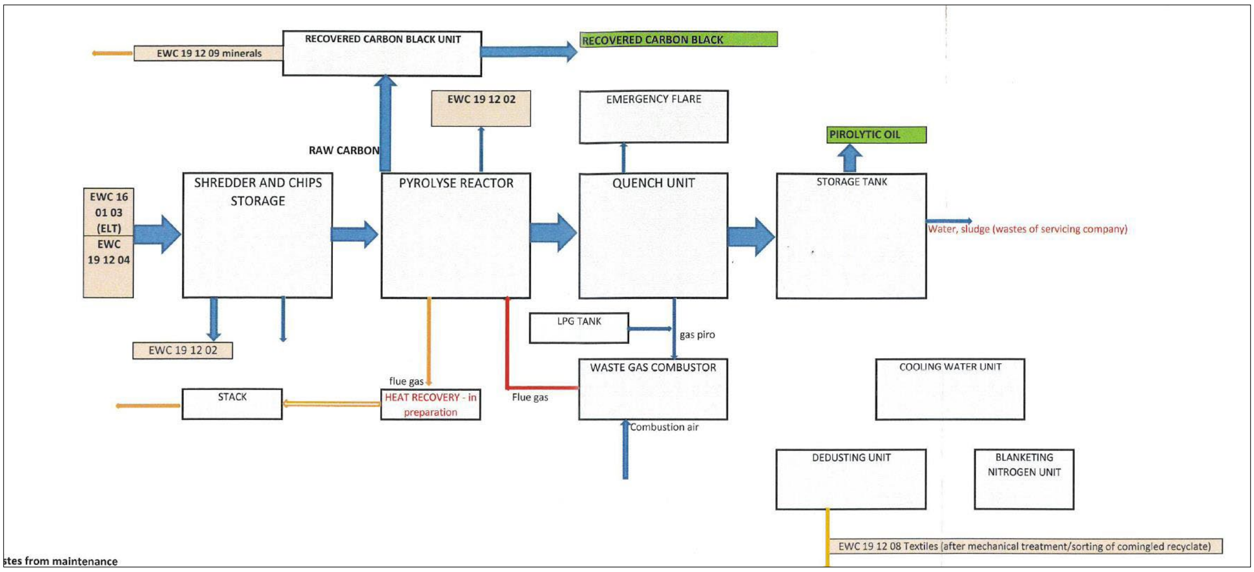

Figure 15: Schematic outlining the Reoil process

Source: Reoil Sp.

9.2.4 Plant description

The Reoil process consists of the following key system components:

1. tyre handling and preparation system;
2. pyrolyser module;
3. pyrolysis oil collection and handling system;
4. pyrolytic carbon collection system;
5. rCB processing system;
6. syngas collection and combustion system;
7. residual waste handling system;
8. effluent collection system; and
9. stack

9.2.5 Pyrolysis oil processing

The pyrolysis oil is filtered and stored before delivery to offtakers. Reoil has not provided any additional information on processing.

9.2.6 Process outputs

The Reoil process produces the following process outputs:

1. pyrolysis oil which is sold as a heating oil or can be upgraded to renewable diesel.
2. pyrolytic carbon which is upgraded to rCB; and
3. syngas which is used for onsite heating.

9.2.7 Process residue handling and disposal

The primary residues produced by a single Reoil module are as follows:

1. Approximately 300 t/year of an oily sludge which must be disposed of as a hazardous waste.
2. Wastewater from the wet scrubber system will need to be treated onsite or sent for disposal offsite.
3. Flue gas from the furnace which is discharged to the atmosphere.

9.2.8 Operation and maintenance requirements

Reoil has advised that the process is designed for continuous operation at the design throughput for 7,800 hours annually (89% of the available hours per year). The planned maintenance period and the number of outages have not been provided.

No detailed breakdown of operational and maintenance requirements is available publicly. However, based on the information provided on the key component systems, we note the following points.

1. The fuel pre-treatment plant is conventional and straightforward to assess.
2. The rotating pyrolyser is likely to be similar to rotating kilns so staffing and maintenance levels similar to those on a comparable size rotating kiln power plant should be acceptable.
3. The pyrolysis oil treatment process is likely to be similar to treatment of oily sludges in power generating plants powered by low and medium speed diesel units.
4. The upgrading of rCB to a saleable product will required additional specialist staff.

Overall, based on the information supplied by Reoil the plant has been in operation at scale for several years. On that basis Reoil should have developed realistic plant operating costs.

9.2.9 Decarbonisation potential

In tyre pyrolysis approximately 50% of carbon in the feedstock is converted to carbon in the pyrolysis oil. Around 30% of the carbon remains in the pyrolytic carbon for production of rCB. The pyrolysis gas used for heating the process contains approximately 15% of the carbon in the feedstock.

Fossil fuels will be required on start-up and during process disturbances for firing the combustor. CO2 will be released from the furnace and the burners which will burn either the pyrolysis gas or fossil fuel. The process will also consume significant amounts of electricity to drive fans, compressors, pumps

Overall, the process can be considered a low carbon technology for the production of fuels. In addition, the process produces a rCB, which is a key substitute for virgin carbon black in a range of industrial and food related manufacturing processes. However, as the process is for tyres which are largely fossil fuel based in energy content, the process will not be fully net zero even if low carbon electricity is used to power the process and CO2 from the flue gas is captured.

9.2.10 Technology readiness level

The Reoil technology has been demonstrated at scale and has been in commercial operation since 2015. As such the technology is considered to have a TRL of 9. Evidence to support commercial operation can be provided on a confidential basis.

9.2.11 Project pipeline

Reoil has indicated that it intends to build several plants over the next three years with capacities ranging between 20,000 – 40,000 t/year.

9.3 Standard Gas Limited

Standard Gas (SG) is a UK developer of modular pyrolysis systems for the conversion of a variety of biomass and waste derived feedstocks into a pyrolysis gas for the synthesis of CH4 or generation of electricity. SG refers to the pyrolysis gas as a syngas. The company has been developing its pyrolysis technology since 2007 and in 2011 it deployed its first plant, a 3 t/h, 10 MWth plant in Huntingdon, UK. Since then the plant has been operated in campaigns for a total of approximately 2,500 h. The plant produces syngas with a calorific value ranging from 15-20 MJ/Nm3 and the syngas has achieved end-of-waste status with the syngas used to power a gas engine.

According to SG, pyrolysis gas from 4 modules can be supplied to a single methanation unit supplied by Haldor Topsoe for conversion of the pyrolysis gas to grid quality methane, but this step has yet to be demonstrated.

9.3.1 Technology description

Feedstock supplied to the SG process is indirectly heated at atmospheric pressure in a vessel known as the Retort. The Retort is located in a furnace which is heated to 850°C using burners which can be fired on natural gas, pyrolysis gas or a mixture of the two fuels. According to SG the syngas produced consists primarily of H2, CO and CH4. Some acetylene (C2H4) is also present in the gas. Syngas leaves the Retort at 400 – 450°C and is discharged to gas cleaning and conditioning systems prior to supply to syngas engines or the methanation unit.

9.3.2 Feedstock specification

The SG system has been permitted for operation on a wide variety of wastes. To ensure optimum operation, feedstock for the process must be shredded. In addition, limits on the S and Cl content of the feedstock are also necessary. SG has not provided information on restrictions on the ash melting point and the metals content of the feedstock. However, we would expect that the feedstock specification for this process would include defined limits for these parameters. Consequently, feedstock supplied to the process will need to comply with a detailed list of requirements.

9.3.3 Feedstock handling and delivery

Pre-treatment of feedstock for the SG process must include the following processes:

1. removal of ferrous and non-ferrous metals;
2. removal of glass, stones and dense plastics;

3. shredding to 150 mm;
4. screening; and
5. drying of the feedstock to 20 wt% moisture.

Preparation of the feedstock is carried out offsite at the reference plant, but could be done on site using conventional mechanical treatment equipment for future projects. Currently the prepared feedstock is packaged in bales before delivery to the reference site where it is stored. The feedstock is de-baled and emptied into intermediate storage hoppers for delivery to the pyrolyser when required.

9.3.4 Plant description

The SG process consists of the following key system components:

1. feedstock preparation;
2. feedstock delivery system;
3. pyrolyser module;
4. pyrolysis clean up system;
5. syngas conditioning system;
6. syngas storage;
7. syngas engines;
8. methanation reactor;
9. cyclones;
10. ash and char collection and conveying system;
11. effluent treatment and recycling system;
12. enclosed flare; and
13. stack

9.3.5 Syngas clean-up and conversion

The SG process produces syngas which requires treatment in a syngas clean-up system prior to upgrading in a methanation unit if the unit is to produce methane. The syngas is processed as follows:

1. Some of the ash, char and other entrained particulates in the syngas leaving the Retort are removed when the ash is discharged into a hopper box.

2. From the hopper box the syngas flows into a cyclone where entrained solids are removed.
3. Tars in the syngas then undergo high temperature cracking in a three stage process in which the gas is heated to increasingly higher temperatures in a series of pipes known as the cracking pipes.
4. After the cracking pipes the syngas is discharged to a second cyclone before delivery to a wet syngas scrubber.

Following scrubbing the syngas is compressed for storage in a buffer storage tank. From the storage tank the syngas flows through a packed carbon bed for removal of any condensed hydrocarbons prior to delivery to the methanation unit and any other downstream users. Additional syngas clean-up will be carried out in the methanation unit before conversion to grid quality methane.

9.3.6 Process outputs

SG has reported that syngas produced by its process can be converted to grid quality methane (> 90% CH_4). However, this process has not yet been demonstrated.

9.3.7 Process residue handling and disposal

The SG process produces the following main residual streams:

1. A mixture of ash and char is discharged from the hopper box and the two cyclones. If this residue has a total organic content (TOC) <3 wt% then it can be landfilled.
2. Wastewater from the wet scrubber system will need to be treated onsite or sent for disposal offsite.
3. Flue gas from the furnace and exhaust emissions from the syngas engine where the syngas is also being used to generate electricity.

9.3.8 Operation and maintenance requirements

No detailed breakdown of operational and maintenance requirements is available publicly. However, based on the information provided on the key component systems, we note the following points.

1. The fuel pre-treatment plant is conventional and straightforward to assess.
2. The Retort and cracking pipes are not proprietary reactors and are likely to require increased staffing and maintenance levels.
3. The syngas clean-up system is a conventional wet scrubber and should be automatically controlled so should require limited manual input.
4. The methanation unit will require specialist staffing and maintenance personnel.

As the SG pyrolysis system has had limited operation and the methanation step is yet to be demonstrated operating and maintenance costs for the proposed process will need to be assessed based on modelled/estimated costs. However, we would caution, that as the pyrolysis process is yet to be operated at the scale at which it will be deployed commercially and that operations with a methanation unit have not been carried out, the costs will be first-of-a-kind costs and are will not be representative of the likely costs during stable long term operation.

9.3.9 Decarbonisation potential

Approximately 80% or more of the carbon in feedstock is converted to carbon in the pyrolysis gas. Losses of carbon are primarily due to the production of CO2 and tars which can contain up to 10% of the carbon in the feedstock.

Fossil fuels will be required on start-up and during process disturbances for firing the furnace and the cracking pipes. CO2 will be released from the furnace and the burners used by the cracking pipes. The process will also consume significant amounts of electricity to drive fans, compressors, pumps and the methanation unit.

Overall, the process is likely to be a low carbon technology for the production of fuels if the whole chain, from production of the feedstock through to the products is taken into account. It will not be fully net zero unless low carbon electricity is used to power the process and the CO2 released is also captured.

9.3.10 Technology readiness level

To date the SG pyrolysis process has been demonstrated at a smaller scale than will be used for commercial operation. Moreover, the synthesis of CH4 from the syngas produced has not yet been demonstrated. Overall, the SG process has not yet been demonstrated at the scale at which it will be deployed. As such, it is considered to have a technology readiness level of 5.

9.3.11 Project pipeline

SG has indicated that it expects to start construction of its first commercial scale plant in Q3/4 2020. Negotiations are ongoing for funding for other projects.

10 Syngas clean up

10.1 Introduction

Biomass and waste feedstocks consist of a variety of organic compounds, alkali, alkali earth and ash forming elements. The alkali, alkali earth and ash forming elements exist as parts of different organic structures, minerals and salts in feedstock. During gasification, the organic materials undergo thermal degradation (devolatilisation) to produce a mixture of gases, tarry liquids and residual carbon (char). As devolatilisation of the organic material occurs the ash forming elements and alkali metals are released into the fuel bed. Depending on the concentration of chlorine, sulphur and organic salts in the feedstock, these elements either become bound in the ash and char and are discharged as solid residues or adsorb onto particulates and tars and are entrained in the syngas. Collectively, particulates, ash forming elements, alkali metals, tars, and acid and alkaline gases which become entrained in the syngas are known as syngas contaminants. These contaminants can foul and corrode downstream equipment and poison catalysts. Consequently, control of these substances in the syngas is critical to the following:

1. efficient and cost-effective production of fuels; and
2. high plant availability.

Syngas clean-up is the general term for removal of these substances from syngas prior to upgrading for fuel production. Generally, syngas clean-up is an integrated multisystem process in which the component systems are determined by the following:

1. types of contaminants in the syngas;
2. the contaminant loading in the syngas;
3. the maximum allowable concentration of contaminants for protection of the catalysts used in syngas upgrading; and
4. the maximum acceptable concentration of specific contaminants in the fuel produced.

Due to the variable composition of biomass and waste feedstocks syngas clean up is a significant capital and operating cost. Generally, however, an integrated multisystem approach to syngas cleaning minimises capital and operating costs and maximises thermal and carbon conversion efficiencies[24]. Syngas clean-up is classified into two broad categories of primary and secondary methods.

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[24] Dayton, D., Turk, B. Gupta, R. (2019) Syngas Cleanup, Conditioning and Utilisation. John Wiley & Sons Ltd

Primary methods

Primary methods are systems integrated in the gasifier to reduce and/or minimise the production of specific contaminants during gasification. Generally, these methods can be divided into three categories:

1. optimisation of operating conditions;
2. modification of the gasifier design; and
3. addition of catalysts and/or additives in the fuel bed.

Primary methods are typically targeted at minimising tar formation or catalysing the conversion of tar formed in the gasifier.

Secondary methods

Secondary methods are technologies installed downstream of the gasifier. The technologies used are classified as physical or chemical systems and are selected based on the main types of contaminants present and the end use application of the syngas. In physical removal systems the most common gas cleaning systems are wet scrubbers, gas cyclone separators, baffle filters, fabric filters and electrostatic precipitators. Generally, chemical removal systems are used for the catalytic conversion of tars and the adsorption of alkali metals and acid gases.

The sections below, summarise established clean up technologies used for removal of the main contaminants which can impact on the quality of the fuels produced from syngas.

10.2 Wet scrubbing

Wet scrubbing systems are one of the most widely used technologies in syngas cleanup. These systems are used primarily for the removal of particulates, ammonia (NH3), carbonyl sulphide (COS), hydrogen chloride (HCl), hydrogen cyanide (HCN), hydrogen sulphide (H2S), chlorides and tars. The main systems include condensing, cooling and scrubbing towers, venturi scrubbers, cyclonic or centrifugal separators, demisters and tar droplet filters. In these systems, syngas is allowed to come into direct contact with a scrubbing liquid which can be water or a solvent. The removal of particulates from syngas for production of fuels is one of the most stringent requirements for wet scrubbing systems with limits of <0.02 mg/Nm3 being required. Collection efficiencies for wet scrubbers vary according to the particle size distribution in the syngas stream. Generally, collection efficiencies of more than 95% have been demonstrated for venturi scrubbers for particles between 1 – 5 µm whereas simple spray towers can have collection efficiencies ranging from 40-60%.

Packed bed wet scrubbers using Rectisol and Selexol are two established commercial acid gas removal systems in which solvents are used for the removal of H2S and CO2 from the syngas stream. While Rectisol is more costly, it is the preferred system for treating coal-based syngas because it has a much higher capacity for removal of sulphur, and also because it can remove HCN, NH3, and many metallic trace contaminants. Consequently, it provides additional catalyst protection when compared to Selexol. These systems can also be modified to allow for the selective adsorption of specific gases. The major disadvantage of wet scrubbing systems is that contaminants are transferred from the gas phase to a liquid phase so a new contaminant stream is produced which requires the operation of additional treatment systems. A schematic of a wet scrubber system is illustrated in Figure 16.

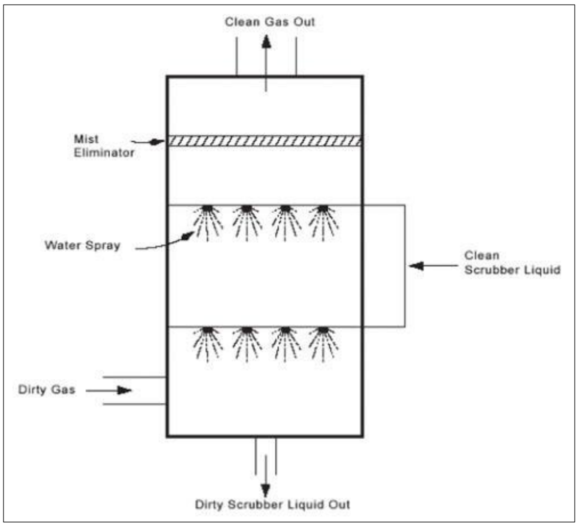

Figure 16: Schematic of a simple scrubber spray tower

Source: USEPA.

10.3 Hot gas cleaning

Hot gas cleaning is the term used to describe systems for the removal of particulates, tar droplets and other solids/semi-solids which become entrained in syngas. Generally, cyclones, electrostatic precipitators, ceramic candles, ceramic fibres and fabrics and metallic filters are the main types of hot gas filtration systems in use.

Cyclones collect particles by using gravitational forces to separate the heavier entrained particles from the gas. Generally, high efficiency cyclones can exhibit a collection efficiency of 99% for particles down to 10 μm. Electrostatic precipitators are operated as wet or dry systems and separate particulates by passing the gas through a strong electric field. Wet electrostatic precipitators have collection efficiencies of > 90% over the entire range of particle sizes to approximately 0.5 μm.

Ceramic, fabric and metal based filters act as a physical barrier to the flow of solids and semi-solids in the syngas whilst allowing the flow of the treated gas. The solids collected coat the external surface of the filter and are removed by flushing the filter with CO2, nitrogen or hot steam.

A major advantage of hot gas cleaning system is the ability to treat syngas at temperatures >500°C which results in higher thermal efficiencies as the sensible heat of the gas can be used in downstream processes where necessary. Additionally, as cooling of the gas does not occur, use of these systems in syngas clean up also minimises the potential for tar condensation.

Generally, hot gas cleaning is installed downstream of the gasifier A schematic showing the operation of a candle filter is shown in Figure 17.

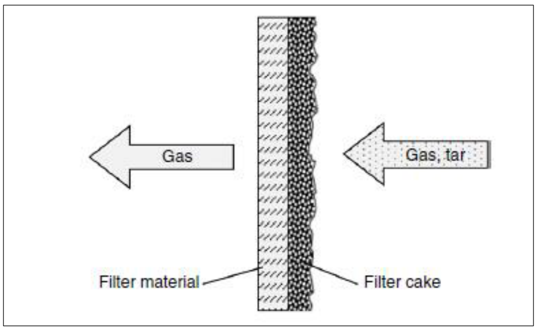

Figure 17: Schematic showing the operation of a barrier filter

Source: Basu, 2010[25]

10.4 Chemical removal systems

In chemical removal systems, contaminants in the syngas become chemically bound to the medium being used. Fixed bed systems of non-volatile inorganic sorbents also known as alkali getters are one of the main types of chemical removal systems used for the removal of alkali metals. Alkali metals typically condense at temperatures <600°C and these sorbents are operated at temperatures ranging from 650–900°C. Generally, these sorbents are aluminosilicates compounds such as kaolin, bauxite, bentonite and emathlite. The most effective alkali getter is bauxite which exhibits adsorption efficiencies of 99%[26].

Acid gas removal systems like Rectisol (Section 10.2) are also classified as chemical removal systems.

10.5 Catalytic and Thermal Tar Removal Systems

Tars are one of the main contaminants in syngas and in fluidised bed systems concentrations of up to 10 g/Nm3 (equivalent to up to 5 wt% of the biomass throughput) can be obtained. In bed primary methods using substances such as olivine, calcined dolomite and nickel based catalysts can convert as much as 97% of the tars to gaseous compounds. Overall, this not only reduces the potential for fouling and coking of downstream systems but it also increases syngas output and can increase the H2 and CO content in the syngas.

Thermal conversion of tars by heating the syngas immediately prior to discharge from fluidised bed gasifiers is also routinely used to reduce the tar content of syngas. Thermal and non-thermal plasma technologies in which the syngas is subjected to pulsed corona discharges have also been developed for the high temperature destruction of tars. However, deployment of plasma technologies for syngas clean up has been limited due to high capital and operating

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[25] Basu, P. (2010) Biomass gasification and pyrolysis – Practical Design and Theory. Elsevier. Amsterdam

[26] Turn, S. et al (2000) Control of alkali species in gasification. National Renewable Energy Laboratory. Colorado

costs as well as technical challenges in effective conversion of tars in the entire volume of syngas produced.

11 Syngas upgrading

11.1 Introduction

Commercial processing of fuels from biomass and wastes does not only require the production of a good quality syngas but reliable technologies for the synthesis and upgrading of the syngas are essential to producing fuels which comply with national and international standards for the safe use of these fuels. Some of the main technologies used in the conversion of syngas to liquid and gaseous fuels are:

1. Methanation;
2. Hydrogen separation
3. Fischer-Tropsch synthesis ; and
4. Hydroprocessing.

This section of the report reviews the main aspects of each of the technologies listed above and highlights the key component systems of each technology. Previous sections have focussed on technologies for the conversion of biomass and wastes to syngas as this is seen to be the part of the process most requiring development. Once an acceptable quality syngas is produced, more conventional or proven techniques to convert the syngas to products can potentially be coupled to the process. Therefore, this section assesses these syngas upgrading systems and where they may be utilised. Whilst several companies manufacture the unit processes for upgrading syngas to fuels, other companies have developed proprietary systems. The proprietary systems developed by Velocys and LanzaTech will also be reviewed in this section.

11.2 Methanation

Methanation is the conversion of CO and H2 in syngas to CH4. Generally, the fuel produced is known as synthetic natural gas (SNG) or Bio-SNG. Prior to methanation, shifting of the H2:CO ratio to approximately 3:1 using the WGS reaction is required to optimise the yield of SNG. In addition, the hydrogen chloride and hydrogen sulphide gas produced in the syngas must be removed during syngas treatment to prevent deactivation of the catalyst. The primary reactions in this process are itemised below:

$CO + 3H2 = CH4 + H2O$

$CO2 + 4H2 = CH4 + 2H2O$

Both reactions are known to be catalysed by nickel based catalysts and several proprietary catalysts have been developed by a range of catalysts speciality companies. The reactions are highly exothermic and the heat produced equates to approximately 20% of the heating value of the syngas. Several companies have developed commercial methanation processes in which the heat produced is recovered for the generation of superheated steam for return to the gasification process. Due to the high exothermicity of the methanation reactions the catalysts selected should have high activity and high thermal stability.

Generally, methanation is carried out at temperatures ranging from 350 - 450°C and at pressures between 10 - 40 bar. As the methanation is based on a chemical equilibrium the maximum yield of SNG is controlled by temperature, pressure and gas composition.

The methane produced is treated to ensure that the composition and quality comply with the requirements of the grid. To date commercial scale methanation technologies for the production of SNG from syngas derived from coal have been developed by Haldor Topsoe. The technology known as TREMP® is in operation at the Qinghua plant in China which is the largest single train SNG plant in the world. The plant has been in operation since 2013 and has a nominal annual SNG output of 1.4 billion Nm3. Haldor Topsoe also supplied the methanation system for the GoBiGas plant (Section7.4) which has a nominal annual SNG output of 19.4 million Nm3. To date GoBiGas is the only large scale biomass to SNG plant.

The schematic below shows the processes upstream and downstream of the methanation unit.

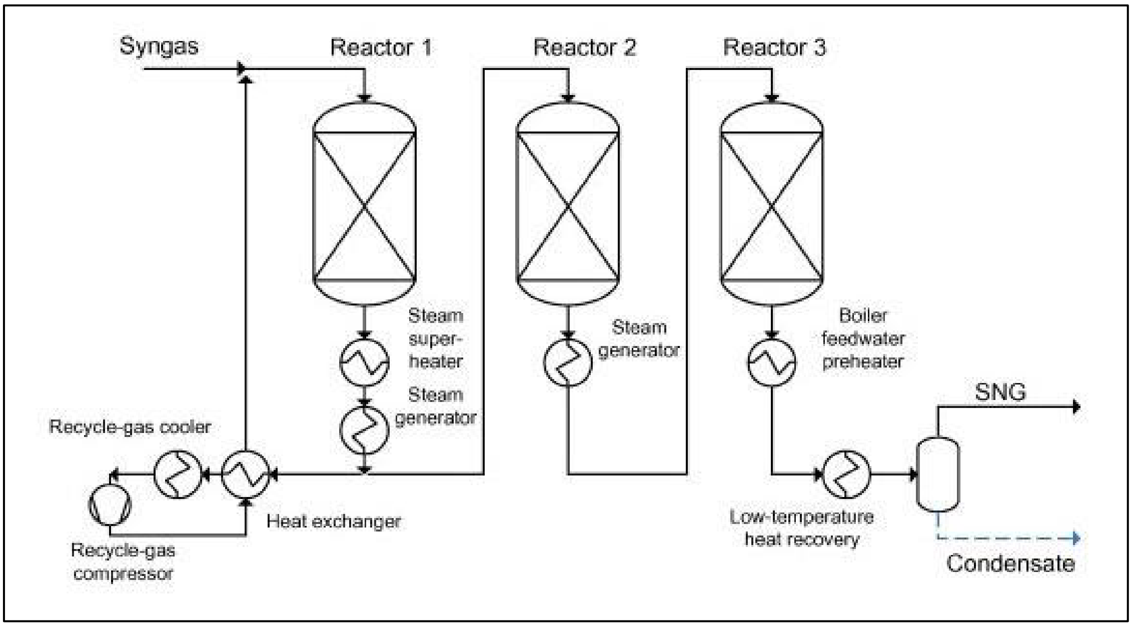

Figure 18: Schematic showing some of the key component systems in the production of methane from syngas.

Source: Haldor Topsoe

11.3 H2 production and separation

H2 production

Since syngas is primarily a mixture of H2 and CO, maximising the production of H2 from syngas requires modifying the H2:CO ratio by steam reforming. This is known as the WGS or the CO shift reaction where CO is reacted with steam to produce H2 and CO2.

$$CO + H_2O \longleftrightarrow H_2 + CO_2 \ -41\ \text{MJ/kmol}$$

The reaction is carried out in several stages in fixed bed or membrane reactors at temperatures ranging from 200°C (low temperature shift) to 500°C (high temperature shift). As the reaction is equimolar, it is independent of pressure.

Low temperature shift reactors are operated between 200 – 270°C using copper-zinc-aluminium catalysts. The low temperature shift was rarely used in reforming syngas from gasification as the catalyst is easily poisoned even at H2S concentrations of 0.1 ppmv. However, several companies have developed cobalt-molybdenum catalysts which can hydrolyse sulphur contaminants such as COS and H2S catalysts even at low temperatures. Consequently, these catalysts are more tolerant to sulphur and are not readily poisoned.

High temperature shift using chromium or copper promoted iron oxide based catalyst is the typical means of carrying out the WGS and is done at temperatures between 300 – 500°C. The catalysts used in the high temperature shift are tolerant of sulphur up to approximately 100 ppmv. Where the shift reaction is carried out before sulphur removal, a cobalt-molybdenum catalyst is used which also promotes the conversion of sulphur contaminants such as COS and H2S. The CO2 produced as a by-product of the shift reaction can be captured using conventional CCUS technologies. The WGS reaction can convert up to 90% of the CO in the syngas to H2.

Large scale WGS reactors are in operation on the Qinghua plant in China with syngas throughput exceeding 200,000 Nm3/h.

H2 separation

Pressure swing adsorption (PSA) is the most common technology used for the separation of H2 from syngas to produce a stream of H2 with up to 99.999% purity. In this process, volatile gases with a low polarity such as H2 are weakly adsorbed whereas other gases such as CO, CO2, hydrocarbons and water vapour are strongly adsorbed onto solid adsorbents such as activated alumina, silica gel, activated carbon and molecular sieves. Adsorption occurs at pressures ranging from 10 - 40 bar and temperatures from ambient to 60 °C until equilibrium loading is achieved

In the separation of H2 from syngas, approximately 80% of the H2 in the syngas flows through the bed unretained. The remaining H2 in the interstitial spaces within the bed and the other gases in the syngas are adsorbed.

Desorption of the adsorbed gases and regeneration of the adsorbent material is then carried out by reducing the pressure to marginally above atmospheric pressure. The tail gas stream discharged from the adsorber contains a mixture of the adsorbed gases and a high percentage of the H2 in the interstitial spaces.

A schematic of the process is illustrated in Figure 19.

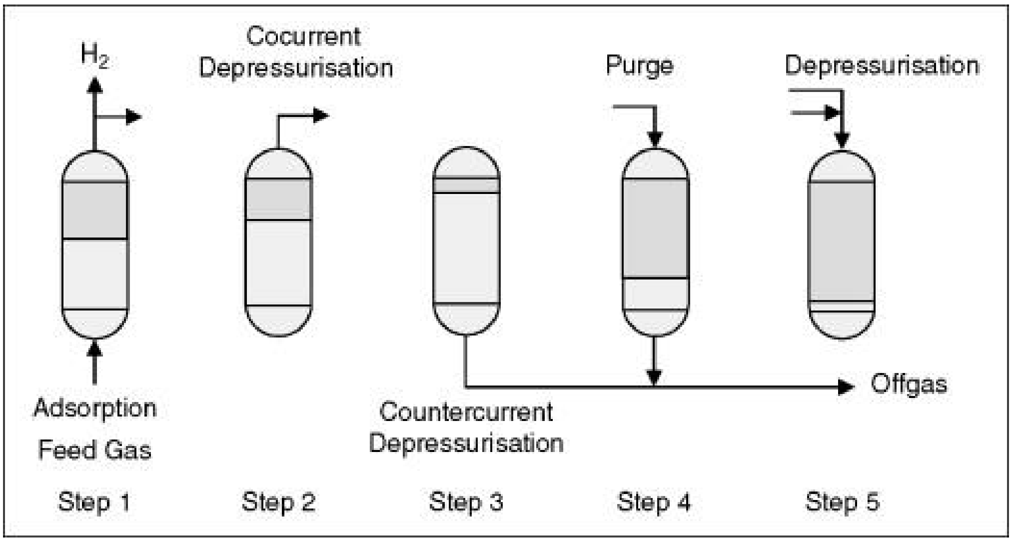

Figure 19: Schematic showing a PSA cycle for each adsorber

Source: Fundamentals of Petroleum Refining[27]

PSA consists primarily of 4 main stages:

1. adsorption;
2. depressurisation;
3. regeneration; and
4. repressurisation

These stages occur as part of a timed cycle in which the syngas initially flows upward through the bed and most of the components of the syngas with the exception of H2 are adsorbed onto the bed material. The H2 remaining in the gas stream is then discharged from the bed. When equilibrium is reached the system is depressurised to atmospheric pressure which releases the adsorbed gases which are then collected for use in syngas engines or are combusted for heat generation. The bed can then be regenerated and repressurised in preparation for continued adsorption.

Separation of H2 through the use of in situ membranes has also been gaining interest as these systems are compact with very few moving parts and provide operating flexibility due to their

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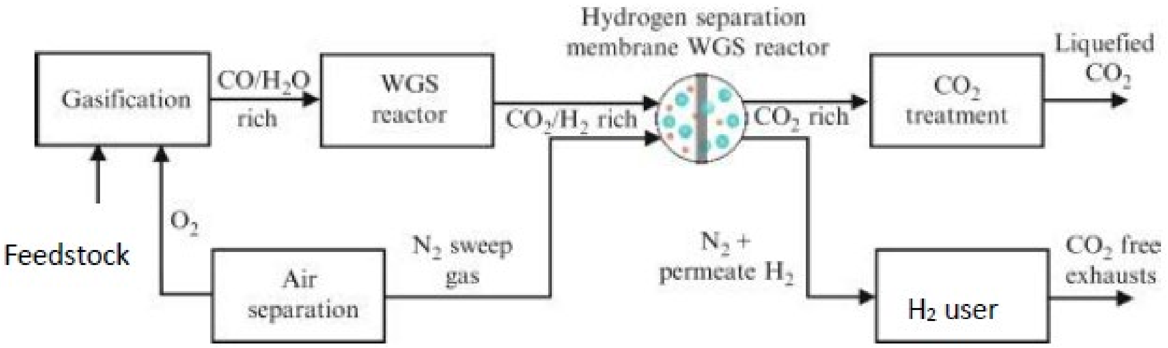
[27] Fahim, M. et al (2010) Pressure Swing Adsorption in Fundamentals of Petroleum Refining: Elsevier Science

modularity. The three main types of membranes under consideration for separation of H2 from syngas are:

1. dense ceramic membranes;
2. microporous membranes; and
3. 3. metal based membranes.

A schematic showing how membrane systems can be integrated within a gasification plant for the production of H2 fuel in Figure 20.



Source: Adapted from Ghasemzadeh et al., 2018[28]

These membranes can be operated optimally at specific temperatures ranging from 300 – 900°C. Unlike PSA, H2 rich gas can only be recovered at low pressure (< 130 bar) using membrane technologies. Consequently, where H2 is required by downstream users such as the transport and industrial sectors at high pressure (350 -700 bar) there will be a large increase in capex and opex as H2 is an extremely small molecule and increased electrical usage will be required for the significant compression required. The other key considerations for these membranes are as follows:

1. H2 selectivity;
2. poisoning by hydrogen sulphide, hydrogen chloride gas and carbon monoxide;
3. failure due to thermal cycling; and
4. capital costs

These membranes are currently in the development phase and none have been operated at commercial scale.

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[28] Coproduction of Electrical Energy and Methanol in IGCC Plants

11.4 Fischer-TrSopsch technologies

FT synthesis is a catalysed chemical process which is used to convert syngas into gaseous, liquid and solid hydrocarbons. It is the core process for the conversion of gas-to-liquids (GTL), biomass-to-liquids (BTL) and coal-to-liquids (CTL). Sasol Limited, an integrated energy and chemical company in South Africa, has been using the FT process to produce transport fuels from coal since 1955 and from natural gas since 2004. Currently, Sasol is the sole producer of 100% synthetic aviation fuel produced from gasification of coal.

An FT plant generally consists of three main process systems, these are:

1. a syngas production system;
2. a system for the conversion of syngas to hydrocarbons and water; and
3. hydrotreating of hydrocarbons to produce fuels.

Of these three processes, the conversion of syngas to hydrocarbons is the most energy and capital intensive and can account for as much as 75% of the capital costs.[29]

Fundamentally, FT is a polymerisation process in which carbon bonds are formed between the carbon atoms in individual CO molecules under the influence of H2 in the presence of a metal catalyst to produce a range of hydrocarbons. The types of hydrocarbons produced are dependent on the reaction conditions and the type of catalyst used.

All FT systems consist primarily of a reactor that receives a clean syngas that is passed through a catalyst bed whilst efficiently removing heat and extracting the products which are collectively known as a syncrude. The syncrude produced by FT is similar to crude oil and can then be refined or upgraded to the final product.

A schematic showing a generalised biomass to liquids process based on FT synthesis is illustrated in Figure 21.

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[29] Speight 2014 'Gasification of Unconventional Feedstocks. Amsterdam:Elsevier

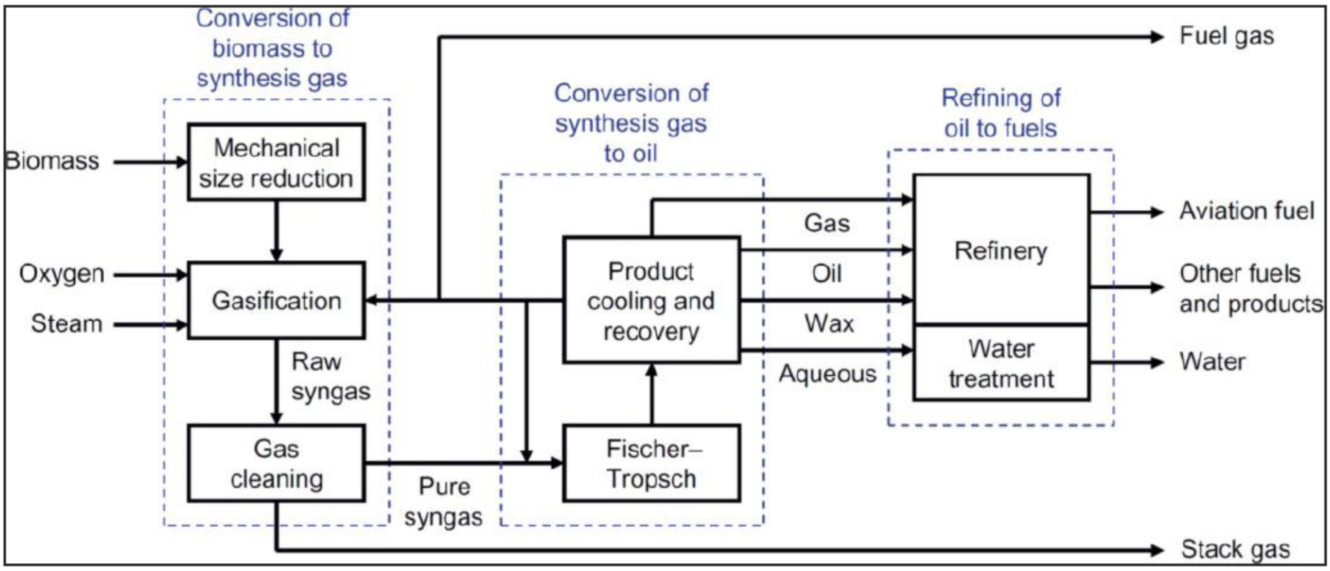

Figure 21: Generalised biomass to liquids process using an integrated FT system

Source: Bioresource Technology 312 (2020)

FT operating temperatures and catalysts

FT systems can be broadly categorised into the two types:

1. high temperature FT (HTFT); and
2. low temperature FT (LTFT).

LTFT processes have operating temperatures in the range of 200-250°C, whereas HTFT operates at around 300-350°C. Operating pressures are generally in the range of 10-40 bar. Both operating temperature and pressure influence product selectivity with lower temperatures and higher pressures generally favouring longer chain hydrocarbon production. As such, HTFT processes are typically chosen when shorter chain hydrocarbons in the gasoline range are desired, whilst LTFT is used when longer chain hydrocarbons in the diesel and wax ranges are desired.

The type of catalyst used is also critical to the operation of FT systems. The FT process is catalysed by a metal-based catalyst. The combination of choice of metal, support structure and mixtures of other metals known as promoters, as well as relative formulation, collectively influence the catalyst’s activity, selectivity and resistance to deactivation.

There are various metals that exhibit some catalytic FT activity but for the most part only, cobalt, iron, nickel and ruthenium have sufficiently high activity to be considered in commercial applications. Industrial interest has largely been centred around cobalt and iron-based catalysts. This is because although nickel is cheap and has a high activity, it also has a higher selectivity for methane and light gases that are undesirable in the production of liquid fuels. Ruthenium is significantly more expensive than iron or cobalt and relatively scarce by comparison.

Iron and cobalt based catalysts are widely used in FT synthesis. Iron-based catalysts are typically selected when the production of gasoline range alkanes is favoured. Unlike cobalt, which is only typically used in LTFT processes, iron-based catalysts can be used in either LTFT or HTFT processes depending on the feedstock and desired product. A key difference between iron and cobalt based FT catalysts is that they have different H2:CO feed ratio requirements. This is less important for iron based catalysts which can facilitate WGS reactions that affect the H2:CO ratio but with cobalt, the H2:CO ratio of the syngas would need to be altered in a separate upstream WGS reactor should it be necessary. Commercially, iron is cheap and although cobalt is more expensive it exhibits greater activity and has a longer life which reduces the frequency of plant shutdown for catalysts changes and increases plant availability.

Whilst syngas pre-treatment and cleaning are important regardless of catalyst selection, iron-based catalysts are more prone to poisoning by hydrogen sulphide and carbonyl sulphide than cobalt. Other contaminants that may be found in syngas produced from biomass include ammonia, hydrogen cyanide, hydrogen chloride, particulates and tars. If these contaminants are not sufficiently cleaned from the syngas prior to being fed into the FT reactor, they would serve to poison, foul or otherwise reduce the activity and performance of the catalyst.

FT reactors

In addition to the choice and formulation of catalyst, reactor type and configuration play an important role in determining product distribution, conversion and selectivity. As the FT process is highly exothermic, a core requirement of the reactor design is the efficient removal of heat to ensure stable reaction conditions. The three conventional FT reactor configurations are:

1. fixed-bed multi-tubular reactors;
2. fluidised bed reactors; or
3. slurry bed reactors.

The arrangement of the FT process may involve staggered bands of different catalyst within a fixed bed or multiple reactors (which can be of a different type) so as to increase the process performance and selectivity for the desired product range. More recent advancements in FT reactor design has also seen the development of microchannel reactors which exploit rapid reaction rates by exercising better control over the removal of heat and transport of materials. Overall, this results in better product selectivity29.

Of the technologies reviewed in section 7, FT synthesis is coupled to the syngas production systems developed by Enerkem, SHI FW and TRI. An FT system will also be integrated into the fuels production process being developed by Kew.

Several companies have developed proprietary systems which are hybrids of fixed bed and slurry bed technologies. Some examples of current FT reactor and catalyst developers and suppliers are Axens, Compact GTL, Haldor Topsoe, Infra, Johnson Matthey and Velocys.

11.5 Hydroprocessing technologies

Hydroprocessing is the name given to a series of chemical reactions which are used in oil refining. All of the processes use hydrogen and include hydrogenation, hydrocracking and hydrotreating. Hydrotreating and hydrocracking processes share many common features, so they are often discussed together as hydroprocessing.

Fuels for commercial usage must comply with stringent specifications to ensure safe operation. In particular, limits are placed on a range of substances including N2, S, unsaturated hydrocarbons and aromatics. Hydrotreating is a catalytic process which is used to remove N2, S and other contaminants and convert unsaturated hydrocarbons. Hydrotreating catalysts currently used in industry are typically a formulation of rare metals along with cobalt and nickel which are widely used in FT synthesis. As with FT, a significant challenge with hydrotreating is the deactivation and poisoning of the catalyst in the process. Therefore, the type of catalyst used is a key parameter influencing the costs of hydrotreating. In the production of fuels from biomass and wastes hydrotreating is used to convert the products from FT synthesis to fuels. The process is also used in the upgrading of pyrolysis oil to a drop-in fuel.

Hydrocracking is also a catalytic process, but it is used to convert heavy oil fractions into lighter, more valuable products. Generally, hydrocracking is used to upgrade the heavier fractions like the waxes into lighter hydrocarbons for the production of aviation fuel and diesel.

Hydrogenation is the process used in methanation for the conversion of syngas to grid quality methane. This process is coupled to the GoBiGas system and will be used in the Standard Gas process. A schematic showing various catalytic hydrotreating and hydrocracking systems used in a refinery and the integration of these processes in the conversion of biomass and wastes to fuels are shown in the figures below.

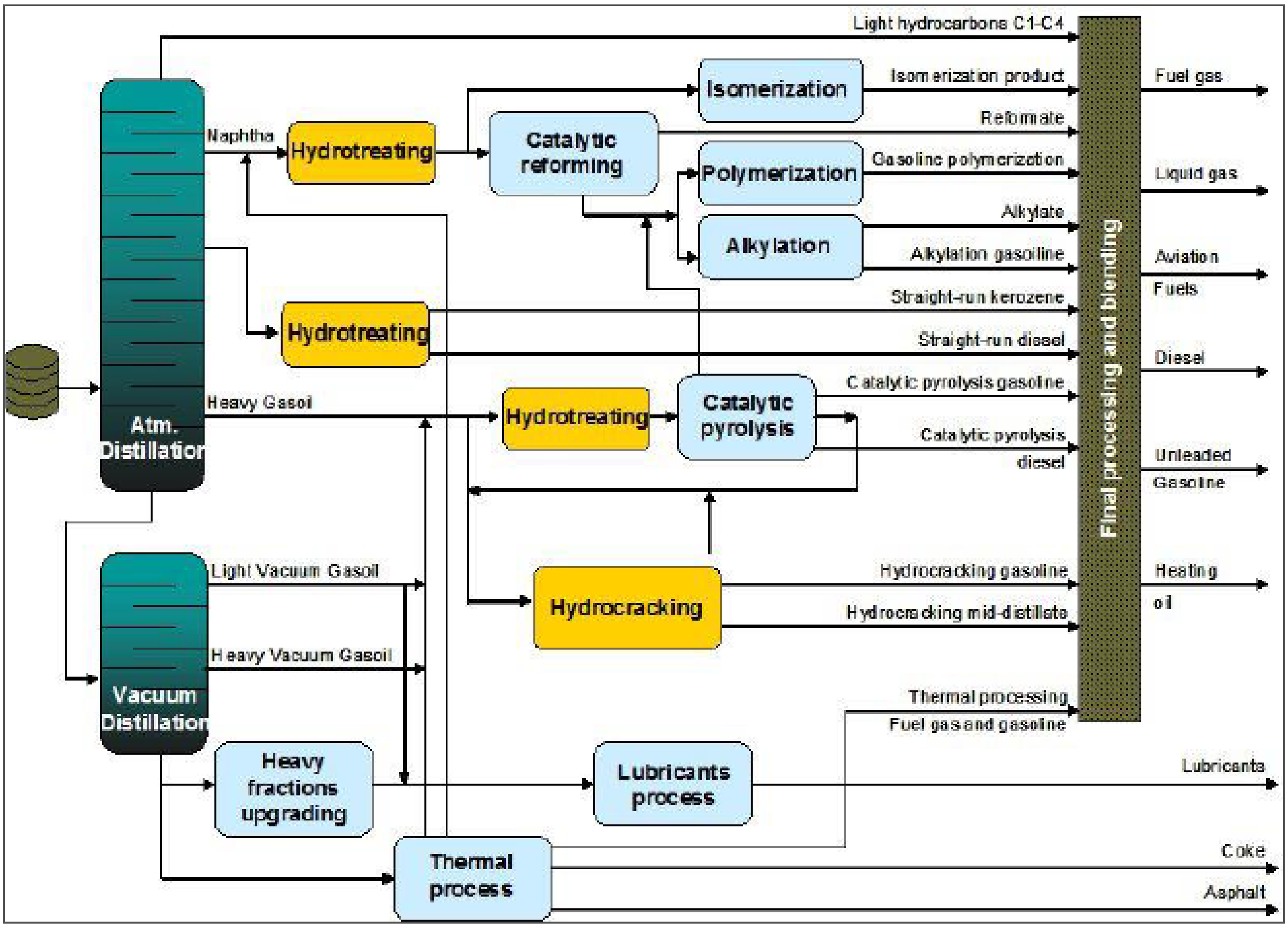

Figure 22: Schematic showing hydrotreating and hydrocracking systems in a refinery

Source: Catalytic Hydroprocessing of Biomass for Liquid Fuels Production

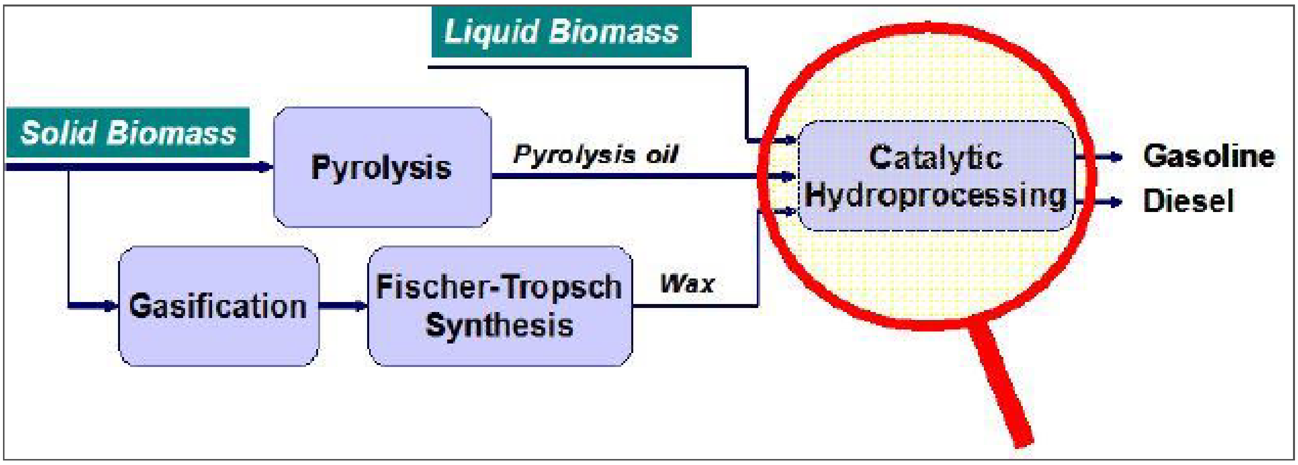

Figure 23: Schematic showing the integration of hydroprocessing systems in a biorefinery

Source: Catalytic Hydroprocessing of Biomass for Liquid Fuels Production

In the conversion of FT process outputs and pyrolysis oil to fuels both hydrotreating and hydrocracking can occur simultaneously and the relative occurrence of each is influenced by the process operating conditions and the type of catalyst selected. However, hydrotreating consumes much more H2 and is more expensive to operate as compared to hydrocracking.

This is an important factor which needs to be taken into consideration when modelling the operating costs for these systems.

Hydroprocessing is well established in petroleum refining and when used in the conversion of biomass and waste derived hydrocarbons it leads to the production of fuels which are stable and fully compatible with petroleum derived fuels. Consequently, the process is integral to the development of drop-in biofuels from waste or biomass.

Several companies, including Johnson Matthey, Galexia and Haldor Topsoe offer a variety of hydrotreating systems for use in biorefineries.

Sections 11.2 and 11.5 reviewed generic solutions for the upgrade of syngas and pyrolysis oil to fuels. These solutions can be retrofitted to gasifiers producing a syngas of suitable quality. Some technology suppliers such as Enerkem have developed their own upgrading systems, whilst others, including TRI and Standard Gas, are planning to use upgrading solutions developed by others. Examples of specific upgrading systems developed for this purpose are given in the following sections.

11.6 Velocys

Velocys is a UK company which has been developing a proprietary FT process for the conversion of syngas from biomass and waste feedstocks to aviation and road transport fuels over the last 18 years. The company has built and operated several pilot and demonstration scale systems. The largest plant to date is a commercial scale demonstrator at ENVIA Oklahoma, USA which has a nominal capacity of 250 barrels (40,000 l) per day of fuel. The plant was commissioned in 2017/2018 and completed operations in 2018. Information in the public domain states that the plant produced 1.6 million litres of fuels and waxes over the operating period. Syngas for the FT synthesis was provided by reforming a mixture of landfill gas and natural gas.

Velocys is currently constructing four FT reactors for the Red Rock Biofuels project in Oregon, USA which will have a nominal design capacity for conversion of 136,000 t/year of woody biomass to 57.1 million litres of renewable fuel. The plant will produce synthetic aviation fuel, drop-in diesel, and gasoline.

11.6.1 Technology description

The Velocys FT process is a multireactor, multistream modular system in which treated and conditioned syngas is synthesised in microchannel reactors using a high selectivity cobalt catalyst. Typically, each multireactor train is made up of 2-4 reactors which are arranged such that each may be taken out of service periodically for regeneration of the catalyst.

The microchannel reactors used by Velocys consists of alternating layers of process and cooling channels to effectively manage the heat flux from the process and to control the rate of conversion and selectivity of the desired products. Each reactor is made up of four blocks of process and coolant channels within a cylindrical pressure vessel.

Velocys has advised that the FT reactor and catalyst have been demonstrated at commercial scale for 5,000 hours.

A diagram and a photograph of the Velocys FT reactor are shown below.

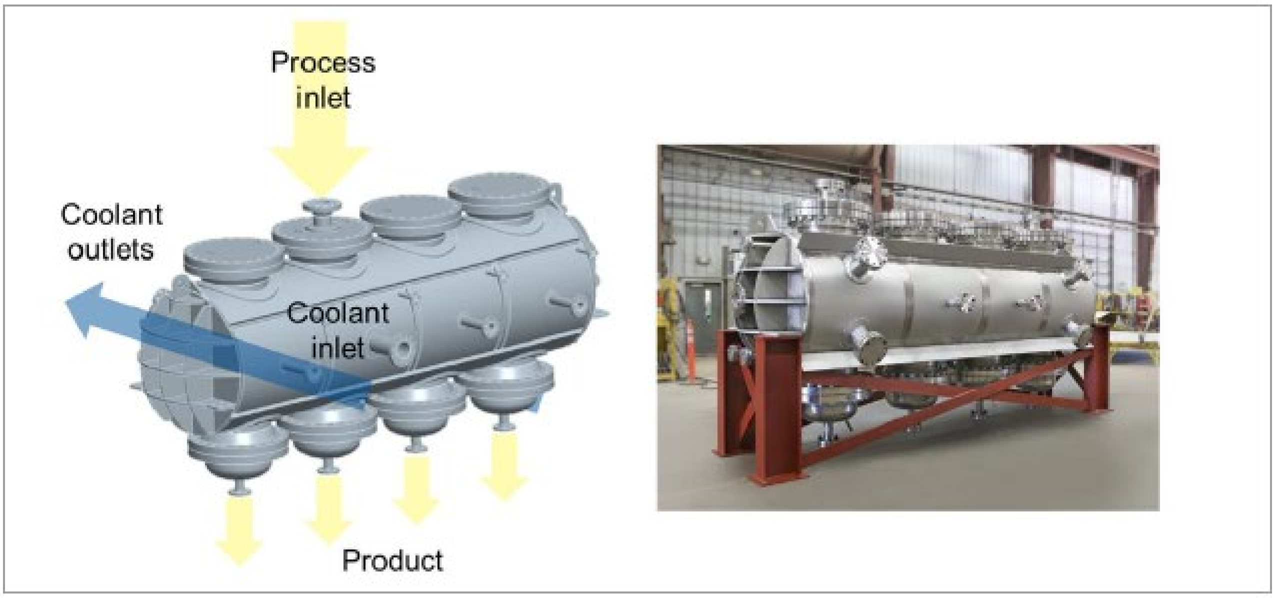

Figure 24: Velocys FT reactor

Source: Velocys plc

11.6.2 Plant description

The Velocys FT reactor train is made up of the following key system components:

1. microchannel reactor;
2. cobalt catalyst;
3. hydrocracker;
4. hydroisomerisation reactor;
5. hydrotreater;
6. air separation unit; and
7. wastewater treatment system

11.6.3 Syngas specification

Details of the operating limits for syngas to be processed in the Velocys FT reactor are confidential. However, Velocys has advised that the following contaminants must be removed from the syngas prior to delivery to the FT process:

1. acid gases, ammonia and particulates entrained in the syngas; and

2. S containing compounds and CO2.

11.6.4 Syngas upgrading

After syngas cleaning the H2:CO ratio must be corrected to the target value in a water-gas shift reactor after which any remaining S is removed by another guard bed before delivery to the FT reactor. The products from the FT reactor are then upgraded in a series of hydroprocessing reactors for production of SPK and synthetic diesel.

11.6.5 Process outputs

In the FT reactor the syngas is converted into the following primary products:

1. a mixture of hydrocarbons known as the light FT liquid (LFTL); and

2. a complex mixture known as the heavy FT liquid (HFTL).

These LFTL and HFTL mixtures are then upgraded by hydrocracking, hydroisomerisation and distillation to produce:

3. synthetic paraffinic kerosene which meets the requirements of ASTM D7566[30];

4. synthetic diesel which complies with EN 15940[31] and ASTM D975[32];

5. naphtha which can be used for the manufacture of chemicals or blended into gasoline.

11.6.6 Process residue handling and disposal

Processing of syngas in the Velocys FT reactor produces the following main residual streams:

1. Sulphur in the S rich offgas is oxidised and washed with a sodium hydroxide solution for recovery of the S in the effluent. The S can then be collected and used for commercial purposes.

2. H2 which is discharged from the WGS reactor can be recovered. The H2 can then be used for commercial purposes.

3. FT tail gas (unreacted syngas) is collected and a portion of it is returned to the reactor for further processing. The remainder is purged into the fuel gas system.

4. A wastewater stream which is treated in the onsite wastewater treatment plant before disposal to the sewer.

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[30] Standard Specification for Aviation Turbine Fuel Containing Synthesised Hydrocarbons" ASTM D7566 stipulates the operating limits of a range of physical and chemical properties for synthetic fuel from coal, biomass and natural gas produced using the FT process.

[31] Automotive Fuels - Paraffinic Diesel Fuel from Synthesis or Hydrotreatment

[32] Standard Specification for Diesel Fuel Oils

11.6.7 Operation and maintenance requirements

The operational and maintenance requirements for the Velocys system are not publicly available. However, based on the information provided on the key component systems, the FT reactor, hydroprocessing and refinery systems are complex and will require specialist operating and maintenance personnel. In addition, O&M costs for the FT and hydroprocessing systems will be specific to the Velocys system and details of these costs will need to be provided by them.

We would caution that whilst Velocys has operated reactors at scale, these systems have not been operated for extended periods and the technology is yet to be deployed commercially. Consequently, the information gathered on O&M requirements and costs will not be representative of the likely costs during stable long term operation.

11.6.8 Decarbonisation potential

As part of an integrated process for the conversion of feedstock to synthetic fuels, operation of the component systems of the Velocys process will require significant amounts of electricity for operation of pumps, compressors and other similar equipment. Therefore, whilst the overall conversion process is expected to be a low carbon technology for the production of fuels if the whole chain, from production of the feedstock through to the products is taken into account. It will not be fully net zero unless low carbon electricity is used to power the process.

11.6.9 Technology readiness level

Velocys has deployed its FT process at scale and from the information provided each of the two reactors has been operated for approximately 2,500 hours on syngas derived from the reforming of landfill and natural gas. The process produced naphtha, diesel and chemical grade wax. This suggests that the actual system has been completed, tested and validated. On this basis the process is considered to have a technology readiness level of 8.

11.6.10 Projects

Velocys has indicated that the following projects are underway:

Table 7: Syngas to fuels projects using the Velocys technology

Project Name	Feedstock	Product	Plant capacity (l/year)	Project status
Altalto	MSW	Aviation fuel	90,000,000	FEED study ongoing
Bayou Fuels	Woody biomass	Fuels	109,000,000	FEED study ongoing
Red Rock Biofuels	Woody biomass	Fuels	68,000,000	Construction

Source: Velocys plc

11.7 LanzaTech

LanzaTech was founded in New Zealand and is a carbon recycling company which has developed a proprietary microbial fermentation process for the conversion of CO rich industrial waste gases and syngas to ethanol. In 2005, the company began identifying microbial strains for optimisation of ethanol production from industrial flue gases. Between 2005 and 2019 several pilot and demonstration plants in India, Japan, New Zealand and the USA were operated on waste gases from industry and on syngas from gasifiers. The production capacity of these plants ranged between 19,000 – 380,000 L annually. In May, 2018, operation of the first commercial plant started at the Jingtang Steel Mill in China. The plant at Jingtang is designed for the production of 58,000,000 L of ethanol annually. According to publicly available information between May 2018 and October 2019, the plant had produced 41,000,000 l of ethanol.

LanzaTech is currently in discussions with ArcelorMittal in Ghent, Belgium for development of a commercial scale demonstrator which will have a production capacity of 78,000,000 l annually of ethanol. Construction of the plant began in 2019 and is expected to be completed in 2022.

LanzaTech has also developed a pilot plant for the catalytic conversion of ethanol to aviation fuel. Negotiations for the development of a demonstration scale system are currently ongoing.

11.7.1 Technology description

In the LanzaTech process, gases containing CO, CO_2 and H_2 or CO only in a range of concentrations are converted by a group of microbes known as acetogens to ethanol in continuously operated bubble column/gas lift loop reactors. LanzaTech has reported that flue gases from various industrial processes including steel mills and syngas from the gasification of biomass and wastes are suitable for conversion. According to LanzaTech, the process does not require a specific ratio of H_2:CO to be present in the process gases. Gases from the process are cooled and contaminants removed before the gas is supplied to the microbial reactors. A schematic illustrating the LanzaTech process and a photo of several bioreactors at the LanzaTech plant in China are shown in Figure 25 and Figure 26.

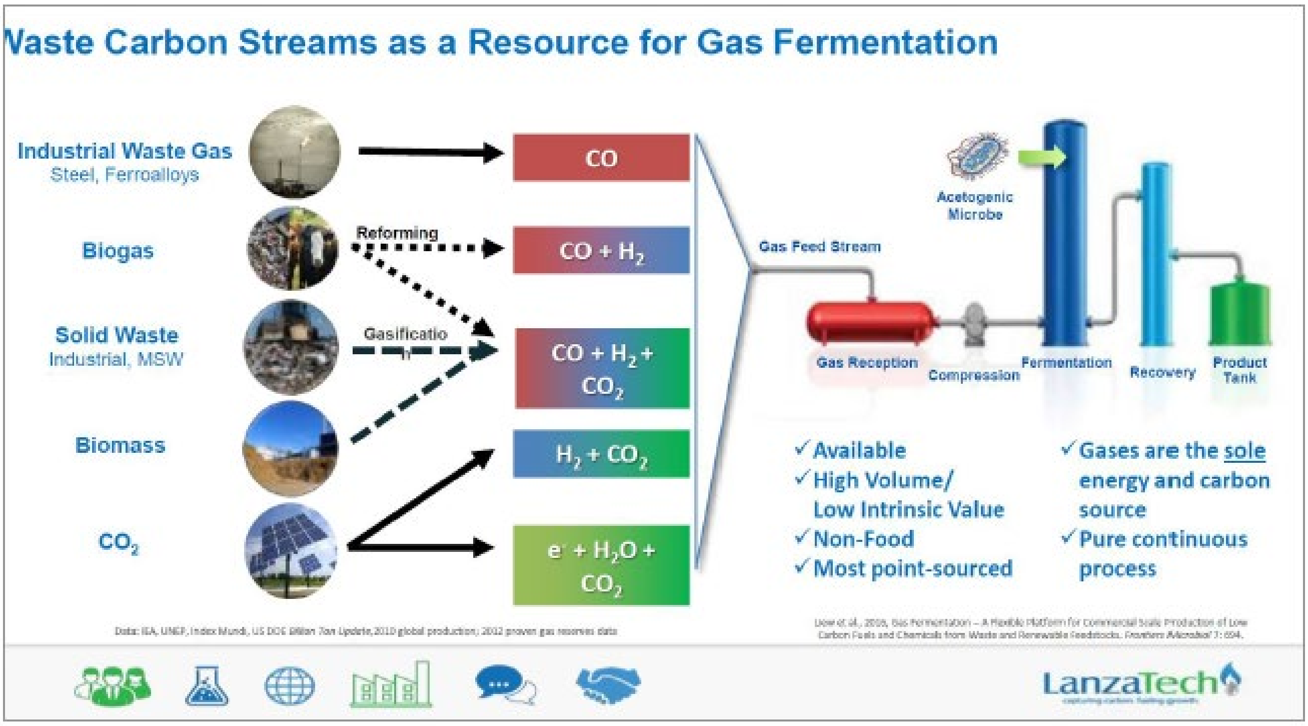

Figure 25: Waste gas streams which can be converted to ethanol by the LanzaTech process.

Source: LanzaTech

Figure 26: Photo of commercial scale LanzaTech bioreactors

Source: LanzaTech

11.7.2 Plant description

The key component systems in the LanzaTech process have not been provided for review. However, based on schematics and other gas fermentation processes the main components in the LanzaTech process are as follows:

1. gas conditioning system;
2. gas compression;
3. bioreactor;
4. cell separation and product recovery system (distillation);
5. cell recycling system;
6. product storage tanks; and
7. Wastewater treatment system

11.7.3 Gas conditioning

Waste gases supplied to the bioreactor are first treated for the removal of several contaminants typically found in these gases. These include entrained particulates, tars, acid gases, ammonia, nitrous oxides and other similar substances.

11.7.4 Process outputs

In the LanzaTech process waste gases are converted primarily into ethanol. Some 2,3-butanediol is also produced.

11.7.5 Operation and maintenance requirements

Operations and maintenance information on the LanzaTech process is not publicly available. However, based on the key component systems, the bioreactor and cell separation and product recovery systems are complex and will require specialist operating and maintenance personnel. Similarly, systems for maintaining viable microbial cultures will also require specialist O&M. Details of these costs will need to be provided by LanzaTech.

11.7.6 Decarbonisation potential

As part of the process for the conversion of waste gases to ethanol, operation of the component systems of the LanzaTech process will require significant amounts of electricity for operation of pumps, compressors, cooling systems and other similar equipment. Therefore, whilst the overall conversion process is expected to be a low carbon technology for the production of ethanol if the whole chain, from production of the feedstock through to the products is taken into account. It will not be fully net zero unless low carbon electricity is used to power the process.

11.7.7 Technology readiness level

The LanzaTech fermentation technology has been demonstrated at scale and based on the publicly available information the technology has been in commercial operation since 2018 and to date production is approximately 70% of the plant capacity.[33] As such the technology is considered to have a TRL of 9. Evidence to support commercial operation will need to be provided on a confidential basis.

11.7.8 Projects

LanzaTech has advised that the following projects are in discussion:

Table 8: Proposed waste gases to ethanol projects **Project location**	**Gas feedstock**	**Plant capacity (l/year)**
California, USA	Syngas from biomass	30,000,000
Panipat, India	Refinery offgas	49,000,000
South Africa	Ferroalloy-offgas	53,000,000

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[33] The design output has not been provided for review.

12 Gasification and Pyrolysis – A route to Net Zero

12.1 Introduction

The main purpose of this review is to highlight ways to contribute to decarbonisation and ultimately to achieving net zero within the timeframes set out by the UK Government. Reducing carbon dioxide emissions to zero is straightforward goal but assessing the contributions of various technologies is complex. It is outside the scope of this review to carry out such an assessment, but any technology selected for further evaluation and ultimate development must make a significant impact to the aim.

It will be necessary to develop comprehensive methods to assess the impact of technical solutions in a fair and accurate manner. This will allow competing technologies, or sectors, to be compared so that those solutions which offer the most promising results can be prioritised. A clear methodology or overarching software package will need to be developed. This will need to consider the full life cycle of any solution. For the technologies considered in this review, this is a significant challenge.

1. This report considers a wide variety of feedstocks. These will all have different impacts on carbon emissions.

    a. Whilst biomass is considered to be carbon neutral as growing the biomass removes as much carbon dioxide from the atmosphere as is ultimately released, there will still be excess carbon releases due to growing, harvesting, preparation and transport unless 100% renewable sources are used for this purpose.

    b. Similarly, the biogenic content of MSW or C&I waste is considered to be carbon neutral, but MSW and C&I waste also contains significant amounts of fossil fuel based materials such as plastics. Only a proportion of the products will therefore have been sourced from renewable sources. However, if the waste was sent to a landfill, it would have significant releases of carbon to atmosphere as the biogenic proportion of the waste decayed. If the waste was sent to an energy from waste plant, all the carbon would be released as carbon dioxide once burnt.

    c. Waste plastics are currently almost entirely fossil fuel based so will have a more limited impact on carbon reduction. However, if waste plastics can be used to displace fossil fuel streams, they still can make a significant contribution, also avoiding other negative aspects of waste plastic releases to our environment. Ultimately it could be foreseen that a closed loop system could be created whereby plastics are created via AGT process and then collected and reused as the feedstock for the AGT.

2. Most solutions will require the use of some fossil fuels for start-up and shut down, although it would also be possible to use some of the product to displace these fossil fuels.

3. The technologies selected will all have their own carbon releases. All the technologies will consume electricity and many of the consumables required such as steam, oxygen, nitrogen or catalysts will potentially release carbon in their production.

4. Building and maintain the plants will have their own carbon releases which will vary depending on the complexity of the solution.

5. The technologies will have different waste streams. Some may release CO_2 as exhaust gases. Others will have solid and liquid waste streams which may have carbon releases.

6. The products produced need to be considered in the wider picture. If the products are hydrocarbons, then when used they will release carbon dioxide.

7. Many of these technologies will bring the opportunity to combine the process with CCUS. If CCUS is fitted, the processes may have the capability to become carbon negative. For example, if a biomass plant is used to produce hydrogen and is fitted with CCUS, overall carbon can be removed from the atmosphere by growing the biomass, capturing any carbon releases and then displacing fossil fuels when the hydrogen product is used.

8. Developing software to assess the various impacts of different technologies will become important in estimating actual carbon contributions from sectors and processes in a fair and accurate manner.

12.2 Hydrogen

Solutions seeking to generate hydrogen will be able to generate significant amounts of hydrogen which may be required if the hydrogen economy takes off. Hydrogen is a very important potential fuel for as combusting hydrogen only creates water. Hydrogen is likely to become a very important fuel of the future for transport, heat and balancing electrical generation at times when renewables such as solar and wind are unavailable. As hydrogen will directly displace fossil fuels and not release any carbon when used, the impact of it as a product is relatively straightforward to calculate.

However, if hydrogen is generated from biomass or waste fuels, these fuels contain significant amounts of carbon. In producing the hydrogen product, the fate of the carbon in the fuels needs to be carefully assessed. Some of this carbon could be used to provide energy to produce the hydrogen or to generate electricity, so displacing other fossil fuels. However, to have a significant impact towards net zero, the carbon supplied in the biomass and waste would need to be captured and used or stored.

12.3 Methane

The most likely use of methane produced from biomass or waste would be to displace natural gas used in the gas network. As is already done with some anaerobic digestion processes, the fuels can be converted to methane and then directly injected into the gas grid to displace natural gas. The amount of methane generated from biogenic sources would then directly displace fossil fuel methane.

However, as with hydrogen, biomass and waste will have higher carbon to hydrogen ratios than methane. Therefore, converting these fuels to methane will leave an excess of carbon which needs to be accounted for to achieve low carbon. Any excess carbon releases would preferentially be captured and stored or used to have a significant impact.

Any process producing methane has to be carefully controlled to prevent methane releases as methane is a far more potent greenhouse gas than carbon dioxide.

12.4 Liquid fuels

The technologies assessed have the capability to make different liquid fuels such as diesel, ethanol or aviation fuel. These will directly displace fossil fuels used for transport. The amount of carbon emissions reduced will depend on how biogenic the fuel produced is. As biomass is carbon neutral this will be more significant than fuels with large amounts of plastic. However, as biomass or waste will not have the exactly the same carbon to hydrogen ratio as the liquid fuel to be produced, there will still be an imbalance with some potential release of carbon which will need to be managed and preferentially used or stored.

12.5 Syngas to chemicals

It is also possible to use the technologies considered to make chemicals, typically from a chemical feedstock such as methanol which can then be converted to other chemicals. These chemicals are today produced from fossil fuels and so this provides the opportunity to avoid direct use of fossil fuels in producing these chemicals. Depending on how these chemicals are used, they may still release carbon dioxide. Assessing the actual contribution to net zero is therefore quite complex, as some of the chemicals may be released relatively quickly as carbon dioxide if the products are consumed and releases not controlled, whilst others potentially bind in the carbon removing it from the atmosphere. For example, if the chemical feedstock is used to produce plastics and the plastic is collected after use and disposed of in a controlled manner, the carbon will be locked away, Ultimately a solution could be foreseen whereby plastics are collected and used as the fuel to the AGT, creating a closed recycling loop.

As with all the other products proposed, there will be an inevitable imbalance between the carbon to hydrogen ratio in the fuel and in the product stream, so management of any excess carbon will be required to avoid carbon releases.

13 Process safety

13.1 General health and safety

Gasification and pyrolysis plants are process plants which in addition to the usual inherent health and safety hazards will have specific hazards related to the storage, handling and processing of flammable feedstocks, syngas, pyrolysis oil, pyrolytic carbon and ultrafine carbon dusts. While the general hazards should be readily manageable through good plant design, maintenance and operation, several areas of the process plant will have specific hazards which will need to be addressed.

13.2 Fire and explosion risks

Gasification and pyrolysis plants receive, store and handle biomass, waste derived fuels and tyre crumb which are flammable and when not stored correctly can lead to spontaneous combustion of the feedstock piles. Furthermore, syngas, pyrolysis oil, light hydrocarbons and intermediates produced during upgrading are all flammable. In addition, the jet milling process for the upgrading of pyrolytic carbon to rCB will generate ultrafine carbon dusts which is also combustible.

Consequently, the following risks will exist.

1. Risk of spontaneous combustion of flammable particulates and ultrafine carbon dusts if the dust level in the plant is not controlled according to the required standards.
2. Risk that the syngas could leak from plant/equipment and mix with ambient air to create a potentially explosive atmosphere.
3. Risk that air could leak into the system and mix with syngas to produce a potentially explosive mixture.
4. Risk of spontaneous combustion of flammable vapours from the hydrocarbon production, handling and storage process.

Consequently, detailed fire risk assessment studies are essential for these plants to identify the potential risks and to design the appropriate systems to manage and to mitigate against the risk of fire.

13.3 Toxicity risks

Both gasification and pyrolysis produce gases which contain high concentrations of CO which is toxic. Moreover, in emergency situations it is not possible to stop either process unless a nitrogen blanketing or other quenching system is used.

Consequently, zoning studies are essential on completion of detailed designs to determine the ATEX zoning for the plant and to inform the instrumentation selection process. Additionally, suitable locations for building CO detectors need to be identified as part of the Dangerous Substances and Explosive Atmospheres (DSEAR) assessment (or equivalent). We would also recommend the use of CO detectors for personnel protection and protection against the risk of fire/explosion.

13.4 Safety studies

Like petrochemical plants, robust and detailed safety studies are needed at the design stage to assess the process and general safety risks. Key studies will include the hazard and operability (HAZOP) studies, dangerous substances and explosive atmospheres risk assessment, hazardous area zoning studies and safety integrity level assessments. Functional safety assessments will be required prior to finalising the design of integrated control systems.

14 Commercial assessment

14.1 Technical assumptions in project models

When developing a financial model for an advanced gasification technology projects, a number of technical parameters are needed. As many technical parameters interact with each other (for example, waste throughput, waste calorific value and fuel output are not independent), it is important to determine which parameters are assumptions and which can be determined from other parameters.

We consider that the following technical assumptions are critical.

1. Waste processing capacity

This should be per hour and based on the thermal input rather than tonnage. This is because the processing capacity (in tonnes) varies depending on the calorific value of the waste.

2. Operating hours

This can vary by year if major maintenance is known about.

3. Conversion rate of waste to fuel

For plants which are primarily intended to produce fuel, this is the key output parameter. It should be set as a conversion rate rather than a tonnage rate so that the production rate will vary depending on waste availability and operating hours.

If the plant is primarily sized for fuel production, then the primary assumption could be the fuel generation capacity and the model could calculate how much waste is needed to make the fuel.

4. Power generation

Many technologies generate power as a by-product even if this is not the primary output.

5. Parasitic load

6. Consumption rates for consumables

These should be set as consumption rates per tonne of waste or maybe per tonne of fuel.

14.2 Cost of feedstock pre-treatment

As described in section 4, the cost of pre-treatment will vary widely depending on the feedstock and the AGT process requirements. Some of the potential feedstocks such as waste wood, waste plastics or agricultural waste streams will be relatively homogeneous and need little additional pre-treatment other than some screening and magnets to safeguard downstream equipment. This type of equipment would typically be built into the fuel storage and handling equipment and the costs would be included there.

RDF would normally be delivered in the form needed for the process, so the cost of preparing the RDF would be included in the gate fee received for the material, which will be significantly lower than for untreated MSW or C&I waste. As with waste wood, screening and additional metal separation would normally be included within the fuel store/handling equipment. There may be unbaling costs which is normally achieved by using a shredder capable of taking whole bales.

Some fuels may require additional drying. This would typically be achieved using a rotary drier or similar to improve efficiency and net zero potential. If drying is carried out on site this would normally use waste heat from the process. Estimating the cost is very dependent on the initial moisture in the fuel, the required moisture for the AGT process and the source of the heat. This therefore needs to be estimated on a case by case basis.

Pre-treatment costs are estimated below. These costs include the operating and maintenance cost of the equipment, plus its initial cost, on a £/t basis over the life of the project. They are estimated as the on-site costs and exclude the cost or gate fee for the delivered material and storage costs. For the reasons stated above, drying costs are not considered.

1. Wood chip

If chipped this may either be carried out at source, for example if the wood is imported, and therefore the cost of chipping will be included in the cost of the fuel, or it may be carried out on site if the wood delivered is roundwood, branches or forestry trimmings. In this case a wood chipper would be used on site, powered by electricity for net zero purposes. Chippers are relatively expensive, need frequent maintenance to replace blades and use a reasonable amount of electricity. The operating and maintenance cost is likely to amount to about £10-12/t of virgin wood chip. Wood chip may also require drying but as this is process dependent any such costs need to be assessed on a case by case basis. Once chipped the wood is likely to be stored inside, especially if dried, to prevent rain wetting it.

2. Wood pellets

Wood pelletising will be carried out at source prior to shipping. The cost of pelletising will be therefore included in the delivered fuel price. Pelletising is relatively expensive, requiring grinding, drying and then pelletising, all requiring energy and high maintenance equipment. Producing wood pellets is estimated[34] to cost about €30-60/t of pellets for the pelletising stage alone. However, there will be no additional fuel pre-treatment costs at site. Pellets must be received, handled and stored internally as the pellets will absorb water and lose their form.

3. Waste wood

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[34] Wood pellet supply chain costs – A review and cost optimization analysis L. Visser*, R. Hoefnagels, M. Junginger Copernicus Institute of Sustainable Development, Utrecht University, Princetonlaan 8a, 3584 CB, Utrecht, the Netherlands

Most waste wood will be sourced from wood recyclers who separate waste wood streams into recyclable streams and streams more suited to energy recovery. As such, most pre-treatment is likely to have been carried out off site with the waste delivered to the AGT plant against a specification. Normally the plant will require screens and additional magnets to protect against some undesirable material slipping through, but this would be built in to the fuel storage facility.

4. Untreated MSW or C&I waste

Few, if any, AGT processes will be able to take untreated MSW. If untreated waste is received and it is processed on site, the cost is very dependent on the quality of material required by the AGT process. Some processes may be able to handle basic RDF, where the waste has been shredded to the desired size and metals removed by magnets. Such material is likely to cost £15-20/t to produce. Other AGT processes are likely to require more advanced processing, including pre-shredding, metal, stone and glass separation, mechanical sorting and then secondary shredding to the desired size. Depending on the quality of RDF required, such processing is likely to cost £25-40/t, bearing in mind some of the separated material needs to be disposed of as a waste stream at a cost. Some processes will also require drying, but as stated above the cost of this needs to be assessed on a case by case basis. Reception, pre-treatment and storage will all require to be inside to control odours and dust.

5. IEA Bioenergy has produced a report[35] assessing the costs for pre-treatment of MSW for gasification. This estimates the mechanical treatment of MSW in Germany to produce a rough RDF costs €5-15/t of incoming waste. As with the estimate above, this is based on the capital and operating cost of the equipment, so is comparable. The same report also estimates the operating cost of Italian mechanical biological treatment plants which will produce a higher quality RDF to be €52-118/t of incoming waste. However, the cost basis is different, including the disposal cost of relatively small amounts of the high quality SRF as well as all the other output streams, which explains why the cost is significantly greater than estimated above.

6. RDF

RDF is produced from MSW or C&I waste. It can be produced off-site to a specification, in which case on-site pre-treatment is limited and the cost is included in the reduced gate fee received for the RDF. Depending on quality, the gate fee received for RDF can be £15-40/t less than untreated MSW. Where off-site RDF is provided, some on-site screening and metal separation is likely to be beneficial to reduce problems in the AGT process. The cost of this equipment would be built into the reception and storage facility. Reception, pre-treatment and storage will all require to be inside to control odours and dust.

Estimated costs are summarised in the table below.

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[35] Biomass pre-treatment for bioenergy. Case study 3: Pretreatment of municipal solid waste (MSW) for gasification. IEA Bioenergy 2019

Table 9: Estimated On-Site Pre-Treatment costs

Feedstock	Main pre-treatment	On-site treatment	On-site costs	Exclusions
Wood chip	On or off-site	Chipper	£10-15/t	Drying. Screens/magnets to be included in storage costs
Wood pellets	Off-site	None	-	Screens to be included in storage costs
Waste wood	Off-site	None	-	Screens/magnets to be included in storage costs
Agricultural waste	Off-site	None	-	Screens/magnets/debaler to be included in storage costs
MSW	On-site	Shredder/magnet Full mechanical treatment	£10-15/t £20-45/t	Drying
C&I	On-site	Shredder/magnet Full mechanical treatment	£10-15/t £20-45/t	Drying
RDF	Off-site	None	-	Screens/magnets/debaler to be included in storage costs
Plastic waste	Off-site	None	-	Screens/magnets/debaler to be included in storage costs

14.3 Plant availability

Assessing the availability of an advanced gasification technology is not as simple as it might appear. This is because availability can be described in a number of different ways and while they may all be valid in the correct context, they may be misleading if used incorrectly.

There are three broad ways to assess how much a plant is available.

1. Time-based availability.

This is the simplest approach. If a plant is capable of receiving waste at any point, then it can be said to be available. However, this does not show the full picture as the plant may not be capable of operating at its full capacity, or it may not be capable of producing the output at full capacity even if it can process waste. For plants which operate in semi-batch mode, such as plants which process solid waste into a syngas and then store the syngas before processing it, it is important to identify which part of the plant the availability relates to.

If the primary concern is whether the plant will receive and process waste, and therefore receive gate fees, then time-based availability may be sufficient. If the assessment of the plant performance also takes account of the throughput, then using a time-based availability combined with a factor for the operating capacity may be appropriate.

2. Feedstock availability.

Another way to express availability is as a percentage of the maximum feed capacity. For example, if the plant has a design throughput of 10 tonnes per hour then it could theoretically process 87,600 tonnes of waste in a year. If it actually processed 75,000 tonnes then the availability could be expressed as 75000/87600 = 85.6%.

One problem with this method is that waste varies. Some plants are more likely to be limited by thermal capacity, so availability could be expressed in relation to that instead. Another problem is that the main purpose of the technologies considered in this report is the production of fuel; focusing on the ability to process waste may not be sufficient.

3. Power or output availability.

For plants or technologies whose primary output is a material product, the availability can be expressed as a percentage of the output capacity. In order to produce the material product, such as fuel, all of the plant needs to be operating and the total output can easily be added together over the whole year. To give a full picture of plant performance, the amount of waste needed to produce the output can be used as an additional parameter and this can vary depending on the type or composition of waste being processed.

For plants whose primary output is electricity, particularly if the processing capacity is limited by the thermal capacity, expressing availability as a percentage of the maximum power output can give the most useful assessment.

Our preferred approach is to consider the output availability, as this takes account of the operating hours and the operating capacity in one simple measure.

Appendix A: Gasification technologies

A.1 A.H.T Syngas Technology

A.1.1 Technology description

The A.H.T Syngas Technology (A.H.T) gasifier is a double-fired air blown downdraft-updraft modular gasifier. The term double-fired refers to the ability to operate in both downdraft and updraft mode. A.H.T has reported that its system can be fuelled by a range of coals, virgin wood chip and a variety of waste biomass feedstocks.

The A.H.T system consists of one or more downdraft-updraft gasifiers coupled to a cyclone separator, wet syngas clean up system and a syngas engine. The gasifier can have an operational temperature of up to 1200°C in the oxidation zone. Some of the ash entrained in the syngas is recovered in the cyclone. Extraction of some of the other contaminants in the syngas occurs in the wet syngas clean up system. The syngas is then burnt in a syngas engine to produce electricity. A schematic of the A.H.T gasifier is shown below.

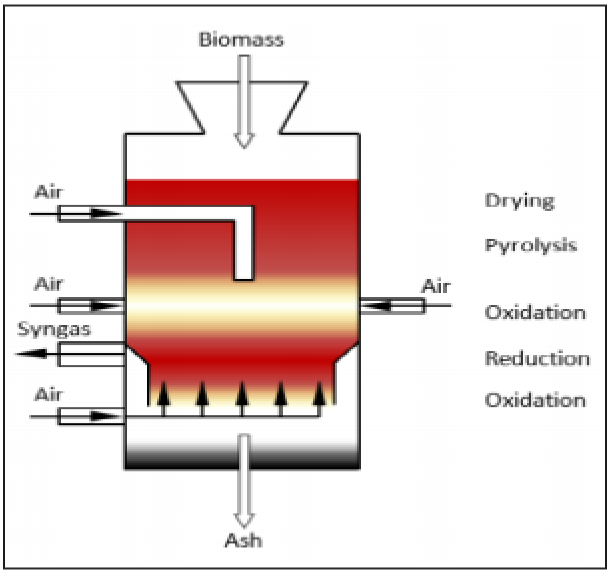

Figure 27: Schematic of the A.H.T gasifier system

Source: A.H.T Syngas Technology

According to A.H.T, the system can generate approximately 400 kWe from a throughput of 330 kg/h of clean wood. Currently, the technology is configured solely for the production of electricity.

A.1.2 Reference plants

We are aware of the A.H.T technology being used at the 4 reference facilities listed below.

Table 10: A.H.T. Syngas Technology N.V. reference plants

Location	Feedstock	Date Operational	No. of modules	Output (kWe)
Chur, Switzerland	Hydrochar	Under construction	1	200
Kessennuma, Japan	Clean woodchip	2015	2	800
Kalimantan, Indonesia	Black coal	2011	7	6,930
	Biomass	Unknown	1	200

A.1.3 Conclusion

The A.H.T gasifier is a small modular system which is designed for gasification of clean feedstocks using an air blow system to generate power. The low throughput capacity and limited application for complex waste feedstocks make it unsuitable for any further consideration in this study.

A.2 Alter NRG / Westinghouse Plasma Corporation

A.2.1 Technology description

The Alter NRG plasma gasification technology was acquired from Westinghouse Plasma Corporation (WPC) in 2007 when Westinghouse was bought by AlterNRG. According to public information the process was intended to be able to run on MSW, RDF, automotive shredder residue (ASR) and waste tyres.

The Alter NRG process is a conventional fluidised bed gasification system in which air is used as the gasifying agent. Plasma torches located near the solids discharge outlet of the gasifier produce a plume of very hot air (5,000 – 7,000°C) which is then used to melt ash entrained in the syngas. The slag produced is removed from the bottom of the reactor in a molten state. Syngas which leaves the reactor at 890-1100°C is cooled and cleaned before being combusted to produce steam to drive a steam turbine or is burned in a gas turbine. A schematic of the Alter NRG gasification reactor is shown below.

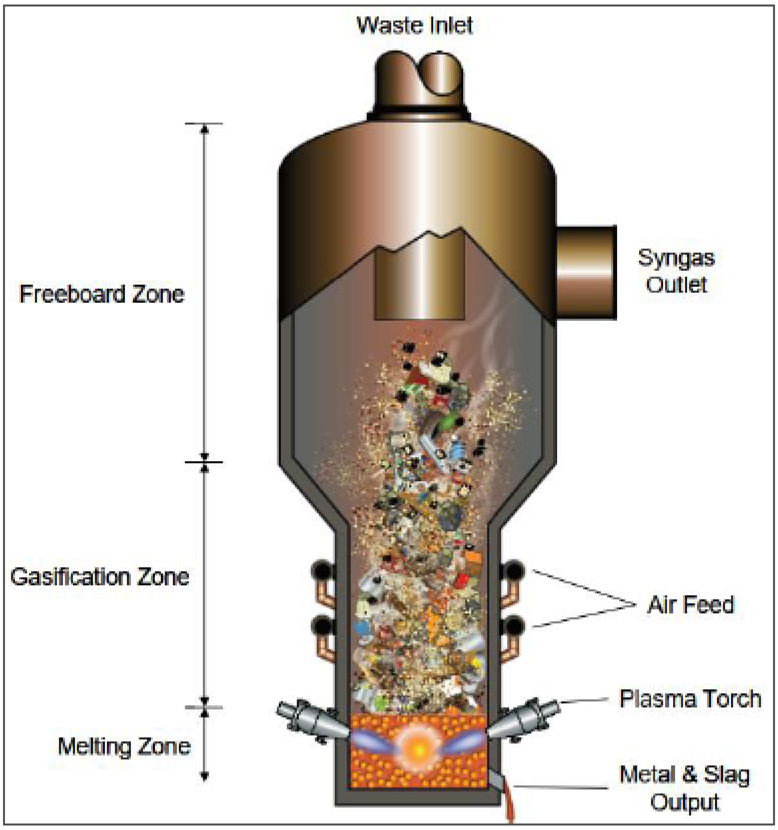

Figure 28: Schematic of the Alter NRG plasma gasification system

Source: Alter NRG

A.2.2 Reference plants

The Alter NRG/WPC technology has seven reference plants which are listed below.

Table 11: Alter NRG/WPC reference plants

Location	Feedstock	Date operational	Throughput	Output
Yoshii, Japan[36]	MSW	1999	24 tpd	Steam
Utashinai, Japan[37]	MSW and ASR	2003	55,000 tpa	4.7 MWe[38]
Mihama-Mikata, Japan	MSW and sewage sludge	2003	7,000 tpa	Domestic hot water
Pune, India	Hazardous waste	2009	72 tpd	1.6 MWe[39]

Figure 28: Schematic of the Alter NRG plasma gasification system

Source: Alter NRG

A.2.2 Reference plants

The Alter NRG/WPC technology has seven reference plants which are listed below.

Table 11: Alter NRG/WPC reference plants

Location	Feedstock	Date operational	Throughput	Output
Yoshii, Japan[36]	MSW	1999	24 tpd	Steam
Utashinai, Japan[37]	MSW and ASR	2003	55,000 tpa	4.7 MWe[38]
Mihama-Mikata, Japan	MSW and sewage sludge	2003	7,000 tpa	Domestic hot water
Pune, India	Hazardous waste	2009	72 tpd	1.6 MWe[39]
Wuhan, China	Biomass	2013	100 tpd	Diesel fuel[40]
Shanghai, China[41]	Hazardous waste	Unknown	30 tpd	Electricity (MW unknown)
Tees Valley, UK	RDF	Project abandoned	700,000 tpa	50 MWe

A.2.3 Conclusion

The AlterNRG process hit significant problems in the UK when Air Products used it to build two lines at Tees Valley to process RDF. The first line only ran a few hours due to significant technical problems which led to Air Products abandoning the scheme after very significant investment.

Like most fluidised bed systems, rather than burning the syngas generated it would be possible to couple the fluidised bed with a syngas clean-up and upgrading system to generate liquid fuels or chemicals. However, Alter NRG does not currently supply any such system. Consequently, it will not be considered in any further detail in this study.

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[36] This was a commercial demonstrator, it is no longer operating as it was decommissioned after the end of the pilot program.

[37] Closed due to technical issues and loss of long term feedstock contracts.

[38] Net export potential.

[39] This was design intention but it has been reported that due to technical issues it has never produced any power.

[40] We are unable to verify if this plant has successfully produced diesel fuel at a commercial scale.

[41] Demonstration facility.

A.3 Babcock & Wilcox Volund

A.3.1 Technology description

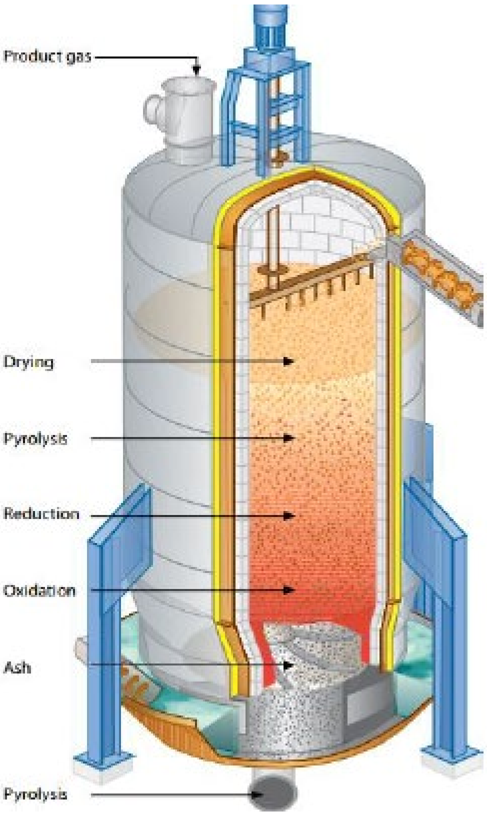

Figure 29: Schematic of B&W Volund updraft gasifier

Source: B&W Volund

Babcock & Wilcox Volund (BWV) developed an updraft gasifier capable of gasifying clean wood chips. In the BWV gasifier, wood chips are continuously fed into an upright cylindrical furnace. The feedstock is heated by hot air which is drawn up through the revolving grate and which flows from

the base to the top of the fuel bed. Gasification takes place at around 800-1100°C. The syngas produced is then cleaned and particulates are removed before it is combusted in gas engines to generate electricity. An illustration of the BWV gasifier is shown in Figure 29

A.3.2 Reference plants

Five BWV reference plants are listed in the table below. BWV has also reported that plants based on the a similar design were built in Japan in 2005 after the technology was licensed to the Japanese company JFE Engineering Corporation.

Table 12: BWV gasification reference facility

Location	Feedstock	Date operational	Thermal input	Output
Harboøre Varmeværk, Denmark	Wood chips	2001	3500 kW	1 MWe, 1.9 MWth
Ansager, Jutland, Denmark	Wood chips	2006	200 kW	37 kWe
Yamagata, Japan	Wood chips	2007	8 MW	2 Mwe
Ishikawa, Japan	Wood chips	2008	9 MW	2.5 MWe
Shikokuchuo-shi, Japan	Wood chips	2008	12MWth	Fuel gas

A.3.3 Conclusion

BWV is no longer supplying gasification plants and has withdrawn from the gasification sector. On this basis the technology will not be considered in any detail in this study.

A.4 Biomass Engineering Limited

A.4.1 Technology description

Biomass Engineering Limited (BEL) supplies modular downdraft air-blown gasifiers that are fuelled by clean wood. Syngas produced in the vessel is filtered and cooled from 400-500°C to 20-30°C before being combusted in a syngas engine to generate electricity. Residual ash and char falls through the grate and are collected in the ash collection system. A schematic of the BEL process is shown in Figure 30.

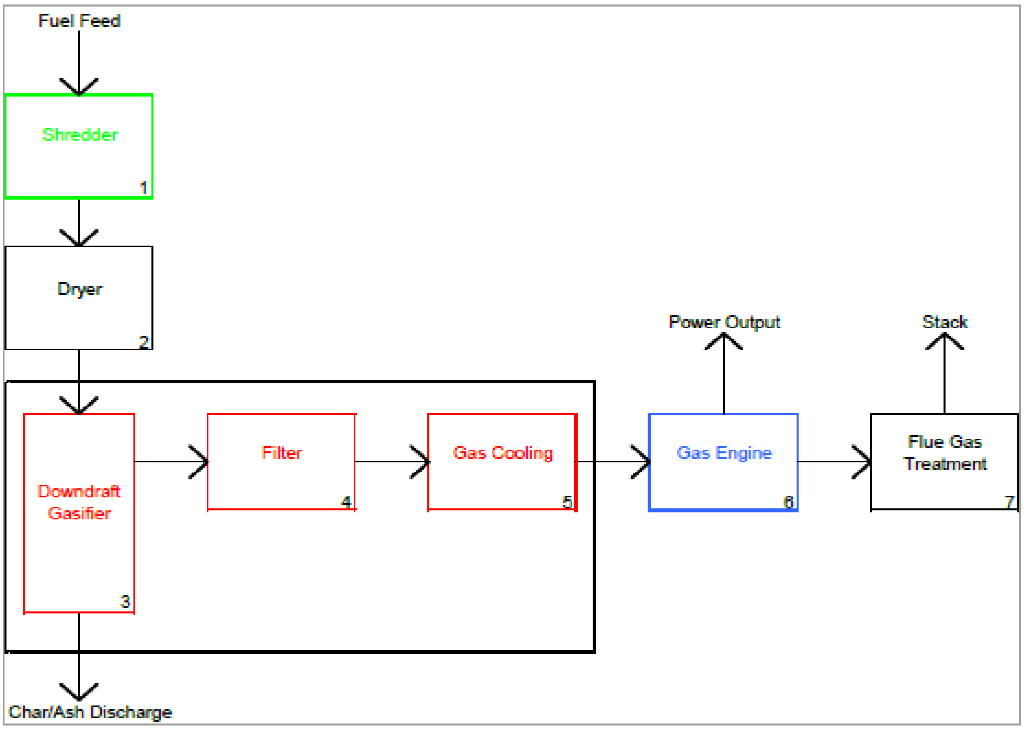

Figure 30: Schematic of the BEL gasification system

Source: Biomass Engineering Limited

The largest BEL gasification vessel has a throughput capacity of 250 kg/hr of wood fuel, nominally generating 250 kWe of electricity.

A.4.2 Reference plants

Up to nine plants were expected to be built mainly in the UK. However, we have been unable to find any evidence in the public domain to suggest that any of these plants are in operation We are aware of nine BEL references plants which are listed below.

Table 13: BEL commercial reference plants

Location	Feedstock	Date Operational	Output (kWe)
Wildshausen	Clean wood	June 2006	270
Culcheth	Clean wood	July 2006	85
Oxford	Clean wood	September, 2006	250
Penrith	Clean wood	December, 2006	1,000
Dortmund	Clean wood	December, 2006	270
Merseyside	Clean wood	March, 2007	2,000
Preston	Wood/coppice	March, 2007	1,000
Merthyr Tydfil	Waste wood	April, 2007	1,000
Stoke	Reclaimed wood	May, 2007	3,000

BPL has supplied the gasification technology for the Hoddesdon and Belfast gasification plants which are operational. A schematic of the BPL process is shown below.

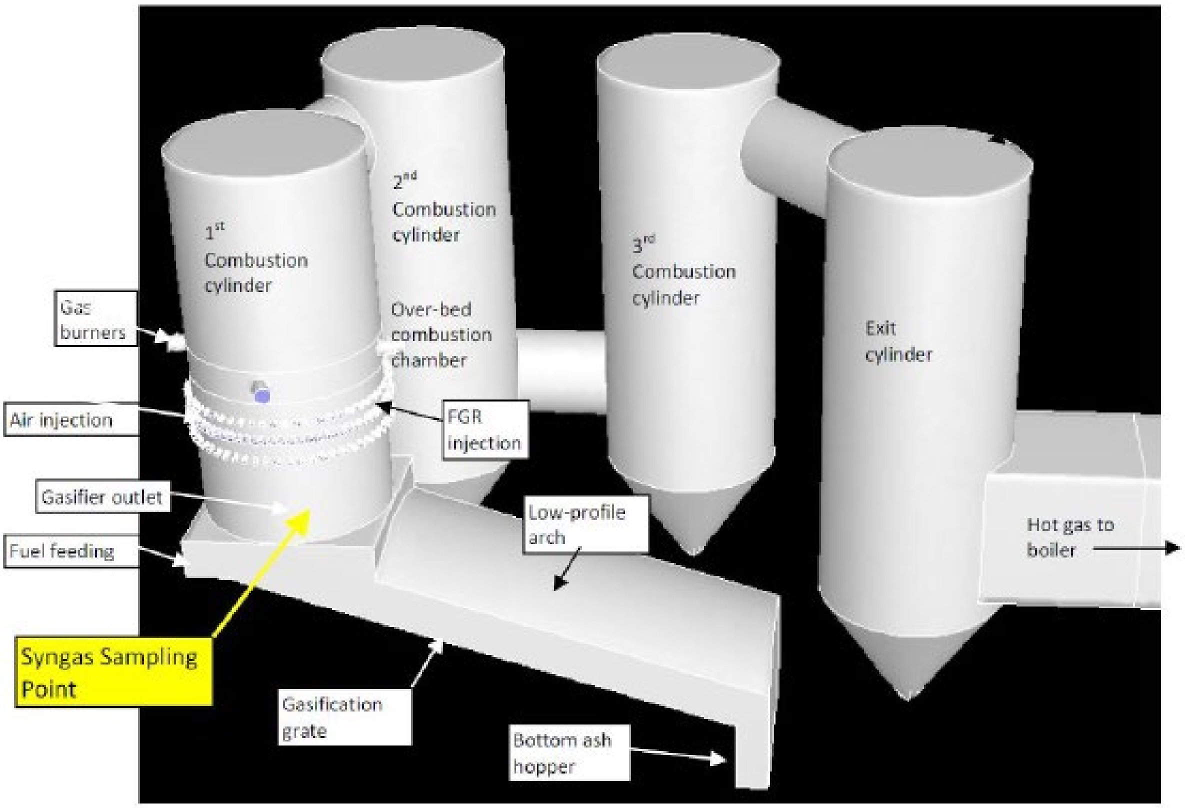

Figure 31: Schematic of the BPL inclined moving grate gasifier and secondary combustor system

Source: Biomass Power Limited

BPL went into voluntary liquidation in 2019.

A.5.2 Reference plants

The six BPL gasification and combustion reference plants are listed below.

Table 14: BPL grate combustor and gasifier references

Location	Feedstock	Date Operational	Plant Type	Thermal input (MWth)	Energy Recovery
Norbord, UK	Chipboard plant residues	2006	Moving grate combustor	12	10 MWth
Eccleshall, UK	Biomass	2007	Moving grate combustor	13	2.65 MWe
Enviropower, UK	Biomass	2009	Moving grate combustor	2 x 13	5.08 MWe
Bagnolo, Italy	Woodchip	2012	Moving grate combustor	17.4	3.7 MWe
Hoddesdon, UK	RDF	2020	Moving grate gasifier	2 x 23	9 MWe
Belfast, UK	RDF	2019	Moving grate gasifier	3 x 23	15 MWe

A.5.3 Conclusion

BPL is in voluntary liquidation.

Moving grate gasifiers produce a syngas which has a very low concentration of H_2 and CO and a high concentration of particulate matter and other contaminants entrained in the syngas. Increasing the H_2 and CO

content of the syngas from these systems will require significant investment which is likely to be prohibitive. Furthermore, the syngas will require extensive clean up prior to syngas conversion which will have a low yield. On this basis the technology will not be considered in any detail in this study.

A.6 British Gas/Lurgi

A.6.1 Technology description

Whilst similar to the Lurgi dry-ash gasifier, the British Gas/Lurgi (BGL) consortium gasifier operates at a much higher temperature (~2000°C) so as to produce a non-leaching slag instead of dry ash. Unlike the Lurgi dry-ash gasifier, the BGL gasifier incorporates a motor driven distributor/agitator for the distribution of incoming coal feed. It has been reported that the BGL gasifier can co-gasify coal with RDF pellets and briquetted sewage sludge. Publicly available information on the technology also claims that the technology can co-gasify sewage sludge with a limited amount of shredded wood waste (up to 10%), however it is not known if long term operation under these conditions has been demonstrated. The technology is currently jointly owned by Envirotherm and Zemag Clean Energy Technology. A schematic of the BGL process is shown in Figure 32.

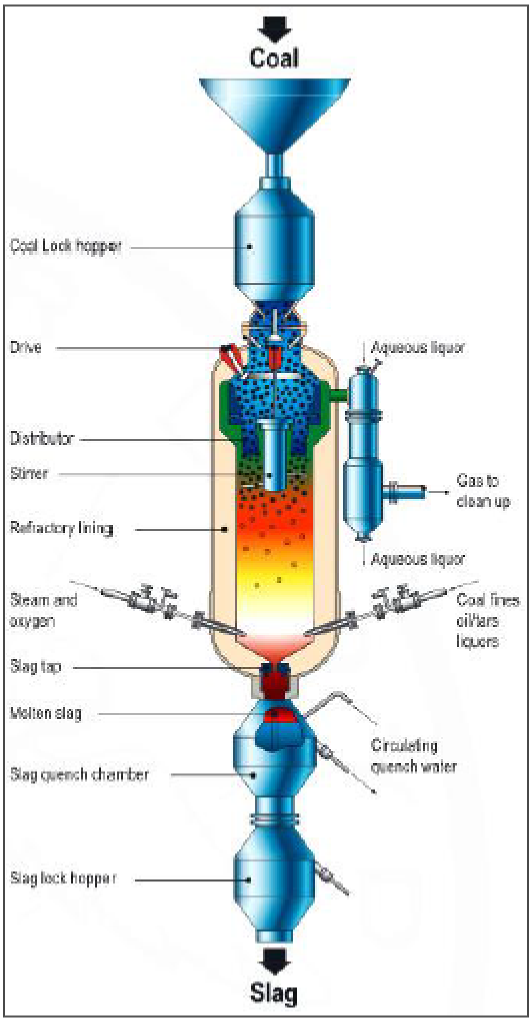

Figure 32: Schematic of the BGL slagging gasifier

Source: British Gas/Lurgi

A.6.2 Reference plants

As of 2018, Envirotherm reported the following BGL reference/test facilities.

Table 15: BGL operating reference facilities

Plant	**Location**	**Start-up year**	**Capacity (t/h)**	**Feedstock**	**Output**
SVZ Schwarze Pumpe	Schwarze Pumpe, Germany	2000	35	Hard coal, Lignite, RDF	35,000 Nm$_3$/h syngas
Yuntianhua	Hulunbeier, Inner Mongolia, China	2012	130	Dried and briquetted lignite	500,000 t/y ammonia, 800,000 t/y urea
Yituo	Luoyang, Henan province, China	2013	30	Local hard coal	Fuel gas for industrial complex
China National Coal	Ordos Tuke, Inner Mongolia, China	2013	210	Bituminous coal	1,000,000 t/y ammonia, 1,750,000 t/y urea
Freiberg University of Mining and Technology[42]	Freiberg, Germany	2014	1.4	Lignite and others	2,300 Nm3/h syngas

A.6.3 Conclusion

With the exception of the plant at Schwarze Pumpe, the British Gas/Lurgi technology has been operated on a variety of types of coal. At the Schwarze Pumpe plant a mixture of RDF, plastic waste and coal were used to fuel the plant to produce syngas for power generation and for the production of methanol. Overall, the technology has been operated commercially on coal and demonstration of the technology on mixtures of coal, RDF and plastics has been done. We have not found any publicly available information to suggest that the technology has a track record in converting biomass and waste derived feedstocks to fuels. On that basis this process will not be considered in any further detail in this study.

A.7 Chinook Sciences

A.7.1 Technology description

Chinook Sciences has developed and operated a batch gasification process known as the RODECS® system for the recovery of metals from automotive shredder residue (ASR). According to Chinook, the gasifier system can be operated on a wide variety of wastes including RDF and MSW and pre-treatment of the wastes is not required.

Batches of feedstock are heated to 550 - 600°C using air and the syngas produced is discharged to a conventional boiler where the heat from combustion of the syngas is used to raise the steam to drive a steam turbine. Particulates collected by the cyclone are discharged to the RODECS bin. The batch cycle is completed when gasification is completed and the particulates along with the residual waste in the bin are discharged. Currently the technology is not configured for the production of liquid fuels.

A.7.2 Reference plants

We are aware of three Chinook reference plants which are listed in the table below.

Table 16: Chinook reference plants

Location	**Feedstock**	**Date Operational**	**Gross electrical output (MWe)**
New Jersey, USA	Various metal based residues, MSW	2010	N/A
Pennsylvania, USA	Various metal based residues, MSW	2011	N/A
Oldbury, UK	ASR and industrial waste	2015	11

A.7.3 Conclusion

The Chinook process has only been used to date for metal recovery from waste streams or for power production.

The batch process used by Chinook produces syngas of variable quality over the batch cycle. In our view this type of process is unlikely to provide consistent, suitable syngas as required for a chemical conversion process to make quality fuels or chemicals. On this basis the technology will not be considered in any detail in this study.

A.8 Concord Blue

A.8.1 Technology description

In the Concord Blue (CB) staged reforming technology, the fuel initially undergoes pyrolysis to produce a high calorific value pyrolysis gas. The pyrolysis gas is then discharged to a reformer where a mixture of steam and O_2 are used to reform the pyrolysis gas into a syngas with a high hydrogen content. The syngas produced is then treated in a series of gas clean up systems for the removal of tars and particulates. The treated syngas is then stored before being used on demand by syngas engines. CB has also said that the syngas can be used for the production of commodity liquids.

CB has stated that the process can be operated on a wide range of organic fuels including MSW, RDF, wood chip and hazardous effluent. A schematic of the CB process is shown below.

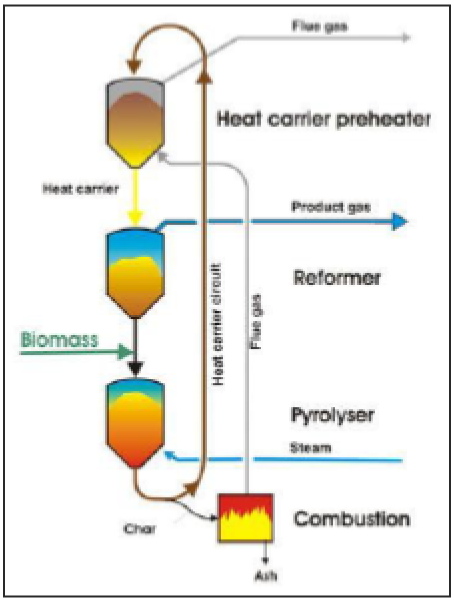

Figure 33: Schematic of the Concord Blue Reformer process

Source: Concord Blue

A.8.2 Reference plants

Concord Blue has 7 reference plants which are listed in the table below.

Table 17: Concord Blue reference plants

Country	Location	Feedstock	Date operational	Feedstock Throughput (t/h)	Plant Output
India	Vasai	MSW	Unknown	0.04	250 kWth; 30 kWe
	Mahad	Sludge digestate	2011	1	3 MWth
	Sikar	MSW	Unknown	4.2	1 MWe[43]
	Pune	MSW	2012	2.5	3 MW
Japan	Omuta	Sewage sludge	2011	5	Hydrogen
	Izumo	Woodchip	2006	1 t/day	0.25 MWe[44]
USA	Owego	Wood	2016	0.45	0.25

A.8.3 Conclusion

There is the potential for the Concord Blue technology to be used for the production of hydrogen and liquid fuels. However, Concord Blue does not currently supply any such system and its development plans are not publicly available. Consequently, the technology will not be considered in any further detail in this study.

A.9 Energos

A.9.1 Technology description

The Energos gasification technology is a close coupled combustion process in which drying, partial combustion and gasification of waste occur on a horizontal oil cooled moving grate. The grate is divided into several separate sections, each with a separate primary air supply generating a syngas. The bottom ash is discharged from the gasification unit at the end of the grate and is cooled in a water-basin before being transported to the bottom ash storage area.

Syngas from the grate then undergoes complete combustion using a mixture of air and recycled flue gas. The heat from the exhaust gases is then used to raise steam for electricity generation. A schematic of an Energos plant is shown below.

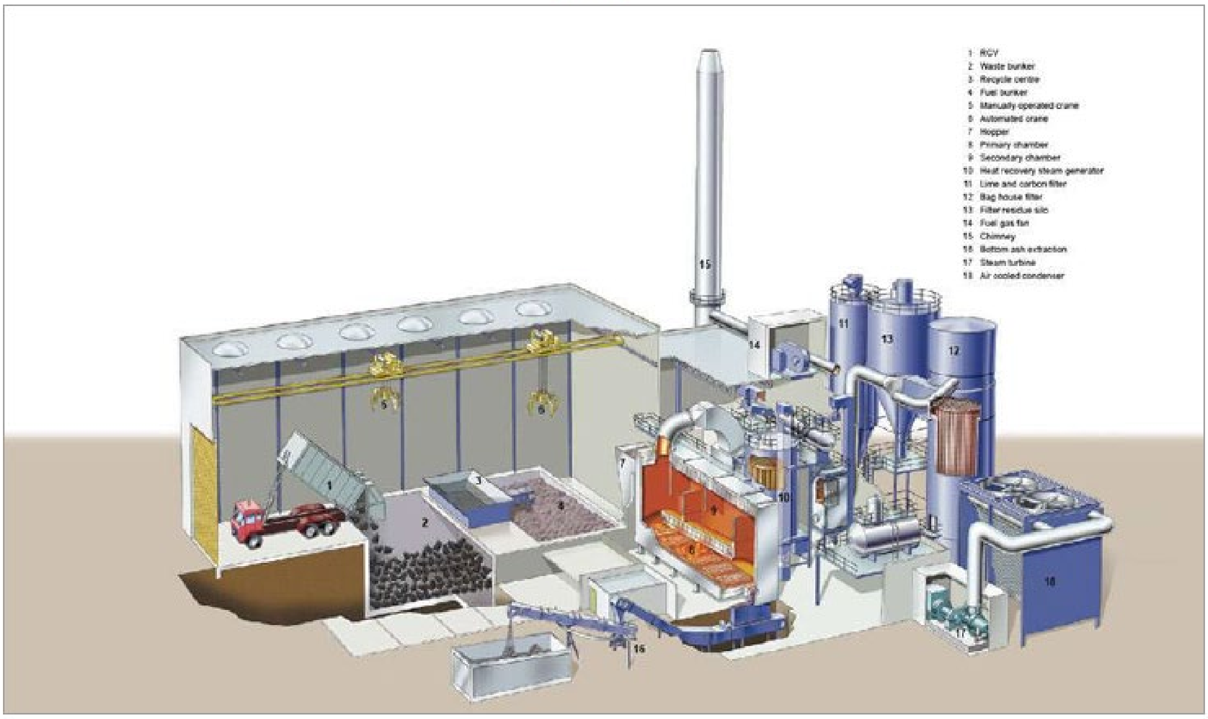

Figure 34: Schematic of the Energos gasification system

Source: Energos

A.9.2 Reference plants

There are 11 Energos reference plants which are listed in the table below.

Table 18: Energos reference plants

Location	**Waste Type**	**Commissioned**	**Capacity (tpa)**	**Output**
Ranheim, Norway	Industrial and Commercial	1997	10,000	Steam
Averoy, Norway	MSW	2000	30,000	Steam and electricity
Minden, Germany	C&I	2000	39,000	Steam
Hurum, Norway	MSW and Commercial	2001	39,000	Steam
Forus, Norway	MSW	2002	39,000	Steam and electricity
Sarpsborg I, Norway	MSW and Industrial	2002	78,000	Steam

Isle of Wight, UK	MSW and Commercial	2009	30,000	Electricity
Sarpsborg II, Norway	MSW and Industrial	2010	78,000	Steam
Milton Keynes, UK	RDF	2018	94,000	Electricity
Derby, UK	RDF	2019	144,000	Electricity
Glasgow, UK	RDF	2019	144,000	Electricity

A.9.3 Conclusion

Energos went into administration in 2017 and no longer markets the technology.

Moving grate gasifiers produce a syngas which has a very low concentration of H_2 and CO and a high concentration of particulate matter and other contaminants entrained in the syngas. Increasing the H_2 and CO content of the syngas from these systems will require significant investment which is likely to be prohibitive. Furthermore, the syngas will require extensive clean up prior to syngas conversion with a low yield. On this basis the technology will not be considered in any detail in this study.

A.10 Enerbee

A.10.1 Technology description

The Enerbee gasification technology is a grate fired staged combustion process which is based on the technology developed by KIV and is similar to the Energos and BPL designs. According to Enerbee the technology was developed for the conversion of biomass and wastes. Each stream has a thermal capacity of 15 - 25 MWth. An indicative schematic of the Enerbee process is shown below.

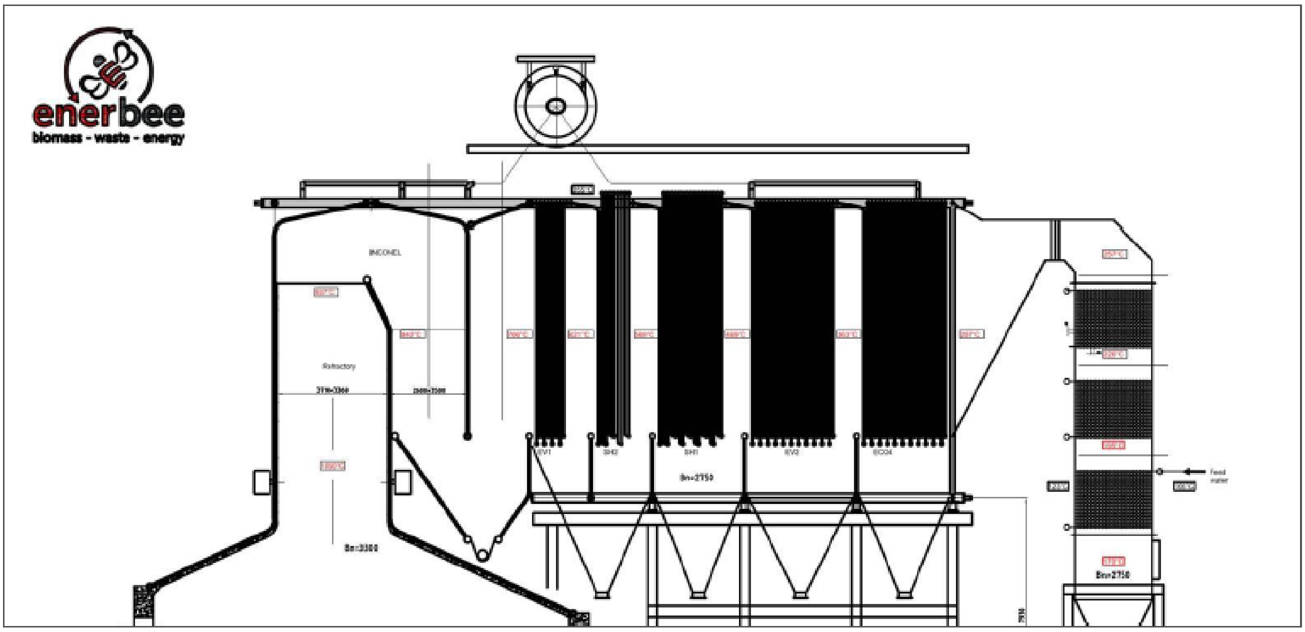

Figure 35: Indicative Enerbee gasification plant schematic

Source: Enerbee

A.10.2 Reference plants

Enerbee has no direct references of their own and issues the reference plants using the KIV technology. A list of the reference plants using the KIV technology are included in the table below.

Table 19: Selected KIV references

Location	Waste Type	Thermal input capacity (MWth)
Celje, Slovenia	RDF + sludge	18
Tyrone, UK	Waste wood	13
Hrast, Croatia	Virgin biomass	20
Sulzbach, Germany	Virgin biomass	22

A.10.3 Conclusion

Enerbee is no longer marketing this technology.

Moving grate gasifiers produce a syngas which has a very low concentration of H_2 and CO and a high concentration of particulate matter and other contaminants entrained in the syngas. Increasing the H_2 and CO content of the syngas from these systems will require significant investment which is likely to be prohibitive. Furthermore, the syngas will require extensive clean up prior to syngas conversion. On this basis the technology will not be considered in any detail in this study.

A.11 Europlasma

A.11.1 Technology description

Gasification in the Europlasma process occurs on a modified grate and is similar to the BPL, Energos, and Enerbee systems. However, unlike other grate based gasification processes the syngas produced is then subjected to hot gas clean-up by the application of thermal plasma at approximately 1,200°C. The treated syngas is then passed through a heat exchanger to remove the sensible heat of the gas followed by treatment in a wet scrubber system. The syngas is then injected into syngas engines. A second plasma torch is used to vitrify the solid ash and char residues into an inert material which Europlasma believes to be suitable for reuse.

Europlasma has reported that these gasifiers can accept a wide range of feedstocks including non-hazardous industrial, commercial and house-hold waste, clean biomass and refuse from automotive grids. Additionally, the waste can be used to fuel the gasifier without prior separation or pre-treatment. Proposed developments using this technology have a maximum gross power output of 12 MWe. An illustration of the plasma assisted gasification process is shown below.

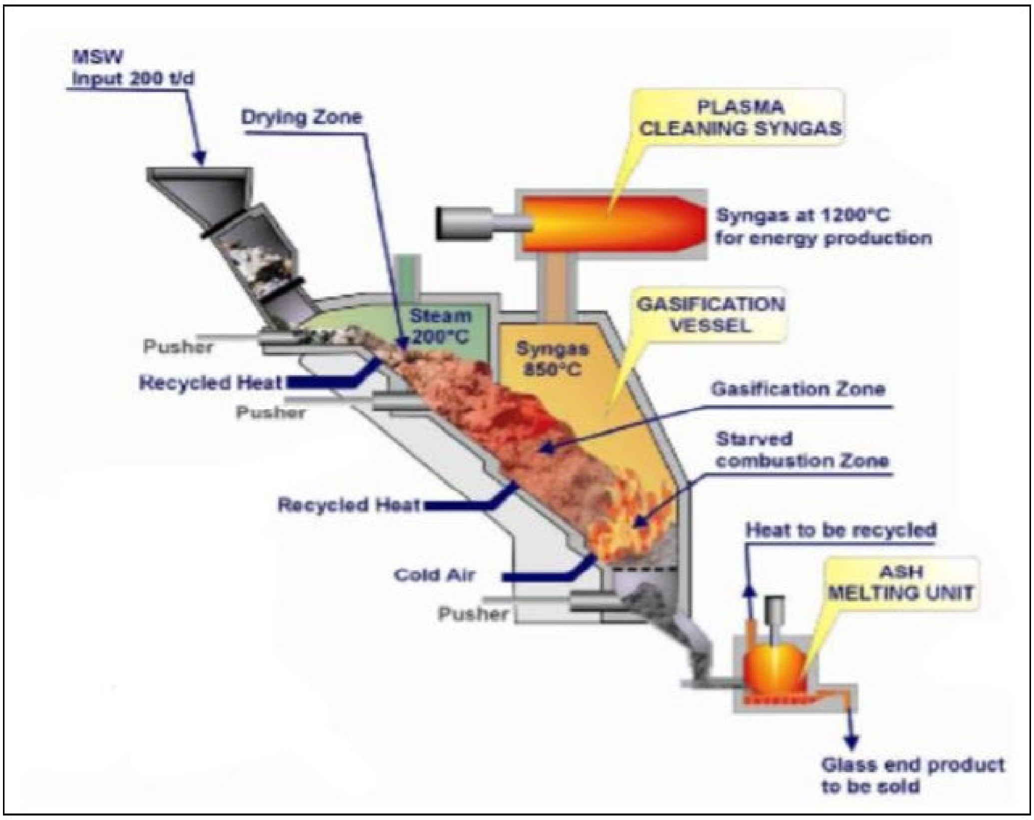

Figure 36: Europlasma gasification process

Source: Europlasma

A.11.2 Reference plants

Currently, there is only a single Europlasma reference plant.

Table 20: Europlasma reference plant

Plant	Commercial operations	Feedstock	Throughput	Output
CHO Morcenx (Landes, France)	June 2017	Woodchips and biomass (15,000 tpa), C&I waste (37,000 tpa)	55,000 tpa	10 MWe, 18 MWth

A.11.3 Conclusion

Publicly available information on Europlasma suggests that the Europlasma gasification system produces syngas with a higher NCV than ‘conventional’ grate gasifier systems. However, Europlasma does not currently supply any system for the production of syngas for upgrading to fuels. On this basis, it will not be considered in any further detail in this study.

A.12 Future Energy Resources Corporation

A.12.1 Technology description

Future Energy Resources Corporation's (FERCO) is the North American licensee of the Battelle circulating fluidised bed (CFB) gasifier technology. Dried biomass fuel is heated in an air-blown gasification system which is indirectly heated by hot sand carried over from the combustion reactor. The combustion reactor provides the heat for the process by combusting residual char and heating up the sand which acts as a heat carrier. The syngas produced is then intended to be used to generate electricity in a combined cycle gas turbine (CCGT). In 2006 FERCO became the SilvaGas Corporation before going to be acquired by Rentech in 2009 and subsequently Sunshine Kaidi New Energy Group Co. Ltd. In 2014. A schematic of the CFB gasifier is shown below.

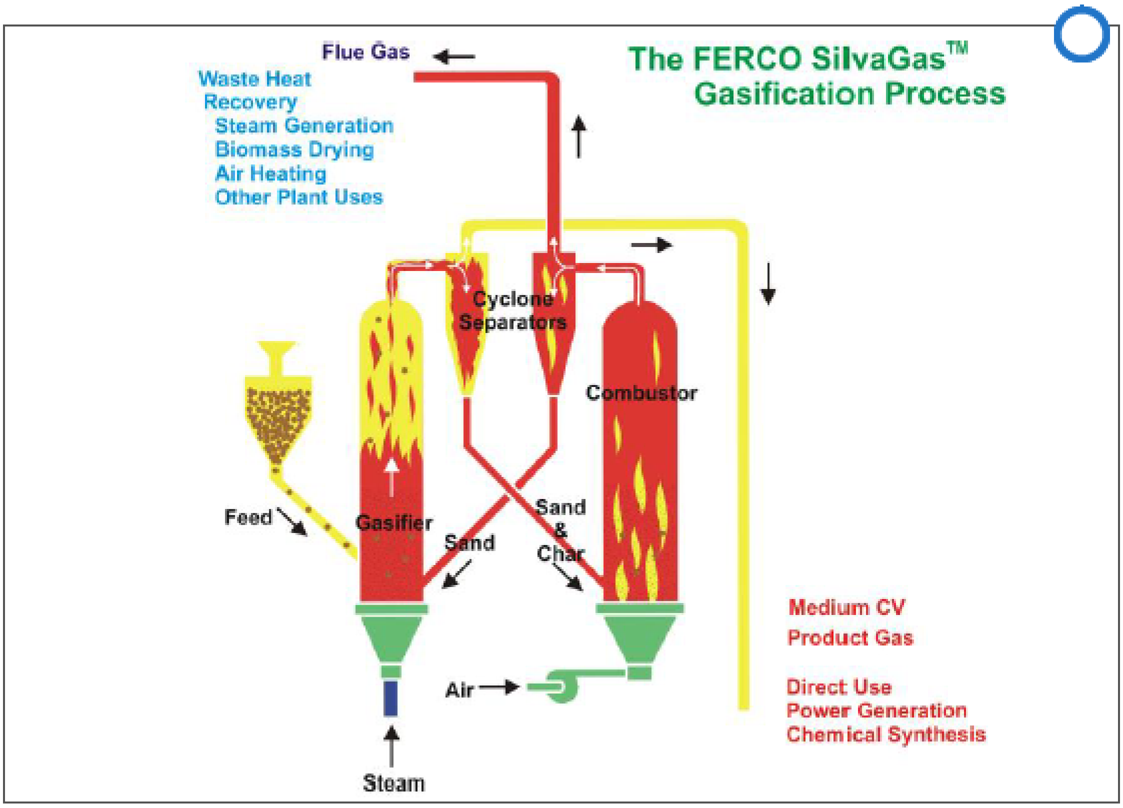

Figure 37: Illustration of FERCO circulating fluidised bed gasifier

Source: FERCO

A.12.2 Reference plants

To date only a single demonstration plant using the FERCO/SilvaGas technology has been built. This plant operated from 1998-2002 in Vermont, USA and had a throughput capacity of 200 tpd (40 MWth). The plant added an additional 7 MWe capacity to the existing boiler at the Joseph C. McNeil Generating Station. Whilst it was claimed that the process could be used to produce synthetic fuels and chemicals, no plants were ever constructed.

A.12.3 Conclusion

The FERCO technology has not been proven and this process will not be considered in any further detail in this study.

A.13 Kobelco Eco Solutions

A.13.1 Technology description

Kobelco Eco Solutions supplies a fluidised bed gasifier system which can be fuelled by a variety of wastes including MSW, C&I waste, and sewage sludge. Gasification is carried out using air.

The Kobelco fluidised bed gasifier system consists of a fluidised bed gasifier coupled to a swirl flow melting furnace. In this system, syngas generated in the gasifier undergoes combustion at approximately 1200°C in the swirl flow melting furnace. The hot flue gases produced are then typically used to produce steam to generate electricity in a steam turbine. Any particles entrained in the syngas undergo combustion in the melting furnace to form a molten slag which is continuously discharged through a tapping hole at the base of the furnace. Incombustible solids in the fuel bed are discharged from the base of the gasifier. A schematic of the Kobelco gasification system is shown in the figure below.

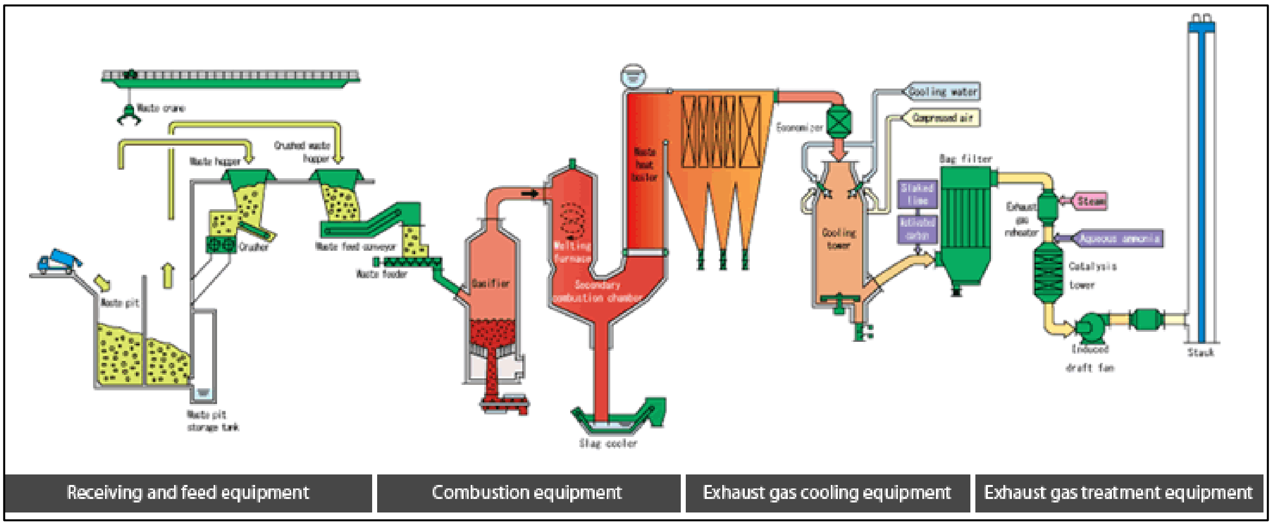

Figure 38: Schematic of the Kobelco gasification system showing the key system components

Source: Kobelco Eco Solutions

According to Kobelco, approximately 28 MWe can be generated from an EfW plant fuelled with an RDF throughput of approximately 300,000 tpa. Currently, the technology is configured solely for the production of electricity. Kobelco has reported that it is considering the development of liquid fuels, but details of the company’s plans have not been made public.

A.13.2 Reference plants

Koebelco has 19 reference plants and these are listed in the table below.

Table 21: Kobelco Eco Solutions reference plants

Location	Waste Type	Start-up Year	No. of Lines	Plant Throughput t/day/stream	Energy Recovery
Chubu-Kamikita, Aomori, Japan	Mixed MSW	2000	2	30	Hot water
Aiki, Hiroshima, Japan	Mixed MSW	2002	2	65	Hot water, 1.3 MWe
Kazuno, Akita, Japan	Mixed MSW	2002	2	30	Hot water and heating
Ishinomaki, Myagi, Japan	Mixed MSW	2003	2	115	Hot water, 2.6 MWe
Nakatsugawa, Gifu, Japan	Mixed MSW	2004	2	49	Hot water, 0.9 MWe
Ono-Katsuyama, Fukui, Japan	Mixed MSW	2006	2	42	Hot water
Nemuro-Hokubu, Japan	Mixed MSW	2007	2	31	Hot water and heating
Sashima, Ibaragi, Japan	Mixed MSW	2008	2	103	Hot water, heating and 3 MWe
Iwade, Wakayama, Japan	Mixed MSW	2008	2	30	Hot water
Pangyo, Seoul, Korea	Mixed MSW	2009	2	45	Steam supply
Kawagoe, Saitama, Japan	Mixed MSW	2010	2	132.5	Hot water, heating and 4 MWe
Sagamihara, Kanagawa, Japan	Mixed MSW	2010	3	175	Hot water, heating and 10 kWe
Paju, Seoul, Korea	Mixed MSW	2011	2	45	Steam supply
Nishi-Akigawa, Tokyo, Japan	Mixed MSW + dug out landfill waste	2014	2	58.5	Hot water
Haga, Tochigi, Japan	Mixed MSW + sewage sludge	2014	2	71.5	Heating and 2 MWe
Kofu, Yamanashi, Japan	Mixed MSW	Under construction	3	123	Not provided
Sennan, Myagi, Japan	Mixed MSW	Under construction	2	100	Not provided
Yamagata Koki, Yamagata, Japan	Mixed MSW	Under construction	2	75	Road heating
Kamilina, Koki, Nagaro, Japan	Mixed MSW	Under construction	2	59	Road heating

Source: Kobelco Eco Solutions

A.13.3 Conclusion

Like most fluidised bed systems, rather than burning the syngas generated it would be possible to couple the fluidised bed with a syngas clean-up and upgrading system to generate liquid fuels or chemicals. In addition, the fluidised bed could be converted to use steam/oxygen instead of air to increase yields. However, as Kobelco does not currently supply any such system and its development plans are not publicly available, it will not be considered in any further detail in this study. It is possible that in the future it could develop its fluidised bed to be used to produce syngas for conversion to fuels in cooperation with other suppliers.

A.14 Lurgi

A.14.1 Technology description

Lurgi (which was acquired by Air Liquide in 2007) is a German developer of a fixed bed updraft gasification system that was first developed in the 1930s. Lurgi’s modular dry-ash gasifiers are designed for operation on lignite and bituminous coals. Coal is fed into the top of the reactor and onto a fixed bed supported on a rotating grate whilst steam and oxygen are fed up through the bottom. Coal is gasified under pressure and gasification takes place around 800°C. Lurgi also developed a CFB fluidised bed gasifier for operation on coal at the Cemex plant in Rudersdorf. This gasifier has since been modified by Outotec.

A schematic of the Lurgi coal gasifier is shown below.

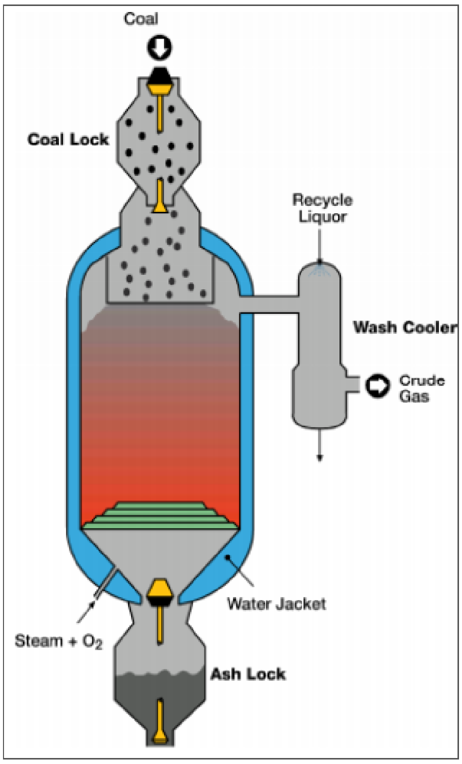

Figure 39: Schematic of the Lurgi gasifier

Source: Lurgi

In conjunction with the Karlsruhe Institute (FZK), Lurgi developed an alternative biomass-to-liquids process with the first stage of the two-stage pilot plant having been reported as completed in 2007. The second stage was planned to be installed in FZK by 2011 but there have been no reports on the status of this pilot. There are no known commercial scale examples of the FZK/Lurgi process. The proposed biomass-to-liquids system divides the process into a fast pyrolysis stage (which is envisioned to be decentralised) followed by a centralised gasification plant that accepts a slurry of pyrolysis oil mixed with pyrolysis coke from the pyrolysis plant.

A.14.2 Reference plants

There are roughly 150 Lurgi dry-ash coal gasifiers in operation in South Africa, China and the United States. The majority of these references are in South Africa where they form an integral part of Sasol’s chemical facilities producing Fischer-Tropsch fuels, ammonia, phenols, anode coke and sulphur. There are no known plants operating on biomass.

A.14.3 Conclusion

The Lurgi technology has only been operated on coal and we have not found any information to suggest that the technology has a track record in converting biomass and waste derived feedstocks to fuels. On that basis the process will not be considered in any further detail in this study.

A.15 New Earth Advanced Thermal

A.15.1 Technology description

New Earth Advanced Thermal (NEAT) gasification system is a modular air-blown system. Each module has a thermal input capacity of 4.2 MWth. According to NEAT the process can be fired on biomass or waste feedstocks. The syngas produced is burnt in a combustor to raise steam for generation of electricity in a steam turbine. A schematic of the NEAT process is shown below.

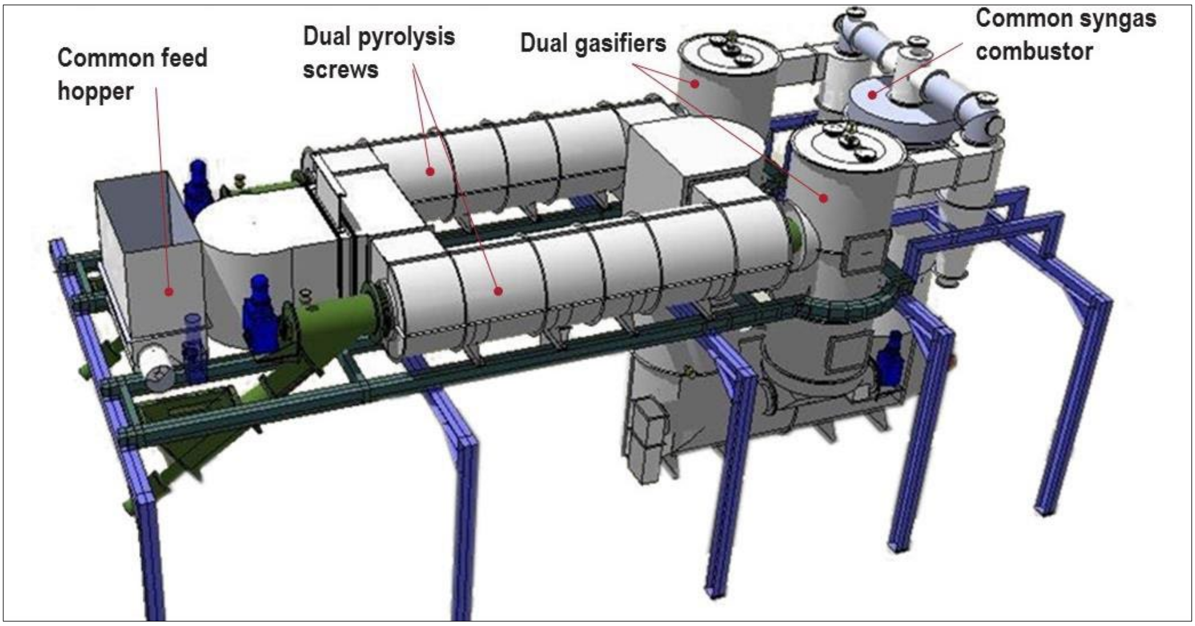

Figure 40: NEAT gasifier module

Source: NEAT

A.15.2 Reference plants

NEAT had a single operational reference plant at Avonmouth, UK which was closed in 2016.

A.15.3 Conclusion

New Earth became insolvent in 2016 and the NEAT gasifier was discontinued. The NEAT process has not been proven and will not be considered in any further detail in this study.

A.16 Nexterra

A.16.1 Technology description

Nexterra supplies an updraft gasifier which can be fuelled by clean wood, waste wood and RDF. In the Nexterra process the feedstock is converted to a tarry syngas which is discharged from the gasifier into a thermal oxidiser where it is burnt and the heat produced is used to raise steam for the generation of electricity in a steam turbine. An illustration of the Nexterra gasification reactor is shown below.

Figure 41: Schematic of the Nexterra gasifier reactor

A.16.2 Reference plants

Nexterra has 11 reference plants which are listed in the table below.

Table 22: Nexterra gasification plants

Location	Waste Type	Status	Thermal Capacity (MWth)	Gross electrical output[45]
Dartmoor BioPower, UK	Waste wood	Operational	20.4	3.5 MWe
Welland BioPower, UK	Waste wood	Operational	40.8	9 MWe

Birmingham Biopower, UK	Waste wood	Operational	40.3	9 MWe
Veterans Affairs Hospital, USA	Construction & demolition and waste wood	Not operational	11.6	2 MWe + building heating
University of British Columbia, CA	Construction & demolition waste wood	Operational	9.3	District heating
University of Northern British Columbia, CA	Bark/wood chip	Operational	---	District heating
US DOE Oak Ridge National Labs, USA	Bark/ wood chip	De-commissioned	21	District heating
Kruger Products, USA	Construction & demolition waste wood	Operational	9.2	Process heating
Dockside Green	Construction & demolition waste wood	Not operational	8.5	District heating
University of South Carolina	Bark/ wood chip	Decommissioned	NA	1.3 MWe + building heating
Tolko Industries Ltd – Plywood mill	Bark/ wood chip	Not operational	NA	Process heating

A.16.3 Conclusion

The Nexterra process produces syngas which has a low H_2:CO ratio and very high concentrations of tar and other contaminants. The syngas is unsuitable for the production of fuels without significant investment in syngas clean up and conditioning, resulting in a low yield. Consequently, the process will not be considered in any further detail in this study.

A.17 Outotec Energy Products

A.17.1 Technology description

The Outotec Energy Products (OEP) staged gasification system is a refractory lined air-blown BFB gasifier which can be fuelled by a variety of biomass feedstocks. Syngas generated in the fuel bed is immediately burnt in a close coupled combustor and the heat generated is used to raise steam to generate electricity in a steam turbine. The OEP system is currently configured solely for the production of electricity. A schematic of the OEP process is shown below.

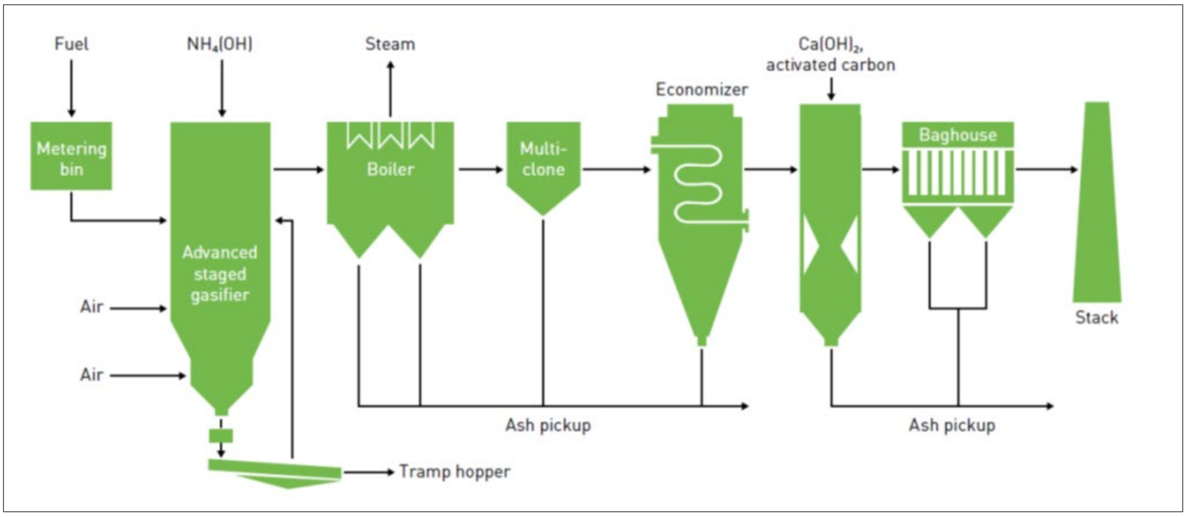

Figure 42:

Schematic of an OEP gasification plant

Source: OEP

A.17.2 Reference plants

To date, OEP has supplied 108 fluidised bed combustor and gasification systems, most of which are in the United States of America (USA) and Canada. Some of the fluidised bed gasifier reference plants are listed in the table below.

Table 23: OEP fluidised bed gasifier systems

Location	Waste Type	Status	Steam Temperature (°C)	Steam Pressure (bara)	Steam Production (tph)	Energy Recovery
Barry, UK	Waste wood	Commissioning	400	45	NA	10 MWe
Boston, UK	Waste wood	Commissioning	400	45	NA	10 MWe
Charlton Lane, UK	RDF	Commissioning	400	45	NA	3.65 MWe
Hull, UK	Waste wood	Commissioning	400	45	NA	22 MWe
Hull, UK	RDF	Commissioning	400	44	NA	28 MWe
Ince, UK	Waste wood	Operational	450	61	NA	21.5 MWe
Levenseat, UK	RDF	Commissioning	400	46	54.6	10 MWe
Connecticut USA	Construction & demolition waste and green wood	Operational	513	101	158	37.5 MWe
Oregon, USA	Biomass	Operational	541	105	152	35 MWe
Mississippi, USA	Board trim and hog fuel	Operational	NA	55	45	Process heat
Maine, USA	Biomass	Operational	399	45	84	Process heat
Washington USA	Paper sludge, deinked sludge	Operational	NA	NA	9	Process heat
Northwest Ontario, Canada	Hog fuel, sander dust, hogged board trim	Operational	NA	NA	NA	Hot water
Tennessee, USA	Wood waste	Operational	NA	NA	NA	5 MWe

Iowa, USA	Wood waste	Operational	441	31	27	6 MWe
New Jersey, USA	Sewage sludge	Operational			5	0.75 MWe
California, USA	Agricultural and yard waste	Operational	NA	19	20	Municipal heating
United Kingdom	RDF	Demonstration	NA	NA	NA	2 MWe

A.17.3 Conclusion

OEP has been put up for sale by its parent company Outotec, and therefore any development plans are unclear. Like most fluidised bed systems, rather than burning the syngas generated, the fluidised bed can be coupled with a syngas clean-up and upgrading system to generate liquid fuels or chemicals. In addition, the fluidised bed could be converted to be fluidised by steam/oxygen rather than air to increase yields. However, OEP does not currently supply this type of system and its development plans are not publicly available. Consequently, the OEP technology will not be considered in any further detail in this study. It is possible that in the future it could develop its fluidised bed to be used to produce syngas for conversion to fuels in cooperation with other suppliers.

A.18 Plasco Conversion Technologies Inc.

A.18.1 Technology description

The Plasco moving bed gasifier is a grate based gasifier system which is fuelled by shredded MSW. Air is used as the gasifying agent and the syngas produced is treated in a gas clean up system before combustion in syngas engines. Plasco has also said that the syngas can be used to fuel CCGT systems. A schematic of the Plasco gasification system is illustrated below.

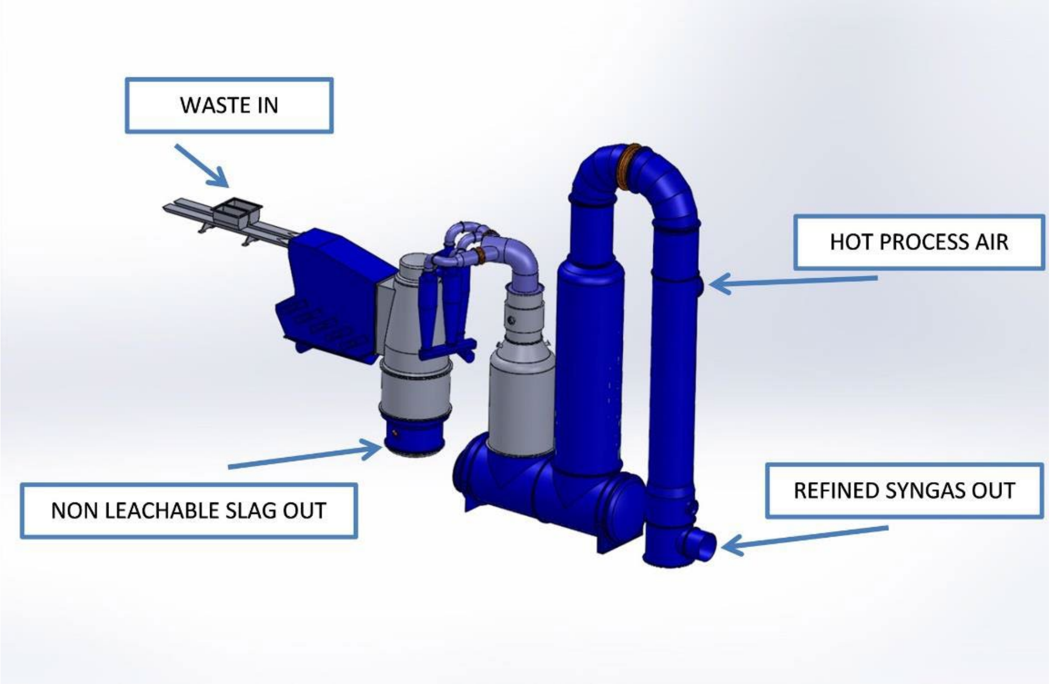

Figure 43: Schematic of the Plasco grate based plasma gasification system

Source: Plasco

A.18.2 Reference plants

In 2008 Plasco began operation of a 3.5 t/h commercial scale demonstration facility in Ottawa, Canada which was fuelled by post-recycled MSW (similar to RDF). Publicly available information indicates that the plant was operated, and electricity produced intermittently between 2008 and 2014 while various unit operations were tested. Reports indicate that the plant had a rated output of 5MWe but due to various technical issues was unable to achieve a reasonable availability or capacity factor. For reasons which are unclear the operation was closed in 2014 and no new plants have been built since then.

A.18.3 Conclusion

The Plasco technology has been developed to generate electricity and will not be considered in any further detail in this study.

A.19 Thermoselect

A.19.1 Technology description

The Thermoselect technology consists of an initial pyrolysis stage followed by gasification in a high temperature oxygen blown, fixed bed system. The process can be fired on MSW, RDF, ASR and industrial waste. The syngas produced can be burnt in a boiler to raise steam for the production of electricity or the gas can be burnt directly in syngas engines to produce electricity. Some of the electricity generated is used in an air separation unit to produce the O_2 required for gasification.

Vivera, the company that owns the Thermoselect technology, has said that there is the potential for the production of H_2, methanol, ammonia and diesel or kerosene from the syngas. A schematic of the Thermoselect process is shown in Figure 44.

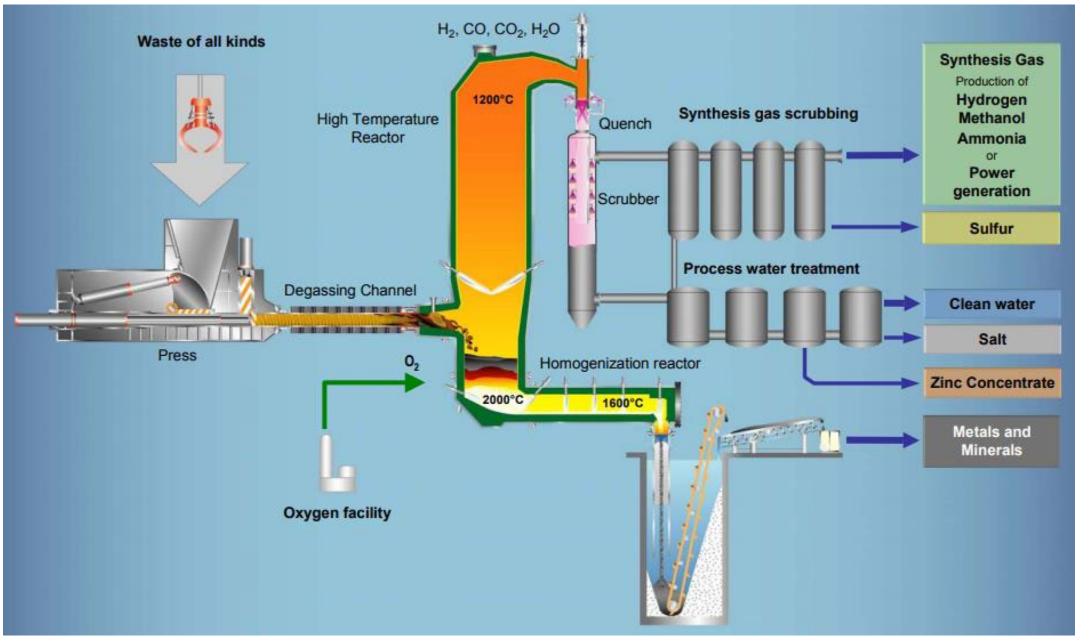

Figure 44: Schematic of the Thermoselect process

Source: Vivera

A.19.2 Reference plants

There are 7 reference plants for the Thermoselect technology. The plant at Karlsruhe was closed in 2004 and the operating status of the remaining plants is unclear. No new plants have been built since 2006.

Table 24: Thermoselect reference plants.

Location	Commercial operation	Feedstock	Capacity (tpd)	No. lines	Syngas use
Karlsruhe, Germany	1999	MSW	720	3	Power generation and district heating (10 MWe + 50 MWth)
Chiba, Japan	1999	Industrial waste	300	2	Export
Mutsu, Japan	2003	MSW	140	2	Gas engine
Tokushima, Japan	2005	MSW	120	2	Gas engine
Yorii, Japan	2005	Industrial waste	400	2	Boiler
Nagasaki, Japan	2005	MSW	300	3	Gas engine
Kurashiki, Japan	2005	Industrial waste	555	3	Export
Osaka, Japan	2006	Industrial waste	95	1	Boiler

Source: http://www.iwtonline.com/ and http://www.viveracorp.com/

A.19.3 Conclusion

Whilst Vivera claims that the Thermoselect technology can be used for the production of H_2 and liquid fuels the company does not currently supply any systems and its development plans are not publicly available. Consequently, the technology will not be considered in any further detail.

A.20 Valmet

A.20.1 Technology description

Valmet is a major supplier of fluidised bed system, mainly combustion systems for biomass and waste. It also supplies air blown CFB gasifiers which are designed for operation on biomass and RDF produced from processed MSW. The syngas produced is currently cleaned in a hot gas clean up system using a hot gas filter before combustion in a gas boiler to raise steam to drive a steam turbine. A schematic of the Valmet gasification system at Lahti is shown below.

Valmet adjusts its combustion and gasification systems to match potential fuels and markets and would be capable of converting its systems to make higher quality syngas if there was a commercial opportunity.

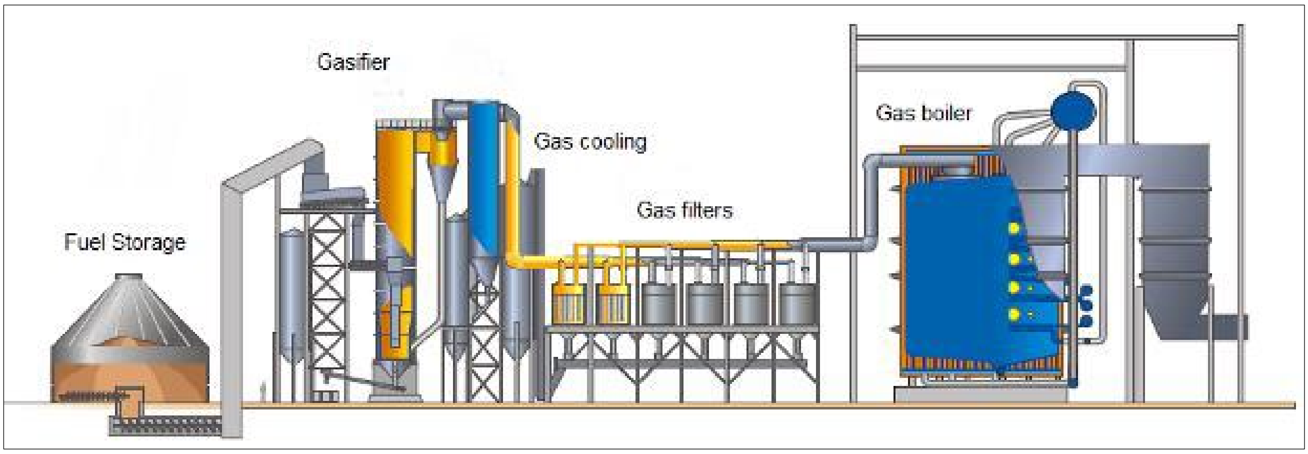

Figure 45: Schematic of the Valmet gasifier system

Source: Valmet

A.20.2 Reference plants

Valmet has five reference gasification plants which are listed in the table below.

Table 25: Valmet gasification plants

Plant	Waste Type	Date Operational	Capacity (MWth)	Output
Vassa, Finland	Biomass	2006	140	230 MWe, 170 MWth
OKI Paper Mill, Indonesia	Biomass	2009	2 x 110	Unknown
Lahti, Finland	SRF\RDF	2012	160	50 MWe, 90MWth
Äänekoski, Finland	Biomass	2017	87	Unknown
Huanggang, China	Biomass	Unknown	50	Unknown

Source: Valmet

A.20.3 Conclusion

Like most fluidised bed systems, rather than burning the syngas generated it would be possible to couple the fluidised bed with a syngas clean-up and upgrading system to generate liquid fuels or chemicals. In addition, the fluidised bed could be converted to use steam/oxygen instead of air to increase yields. However, as Valmet does not currently supply any such system and its development plans are not publicly available, it will not be considered in any further detail in this study. It is possible that in the future it could develop its fluidised bed to be used to produce syngas for conversion to fuels in cooperation with other suppliers.

B Pyrolyser Technologies

B.1 American Renewable Technologies Inc.

B.1.1 Technology description

American Renewable Technologies Inc. (ARTI), formerly American Combustion Technologies Incorporated, supplies modular pyrolysis systems. The pyrolysis system consists of a series of two externally heated augers that carry feedstock through the pyrolyser. Feedstock enters the pyrolyser counter-current to the hot gases that heat the outside of the screw augers to around 550-650°C. As feedstock moves through the pyrolyser, syngas is continuously extracted, cooled, cleaned and stored in a pressurised storage tank. A portion of the syngas is fed back to low NOx burners to provide the required heat for the process. The stored syngas can then be fed to syngas engine to generate electricity. According to ARTI's website, they have supplied systems that have run on a variety of feedstocks including coal, manure, tyres, MSW, sewage sludge and other biomass. A schematic of the ARTI pyrolysis system is shown below.

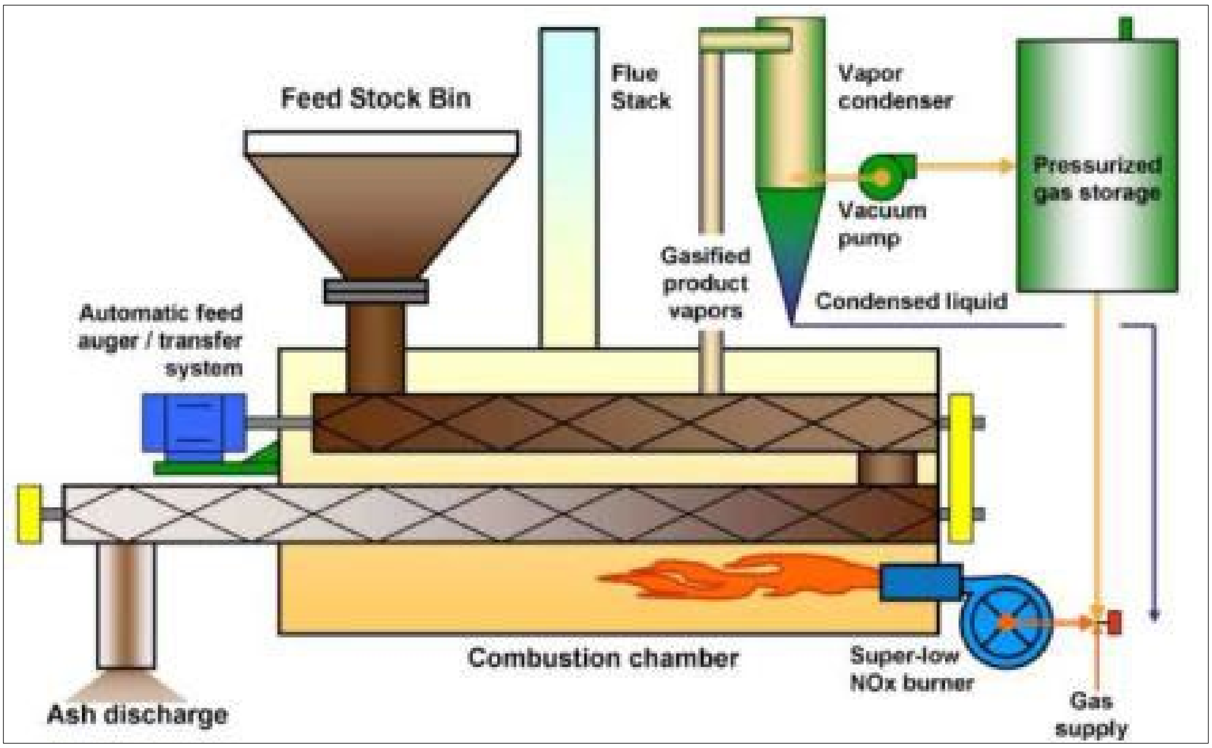

Figure 46: Schematic of the ARTI pyrolysis system

We have not seen any publicly available information confirming the capability of ARTI's system to produce liquid fuels or indicating that it has been used to generate electricity.

B.1.2 Reference plants

ARTI lists the following 17 facilities on their website as reference facilities.

Table 26: ARTI reference plants

Location	Year	Feedstock	Throughput	Output

Dalian, China	1993	Tyres	73,000 t/y	Not stated
Chino, CA	2004	Cow manure	1,500 t/y	Syngas
Milan, Italy	2006	Waste plastic	1,000 t/y	Syngas
Tennessee	2007	MSW	1,000 t/y	Not stated
Tacoma, WA	2007	Tyres	454 kg/hr	Pyrolysis oil and carbon
Zhejiang, China	2008	Medical waste	8,000 t/y	Not stated
Carson, CA	2008	Bio solids	113 kg/hr	136 m3/yr diesel
Korea	2009	Tyres	1,000 t/y	Not stated
Brisbane, Australia	2012	Coal	16,000 t/y	Not stated
Portland, PA	2012	Plastic	8,000 t/y	Not stated
Chino, CA	2012	Cow manure	15,000 t/y	Pyrolysis oil
Bistrita, Romania	2013	MSW, tyres	8,400 t/y	Not stated
Hudson, CO	2013	Tyres	52,000 t/y	Not stated
Turkey	2014	Chicken manure	12,600 t/y	Not stated
Aruba	2014	MSW	26,200 t/y	Not stated
Slovakia	2015	Biomass	8,000 t/y	Not stated
Los Angeles, CA	2015	Sewage sludge	24,000 t/y	Not stated

Source: http://www.americanrenewabletech.com/

B.2 Graveson Energy Management Limited

Graveson Energy Management Limited (GEM) developed a pyrolysis process in which prepared feedstock was heated on a hot surface at 800$_{o}$C in the absence of oxygen. Feedstock in contact with the hot inner surface of the vessel was converted into syngas and char. The produced syngas was rapidly cooled using blast coolers or a series of heat exchangers to prevent the formation of dioxins and furans. A small stream of syngas was diverted to provide the heat necessary to sustain the conversion process. The original concept was for the remaining syngas to be used to fire boilers or generate electricity through conventional engines or turbines. An illustration of the GEM converter is shown below.

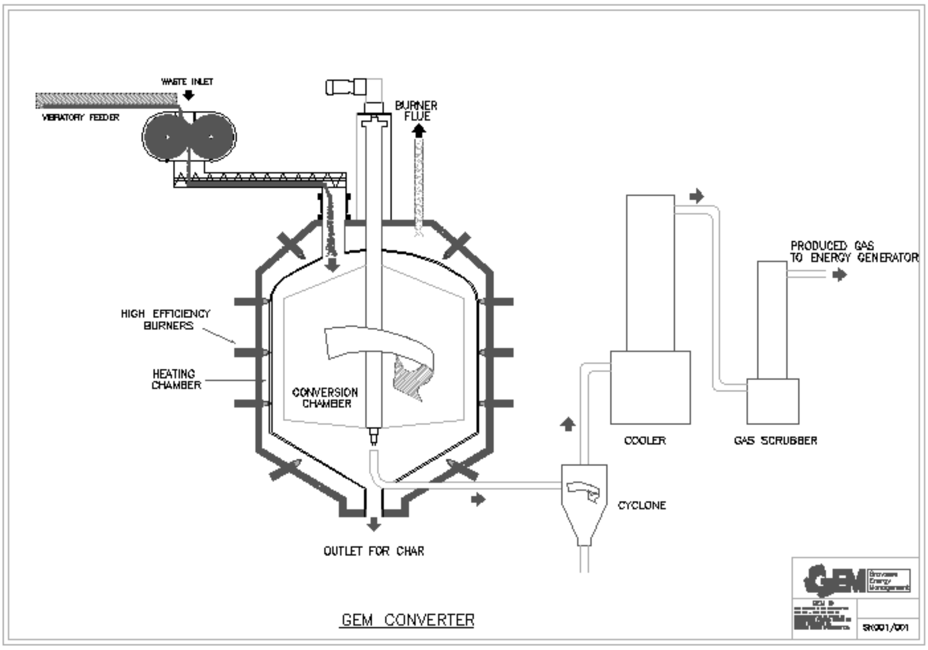

Figure 47: Illustration of GEM converter

Source: GEM

B.2.1 Reference plants

As of late 2007, GEM had built one commercial plant in Ohio, USA and the Yorwaste plant at Bridgend, UK but did not have any full scale operational facilities. The plant in Ohio was to supply syngas to a steel manufacturing process and not to generate electricity.

B.3 Prestige Thermal Energy

B.3.1 Technology description

The Prestige Thermal Energy (PTE) licenses a proprietary process through C6 Technologies. The technology at its core is a pyrolysis process for the treatment of MSW. The process receives MSW which is sterilised in an autoclave prior to a sorting and separation process. The sorting and separation stage segregates recyclates from the organic material which goes on to be dried in a steam heated dryer. Dried organic material is then fed into the pyrolysis system which consists of 3 areas: pre-pyrolysis, the pyrolyser and the vitrification furnace. In pre-pyrolysis, feedstock is further dried in a flue gas heated rotary drum before it is discharged to the pyrolyser itself. During pyrolysis, organic feedstock breaks down to produce syngas, condensable vapours (tars and oils) and char. Heat for the pyrolyser comes from either heat leaving the vitrification furnace, firing a portion of the syngas or firing LPG when there is insufficient syngas available.

The produced syngas is piped to a cleanup system, solid residues are discharged to the vitrification furnace and the pyrolyser heating gases are discharged to a waste heat recovery boiler. In the vitrification furnace, solid residues and tars recovered from syngas cleaning are combusted – leaving molten slag which falls into a water bath. Power generation from the proposed process comes from the combustion of cleaned syngas in a bank of gas engines and a steam turbine driven by steam produced from the waste heat recovery boiler. A simplified illustration of the process flow is shown below.

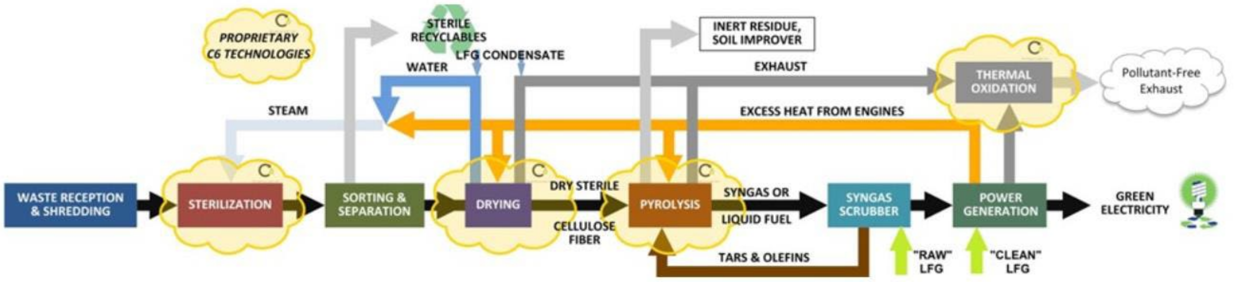

Figure 48: Process flow for the C6 Technologies pyrolysis process

Source: Prestige Thermal Energy

B.3.2 Reference plants

We are not aware of PTE having supplied any operational commercial reference plants.

B.4 TechTrade

B.4.1 Technology description

TechTrade offers an end-of-life tyre pyrolysis process that was marketed in the UK by Wastegen. The process receives shredded tyres that are then granulated to a finer tyre crumb whilst the steel wire is removed by conventional tyre processing technology. Tyre crumb is fed into the rotary kiln where it is heated up to a maximum of 550°C in the absence of oxygen. During this stage, the feedstock decomposes to yield a syngas, pyrolysis oil and pyrolytic carbon. A portion of the extracted syngas and entrained pyrolysis oil is combusted and the heat of the flue gases is used to heat the outside of the rotary kiln to drive the process. The remaining gaseous products are burned to produce hot flue gases which are used to raise steam and drive a steam turbine.

The pyrolytic carbon produced is upgraded to recovered carbon black through a process involving jet milling and prilling or pelletising.

A schematic of the TechTrade process is shown in Figure 49

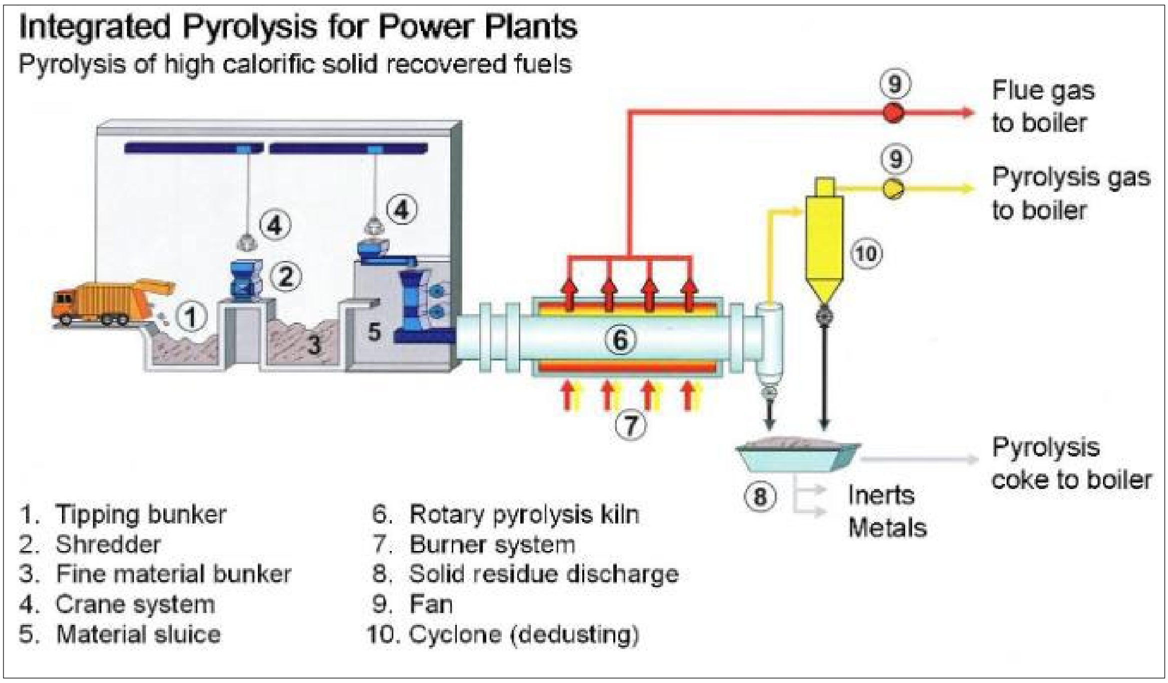

Figure 49: Schematic of TechTrade pyrolysis process

Source: TechTrade

B.4.2 Reference plants

TechTrade has several references for thermal treatment plants that involve treating materials such as contaminated soil and waste oils. We are not aware of TechTrade having any operational commercial pyrolysis references that are generating power or liquid fuels.