Review of emerging techniques for hydrogen production by gasification, pyrolysis and other emerging technologies

December 2025

Version: 1

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1. Executive summary

In the UK, commercial hydrogen production requires an environmental permit from the appropriate environmental regulator. Regulators must ensure that permits include appropriate measures to protect the environment by considering Best Available Techniques (BAT). Where there are no relevant existing BAT Reference documents (BRefs) or UK BAT documents, UK environmental regulators hold responsibility for determining BAT for installations.

This report provides evidence for emerging gasification, pyrolysis and other technologies for hydrogen production activities that are not already covered by existing UK BAT or guidance on emerging techniques (GET) documents. The evidence can be used to support development of non-statutory GET, in consultation with industry, UK regulators and other stakeholders. The information focuses on key environmental aspects, based on information available in the public domain.

The emerging technologies covered for hydrogen production are at pilot or commercialisation stage, hence publicly available information is limited and continues to emerge. This report provides an initial assessment and will be updated through future engagement with industry and others, as technologies are developed and deployed. It focuses on technologies likely to come forward in the next five years (from 2025), including those eligible for future UK Government Hydrogen Allocation Rounds (HAR).

The research process focussed on literature review. Several stakeholders were contacted to investigate the availability of further evidence, but no responses were received. The information reviewed came from government-commissioned research reports, academic literature and industry reports. Information collated has limitations in that it stems from a combination of theoretical, research, feasibility studies and model-based sources.

The following information quality aspects are noted:

- Information in reports focussed on cost and technical feasibility, with limited detail (or none) on environmental management and release minimisation and abatement
- Assumptions made across sources were not comparable (for example technology configurations, feedstock compositions).
- Strong sources of information included UK government commissioned reports and research papers - Information from modelled plant configurations was available (for example for gasification) but not from operational plant - Information from pilot plant operators was limited to that from funding application documents
- No information was available from pilot plant - However, this information may become available later.

The following aspects are noted regarding the technologies:

- There is a lack of information on the likely scale of commercial plant.

- There is no clear indication of specific design considerations relevant to the technologies - These will, however, be specific to the precise technology and configurations deployed.
- It is not clear, in all cases, which feedstock is being used for current pilot plant projects - This is due to a requirement to remain flexible and test the effect on processes and hydrogen production of feedstock types.
- There is a general lack of data on inputs, outputs and releases to the environment from plant on which to provide benchmarks or ranges.
- There is a lack of information regarding process optimisation to minimise potential releases to the environment or to abate those potential releases.
- Information on pyrolysis for hydrogen production is more limited than that for gasification.

The implications of the information gaps are:

- As pilot projects come to completion, work is required to compile specific information on outcomes.
- The focus of information requested from the pilot projects should extend beyond cost, programme and broad justification for funding.
- Information collected from pilot projects should extend to include mass balance and operational optimisation practices with the objective of preventing and minimising resource consumption and releases to the environment.
- There is no guidance on emission limits that would be appropriate for inclusion in future permits.

In the absence of information from operational plant (pilot or commercial scale), section 6.3 outlines the key process and environmental aspects, and the likely permitting information needs and, or gaps. The main aspects and information requirements in an environmental permitting context; are across the following:

- Feedstock characteristics and influence on the process: for example, impact on process conditions and control, pollutant generation, and releases to the environment.
- Utility demand and management: for example, factors affecting natural gas requirement and, or consumption, energy efficiency measures, water demand minimisation and local resources, and process heat recycling.
- Emissions to air and water, wastes and their mitigation, treatment and management: for example, pollutants in flue gas, tail gas combustion options, noise and vibration considerations, CO_2 capture and storage options, effluent stream composition, volume and management, recovery of metals and inert materials from feedstock preparation, ash, char composition and management.
- Unplanned emissions and accidents: for example, pollution prevention, fugitive emissions management, governance protocols, and fire prevention planning.

2. Introduction

2.1. Project context

In the UK, commercial hydrogen production at any scale must have an environmental permit from the appropriate environmental regulator. It is the regulators' role to ensure that permits include appropriate measures to protect the environment. This is achieved by considering Best Available Techniques (BAT) at the permit determination stage, attaching conditions to the permits, and by monitoring compliance with those conditions.

'Best Available Techniques' (BAT) means using the most effective and advanced methods of operation that are technically and economically viable. These techniques form the basis for setting emission limits and other permit conditions to prevent or, where that is not possible, reduce emissions and environmental impact.

Where there are no relevant existing BAT Reference documents (BRefs) or UK BAT documents, UK environmental regulators hold responsibility for determining BAT for installations which will be permitted under the Environmental Permitting Regulations (England and Wales) 2016, Environmental Authorisation (Scotland) Regulations 2018, and Pollution Prevention and Control (Industrial Emissions) Regulations (NI) 2013.

Where there is no relevant information in existing BRefs or UK BAT documents and limited data from operating plant, there remains a need to apply the principles of BAT and produce guidance for regulators and industry to enable plants to be permitted with appropriate controls to prevent pollution and harm to people.

2.2. Purpose of this document

This document presents evidence for emerging gasification, pyrolysis and other techniques for hydrogen production activities that are not already covered by existing UK BAT or guidance on emerging techniques (GET) documents. The evidence can be used to support development of non-statutory GET, in consultation with industry, UK regulators and other stakeholders. Further development will be required to shape statutory UK BAT requirements as evidence from pilot and operating plants becomes available.

The document presents information on the key environmental aspects to address and where available, emissions abatement for hydrogen production from gasification, pyrolysis and other emerging technologies. The application of the technologies for hydrogen production is at pilot or commercialisation stage; hence publicly available information is limited and continues to emerge. This document is intended to provide a first assessment and will be built upon through future engagement with industry and others, as technologies are further developed and deployed. The technologies presented in here are those considered most likely to be proposed by permit applicants in the short to medium-term (1 to 5 years).

The focus of this document is on evidence of environmental aspects relevant to GET for hydrogen production (other than electrolysis of water, or steam methane reforming: SMRtype production). The focus is on techniques for which applications are likely to come forward for in the next five years (from 2025), including those which are eligible to be funded through any future UK Government Hydrogen Allocation Rounds (HAR). The techniques comprise gasification (with or without carbon capture and storage), pyrolysis (thermal, catalytic, plasma pyrolysis) and other emerging hydrogen production techniques utilising a variety of feedstocks.

The information in this document is not a regulatory requirement. It does not have the same regulatory status as BAT reference documents or related BAT conclusions. However, operators would need to explain and justify in permit applications where alternatives to methods and performance described are proposed.

2.3. Overview of the research process

The research process undertaken to collate and review the evidence presented in this document was conducted between November 2024 and March 2025 and included the following components:

- Evidence gathering: following agreement of a search protocol, a thorough literature review was carried out encompassing government, industry, academic and research sources
- Source screening: literature sources were screened and prioritised to identify the most relevant sources
- Information extraction: information was extracted for assessment, review and evidence compilation from the screened sources
- Addressing evidence gaps: several selected stakeholders were contacted to investigate the availability of and collate further evidence (not a full consultation), but no responses were received
- Reporting: provision of draft reports for review and subsequent finalisation

A total of 114 sources were identified in the literature review. The sources were screened using a search protocol resulting in 51 sources being selected. The screened sources were supplemented by a further 16 sources due to a potential for them to contain useful information. A total of 67 documents were reviewed for possible information extraction, and information has been referenced from 32 of these reviewed documents.

The project was supported by an advisory group from within the Environment Agency which convened regularly throughout the research process.

2.4. Limitations

The research process was limited to literature research, review and analysis. The nature of information identified was characterised by government commissioned research reports, academic literature focussed on researching the techniques and other general reports from industry on the subject. Consequently, information presented has limitations in that it stems from a combination of theoretical, research and model-based sources at this time.

3. Definition of scope and boundaries

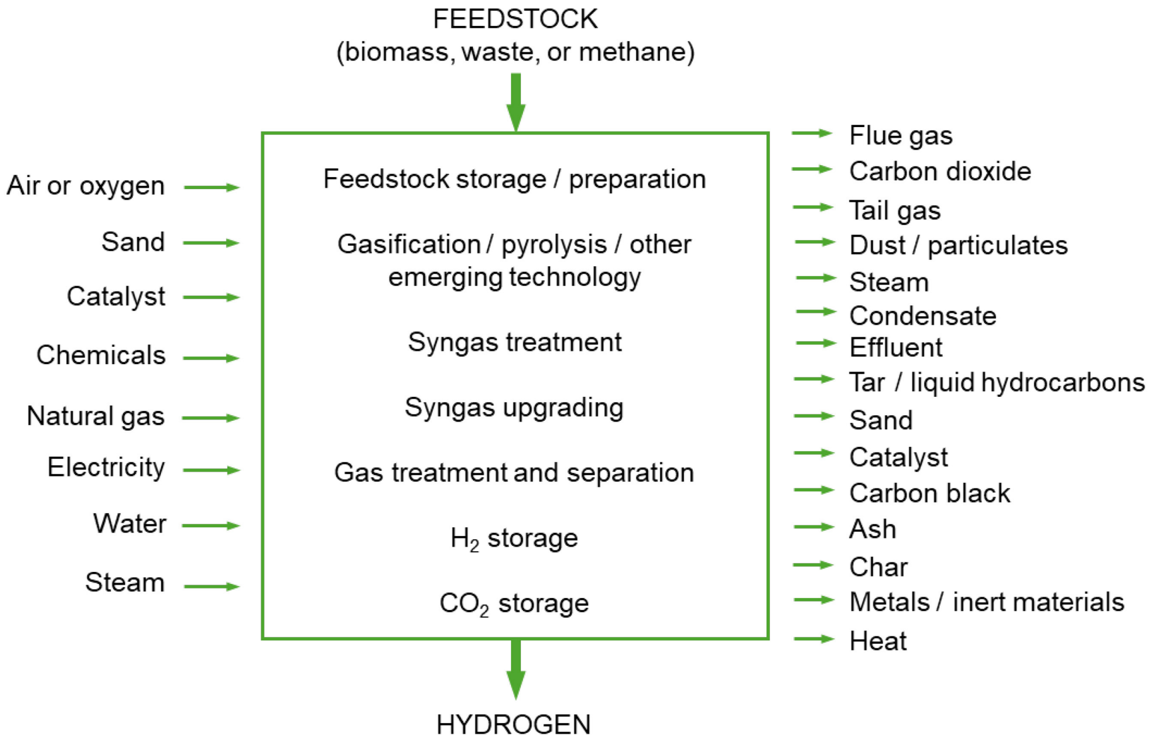
3.1. Introduction

This section presents a summary of the technologies considered within this document defining their scope and boundaries and noting exclusions. The feedstocks, inputs and products together with the utilities required and the emissions, effluents and wastes are summarised.

An overview of relevant existing guidance is presented including an indication of the aspects of interest relevant to the technologies.

Figure 3.1 was developed by WSP UK Ltd following a review of literature and provides a representation of the scope boundaries. Figure 3.1 depicts the possible feedstocks (top), inputs of raw materials and utilities (left arrows) and the outputs of products, wastes, emissions and effluents (right arrows). All of these are described in the following sections. The precise combination of feedstock, inputs and outputs will differ, depending on the specific technology selection and configuration. Specific technology combinations are not defined at scope boundary level. Not all inputs and outputs may arise, nor all process stages in any given configuration.

Figure 3.1 Scope boundary for gasification, pyrolysis and emerging technologies



Out of scope from the evidence review were:

- Upstream production and management of feedstocks

- Generation, transmission, and distribution of electrical power supply and production of sand, catalysts, chemicals, steam and water used in processes
- Downstream treatment and use applications of char, carbon black, ash, tar, and hydrocarbon liquids
- Pipelines or other means of transmission and distribution of hydrogen product
- Hydrogen use applications, for example, in generating power or heat, or use in transport applications

3.2. Technologies

Potential technologies are identified, considering:

- Technologies for which applications are likely to come forward in the next five years (from 2025), including those which are eligible to be funded through any future UK Government Hydrogen Allocation Rounds
- Those technologies that may be able to achieve production scales meeting the requirements of industrial applications
- Technologies known to be under consideration by UK project developers
- Other emerging technologies

Based on these criteria, the following technologies have been considered:

- Gasification technologies using biomass or waste as a feedstock
- Pyrolysis technologies using biomass, waste or methane as a feedstock
- Emerging technologies at early stages of development and testing with low technology readiness levels (TRLs)

3.3. Plant scale

At present, gasification and pyrolysis technologies are operating as pilot projects in the UK. However, potential commercial plants are indicated in literature review for hydrogen production:

- **Gasification:** one source indicates that, once technologies are demonstrated, it is likely that fluidised bed based systems may be scaled up to units in excess of 100,000 tpa whilst small-scale modular approaches may have capacity to process 12,000-15,000 tpa of biomass or wastes with a thermal capacity of 7 MWth [1]; a second source indicates a range of 2 to 10 t/h (66-333 MW) for double-bed bubbling and entrained flow gasification plant with a biomass feedstock [2]
- **Pyrolysis:** modular plant with throughput capacities ranging from 7,000 to 10,000 tpa for the conversion of niche waste streams or the production of niche fuels are indicated [1] [3]

3.4. Feedstock

Biomass, wastes, methane

Description: biomass or wastes (or combinations) may be feedstocks for gasification whereas pyrolysis may receive biomass, wastes (or combinations) or methane:

- Biomass: for example, virgin wood, energy crops
- Wastes: for example, waste wood, agricultural residues, municipal solid waste (MSW), refuse derived fuels (RDF), plastics waste
- Methane: for example, natural gas or biogas containing mostly methane

Exclusions: upstream production and management of feedstocks (for example, growing and production of biomass, collection and sorting of waste materials, production of methane).

Notes or basis: feedstocks may require preparation and processing to achieve the feedstock specification as required by the precise technology and configuration to be used.

3.5. Inputs

Air or oxygen

Description: air or oxygen required for gasification processes.

Exclusions: production of oxygen.

Notes or basis: air or oxygen required as gasifying agents.

Sand

Description: sand required for certain types of gasification and pyrolysis reactors (for example fluidised bed) to promote an even heat transfer through the reaction bed.

Exclusions: production of required sand.

Notes or basis: sand may be recovered and reused in the process.

Catalyst

Description: catalysts are required for syngas upgrading processes.

Exclusions: manufacture of catalysts.

Notes or basis: various catalysts may be used in proprietary technologies.

Chemicals

Description: chemicals required for syngas treatment and reforming and for separation of hydrogen and CO_2.

Exclusions: properties and manufacture of chemicals.

Notes or basis: chemical types and use will vary depending on the specific technologies deployed and syngas properties and requirements.

3.6. Utilities

Utilities requirements for the processes are identified as follows.

Natural gas

Description: gas may be required for initial heat raising during start up and during the process.

Exclusions: upstream production and distribution of natural gas.

Notes or basis: for gasification, natural gas is primarily used for start-up but may be required to maintain the required process temperature from time to time. For pyrolysis, a continuous heat supply is required given its endothermic nature.

Electricity

Description: process electricity required for powering pumps, compressors, fans, and other process aspects such as to provide heat and so on.

Exclusions: generation, transmission, and distribution of electrical power supply to the site.

Notes or basis: to offset imported electricity requirements, electricity generation from syngas combustion may be integrated depending on the specific technology configuration.

Water

Description: water required for syngas treatment, upgrading, and gas separation.

Exclusions: upstream water abstraction and, or collection, off-site processing and supply to the site.

Notes or basis: water supplied from mains systems is appropriate for use.

Steam

Description: steam required in gasification processes, syngas upgrading and other points in the process.

Exclusions: none noted.

Notes or basis: steam is generated on site although for gasification, water may be introduced and due to the high temperatures is instantaneously converted into steam. Energy to raise steam may be provided by syngas or tail gas combustion, or from heat recovery from the process depending on the specific technology and configurations.

3.7. Emissions to air, and liquid and solid wastes

Emissions to air, and relevant liquid and solid wastes for the processes are identified as follows.

Flue gas

Description: released at the end of the process and comprising predominantly nitrogen with smaller proportions of CO_2, O_2 and water.

Exclusions: none noted.

Notes or basis: precise composition will vary depending on specific process.

Carbon dioxide

Description: CO_2 released at the gas separation and treatment stage.

Exclusions: none noted.

Notes or basis: potential for CO_2 capture and use and, or storage depending on availability of CO_2 capture infrastructure. CO_2 generated by all Schedule 1 listed activities in the Environmental Permitting (England and Wales) Regulations 2016, and other UK equivalents, are controlled by the UK Greenhouse Gas Emissions Trading Scheme Regulations 2012 for the purpose of implementing Directive 2003/87/EC establishing a scheme for greenhouse gas emission allowance trading within the EU.

Tail gas

Description: tail gas (controlled releases from planned and unplanned operations) may require venting and or flaring for safe release. Tail gas may also be fed back into the process for combustion.

Exclusions: none noted.

Notes or basis: an elevated or ground flare system may be required for controlled releases from planned and unplanned operations, such as planned and unplanned start-up and shutdown events, process upset or emergencies.

Dust and particulates from feedstock preparation

Description: fugitive releases of dust and particulates released from movement and preparation of feedstocks.

Exclusions: none noted.

Notes or basis: occurrence dependant on the nature of the feedstock (for example dry and dusty) and feedstock handling (for example mixing, transfer) required on site.

Steam and, or condensate

Description: steam or condensate released from feedstock drying.

Exclusions: none noted.

Notes or basis: depending on their nature and moisture content, some waste feedstocks may require drying on-site prior to use, using established heating and drying processes.

Effluent

Description: effluent from various process stages (for example scrubbers for syngas treatment and other process fluids).

Exclusions: none noted.

Notes or basis: not all processes may generate effluents. Depending on composition, effluents may require treatment prior to discharge to sewer or may require offsite disposal.

Tar and or liquid hydrocarbons

Description: from syngas treatment, syngas upgrading.

Exclusions: offsite recovery processes.

Notes or basis: tars (heavier fraction hydrocarbons) and liquids (lighter fraction hydrocarbons) are not the target products and are sent for disposal or recovery.

Sand

Description: waste sand from fluidised bed technologies.

Exclusions: processing of sand (if required) prior to reuse in the process or for other purposes.

Notes or basis: sand may be recovered and reused in the process several times.

Catalyst

Description: spent catalysts from syngas upgrading processes.

Exclusions: recovery and or regeneration of catalysts.

Notes or basis: various catalysts may be used in proprietary technologies and be sent for recovery and or regeneration.

Ash

Description: ash may be recovered from the gasification, pyrolysis or syngas treatment stages. In gasification, ash is the main solid waste generated. In pyrolysis, ash may be contained within char together with other fixed carbon components.

Exclusions: processing of ash for downstream use.

Notes or basis: ash is collected (for example by cyclones) for disposal or reuse. Ash may be disposed of, or if inert, used in secondary aggregate production.

Char

Description: char is generated in gasification and pyrolysis processes and comprises the fixed carbon content of the feedstock, ash and hydrocarbons.

Exclusions: processing of char for downstream use.

Notes or basis: char may be recovered for use in various applications (for example, as an adsorbent, catalyst, reducing agent, for use in soil improvement and in secondary aggregate production).

Metals and inert materials removed from feedstock preparation

Description: metals and inert materials removed from waste feedstock in preparation if feedstock is not ready for direct use.

Exclusions: none noted.

Notes or basis: some waste feedstocks may require preparation on site using established processes (for example, size reduction, screening, densification, metal extraction) prior to use.

Heat

Description: heat will be generated from the processes.

Exclusions: none noted.

Notes or basis: heat from the process may be reused (for example in biomass drying).

3.8. Products

Hydrogen

Description: hydrogen product quality suitable for either fuel cell electric vehicles (FCEVs) or heat grade for combustion as industrial or domestic fuel.

Exclusions: hydrogen transmission and distribution networks.

Notes or basis: hydrogen meets the requirements of the International Standards Organisation, Hydrogen Fuel Quality – Product Specification, ISO 14687, First Edition 2019. Hydrogen meeting this standard is suitable for use in fuel cell vehicles (hydrogen ≥ 99.97 vol%) or combustion (hydrogen ≥ 98 vol%). Compression may be required for transportation or delivery to users, local storage or requirement for downstream process.

Carbon black (also referred to as solid carbon)

Description: a byproduct that is a fine form of pure carbon.

Exclusions: None noted.

Notes or basis: carbon black may be generated by some process configurations. It can be recovered for use in various applications (for example, pigment, tyre reinforcement, lithium-ion batteries, rubber goods).

3.9. Existing guidance

Under the EU legislation Best Available Technique (BAT) and BAT Reference (BRef) documents must be taken into consideration to ensure that the impact on the environment from an industrial installation is minimised. This includes, but is not limited to, the design, construction, maintenance, operation and decommissioning of an installation. These were adopted and applied across the EU by the European Commission but continue to have effect in the UK through the EU Withdrawal Act 2018.

Industrial installations that contain prescribed activities have relevant BAT and BRef documents. Where these do not exist or provide sufficient information, the Industrial Emissions Directive (IED) 2010/75/EU Article 14(6) and Annex III must also be consulted to ensure compliance with the stated requirements.

The UK regulators have recently developed guidance documents for newly emerging technologies in lieu of appropriate existing BRef documents. These are not a regulatory requirement but identify best practice for environmental protection.

Existing guidance documents relevant to the installations identified for hydrogen production activities considered in this report are identified in Table 3.1, with an explanation on relevance to the review. Table 3.2 presents other guidance documents that are likely to be relevant to the whole installation.

Table 3.1: Existing guidance documents relevant to the technologies and activities

Technology	Specific guidance	General comment	Specific comment	Gaps
Gasification of biomass or waste **Pyrolysis of biomass or waste**	**Waste incineration BRef 2019**	Includes consideration for the following operational activities or techniques that are still applicable: • Pre-treatment • Thermal treatment stage • Energy recovery stage • Applied flue-gas cleaning and control systems • Wastewater treatment • Solid residue treatment • Emission limits	Aspects applicable to all technologies relevant to this report: • Production of syngas. • Syngas cleaning (treatment) and then combustion to utilise the syngas energy • Syngas may be used for its chemical value as a raw material after pre-treatment if required • Non-waste fuels may be added to the waste to produce syngas with a desired chemical composition • BAT is to re-use flue gas for energy efficiency	Aspects applicable to all technologies relevant to this report: • There is no consideration in the waste incineration BRef for syngas upgrading and gas separation to produce hydrogen • Catalytic and plasma pyrolysis as a waste treatment is not considered within the document • Catalytic gasification as a waste treatment is not specifically considered within this document other than in relation to reducing emissions to atmosphere • Methane as a feedstock for pyrolysis is not considered

Table 3.2: Existing guidance documents relevant to gasification and pyrolysis installations

Existing guidance	Relevance to this review
Best Available Technique Reference document on BAT for industrial cooling systems, 2001	Cooling water systems.
Best Available Technique Reference document on BAT for energy efficiency, 2009	Energy efficiency and integration management.
Best Available Technique Reference document on BAT for Emissions from storage, 2006	Storage, transfer and handling of materials. Includes raw materials and products.
Best Available Technique Reference document on BAT for Large Combustion Plants, 2017; and BAT conclusions for large combustion plants 2021	If natural gas is to be used then BAT for large combustion plants apply, including measures to reduce emissions of pollutants from combustion processes, BAT-associated emission levels, and energy efficiency. Gasification and in particular the integrated gasification combined cycle is considered in these documents.
Reference Report on Monitoring of emissions to air and water from IED Installations 2018	Emissions monitoring.
Best Available Technique Reference document on BAT for Large Volume Organic chemical (LVOC), 2017	Syngas treatment and or upgrading to useable products, likely to be organic chemicals (for example, naphtha). Some hydrogen production processes and techniques are covered in this BRef
Best Available Technique Reference document on BAT for Large Volume Inorganic chemical (LVIC) (2007)	Production of hydrogen is a schedule 4.2 activity, and its production is covered in this BRef.
Post combustion CO_2 capture: emerging techniques, 2024	Novel techniques for an industrial activity that can be used to store CO_2 for use as a product.
Best Available Technique Reference document on BAT for Common wastewater and waste gas treatment / management systems in the chemical sector, 2017; and UK Best Available Techniques for Waste Gas treatment in the Chemical Sector – to be published	Syngas upgrade to the production of organic chemicals would require consideration of this BRef for the discharge of wastewater activities. Wastewater streams might contain tar, condensate, catalyst residues and other effluents.

3.10. Considerations for other emerging technologies

In preparing this document, a number of other emerging technologies have been identified for the production of hydrogen and the optimisation of processes. The technologies are typically at bench or pilot stage. The technologies identified were:

Hydrogen production processes include plasma splitting, plasma pyrolysis, microwave assisted pyrolysis, dark fermentation of biomass, microwave plasma conversion of biogas, and rising pressure reformer. These are briefly described below.

Plasma splitting: using methane as a feedstock, the use of an input electricity source to drive plasma torches or generate microwaves to create localised extremely high temperatures, in the absence of any air. Upon cooling of the plasma, carbon precipitates, and a gaseous hydrogen is produced.

Plasma pyrolysis: use of an input electricity source to drive plasma torches that operate at localised high to very high temperatures, in the absence of any air. The technique has been tested on methane, non-recyclable plastic waste and biomass. Solid carbon precipitates out and is collected, and the gaseous hydrogen stream is purified.

Microwave assisted pyrolysis: using plastic waste as a feedstock, a technology that mixes a microwave absorbent material with the feedstock to provide the required heat for the pyrolysis process.

Dark fermentation of biomass: the use of anaerobic microorganisms in darkness between 25°C and 80°C or high temperatures (>80°C) for bio-hydrogen production.

Microwave plasma conversion of biogas: conversion of biogas from sewage sludge treatment to hydrogen and graphene using microwaves to ionise the methane gas creating a plasma.

Rising pressure reformer: a gasification technology using biomass as a feedstock.

Optimisation processes include Triboelectric plasma reforming Bio-hyPER process and Pressurised water absorption (PWA). These processes are briefly described below:

Triboelectric plasma reforming: focussed on the thermal cracking of tars and other contaminants from syngas from gasification - This is a technology based on external sources of plasma energy to create an ionised environment to break the carbon hydrogen bonds of aromatic tars and release hydrogen components

Bio-hyPER process: a sorption enhanced reforming (SER) technology aimed at enhancing gasification processes

Pressurised water absorption (PWA): a technology for hydrogen-CO_2 separation aimed at separating hydrogen and CO_2 in a syngas stream under pressure

The technologies are described in section 4.4.

Future assessment of BAT criteria and emerging techniques should consider the following aspects, where appropriate, in technology selection, overall plant design, and development of operational philosophies and procedures.

Technology selection should include, but should not be limited to, the following key considerations:

- Emissions to air
- Emissions to water
- Conversion efficiency and energy efficiency
- Source of water
- Optimisation of water usage
- Use of scarce raw materials
- Waste minimisation and waste treatment (liquid and solid waste streams)
- Abatement techniques to reduce emissions (for example, emissions to air, wastewater, other wastes)
- Noise (for example, equipment such as pumps, compressors, fans and flares)
- Reliability and maintainability

Plant design and operations should consider the points above and those below, with reference to existing relevant standards, including but not limited to:

- Monitoring standards for stack emissions (including averaging periods)
- Monitoring standards for discharges to water (including averaging periods and arrangements for flow monitoring)
- Air dispersion modelling standards
- Ambient or deposition monitoring standards
- Maximising energy efficiency (including heat integration and optimisation, considering for example, opportunities for heat recovery from the electrolysers and compression systems)
- Water use efficiency (for process use and cooling systems)
- Optimisation of use of raw materials including water re-use
- Minimisation of waste (using the water hierarchy of prevention, re-use, recycling, recovery of wastes)
- Treatment of emissions to air, effluents and wastes
- Treatment of hydrogen (dependent on quality requirements)
- Start-up and shutdown of operations (including variable production rates) other than normal operating conditions
- Accident management, leak monitoring and containment arrangements
- Future proofing of technology for climate change resilience

4. Technologies overview

4.1. Introduction

This section presents an overview of the technologies within the scope of this guidance:

- Gasification
- Pyrolysis
- Other emerging technologies

At the time of writing (early 2025), whilst technologies are being tested and demonstrated for hydrogen production, commercial scale operations are yet to be developed. Technologies are however, being operated as demonstrators with the aim of testing and validation.

4.2. Gasification

Gasification is the thermochemical conversion of any carbon-containing material using less oxygen than is required for stoichiometric combustion. Various gasifying agents can be used, including air, oxygen, steam or mixtures of these, across a temperature range of 700°C to 1,000°C. The main product of gasification for hydrogen production is a syngas (a gas mixture with varying amounts of mainly hydrogen and carbon monoxide, although other gases such as CH_4 and CO_2 may be present), solid products including ash and char are also formed. Gasification enables solid carbon-containing fuels such as biomass and wastes to be converted to a different form, mainly gases. [1] [4] [5]

In 2023, gasification for hydrogen production was assessed as being at a Technology Readiness Level (TRL) 6 – large scale (see section 4.4 for TRL definitions). [3] [6].

The precise process stages and sequence are specific to any given configuration, for example, syngas upgrading and gas separation may be integrated into a single stage. The generalised stages of both biomass and waste gasification technologies for hydrogen production are:

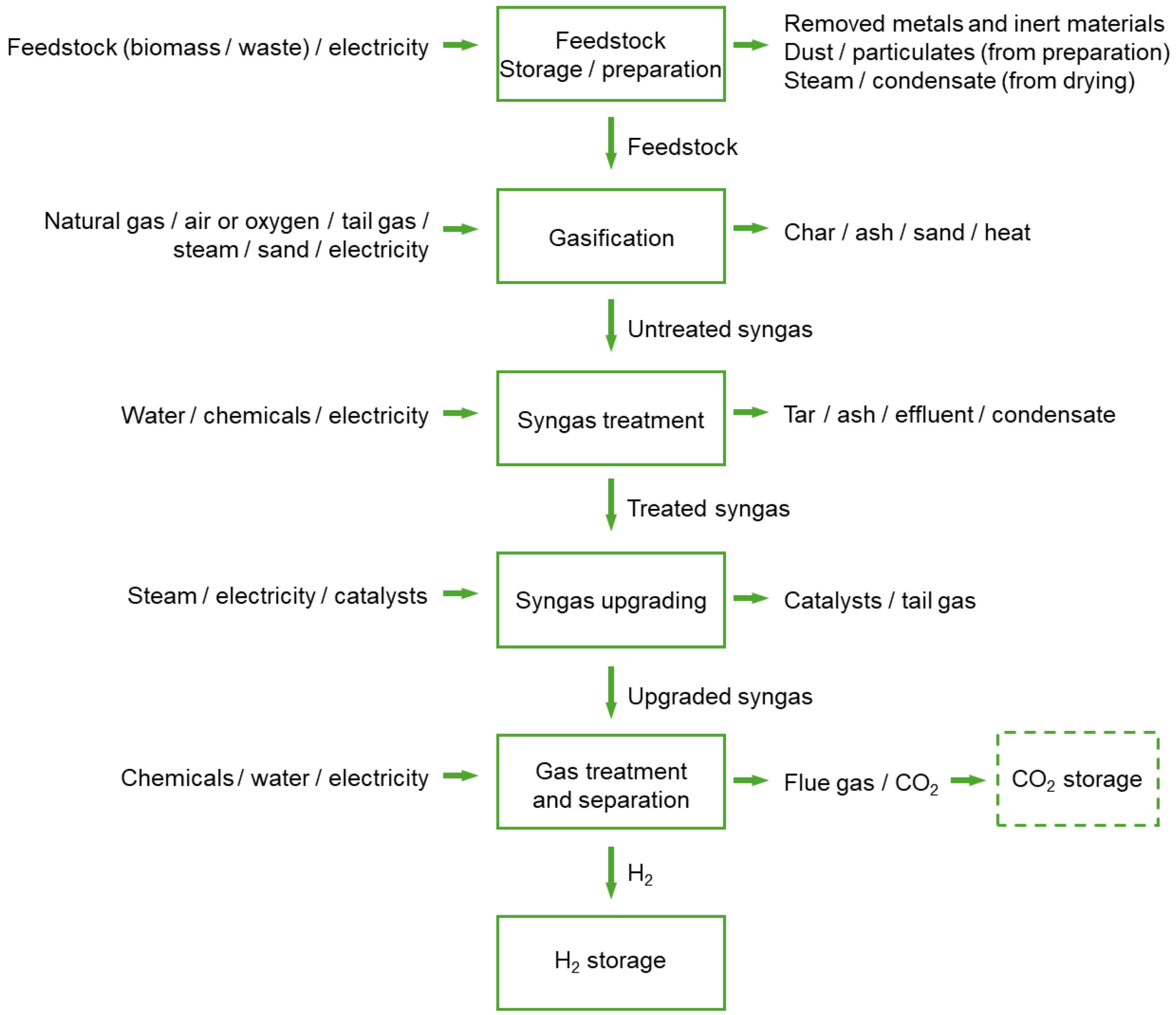
- Feedstock storage and or preparation
- Gasification
- Syngas treatment (removal of impurities and contaminants from the raw syngas, for example, particulates, sulphur, ammonia, chlorides, and trace metals)
- Syngas upgrading (conversion syngas, which is a mixture primarily of hydrogen and CO, into the desired product)
- Gas treatment and separation
- Hydrogen storage (and potentially CO_2 storage)

Depending on the specific technology configuration, not all the above stages may occur, or in the above sequence, for example, syngas may undergo direct upgrading without the need for treatment.

The nature of feedstock preparation, syngas treatment, syngas upgrading and gas separation will differ depending on the precise feedstock used and technology configuration. Optimisation of plant performance to include recycled streams, and a high efficiency of heat integration should be included when feasible to increase product yields. CO_2 can be separated using established technologies such as by chemical solvents, physical solvents and pressure swing adsorption (PSA) and then compressed and sent via pipeline for use or storage. Technology configurations may be fully integrated from feedstock through to syngas upgrading, whereas others may utilise a combination of different third-party technologies, for example, third-party gasification process with proprietary syngas treatment and upgrading system processes. [3] [5] [7]

The Figure 4.1 presents a simplified flow diagram for biomass and waste gasification processes indicating inputs, outputs and main stages and developed by WSP UK Ltd following a review of literature. Further information on the stages is presented in the sections below. The process stages are generic and will depend on the specific technology configurations, not all the above stages may occur, or in the above sequence, for example, syngas may undergo upgrading without the need for treatment. Not all inputs and outputs may be present in any given configuration, for example, if the feedstock is prepared to the required specification prior to arrival at the facility, there may be no outputs from the feedstock storage and preparation stage other than to the gasification stage.

Figure 4.1 Simplified gasification flow diagram



Feedstock storage and or preparation

Feedstocks including biomass materials and wastes may be used for gasification. Preparation of feedstock may be required; processes and techniques commonly used for waste treatment generally, and related Best Available Techniques (BAT) Reference Document for Waste Treatment, 2018. [8] Biomass feedstock is generally a simpler fuel to process than waste feedstock (which is more heterogeneous) but may have a higher associated cost. For gasification technologies, preparation of feedstock may be required to meet input specifications of the specific technology and operation conditions. [3] [9]

The combination of feedstock used, gasification technology and operation conditions are specific, for example, a technology which uses virgin wood will need modifications to operate with waste wood or RDF. Biomass and waste are variable feedstocks and generally, lower cost feedstock materials require more complex processing, for example, wood pellets are typically easier to process than wood chips, which in turn are easier to process than RDF and raw MSW. However, mechanical preparation of waste to RDF is well understood and uses established techniques. [9]

Reception areas and storage facilities are required for feedstocks. Feedstocks will need to comply with specific requirements of the technology used and operational conditions and may require various mechanical and or physical treatment. Biomass feedstocks may require preparation prior to use, such as shredding and screening to a suitable size, drying and densification into pellets. Waste feedstocks may require mechanical treatment and drying to produce the required quality RDF. Where mixed waste plastics require processing onsite, de-baling, removal of ferrous and non-ferrous metals, removal of glass and stones; shredding; screening; and drying may be required. Preparation to produce the required biomass and waste feedstocks is likely to be carried out offsite (and associated environmental aspects management and permitting will be required at such an offsite facility); however, feedstock blending and further preparation such as densification may be required onsite depending on process requirements and feedstock specification. [1]

Moisture content is an important aspect of biomass feedstocks. High-moisture content biomass is not appropriate for thermochemical conversion and drying may be required prior to use. In general, biomass can be processed in a gasifier with a moisture level below 35%, the ideal moisture percentage ranging between 10% and 15%. [10]

The choice of feedstock, and whether preparation is necessary, requires consideration of the heating value (energy content) of the feedstock [11]. Table 4.1 presents the typical characteristics of biomass, RDF and plastics feedstocks.

Table 4.1 Typical characteristics of biomass, RDF and plastics feedstocks [4]

Characteristic	Biomass	RDF	Plastics
Carbon content	20 - 60 wt%	20 - 60 wt%	40 - 80 wt%
Hydrogen content	3 - 10 wt%	3 - 10 wt%	5 - 20 wt%
Oxygen content	10 - 40 wt%	0 - 25 wt%	1 - 30 wt%
Moisture content	15 - 30 wt%	10 - 20 wt%	0 - 15 wt%
Sulphur	Negligible - 1 wt%	0.01 - 2 wt%	Negligible - 1 wt%
Halides	Negligible (below detectable threshold)	0.01 - 0.1 wt%	0.01 - 0.05 wt%
Non-combustible (metals, ash, other)	1 - 10 wt%	7 - 30 wt%	7 - 30 wt%
Calorific value	10 - 25 MJ/m^3	3 - 15 MJ/m^3	15 - 35 MJ/m^3

Different biomass feedstocks have varying characteristics reported, which should be considered when selecting a gasification feedstock for hydrogen production. Table 4.2 presents characteristics reported for wood chip and wood pellet feedstock.

Table 4.2 Characteristics of wood chip and wood pellets as received (ar) [7]

Parameter	Unit	Wood chip	Wood pellets
Carbon	% ar	25.50	47.43
Hydrogen	% ar	3.15	5.86
Nitrogen	% ar	0.15	0.28
Oxygen	% ar	20.89	38.85
Sulphur	% ar	0.01	0.02
Chlorine	% ar	0.01	0.01
Ash	% ar	0.30	0.56
Moisture	% ar	50.00	7.00
Net Calorific Value (NCV)	MJ/kg	8.14	17.24

Gasification

Gasification for the production of fuels is primarily carried out in fluidised bed systems which allow for rapid and efficient heat transfer for the production of syngas. In a fluidised bed, a bed of solid material (silica sand) is fluidised using a gasifying agent (air, oxygen and so on) creating homogeneous bubbles in the bed and allowing the solid material to act as a liquid and enhancing heat transfer from the bed into the feedstock and allowing its conversion from a solid into a gas. Gasification typically requires operation with steam or a mixture of steam and or air, or oxygen to produce syngas. Syngas contains several different components, mainly comprises carbon monoxide and hydrocarbons. Gasification systems may include waste heat boilers or other types of heat delivery systems to provide the energy required for steam generation. [1] [5] [12] [13]

To produce hydrogen through gasification, steam and steam and air mixtures are the required gasifying agents for the production of raw syngas. Steam may be provided by a package boiler which can be fired on natural gas, syngas recycled from the process, or a mixture of the two. [1]

To provide some context on the oxygen and steam requirements for a gasification process, an indicative mass balance was calculated for plant operating with biomass feedstock capacities of 330,000 tpa and 1,000,000 tpa, and with MSW feedstock with capacities of 100,000 and 550,000 tpa were (see Appendix A):

- **Oxygen:** for biomass gasification, 65,900 tpa, and 372,000 tpa were calculated for the 330,000 and 1,000,000 tpa capacity plants; whilst for MSW gasification 29,100 tpa and 160,000 tpa were calculated for the 100,000 tpa and 550,000 tpa capacity plants
- **Steam:** for biomass gasification, 314,000 tpa and 817,800 tpa were calculated for the 330,000 and 1,000,000 tpa capacity plants; whilst for MSW gasification 70,500 tpa and 387,700 tpa were calculated for the 100,000 tpa 550,000 tpa [7]

The purpose of including the mass balance information throughout the document is to provide an indicative quantum of mass balance flows that could occur. The mass balance flows should not be used to benchmark or validate specific technology configurations. Together with the syngas, a mixture of char and fluidising sand is discharged from a fluidised bed system. Fluidising sand may be recovered, and incombustible material collected for disposal or for use as a secondary aggregate if inert. Ash collected from the syngas is collected (for example by cyclones, electrostatic precipitation or filtration) for disposal. Ash and char, which should be inert, may be collected for disposal or use as secondary aggregate. [1] [9]

Syngas treatment

Syngas will contain tars, particulate matter and other contaminants which can foul process systems, poison downstream catalysts (if used) in the syngas upgrading systems and contaminate fuels. Effective control of tars, particulate matter and other contaminants is required to produce a consistent syngas output, from a variable quality input (when a heterogeneous feedstock is used such as waste), without incurring excessive equipment and operational costs. Key contaminants which require removal (if present) from syngas are oxides of nitrogen, alkali metals, hydrogen sulphide, hydrogen chloride, hydrogen cyanide, particulate matter, tars, and volatile metals. Multicomponent syngas clean-up systems are required to prepare syngas for upgrading. [1] [3] [4] [9]

Syngas treatment systems can be deployed to remove contaminants in the syngas and may be carried out at low or mid-to-high temperatures. A quench system may be used to reduce syngas temperature below the tar dewpoint (which may range between 200°C and 250°C) [14], a scrubber system may be used to remove acid gases and particulate matter and activated carbon filters may be used to remove entrained hydrocarbons and other contaminants. The methods selected will be determined by the feedstock, syngas quality, and upgrading techniques requirements, and specific technology configuration. [1] [3] [13]

Table 4.3 presents syngas treatment technologies indicating which can contribute to the removal of which contaminant, and whether tail gas may be produced from the cleaning process. [4] Fields for contaminants showing “Yes”, indicate that particular syngas cleaning technology can contribute to the removal of the contaminant; whereas “Blank cells” indicate that technology is not applicable or not suitable to remove that particular contaminant. It should be noted that while activated carbon filters are effective at removing tar, their high cost generally restricts their use to the final polishing stage of the gas cleaning system. For cleaning technologies including chemical absorption, physical absorption and activated carbon filters tail gas is potentially produced, whereas this do not happen for all the other cleaning technologies shown.

Table 4.3 Syngas treatment technologies [4]

Cleaning technology	Dust	Tar	NO_x	Sulphur compounds	Halides	HCN	Metals
Chemical absorption				Yes	Yes		
Physical absorption				Yes			
Adsorption	Yes	Yes		Yes			
Activated carbon filters	Yes	Yes		Yes		Yes	Yes
Selective non-catalytic reduction			Yes				
Selective catalytic reduction			Yes				
Cyclones	Yes						
Electrostatic precipitator	Yes						
Filters	Yes						
Quench		Yes					
Wet scrubbers	Yes	Yes		Yes	Yes	Yes	Yes
Tar crackers		Yes					
Sorbent injectors		Yes			Yes		

Syngas upgrading

Upgrading processes are applied to convert syngas into hydrogen and CO_2 and to remove contaminants such as carbon monoxide or methane. Upgrading is typically through application of steam reforming (to react hydrocarbons with water to produce CO and hydrogen) followed by high temperature water gas shift (WGS) reaction (in which in the syngas reacts with water vapour, typically over an iron, cobalt, copper or nickel-based catalyst to result in CO and water vapour forming CO_2 and hydrogen. Nickel is preferred due to its low cost and good catalytic activity). [1] [3] [13] [15]

Product yield, product quality, catalyst life, and the ability to reliably process the syngas produced by the upstream equipment are challenges for the syngas upgrading stage as are meeting quality requirements without excessive processing costs, waste generation or product wastage. [9] Yield and efficiency is determined by the precise technology deployed and is influenced by for example, catalyst type and performance, overall composition of the gas and performance of the reformer.

To maximise the production of hydrogen from syngas the H_2:CO ratio requires modification by steam reforming. [1] The reaction is carried out at temperatures ranging from 200°C (low temperature shift) to 500°C (high temperature shift). Low temperature shift reactors can be operated between 200°C and 270°C using copper-zinc-aluminium catalysts; however, they are rarely used as the catalyst is easily degraded, even at hydrogen sulphide concentrations of 0.1ppmv. Development of cobalt-molybdenum catalysts has been explored which can hydrolyse sulphur contaminants such as carbonyl sulphide and hydrogen sulphide catalysts even at low temperatures. [1] Steam reforming is considered the most energy efficient, and a suitable syngas upgrading process for large-scale hydrogen production; alternative dry reforming processes result in a lower hydrogen to carbon monoxide ratio compared to steam reforming. [15]

High temperature shift using a chromium or copper enhanced iron oxide-based catalyst is the typical means of carrying out water gas shift reactions and is performed at temperatures between 300°C and 500°C. The catalysts used in the high temperature shift process are tolerant of sulphur up to approximately 100 ppmv. The WGS reaction can convert up to 90% of the syngas to hydrogen. [1]

Among primary catalysts, CeO_2-Ni-CaO (cerium(IV) oxide – nickel – calcium oxide), are efficient in increasing production of the hydrogen volume fraction. Using calcium oxide (CaO), nickel oxide (NiO), olivine (magnesium iron silicate mineral), nickel/dolomite, and nickel aluminium oxide ($NiAl_2O_3$), the hydrogen content by volume in the syngas can increase from 46.0 to 59.6%. [2]

Depending on the technology and product purification requirement, various degrees of syngas upgrading may be needed, with differing proportions (volume) of gases produced. For example, for a bubbling fluidised bed gasifier (BFB) operating at 7 barg and 800 °C, using a mixture of O_2 and steam or air (depending on syngas use) to covert densified RDF, the untreated syngas will: [1]

- Contain a mixture of H_2 and CO of approximately 30%, 30% CO_2 and a 40% mixture of hydrocarbons and N_2
- The above syngas can be then reformed to increase the combined mixture of H_2 and CO to approximately 70%. CO_2 and nitrogen making up the remaining 30%
- The above syngas can be further reformed to increase the H_2 content to >98%

Gas separation and treatment

Hydrogen and CO_2 require separation and treatment using established technologies such as pressure swing adsorption (a gas separation process using adsorbents). Chemical solvents for example, using potassium carbonate (Benfield process) or monoethanolamine (MEA), and physical solvents for example, the Selexol® or Rectisol® approaches may be used. These approaches are mature technologies with high TRLs. Sorption enhanced water gas shift (SEWGS) is in development for application at the syngas upgrading stage that both produces hydrogen and removes CO_2 as it is produced. Research has indicated that each approach can achieve similar levels of gas separation, however, the large thermal load required to regenerate solvents in the chemical solvents processes (MEA and Benfield) results in a lower net energy efficiency than physical capture processes. Modelling of the SEWGS system has indicated potentially better efficiencies than other approaches could be achieved due to low energy cost for sorbent regeneration. The availability of CO_2 transportation and storage infrastructure post capture are challenges to successful delivery of carbon capture. [5] [7] [9] [13]

Hydrogen storage

Following polishing, hydrogen may be stored or transported via pipeline. Storage can occur at high pressure at 350-700 bar. [16] Medium pressures are used for onward pipeline transport. Hydrogen may also be stored or transported as a liquefied gas (as a cryogenic liquid). Further transport solutions may include the use of liquid organic or non-organic hydrogen carriers such as ammonia. The scope of this document terminates at the input to any storage or transport option selected.

CO_2 storage

If not released to atmosphere, CO_2 may be injected into a CO_2 capture and storage system. The collection, treatment, compression and onward transport of CO_2 by pipeline or non-pipeline transport option selected is outside the scope of this document.

Ancillary systems

Where hydrogen is not the only target product (for example where a combustible syngas mixture and hydrogen are produced) ancillary systems may be included such as power generation from combustion of the combustible non-hydrogen portion of the syngas. [3]

4.3. Pyrolysis

Pyrolysis to produce hydrogen requires heating of feedstock to around 700°C, in the absence of oxygen or with the use of less than 5% of the air required for stoichiometric combustion, typically at atmospheric pressure. The process deconstructs the feedstock and due to the absence of oxygen combustion does not occur. Rather than combust, the feedstock thermally decomposes into a syngas (a gas mixture of hydrogen and CO), combustible gases, ash, char, carbon black and other residues depending on the precise feedstock, technology deployed and process conditions. Pyrolysis is an endothermic process; hence, a supply of energy is required for the process to be initiated and maintained. [1] [4] [12] [15]

Whilst pyrolysis is a process that may have a variety of technical configurations, the generalised stages of pyrolysis technologies for the production of hydrogen are:

- Feedstock storage and, or preparation
- Pyrolysis
- Syngas treatment (removal of impurities and contaminants)
- Syngas upgrading (conversion and clean up into the desired product)
- Gas separation and treatment
- Hydrogen storage (and potentially CO_2 storage)

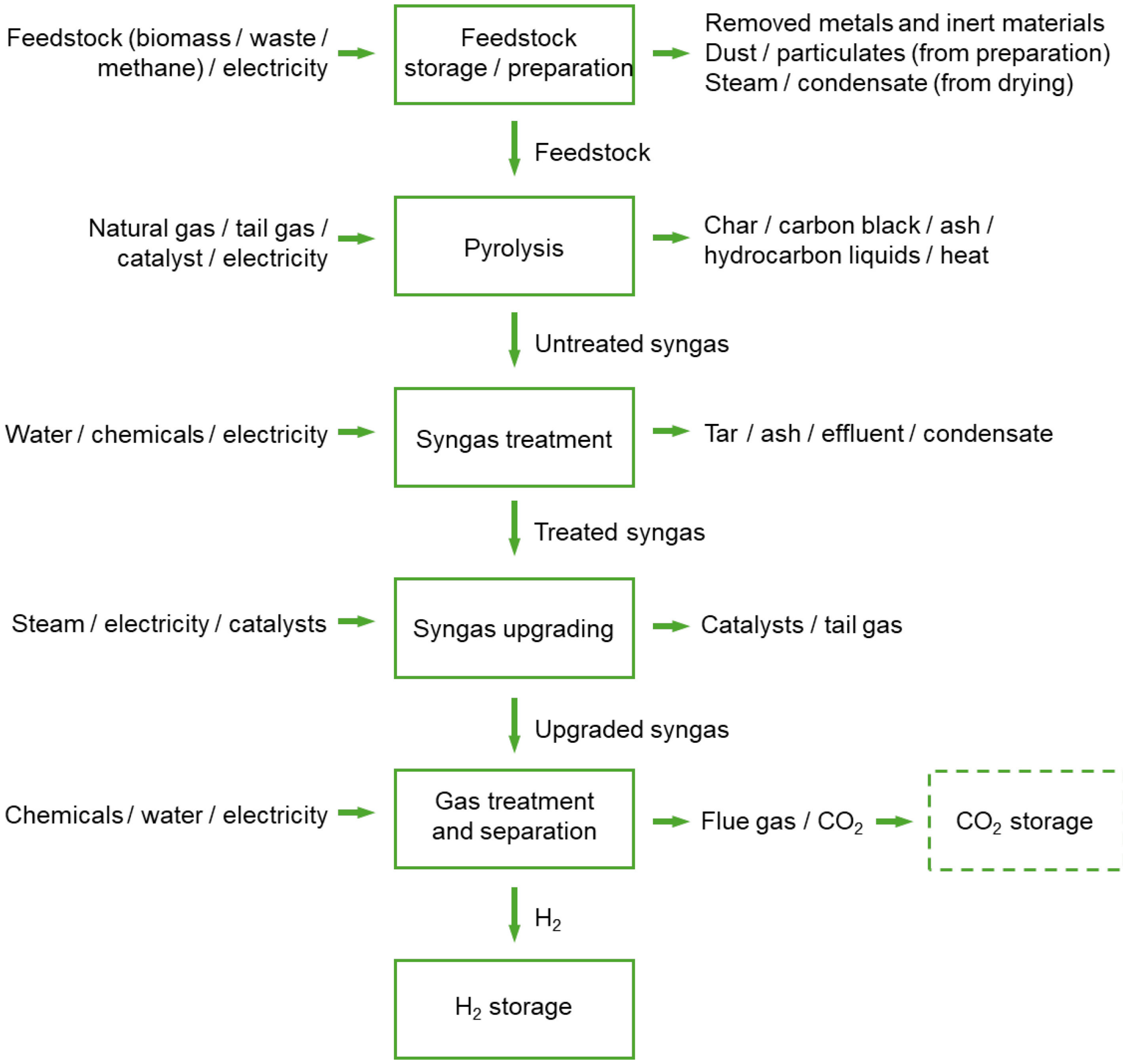
There are limited examples of pyrolysis facilities using MSW as a fuel due to the heterogeneity of its composition. Feedstocks such as virgin or waste wood, or waste plastics are preferred. [12] Methane as a feedstock for pyrolysis (gas splitting) is at a development stage. [5]

As with gasification, the precise nature of the feedstock preparation (if required, for example for biomass or waste), syngas treatment, syngas upgrading and gas separation will differ depending on the precise feedstock used and technology configuration. CO_2 from pyrolysis may be separated using established technologies such as by chemical solvents, physical solvents and PSA prior to compression and storage. Technology configurations may be fully integrated from feedstock through to syngas upgrading, whereas others may combine a variety of third-party unit technologies with proprietary syngas treatment and upgrading processes. [3] [5] [7]

As pyrolysis is an endothermic process requiring the transfer of large amounts of heat across the reactor wall for degradation of the feedstocks, systems are restricted in size. Consequently, systems are primarily modular, and large-scale pyrolysis is dependent on the operation of a number of modules. [1]

Figure 4.2, was developed by WSP UK Ltd following a review of literature, and it presents a simplified flow diagram for pyrolysis indicating inputs, outputs and generalised stages. Not all inputs and outputs may be present in any given configuration, for example, if the feedstock is prepared to the required specification prior to arrival at the facility, there may be no outputs from the feedstock storage and preparation stage other than into the pyrolysis stage. Further information on the stages is presented in the sections below. The process stages are generic and will depend on the specific technology configurations, not all the above stages may occur, or in the above sequence, for example, syngas may undergo upgrading without the need for treatment.

Figure 4.2 Simplified pyrolysis flow diagram



Feedstock storage and, or preparation

The biomass and waste feedstock storage and preparation aspects for gasification (see section 4.2) are also relevant to pyrolysis (for biomass: shredding and screening to a suitable size, drying and densification into pellets; for waste: de-baling, removal of ferrous and non-ferrous metals, removal of glass and stones, shredding, screening and drying). Preparation of feedstock may be required to meet input specifications. When a methane feedstock is required, grid natural gas may be used. [1] [3] [9] [12]

Pyrolysis

Pyrolysis processes have, to date, focussed on the production of pyrolysis oil (or bio-oil) from various feedstocks (biomass, tyres, plastics and RDF) using modular plants with feedstock input capacities of 7,000-10,000 tpa. However, pyrolysis processes have been developed and or are being investigated with a focus on the production of hydrogen from methane cracking. A summary of the main thermal pyrolysis and catalytic approaches is given below. However, early-stage work has been carried out on biomass and waste as summarised in section 4.4. [1] [5]

A) Thermal pyrolysis

Thermal pyrolysis uses an external heat source (either electrical resistive heating or combustion of a significant side stream of the input feedstock) to provide high temperatures, typically using a moving bed or molten metal reactor in the absence of any air. Where methane is used as a feedstock, the temperature is sufficient to split methane and other gaseous hydrocarbons into their component atoms. Solid carbon either precipitates or floats on the liquid metal and is collected, and the gaseous hydrogen stream is purified. Other feedstocks such as wastes, and biomass are also under investigation for hydrogen production in thermal pyrolysis pilot projects. [5] [15]

B) Catalytic pyrolysis

Catalytic pyrolysis uses an external heat source (either electrical resistive heating or combustion of a significant side stream of the input feedstock) to provide high temperatures inside the reactor in the absence of any air. A metal-based catalyst is typically used to assist in splitting the methane and other gaseous hydrocarbons into their component atoms. Solid carbon precipitates and is collected, and the gaseous hydrogen stream is purified. [5]

In a pyrolyser, for biomass and waste feedstocks, feedstocks undergo drying, de-volatilisation (part of the feedstock sublimes, turning into a mixture of gases and liquids) and partial gasification (gases generated react, producing the main components of the raw syngas). Solids are removed from the pyrolyser, while the syngas is passed on for treatment and or upgrading, with cooled condensed liquids recovered. To maximise gas production, a slow heating rate, high final temperature (between 700°C and 900°C), and long gas residence time is required (reducing char production and liquid yields). [4] [12]

Process parameters such as the feed rate, residence time and heat regime are adjustable to enable different product yields to be achieved. The product yield balance across gas, char and other residues is determined by the nature of the feedstock being used and the operational parameters (for example residence time, temperature, additives, catalysts) and reactor type and configuration. Char together with fine carbon particles may be captured in a cyclone. [17] [18]

Catalysts may be used in pyrolysis processes. Metals, including ruthenium, rhodium, and platinum enable strong catalytic activity due to their high activation and resistance to carbon deposition, but have a limited availability and high cost. Nickel, carbon monoxide or iron catalysts demonstrate similar activation at a lower cost. [15]

Production of hydrogen from pyrolysis of waste plastics may require a two-step process. First, waste plastics undergo pyrolysis to produce gas and char. Second, the produced volatiles (gas and liquid) are reformed for further cracking to generate hydrogen-rich gas and by-products such as carbon nanotubes. This two-step process is termed pyrolysis and in-line reforming process (and also pyrolysis-gasification process). [15]

Syngas treatment

As with gasification, syngas will contain contaminants which require removal (see Table 4.3 in section 4.2). Typically, syngas passes through a cyclone to remove particulate matter, electrostatic precipitation may also be used. A quenching unit may be deployed to lower the temperature and liquefy hydrocarbons (if present) to enable their removal. If quenching is deployed, the resulting wastewater may be filtered and reused. If sludge cake is obtained from filtration and has a suitable moisture content, it may be collected and re-introduced into the pyrolysis feed system due to its high calorific value (recovering carbon and converting residual energy back into gas in the process). [12] [17]

The most common contaminants present in syngas are particulate matter, tar, oxides of nitrogen, sulphur compounds, halides, hydrogen cyanide, and metals. Table 4.3 in section 4.2 presents syngas treatment technologies indicating which can contribute to the removal of which contaminant, and whether tail gas may be produced from the cleaning process. Depending on the precise technology configuration, a scrubber system may be deployed to remove acid gases and particulate matter and activated carbon beds may be used to remove entrained hydrocarbons and other contaminants. The methods selected will be determined by the feedstock and specific technology configuration. [1] [3] [4] [13] [17]

Syngas upgrading

Following syngas treatment, as with gasification (see section 4.2), upgrading (reforming) processes are applied. Upgrading is typically through application of high temperature WGS reaction. [1] [3] [13]

Gas separation and treatment

Hydrogen and CO_2 may be separated and treated using established technologies such as by chemical solvents, physical solvents, for example, the potassium carbonate (Benfield), monoethanolamine (MEA), Selexol® or Rectisol® approaches (see “Gas separation and treatment”, for Gasification, in section 4.2). These approaches are mature technologies.

Specific processes may deploy integrated (proprietary) approaches, for example syngas high in methane may be modified to an elevated methane content using a CO_2 scrubber, integrated with CO_2 catalytic methanation and WGS reactors to enhance methane content prior to passing through membrane filters and plasma technology for a final stage of hydrogen production. [17]

Hydrogen storage

Following polishing, hydrogen may be stored or transported via pipeline. Storage can occur at high pressure at 350-700 bar. [16] Medium pressures are used for onward pipeline transport. Hydrogen may also be stored or transported as a liquefied gas (as a cryogenic liquid). Further transport solutions may include the use of liquid organic or non-organic hydrogen carriers such as ammonia. The scope of this document terminates at the input to any storage or transport option selected.

CO_2 storage

If not released to atmosphere, CO_2 may be injected into a CO_2 capture and storage system. The collection, treatment, compression and onward transport of CO_2 by pipeline or non-pipeline transport option selected is outside the scope of this document.

4.4 Emerging technologies

The NDA has published a Guide to Technology Readiness Levels for the NDA Estate and its Supply Chain, which is an approach to assessing technologies and their readiness for on-site deployment. Technology Readiness Levels (TRLs) provide a measure of the technical maturity and associated risk of a technology, but they have limitations: they apply to individual plant items rather than integrated systems, may not directly indicate cost, schedule, or suitability, and can change over time depending on project condition. TRLs provide a nine-point scale to indicate the maturity of a technology, ranging from TRL 9 Operations, TRL 8 Active Commissioning, TRL 7 Inactive Commissioning, TRL 6 Large Scale, TRL 5 Pilot Scale, TRL 4 Bench Scale Research, TRL 3 Proof of Concept, TRL 2 Invention and Research, TRL 1 Basic Principles. [6]

Whilst gasification and pyrolysis processes for the production of hydrogen are being developed and tested, there is also evidence of other technologies being investigated as standalone hydrogen production technologies or as enhancements to gasification and pyrolysis processes. These include plasma splitting, plasma pyrolysis, microwave assisted pyrolysis, dark fermentation of biomass, microwave plasma conversion of biogas, rising pressure reformer, triboelectric plasma reforming, Bio-hyPER process, and pressurised water absorption for hydrogen-CO_2 separation. All these technologies are summarised below with indicative TRLs assigned by WSP based on available information reviewed for this report. The information does not yet reflect potential outcomes from the current pilot projects. Some of the technologies described were funded by the DESNZ Bioenergy with Carbon Capture and Storage (BECCS) Programme to feasibility stage but not funded to demonstration phase.

Plasma splitting

Plasma splitting, with an indicative TRL 8 uses an input electricity source to drive plasma torches or generate microwaves to create localised extremely high temperatures, in the absence of any air. A strong electrical current or microwaves transfer heat directly on a feedstock to generate a plasma, splitting atoms into their component ions of hydrogen and carbon. Upon cooling of the plasma, the carbon precipitates out and is collected, and the gaseous hydrogen stream is purified. Typically, no catalyst is used, although one may be used to lower reaction temperatures. Residual heat is generated as a result of the process rather than being required as an input. [5]

From a review of available literature and information of several proprietary technology providers, development of plasma splitting for the production of hydrogen has focussed on cracking methane and other hydrocarbons rather than biomass or waste.

Plasma pyrolysis

Plasma pyrolysis, with an indicative TRL 4, uses an input electricity source to drive plasma torches that operate at localised high to very high temperatures, in the absence of any air. The plasma generated is responsible for transferring heat into the feedstock, splitting the methane and other gaseous hydrocarbons into their component atoms of hydrogen and carbon. Catalysts may also be used to lower reaction temperatures. The solid carbon precipitates out and is collected, and the gaseous hydrogen stream is purified. [5]

Plasma pyrolysis has received attention due to manageability, rapid heating, and ability to function effectively at low power consumption. Plasma is an ionised gaseous mixture of positively charged ions and negatively charged electrons, produced either through the intense heating of a gas or the exposure of the gas to a strong electromagnetic field. Thermal plasma can be generated by employing direct current, alternating current, microwave discharge, or radio frequency induction. Plasma can also be produced using a 2.45 GHz magnetron from a commercial microwave oven. When waste-derived carbonaceous particles are introduced into plasma, the rapid heating by the plasma induces the release and cracking of volatile materials generating hydrogen and light hydrocarbons such as acetylene and methane. [13]

Plasma pyrolysis of non-recyclable plastic waste has been reported to be at an early stage of development [17] and when using an organic waste (biomass) feedstock, has been shown to produce a solid residue and a combustible gas (gas yield composed of hydrogen, methane, carbon monoxide, acetylene, and ethylene, ranged from 50 to 98 wt%). [13]

Microwave assisted pyrolysis

In microwave-assisted pyrolysis, with and indicative TRL 4, a plastic feedstock is mixed with a microwave absorbent material, such as particulate carbon. The microwave absorbent material provides the required heating for conversion of the feedstock, transforming microwave radiation energy into thermal energy. Unlike conventional reactors, microwave energy is supplied directly to the material via molecular interactions with the electromagnetic field leading to a short heating time. For plastics, a microwave absorbent with a high dielectric constant (has a high electrical resistivity) is required to be mixed with the plastics to absorb microwave energy and attain the required temperature.

The technique offers rapid and uniform internal heating rates, operational flexibility, high-product selectivity, and consistent volumetric heating. Using microwave absorbents on an industrial scale may be challenging given that the heating efficiency may vary greatly for different absorbents. The varying composition of plastic wastes and the lack of knowledge regarding the dielectric characteristics of various materials compound this limitation. Research on microwave-assisted reactors is still in its early stages. [13]

Dark fermentation of biomass

Dark fermentation, with an indicative TRL 5, uses anaerobic microorganisms in darkness (between 25°C and 80°C) or high temperatures (>80 °C) for bio-H_2 production. In addition to H_2, other gases such as CO_2, CO, and hydrogen sulphide are released. A primary source of bio-H_2 is the glucose molecules that occur in carbohydrates and other feedstocks. Research has focussed on increasing bio-H_2 production in terms of yield and productivity (for example methods to optimise fermentation such as different pre-treatment methods, such as homogenisers, alkalis, ultrasonics, and biological processes). [18]

Microwave plasma conversion of biogas

The use of focussed microwaves to directly ionise biogas to create a plasma. This technique, with an indicative TRL 5, directly breaks down the chemical bonds of methane to create hydrogen and carbon using high frequency microwaves to energise electrons in the gas and promote collisions with other molecules, breaking them apart and generating free electrons and positive ion radicals creating a cascade of reactions, which ensures a sustained plasma state as long as the microwave energy continues to be applied. The methane is a plasma, with most of the energy contained in the microwaves delivered directly to the electrons and ions of the gas. When out of the plasma region, the electrons and ions cool and combine to stable compounds, principally molecular hydrogen gas and solid carbon particles in the form of graphene. [19]

Rising pressure reformer

The rising pressure reformer (RiPR) is a gasification technology that aims to utilise biomass to produce a hydrogen rich syngas. The process, with an indicative TRL 5, produces hydrogen at pressure resulting in a reduced energy requirement if high-pressure hydrogen is required post-production. The process has been modelled and experimental tests carried out. The technology is compatible with a wide variety of biomass feedstocks with high moisture contents, variable feedstock particle size and variable feedstock composition. Further work is proposed to test the process on the biogenic fraction of municipal waste such as oversize compost and potentially forestry residues. [20]

Triboelectric plasma reforming

Triboelectric plasma reforming is a technology under investigation (modelling, experimental, pilot plant design) aimed at replacing thermal plasma gasification technologies. The technology with an indicative TRL 5, is based on external sources of plasma energy whereby triboelectric plasma, or “triboplasma”, is generated by controlling and exploiting particle collisions and their resulting electrostatic charges (rather than conventional thermal technologies which rely on direct power input). When triboelectric discharges occur in a controlled manner, the ionised environment is similar to that of a conventional thermal arc. The application of the technology is focussed on the conversion of tars and other contaminants from syngas produced in gasification reactors. [21]

Bio-hyPER process

The Bio-hyPER process, with an indicative TRL 5, is a sorption enhanced reforming (SER) technology that is in development. The process aims to enhance gasification processes using biomass feedstocks. It utilises a high temperature CO_2 capture material (for example, lime) to remove CO_2 from process gas which shifts the equilibrium position of the reactor to favour production of hydrogen (with CO_2 captured by the sorbent). Syngas from gasification has a high oxidised carbon content (more carbon monoxide and CO_2 than methane), requiring less reforming and exothermic carbonation (generating high-grade heat for use). Two main reactors are required for the SER process, a reformer/carbonator operating at between 600°C and 700°C, pressurised and a calciner operating at ~900°C at low pressure. Heat is removed from the reformer/carbonator where catalytic reactions occur. Solids (lime/limestone) are circulated between the two reactors using fluidised or entrained flow reactors.

When natural gas is used as a feedstock, the overall heat balance of reforming and carbonation processes is approximately adiabatic, thus, no additional heat is generated. The benefit of utilising a syngas from gasified biomass is that the exothermic carbonation reaction is dominant as the CO_2:CH_4 ratio is higher, generating heat at between 600°C and 700°C, which can be recovered and used. The generated heat is a function of the carbon monoxide and CO_2 content in syngas mixture, which is determined by the composition of biomass feedstock. [22]

Pressurised water absorption for hydrogen-CO_2 separation

Pressurised water absorption (PWA) is a technology aimed at separating hydrogen and CO_2 in a syngas stream. The process, with an indicative TRL 5, has greater energy efficiency compared to the other technologies such as amine solvent solutions which are already widely used in industry for removing CO_2 from gas. Under pressure, CO_2 is absorbed into a liquid, but the hydrogen is not, resulting in separation. When the pressure of the CO_2 -rich liquid is reduced, CO_2 is released and can be captured. Process testing to demonstrate CO_2 capture at both low, 7 barg and high,30 barg is being carried out. Further work is required to validate the technology in the context of separation of CO_2 and hydrogen. The technology has been used for the separation of other gases (for example, biogas-methane) hence further research and development is required to ensure suitability for hydrogen-CO_2 separation. The technology may be suitable for application with gasification production techniques. [23]

5. Environmental aspects

5.1. Introduction

This section presents an overview the environmental aspects of the processes associated with the following:

- Design considerations
- Inputs
- Utility demand and management
- Emissions to air and water, wastes and their mitigation, treatment and management
- Unplanned emissions and accidents
- Startup and shutdown and non-normal operations
- Monitoring requirements
- Product separation, purification and specification

Gasification and pyrolysis of biomass or waste are currently being tested and demonstrated for hydrogen production; none are yet to be utilised on a commercial scale for this purpose. Information identified regarding environmental aspects is presented in this section however, there are significant gaps. Information gaps and their implications are discussed in sections 6.2 and 6.3, respectively.

5.2. Gasification

5.2.1. Design considerations

As a guiding principle, the overall system should be designed to achieve operational flexibility with maximum efficiency, considering the overall environmental impact. A list of considerations identified includes:

- High efficiency and low environmental impact of the whole facility in addition to individual equipment items
- Input from Original Equipment Manufacturer to ensure that environmental consequences of operation and, or maintenance are considered
- Leak detection and management (including potential for leak-free valve designs) to reduce potential emissions, which have both environmental and safety-related impacts
- Assessment of pressurised storage requirements to manage downstream hydrogen supply
- Understanding of overall system design and performance under a range of operating conditions
- Monitoring and logging of data to demonstrate optimised plant operation
- Review of opportunities to simplify the system design
- Ensuring equipment is appropriately sized (including design margins) to provide best efficiency and to minimise energy use, water use and heat loss
- Designing to operate safely and efficiently for a range of operating scenarios

- Optimising efficiency of operation for the most common operating conditions is essential to minimising environmental impact
- Optimise heat recovery potential
- Expected consideration of materials recovery within the installation
- Utility systems optimisation
- Consideration of environmental impacts to include design of equipment and control schemes for associated equipment
- Evaluation of water supply source including options such as treated industrial wastewater

5.2.2. Inputs

Preparation and processing of feedstock is carried out before gasification to comply with several characteristics. [7] The primary characteristics of interest are:

- Particle size
- Fuel feedstock heating value
- Quantity of non-fluidisable material
- Metal content
- Optimum moisture content

The chemical composition of the fuel determines the feedstock heating value, a key parameter influencing plant performance and efficiency. Fuels with a high content of carbon and a low oxygen content tend to have a higher heating value (HHV). [4]

Various types of biomass, waste feedstocks may be used as feedstocks for gasification to produce hydrogen. [7] Feedstocks may arrive ready for use or require preparation prior to gasification at the facility. The processes for the preparation of feedstock are described in section 4.2. Depending on the characteristics of the feedstock and processes to be used, the following should be considered:

- Removal of ferrous and non-ferrous metals for recovery from waste feedstocks
- Removal of glass and stones for recovery from waste feedstocks
- Optimising drying processes using recycled heat, for example, heat from the gasification process

RDF feedstock is typically delivered loose and may need to be densified into pellets on site. It may be blended with waste wood to improve biogenic content if required and additives or bonding agents may be required to ensure the blended feedstock remains compact. Prepared RDF is typically stored in bunkers on site to be delivered to the gasifier when needed. [1] The techniques for preparation of feedstocks are proven technologies; feedstock preparation systems are commercially proven with many facilities already in operation. [7]

Biomass may be adopted as feedstock for gasification due to its low sulphur and halide content. Biomass sources from virgin wood or energy crops are considered carbon neutral if grown sustainability. However, biomass is an expensive fuel in comparison to RDF due to the costs of growing, harvesting, preparation, and transport. RDF and other waste feedstocks may also attract a gate fee. [1] [4]

Availability, technical challenges, and behaviour in the gasifier are factors to be considered when selecting a biomass feedstock for gasification. These considerations are presented in the Table 5.1.

Table 5.1 Biomass feedstock types, challenges and behaviour in gasification [1]

Biomass type	Technical challenges	Behaviours in gasification	Availability
Virgin wood	Moisture content, particle size and levels of ash, chlorine, sodium and potassium in the fuel	Moisture content can affect syngas product yields. Chlorine, sodium and potassium may cause increased corrosion and slagging, with high levels of sodium and potassium lowering ash melting points and causing operational challenges in fluidised bed systems.	Mostly imported. Clean wood is readily available from international sources.
Energy crops **(Biomass grown for the purpose of providing energy (fast growing species)**	Moisture content of the energy crop, particle size and levels of ash, and high concentrations of chlorine, sodium and potassium in the fuel as it is a fast-growing crop. This may cause corrosion and slagging in the process.	Moisture, chlorine, sodium, potassium, and ash behaviours are similar to that of virgin wood.	Due to their cost and the lack of demand, large quantities of energy crops are not available.

Biomass type	Technical challenges	Behaviours in gasification	Availability
Waste wood	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.	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 may cause increased corrosion and slagging, with high levels of sodium and potassium lowering ash melting points and causing operational challenges in fluidised bed systems. 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.	It is estimated that there is about 5 Mtpa of recycled wood available in the UK. But with much being used in the recycling industry, and additional waste wood fuelled energy plants emerging in the UK, reliable availability of waste wood is limited.
Agricultural residues	Straw contains significant amounts of chlorine, sodium and potassium which can be problematic due to the potential for increasing corrosion of downstream equipment, and a decrease in heat transfer efficiency from ash deposition from these elements. [26] Moisture of straw is typically constant if harvest time is controlled to avoid bad weather, and the straw is properly stored. Straw may generate variable amounts of ash, dependent on mineral uptake, and composition of soil where it was grown, if stones and soil are captured during harvesting and baling. All agricultural waste can contain metal objects or stones from the collection and storage operation which need to be removed.	There has been very limited development of gasification to process agricultural wastes. Agricultural residues tend to be quite specific, and plants would need to be designed with specific measures to counteract the contaminants in the various fuels	The market is reasonably well balanced to match fuel availability and unless new gasification displaces combustion plants for these fuels, agricultural wastes are unlikely to be a significant source of fuel.

Together with operational parameters and the atmosphere used, an elevated presence of oxygen in biomass feedstock can result in a considerable portion of the syngas generated being CO_2 , ranging from 10% to 65%. A lower oxygen content may therefore be preferred. Similarly, a higher moisture content will result in increased energy use to achieve higher temperatures (or increased drying requirements at preparation stage), whilst with sulphur and other chemical contaminants generally absent, a cleaner gas will be produced. [4]

The use of waste feedstocks for gasification operations is more challenging than biomass feedstocks due to the potential for high variability in chemical composition. However, waste feedstocks may be preferred due to the high price of biomass. Residual MSW or commercial and industrial waste contains approximately 50% biogenic matter by energy content (the amount of energy that can be derived from the biogenic content). The biogenic matter, for example, food waste, may be considered carbon neutral if used to generate power, heat or fuels, in a similar way to biomass. For gasification to produce hydrogen, waste feedstocks are focussed on RDF and waste plastics. [1]

The variability of materials contained within RDF can result in changes to syngas composition during the gasification process. The raw syngas generated by an RDF feedstock may present the following characteristics: [4]

- Equal amounts of CO_2 and CO in the syngas leaving the gasifier
- The higher the amount of residual moisture entering the reactor, the higher the amount of CO_2 and hydrogen present in the syngas
- The gas will contain several contaminants in variable quantities depending on the fuel feedstock composition - The main contaminants generated are tars, hydrogen sulphide, hydrogen chloride (traces), metals and particulate matter (comprising unspent carbon and fly ash)

5.2.3. Utility demand and management

Water demand

Water demand for syngas treatment and for gas separation and treatment may be significant. Evaluation of the water supply source including options such as treated industrial wastewater and water recycling should be considered.

Syngas treatment water demand

To provide an indication of the quantum of water that may be required, water demand was calculated in an indicative mass balance (see Appendix A) of 330,000 tpa and 1,000,000 tpa biomass fed gasification plants for hydrogen production for the syngas treatment stage at 150-350 ˚C. The mass balance suggested that 214,100 tpa water may be required for the 330,000 tpa plant, with 1,209,000 water tpa required for the 1,000,000 tpa plant. [7]

Similarly, water demand was calculated in the indicative mass balance of a 100,000 tpa and 550,000 tpa MSW fed gasification plant for hydrogen production for the syngas treatment stage at 150-350˚C. 75,700 tpa water was calculated as required for the 100,000 tpa plant, with 416,000 tpa water required for the 550,000 tpa plant. [7]

Carbon capture water demand

Carbon capture (gas separation and treatment stage) installations are expected to present new water stresses due to additional water needs of chemical and physical processes to capture and separate CO_2 as well as from cooling processes and abating emissions. The main impacts from carbon capture may arise from water use. Emission scrubbing will also generate wastewater, treatable using established technologies. The return of cooling water to water environments may also result in thermal pollution. [27]

Electricity demand

Gasification processes consume electricity to drive fans, compressors, and pumps in the gasifier. [1]

An indication of the quantum of electricity demand was calculated in mass balances (see Appendix A) of 330,000 tpa and 1,000,000 tpa biomass fed gasification plants for hydrogen production. The mass balance that suggested 107,100 MWh/year was required for the 330,000 tpa plant, with 604,500 MWh/year required for the 1,000,000 tpa plant. [7]

Similarly, electricity demand was calculated in mass balances of 100,000 tpa and 550,000 tpa MSW fed gasification plants for hydrogen production. 37,800 MWh/year was calculated as required for the 100,000 tpa plant, with 208,100 MWh/year required for the 550,000 tpa plant. [7]

Integrating carbon capture installations to a gasification plant requires further energy input. Based on the amount of CO_2 captured, heat and electricity are required to operate carbon capture plant, including the dehydration process and the compressors. Thermal energy is one of the most important factors in the carbon capture process, particularly for chemical separation techniques. A mass and energy balance estimated from a demonstration project producing biohydrogen from waste and biomass feedstock and carbon capture indicated use of thermal energy in the range of 4-4.2 MJ/kg CO_2 removed from the gas stream when using chemical solvents. [13]

Natural gas demand

Natural gas is required for start-up of the gasification process (and may be required to maintain combustion temperature).

An indication of the quantum of natural gas demand was calculated in mass balances (see Appendix A) of 330,000 tpa and 1,000,000 tpa biomass fed gasification plants for hydrogen production. The mass balance suggested that 130 tpa was required for the 330,000 tpa plant, with 836 tpa required for the 1,000,000 tpa plant. [7]

Similarly, natural gas demand was calculated in the mass balance of 100,000 tpa and 550,000 tpa MSW fed gasification plants for hydrogen production. 235 tpa was calculated as required for the 100,000 tpa plant, with 1,295 tpa required for the 550,000 tpa plant. [7]

5.2.4. Emissions to air, and liquid and solid wastes

This section provides an overview of the potential emissions to air and water, wastes and, where information is available, their mitigation, treatment and or management. Due to the limited information available, section 6.3 presents a summary of environmental aspects and information needs that may be required in an environmental permitting context.

Flue gas

Flue gas comprising nitrogen, CO_2, oxygen and water will be released. Flue gas composition from biomass gasification has been modelled as containing 6.4% CO_2 mol %, 6.0% O_2 mol % and 15.3% H_2O mol %. [7]

To provide an indication of possible flue gas generated, calculations in mass balances (see Appendix A) of 330,000 tpa and 1,000,000 tpa biomass fed gasification plants for hydrogen production suggest that 492,000 tpa flue gas generated by the 330,000 tpa plant, with 2,805,000 tpa flue gas generated for the 1,000,000 tpa plant. [7]

Similarly, flue gas generated was calculated in mass balances of 100,000 tpa and 550,000 tpa waste fed gasification plants for hydrogen production. 152,500 tpa flue gas was calculated as generated by the 100,000 tpa plant, with 850,700 tpa flue gas generated for the 550,000 tpa plant. [7]

Carbon dioxide

CO_2 from the gas separation and treatment stage will be released. A review of biomass gasification for hydrogen production has indicated that biomass gasification without carbon capture may have a ratio of 0.31 to 8.63 kg CO_2/kg hydrogen compared to -17.50 to -11.66 kg CO_2/kg hydrogen with carbon capture. [28]

The potential CO_2 generated was calculated in mass balances (see Appendix A) of 330,000 tpa and 1,000,000 tpa biomass fed gasification plants for hydrogen production. 248,000 tpa CO_2 was calculated to be generated by the 330,000 tpa plant, with 1,424,500 tpa CO_2 generated for the 1,000,000 tpa plant. [7]

Similarly, CO_2 generated was calculated for the mass balances of 100,000 tpa and 550,000 tpa waste fed gasification plants for hydrogen production. 76,900 tpa CO_2 was calculated as generated by the 100,000 tpa plant, with 432,000 tpa CO_2 generated for the 550,000 tpa plant. [7]

Tail gas

Tail gas may require venting and flaring for safe release or combustion of non-routine controlled (for example, start up and shutdown), upset or emergency releases. Emissions should not be continuous during normal operations. [12] Such gases are released through dedicated release points, where they can be sampled and monitored throughout a gasification plant lifetime. [12] Tail gas may also be reintroduced to the gasifier as a fuel source.

Dust and particulates from feedstock preparation

Fugitive releases of dust and particulates released from movement and preparation of feedstocks may occur dependant on the nature of the feedstock (for example dry and dusty) and feedstock handling (for example mixing, transfer) required on site.

Steam and, or condensate

If feedstock drying is required, condensate will be generated and require collection prior to discharge to sewer or treated for reuse in the process.

If carbon capture facilities are a part of a gasification plant, condensate from compression and, or dewatering activities and cooling system blowdown may be produced. [29]

Effluent

Effluent from syngas treatment may be generated in some configurations. Effluents may require treatment prior to discharge to sewer (for example to remove hydrocarbons).

To provide an indication of possible effluent volume that may be generated, calculation in mass balances (see Appendix A) of 330,000 tpa and 1,000,000 tpa biomass fed gasification plants for hydrogen production was performed. The results suggested that 231,000 tpa effluent to be generated by the 330,000 tpa plant, with 1,302,000 tpa effluent generated for the 1,000,000 tpa plant. [7]

Similarly, effluent generated was calculated in mass balances of 100,000 tpa and 550,000 tpa waste fed gasification plants for hydrogen production. 81,500 tpa effluent was calculated as generated by the 100,000 tpa plant, with 448,100 tpa effluent generated for the 550,000 tpa plant. [7]

If the gas separation and treatment stage uses amine solvents in the final stage of acid washing to minimise emissions of amines and breakdown products to air, an acid scrubbing liquor will be produced which will need treatment prior to discharge. [29]

Tar

Tars are generated during the gasification process. Tars require separation from syngas, collection and storage prior to being sent for disposal. [1] Tars contain a range of polycyclic aromatic hydrocarbons, some of which have been shown to be carcinogenic. [30]

Sand

Waste sand from fluidised bed reactors may be recovered and reused in the process.

Catalyst

Spent catalysts from syngas upgrading processes may be used in proprietary technologies and be sent for recovery and, or regeneration.

Ash and char

Ash is collected for disposal or reuse. The ash may be disposed of or, if inert, used in secondary aggregate production. [1] [9]

Char is a solid waste produced in the gasification of feedstocks to produce hydrogen. Char is discharged from the bottom of the gasifier reactor. [1] [12] Char from hydrogen production comprises mainly carbon with some other hydrocarbons and may be recovered for use in various applications (for example, as an adsorbent, catalyst, reducing agent, or in secondary aggregate production).

Results from the model described in Appendix A indicate that, when using biomass as a feedstock, less than 0.6% of solids in the form of char and ash may be produced, for both capacities assessed, whilst when RDF is used as a feedstock, nearly 11% of ash and char may be produced.

Metals or inert materials

Waste feedstocks may require removal of ferrous and non-ferrous metals and removal of glass and stones, if not already removed prior to delivery, using established processes. Recovered materials should be forwarded for recovery and recycling.

Heat

Heat will be generated from the processes and may be reused (for example in biomass drying).

Noise

No specific information on noise aspects was identified in literature reviewed. Plant will include pumps, compressors, fans and other noise emitting equipment, such as feedstock conveyor systems, if used. Consideration of noise abatement and attenuation should be considered to minimise impacts.

5.2.5 Unplanned emissions and accidents

The UK Low Carbon Hydrogen Standard requires that hydrogen production facilities complete a fugitive hydrogen emissions risk reduction plan prior to operations commencing (hydrogen is an indirect greenhouse gas for example, interacts with hydroxyl radicals to increase the production of ozone, another greenhouse gas). The plan should demonstrate how the hydrogen plant will be designed and operated to manage fugitive emissions and is required to consider each fugitive hydrogen source. Hydrogen production facilities are required to provide the expected future fugitive hydrogen emissions in kg pure hydrogen per year, assuming the mitigation plan is followed. [5]

Process venting, compressors, on-site storage, tail gas flares, and leakage through pipework and joints have been identified as being potential sources of fugitive hydrogen emissions: [5]

Process venting: cold vents are likely to be the most significant source of fugitive hydrogen emissions at a hydrogen production facility. Other sources of venting are, for example, purging from seals, process equipment (for example PSA), instruments and maintenance activities.

Compressors: compressors are likely to be a source of fugitive hydrogen emissions through permeation through seals.

On-site storage: above-ground stationary hydrogen storage is likely to be a significant source of fugitive hydrogen emissions. Compressed hydrogen cylinders, and liquid hydrogen storage can be susceptible to leakage.

Flares: incomplete combustion in flares may result in residual hydrogen being released to the atmosphere. This is expected to be negligible provided that flares are well designed and maintained.

Leakage through pipework and joints: hydrogen leakage through joints, valves and so on, is expected to be negligible provided that best practice is followed, including using welded joints wherever possible and ensuring that equipment is maintained in good condition.

Safety systems, including gas detection, emergency shutdown systems and process shutdown systems are necessary in all facilities to prevent, detect, and mitigate hydrogen releases. [31]

During the operation of waste management sites, fire is a challenging hazard to control. [9] Biomass and waste gasification plants receive, store, and handle feedstocks used in the process, which are flammable and, when not stored correctly, can lead to spontaneous combustion of the feedstock piles. The following risks should be considered: [1]

- Risk of spontaneous combustion of flammable particulate matter and ultrafine carbon dusts if levels in the plant are not controlled according to the required standards
- Risk that syngas could leak from plant and, or equipment and mix with ambient air to create a potentially explosive atmosphere
- Risk that air could leak into the system and mix with syngas to produce a potentially explosive mixture

Currently no information has been found on the likely rate of hydrogen leakage from biomass and waste gasification plants, despite additional targeted monitoring. [32]

5.2.6 Startup, shutdown and non-normal operations

During the start-up process of a gasification plant for hydrogen production, natural gas will be required to initiate combustion producing related combustion emissions. Natural gas may also be required during process upset or outages to maintain process temperature resulting in related emissions of CO_2 and potential tail gas flaring. [1] When the plant is operating normally, no support fuel should be required due to the exothermic nature of the gasification reactions. Hydrogen may be vented during facility start-up and shutdown and process purging. The significance of venting will be dependent on the frequency of start-ups, shutdowns and other unplanned events. [5]

5.3. Pyrolysis

5.3.1. Design considerations

Refer to section 5.2.1 for general design considerations also application to pyrolysis.

5.3.2. Inputs

Methane may be used as a feedstock in pyrolysis technologies where methane is split into CO_2 and hydrogen. Natural gas is likely to be the preferred feedstock for operators.

Methane is a stable molecule with thermal dissociation occurring at high temperatures (between 1,000°C and 1,100°C). Using a catalyst, catalytic decomposition of methane (CDM) occurs, and the thermal dissociation temperature can be decreased to between 500°C and 1,000°C. Methane pyrolysis, through CDM may be carried out over nickel, carbon, noble metal, and iron catalysts. [33]

MSW and, or plastics waste may be used as a feedstock. There are currently limited reference facilities using MSW as a feedstock for pyrolysis, as it is a complex fuel with a variable composition. [12] Virgin or waste wood and plastics, have a reduced risk of product contamination compared to MSW. [12]

A high volatile matter content, and elevated amounts of carbon and hydrocarbon in plastics are favourable attributes of a feedstock for pyrolysis. [15] However, waste plastics may contain fillers and additives which may affect thermal degradation. Additives can give rise to greater energy input and hence higher temperatures, or longer residence times may be required to allow the reaction to attain completion. Poor feedstock quality will also influence water and moisture content and other contaminants, resulting in greater feedstock preparation requirements. [34]

Refer to section 5.2.2, Feedstock characteristics and preparation, for general aspects also applicable to pyrolysis.

5.3.3. Utility demand and management

Water demand

Water demand for syngas treatment and gas separation and treatment may be significant. Evaluation of the water supply source including options such as treated industrial wastewater and water recycling should be considered.

The design proposal for a pyrolysis pilot plant has indicated that 155 kg/h of water may be required for water gas shift reactors per 1,000 kg/h of feedstock throughput. [17]

Refer to section 5.2.3, Water demand, for general aspects also applicable to pyrolysis.

Electricity demand

Pyrolysis processes consume electricity to drive pumps, compressors, and fans in the pyrolyser. The design proposal for a pyrolysis pilot plant has indicated that 1,834.69 kWh of electricity may be required per 1,000 kg/h of feedstock throughput. [17]

Refer to section 5.2.3, Electricity demand, for general aspects also applicable to pyrolysis.

Natural gas demand

Natural gas is required to initiate the pyrolysis process and may be required to maintain the required combustion conditions.

5.3.4. Emissions to air, and liquid and solid wastes

This section provides an overview of the potential emissions to air and water, wastes and, where information is available, their mitigation, treatment and, or management. Due to the limited information available, section 6.3 presents a summary of environmental aspects and information needs that may be required in an environmental permitting context.

Flue gas

Refer to section 5.2.4 for general aspects also applicable to pyrolysis.

Carbon dioxide

CO_2 from the gas separation and treatment stage will be released.

The design information for a pyrolysis pilot study with a waste feedstock has indicated the following CO_2 emissions through the process operating on the mixture of solid recovered fuel and waste plastics, with specific emission values summarised in Table 5.2 based on 7,800 tpa waste feedstock and 1,426 tpa H_2 production. [17]

Table 5.2 Design stage information for CO_2 emissions from a pilot pyrolysis process [17]

Process stage	CO_2 Emissions
Stage 1 – Pyrolysis	0.071 t/h of biogenic CO_2 and 0.115 t/h of non-biogenic CO_2 is captured in char.
Stage 2 – CO_2 stripping and recovery	0.013 t/h of biogenic CO_2 and 0.022 t/h of non-biogenic CO_2 is released in CO_2 purge. The remaining CO_2 is fed to catalytic methanation.
Stage 3 – Catalytic methanation / water gas shift reactor	No emissions – CO_2 is recycled to CO_2 stripping and recovery plant

Process stage	CO_2 Emissions
Stage 4 – Plasma torch	0.725 t/h of biogenic CO_2 and 1.183 t/h non-biogenic CO_2 is captured as carbon black.
Parasitic energy (energy consumed by the pyrolysis plant)	0.022 t/h of CO_2 is associated with grid electricity use to power the system.

Tail gas

Refer to section 5.2.4 for general aspects also applicable to pyrolysis.

Dust and particulates from feedstock preparation

Fugitive releases of dust and particulates released from movement and preparation of feedstocks may occur dependant on the nature of the feedstock (for example dry and dusty) and feedstock handling (for example mixing, transfer) required on site.

Steam and, or condensate

Refer to section 5.2.4 for general aspects also applicable to pyrolysis.

Effluent

Refer to section 5.2.4 for general aspects also applicable to pyrolysis.

Tar

Tars are not target products and are generated from syngas treatment. Tars require collection and storage prior to being sent for disposal.

Catalyst

Spent catalysts from syngas upgrading processes may be used in proprietary technologies and be sent for recovery and, or regeneration.

Ash, carbon black, char and hydrocarbon liquids

Refer to section 5.2.4 for general aspects also applicable to pyrolysis.

The design proposal for a pyrolysis pilot plant has indicated that 100 kg/h of char may be generated per 1,000 kg/h of feedstock throughput. Furthermore, 523.60 kg/h of carbon black (produced from the plasma torch. Its structure is influenced by the speed of cooling, which in turn influences how the material may be utilised) and 70 kg/h of hydrocarbon liquids (pyrolysis oil) may be generated per 1,000 kg/h of feedstock throughput. [17]

Metals or inert materials

Refer to section 5.2.4 for general aspects also applicable to pyrolysis.

Heat

Heat will be generated from the processes and may be reused (for example in biomass drying).

Noise

No specific information on noise aspects was identified in literature reviewed. Plant will include pumps, compressors, fans and other noise-emitting equipment. Consideration of noise abatement and attenuation should be considered to minimise impacts.

5.3.5. Unplanned emissions and accidents

Based on the literature review, no information was identified specific to pyrolysis. Refer to section 5.2.5 for general aspects also applicable to pyrolysis.

5.3.6. Startup, shutdown and non-normal operations

Based on the literature review, no information was identified specific to pyrolysis. Refer to section 5.2.5 for general aspects also applicable to pyrolysis.

5.4. Monitoring requirements

Monitoring and modelling requirements should be developed as part of the operating strategy. Clearly defined operating limits should be developed for individual equipment and operation should observe these limits supported using automated alarms and trips. This should include leak detection and online analysers for hydrogen purity.

Monitoring systems gather data on operational performance of the gasification and syngas treatment and upgrading stages. Automated data collection is typical from modern control systems and should be considered at the design phase including:

- Process performance, for example, gasifier operating parameters
- Energy efficiency (calculated as KPI from process parameters)
- Mechanical performance and mechanical degradation, where this could impact efficiency, fugitive emissions and so on
- Emissions to air and water
- Facilitation of long-term predictive maintenance planning

A preventative maintenance programme to inspect equipment should be implemented in line with vendor recommendations where appropriate.

5.5. Hydrogen purification and specification

Hydrogen product specifications will reflect users' requirements. Use in combustion (for example, for heat) requires lower purity than for use in fuel cells (for example, for transport applications). Information regarding the purity of hydrogen generated from gasification has not been identified. Whilst 99.999 mol% hydrogen is often quoted for fuel-cell applications, the International Standards Organisation, Hydrogen Fuel Quality – Product Specification, ISO 14687, First Edition 2019 requires 99.97 mol%, with specific limits on individual components which can impact operation or life of fuel cells.

Following syngas treatment and upgrading, further stages may be required to condition hydrogen produced to achieve the ISO specification. Stages may include:

- Deoxidisers for example, with catalytic reaction of hydrogen with oxygen at elevated temperature upstream of dehydration
- Dehydration systems for example, using glycol absorption or temperature swing adsorption
- Compression systems for example, with reciprocating compressors for delivery to pipeline or into pressurised storage

The current focus in the UK is the production of gaseous hydrogen. Liquefaction is also a possibility in future for transportation of hydrogen, and for end use in mobility applications (for example, aviation). This would require liquefaction facilities which would be required to be within the scope of future guidance if located within the gasification installation. Technology would likely include refrigeration cycles with multiple compressors or turbo-expanders for pre-cooling and liquefaction, as well as impurity removal, and catalytic ortho- to para-conversion, to facilitate low pressure storage at cryogenic temperatures of around -253°C (20K).

5.6. Emerging technologies

Information regarding environmental aspects of the emerging technologies presented in section 3.10 was not identified. As noted in section 4.4 the technologies are at TRL 4-5. The focus of information sources and work relating to the emerging technologies is on technical feasibility and not on environmental aspects at this time.

6. Information gaps and implications

6.1. Introduction

This section provides an indication of information gaps identified. Implications of the gaps for further work to develop and refine information are indicated.

Due to the stage of development of the technologies, sources of information were from literature. No operational data from pilot plant was available for review or inclusion. As an additional approach to information collection than initially planned to prepare this document, several selected stakeholders were contacted to investigate the availability of further evidence however, no responses were received.

6.2. Information quality and gaps

Information quality

The following information quality aspects are noted:

- Information in reports (government commissioned research, research papers, funding application documents) focussed on cost and technical feasibility, with limited detailed (or none) on environmental management and release minimisation and abatement
- A considerable number of sources were reviewed - The assumptions made in the sources were not comparable between sources (for example technology configurations, feedstock compositions)
- Good sources of information were UK government commissioned reports and a range of research papers
- Information from modelled plant configurations was available (for example for gasification) but not from operational plant
- Information from pilot plant operators was limited to that from funding application documents; such documents focussed on costs, pilot programmes and overall justification for the projects with little or no information on plant inputs, outputs, environmental aspects and their management - Where these were mentioned, it was typically in the context of high-level contributions to decarbonisation rather than plant operation and environmental management
- No information was available from pilot and test plant; however, this information may become available later

Guidance

The following guidance aspects are noted:

Within the Waste Incineration BAT / BRef (2019):

- There is no consideration of these new emerging techniques, specifically regarding pyrolysis

- Syngas is generally used as a fuel to improve energy efficiency; limited consideration is included for onward processing to useful products
- No information is available on the use of methane as a feedstock
- Existing emerging techniques within the document do not include those in this review

Within other UK guidance and BRefs there is currently no reference to the production of hydrogen via these production routes or appropriate BAT.

The technologies

The following aspects are noted regarding:

- There is a lack of information on the likely scale of commercial plant (processing capacity, ranges and so on)
- There is no clear indication of specific design considerations relevant to the technologies - These will, however, be specific to the precise technology and configurations deployed
- It is not clear, in all cases, the type of feedstock and, or characteristics being used for current pilot plant projects - This is due to a requirement to remain flexible and test the effect on processes and hydrogen production of feedstock types
- There is a general lack of data on inputs, outputs and releases to the environment from plant on which to provide benchmarks or ranges
- There is a lack of information regarding process optimisation to minimise potential releases to the environment or to abate those potential releases
- Information on pyrolysis for hydrogen production is more limited than that for gasification and is based on information from research papers

6.3 Implications

The implications of the information gaps are:

- As the pilot projects come to completion, work is required to compile specific information on outcomes
- The focus of information requested from the pilot projects should extend beyond cost, programme and broad justification for funding
- Information collected from pilot projects should extend to include mass balance and operational optimisation practices with the objective of preventing and minimising resource consumption and releases to the environment
- There is no guidance on emission limits that would be expected

In the absence of information from operational plant (pilot or commercial scale), below are described what are considered to be significant process and environmental aspects, as well as likely permitting information needs or gaps. The purpose is to set out the significant aspects and information requirements that are required in an environmental permitting context. The information will benefit from revision following engagement with industry and when information from operational plant becomes available.

Feedstock characteristics and influence on the process

The relevant process stages for this section on feedstock characteristics include feedstock storage and, or preparation; gasification or pyrolysis; and syngas treatment. Feedstock areas to be described include feedstock heating value, net calorific value, composition, quality, and variability.

Establish understanding of the impact of feedstock heating value and, or net calorific value on the process, is relevant as it may influence:

- process control
- requirement for supplementary fuel (gas) use (e.g., to maintain process temperatures and process conditions)

Identify and establish the impact of feedstock composition on potential pollutant generation (e.g. production of dioxins, furans, polyaromatic hydrocarbons, volatile organic compounds). This will help to:

- understand potential pollutants
- identify and define any abatement and treatment requirements

Establish the required feedstock quality requirements for the specific process and how these are assured (e.g., process tolerance for carbon, hydrogen, oxygen, moisture, sulphur, halide, non-combustible content and the calorific value). This can have an impact on:

- process control
- process efficiency

Assess the impact of diverging from the required or baseline feedstock quality requirements on the process and on releases to the environment. This is to evaluate:

- impact on process efficiency
- releases to the environment resulting from feedstock variation

Understand and manage the feedstock variation on the process operation, process control and process efficiency, as this may promote:

- a greater ash formation (ash variations may be more prone in waste feedstocks than in biomass feedstocks due to their heterogeneous nature)
- ash sintering or agglomeration in a fluidised bed technology, thus defluidising the bed and creating operational issues (normally above 850°C)
- ash agglomeration in equipment (if not removed)

You can refer to section 5.2.2 and Table 5.1 for further information on the above points.

Utility demand and management

Identify the natural gas consumption requirement for startup and or for maintaining the required process temperature (relevant for both gasification and pyrolysis). This can have an effect on:

- process efficiency
- reduced natural gas consumption

Establish how energy efficiency can be optimised in the process (for example by integrating steam production (if required) into the gasification or pyrolysis processes). This is relevant for feedstock storage and, or preparation; gasification or pyrolysis; syngas treatment; syngas upgrading; gas treatment and separation; and hydrogen storage. It can help to minimise:

- electricity and, or natural gas consumption
- associated environmental impacts

Water consumption, water efficiency and water supply areas are relevant for syngas treatment as follows. Establishing water consumption requirements in the context of local water availability can help to consider:

- local water scarcity
- process demand

Establishing opportunities for water efficiency, optimisation, recycling and reuse in the process configuration, can help to minimise and optimise:

- water consumption
- water reuse

Establishing early discussions with water supply companies or regulator if an abstraction licence is proposed to source water needs, can help to:

- address local water resource availability
- identify the need of an abstraction licence

Steam requirements are relevant for feedstock storage and, or preparation; gasification or pyrolysis; syngas upgrading; and gas treatment and separation. Establish process steam requirements and consider steam recycle options across the process, to:

- optimise process by reducing steam demand
- lower overall energy demand

Heat recycling considerations are relevant for feedstock storage and, or preparation. Consider heat recycling in the process to reduce energy demand (e.g. optimising drying of feedstock processes through the use of recycled heat from the gasification process). This supports:

- process efficiency
- avoids environmental impacts from heat generation (from natural gas and, or electricity consumption)

Emissions to air and water, wastes and their mitigation, treatment and management

Trace pollutants in the flue gas are relevant for gas treatment and gas separation process stages. Consider potential trace pollutants in flue gas which may be influenced by the feedstock selected (e.g. dioxin and, or furan formation). This helps to establish:

- flue gas treatment needs
- pollutants abatement

Tail gas combustion options are relevant for syngas upgrading and needs to be considered because tail gas may:

- be reused in the combustion process rather than flared in normal operation
- minimises the demand for natural gas

Evaluation of noise and vibration impacts is relevant to process stages including feedstock storage and, or preparation; gasification or pyrolysis; syngas treatment; syngas upgrading; gas treatment and separation; and hydrogen storage. Processes may have specific noise and, or vibration aspects associated with startup, shutdown or routine operation. In addition, feedstock delivery, preparation and handling processes may result in noise and, or vibration. This can influence:

- specific technology selection
- assessment of potential for and mitigation of noise and / or vibration impacts both within and outside the site boundary

Establish potential aspects regarding particulates arising from feedstock handling and preparation processes. This is relevant for feedstock storage and preparation, as:

- materials handling and transport movements need to be considered
- avoid particulates both within and outside the site boundary

Carbon dioxide (CO_2) release to air is relevant for gas treatment and separation. However, capture and storage may also be possible if the necessary CO_2 capture infrastructure is available. This can help to establish and evaluate:

- CO_2 capture and storage options that may fall within permit requirements
- specify or define CO_2 capture efficiency

Hydrogen emission potential is relevant for process stages including syngas treatment; syngas upgrading; gas treatment and separation; and hydrogen storage, as hydrogen is an indirect greenhouse gas. Identify potential for emissions of hydrogen for operational, start-up, shutdown or emergency purposes and consider appropriate methods to avoid, recover, treat, flare or vent, hydrogen emissions. This is to avoid:

- hydrogen emissions
- hydrogen interactions with hydroxyl radicals to increase ozone production (another greenhouse gas)

Effluent stream considerations are relevant for syngas treatment, and gas treatment and separation. Establish source, volume and composition of effluent streams from various process stages is relevant because effluents may or may not be appropriate for reuse in the process or discharge to sewer due to:

- composition (e.g. if glycol is added to process water from adsorption processes)
- temperature (if used as cooling water)

Condensate management is relevant for feedstock storage and, or preparation, and their requirements should be considered because it may require:

- removal of contaminants in the condensate
- treatment prior to discharge to sewer or condensate reuse

Management of metals or inert materials such as glass or stones, is relevant during feedstock storage and, or preparation. The management is relevant as will allow to:

- identify materials to be removed
- assess if materials can be recycled

Ash and char composition are relevant for gasification, pyrolysis and syngas treatment; these parameters are to be established because:

- ash may be collected for recycling in aggregate (if inert)
- char may be collected for use in, e.g. aggregate or metallurgy

Tar or liquid hydrocarbons are relevant for gasification or pyrolysis, and during syngas treatment. Tar or liquid hydrocarbons are not the target products, but their composition should be established together with the potential for them to cracked, as this can help to:

- enable use: produce useable products
- define or identify treatment needs
- determine disposal options

Identify reuse options for fluidising sand in the process is relevant for gasification or pyrolysis, as it helps to minimise:

- consumption
- waste generated

Catalysts regeneration is relevant for gasification or pyrolysis; and syngas upgrading, as it can help to:

- establish whether catalysts can be regenerated for reuse

- minimise waste generated

Startup, shutdown and non-normal operations

Identify releases to air, water and wastes generated is relevant for gasification or pyrolysis; syngas treatment; syngas upgrading; and gas treatment and separation. Establish these can enable:

- identify releases at start-up, shutdown and during non-normal operations
- determination of environmental aspects requiring management

Unplanned emissions and accidents

Pollution prevention measures are relevant to feedstock storage and, or preparation. Establish measures to be deployed in the event of accidental releases (e.g. contaminated run-off from feedstock storage, loss of primary containment, failure of effluent treatment prior to discharge to sewer or controlled waters), can help to:

- prevent pollution
- develop emergency preparedness

Fugitive hydrogen emissions are relevant for gasification or pyrolysis; syngas treatment; syngas upgrading; gas treatment and separation; and hydrogen storage. Potential sources include process venting, compressors, on-site storage, tail gas flares, and leakage through pipework and joints. Assessment of fugitive hydrogen emissions risk and development of an associated emissions reduction plan (see section 5.2.6), can help to demonstrate how the process will:

- be designed and operated to prevent and manage fugitive emissions
- follow principles of Leak Detection and Repair (LDAR)

Governance and communication protocols are relevant for gasification or pyrolysis; syngas treatment; syngas upgrading; gas treatment and separation; and hydrogen storage process stages. Establish these protocols on site and with neighbours, emergency services and regulators can enable:

- rapid response and management of unplanned emissions
- response to accidents (also required if the site is regulated under the Control of Major Accidents and Hazards (COMAH) Regulations)

Fire and explosion are relevant for feedstock storage and, or preparation; gasification or pyrolysis; syngas treatment; syngas upgrading; gas treatment and separation; and hydrogen storage. A Fire Prevention Plant will be required. Establish fire and explosion risks and hazards can prevent or minimise:

- spontaneous combustion of flammable particulate matter and ultrafine carbon dusts (e.g., during biomass and waste feedstocks storage and preparation)

- syngas leakage from plant and, or equipment creating a potentially explosive atmosphere
- formation of explosive gas mixtures (e.g., air leakage into the system and mixing with syngas)

Other aspects

Process efficiency will have an impact on feedstock storage and, or preparation; gasification or pyrolysis; syngas treatment; syngas upgrading; gas treatment and separation; and hydrogen storage. The overall system should:

- be designed to achieve operational flexibility with maximum efficiency
- take into account the overall environmental impact (refer to section 5.2.1: design considerations)
- optimise process flexibility and efficiency

The overall mass and energy balances of the process are relevant for feedstock storage and, or preparation; gasification or pyrolysis; syngas treatment; syngas upgrading; gas treatment and separation; and hydrogen storage. Determining mass and energy balances helps to:

- understand and be able to track the flow and change of materials through the process
- enables balance of materials including inputs, outputs, and accounting for any losses or gains
- identify areas of energy efficiency
- identify process optimisation areas

Identify the key process parameters influencing gasification or pyrolysis as it is relevant for process optimisation and process control. This can be achieved by establishing:

- the impact they have on syngas
- how they are controlled to optimise the process (e.g., equivalence ratio, temperature, heating rates, pressure, residence time, gasifier design and, or configuration (fluidised bed, fixed, bed, circulating fluidised bed, etc.))
- catalyst type
- feedstock composition (moisture, ash content, etc.)

Environmental performance is relevant for feedstock storage and, or preparation; gasification or pyrolysis; syngas treatment; syngas upgrading; gas treatment and separation; and hydrogen storage. Identifying key aspects affecting overall environmental performance and which aspects of environmental performance specifically (e.g., feedstock characteristics, process conditions, syngas treatment techniques, syngas upgrading techniques, gas separation techniques), can enable to:

- focus on main environmental aspects of concern
- identify which aspects can be influenced and how

Feedstock details from the supplier can have an impact on the feedstock storage and, or preparation steps. Obtain information from the supplier of biomass, its transportation and storage requirements, is essential as:

- storage on site may require a waste operation within the permit
- the storage location may extend the site operational boundary
- it may have implications for technical connections and directly associated activities

Defining the off-take routes for hydrogen is relevant for the hydrogen production and or hydrogen transportation steps. Determine off-take routes for hydrogen is relevant as it may:

- trigger requirements of the COMAH Regulations for on-site storage
- trigger planning requirements associated with Hazardous Substance Consent for on-site storage
- require pipeline ownership and or technical connection considerations for hydrogen delivery to a customer
- require considerations of relevant legislation and regulations particularly the Pipeline Safety Regulations

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List of abbreviations and terms

Abbreviation	Definition
% ar	Percentage as received
AGT	Advanced gasification technology
bar	Unit of pressure (equal to 100,000 pascals)
barg	Pressure in bars above atmospheric pressure
BAT	Best Available Techniques
BECCS	Bioenergy with Carbon Capture and Storage
Benfield process	A process used to remove CO_2 from the gas stream by passing the gas through a potassium carbonate solution.
BRef	BAT Reference document
CCS	Carbon capture and storage
CDM	Catalytic decomposition of methane
CH_4	Methane
COMAH	Control of Major Accidents and Hazards Regulations
CO	Carbon monoxide
CO_2	Carbon dioxide
CO_2/kg	Carbon dioxide per kilogram
GET	Guidance on Emerging Techniques
GHG	Greenhouse gas
GHz	Gigahertz

Abbreviation	Definition
H_2	Hydrogen
HHV	Higher heating value
HCN	Hydrogen cyanide
ISO	International Standards Organisation
kg/h	Kilogram per hour
kg/odt	Kilogram oven dried tonnes
kWh	Kilowatt-hour
LCA	Life Cycle Assessment
MEA process	Monoethanolamine. A process used to remove CO_2 from the gas stream by passing the gas through MEA.
MJ/h	Megajoule per hour
MJ/kg	Megajoules per kilogram
MJ/kmol	Megajoule per kilomole
mol %	Percentage amount of substance
MSW	Municipal solid waste
Mtpa	Million (mega) tonnes per year
MWe	Megawatt electric
MWth	Megawatt thermal
MWh_{th}/year	Megawatt hours of heat per year
MWh/year	Megawatt-hour per year

Abbreviation	Definition
N_2	Nitrogen
NDA	Nuclear Decommissioning Authority
NOx	Oxides of nitrogen
O_2	Oxygen
ppmv	Parts per million volume
PWA	Pressurised water absorption
RDF	Refuse derived fuel
Rectisol ® process	A process used to remove CO_2 from the gas stream by physical absorption on to methanol.
RiPR	Rising pressure reformer
Selexol ® process	A process used to remove CO_2 from the gas stream by physically absorption into a solvent called Selexol (a mixture of dimethyl ethers of polyethylene glycol (DEPG)).
SER	Sorption enhanced reforming
SEWGS	Sorption enhanced water gas shift
t/d	Tonnes per day
Tail gas	Controlled gas releases from planned and unplanned operations
t/h	Tonnes per hour
tpa	Tonnes per annum
Tail gas	Controlled gas releases from planned and unplanned operations
TRL	Technology Readiness Level

Abbreviation	Definition
Vol%	Percent by volume
WGS	Water gas shift. The reaction of carbon monoxide and water vapour to form carbon dioxide and hydrogen: $CO + H_2O \rightleftharpoons CO_2 + H_2$.
wt%	Weight percent

Appendix A: Modelled mass balance information

Within the Advanced Gasification Technologies – Review and Benchmarking: Technical assessment and economic analysis - task report 5; a process model was developed to estimate the key process inputs to and outputs from oxy-steam gasification of biomass, woodchip and RDF for the production of hydrogen [7]. Some of the data and model results from this model were referred in this report, and some key aspects have been included in this Appendix A, for reference. Please refer to the original report for more extensive, detailed information on the model. [7]

Plant description

Key system components:

- Feedstock storage [35] and delivery system
- Bubbling fluidised bed gasifier
- Ash and char handling system
- Multistage syngas clean up system
- Syngas compression
- CO shift reactor
- Pressure swing adsorption
- CO_2 scrubbing and compression
- Thermal oxidiser for waste gases
- Heat recovery systems
- Storage tanks for products, oxygen and nitrogen
- Auxiliary systems to provide effluent treatment, start-up boiler, cooling, compressed air and so on
- Stack

Process model assumptions

The model was developed based on an evaluation of process data from several technology providers coupled with experience in the assessment of gasification systems and technologies. The model was based on a single pass, first-of-a-kind plant in which all of the feedstock delivered to the gasifier was used to produce Fischer-Tropsch fuels and did not consider the number of process' recycles, nor use of any excess energy for power generation.

The key assumptions were as follows:

- 100% conversion of feedstock to syngas, ash and char

- The primary syngas components considered were CO, H_2, CO_2, H_2O, O_2, N_2, CH_4, NH_3, HCl and H_2S
- Equilibrium gas composition in the gasifier
- Benzene and naphthalene were used as the model component for tars
- The gasifier was assumed to operate at between 700°C and 800°C at pressures higher than atmospheric
- 100% conversion of CO in a single pass
- 70% efficiency of capture of H_2 from the shifted syngas
- The estimated net calorific value of H_2 was 94 MJ/kg (as the hydrogen is 98.5% pure)
- Electricity consumption was based on data provided by suppliers
- The main consumables were derived from the model based on the process requirements
- Operation at the maximum feedstock throughput for 85% of the hours in a year (7,446 h)

The results from the model for the two biomass plant sizes considered of 330,000 tpa and 1,000,000 tpa are presented in Table A.1.

Table A.1. Biomass to H_2 process model

Model parameter	Units	Plant size 330,000 tpa	Plant size 1,000,000 tpa
Process streams	---	1	1
Feedstock throughput	t/h	44	134
Thermal input rate	MWth	100	643
Thermal input rate	MWh_{th}/year	744,600	4,788,000
Syngas output from gasifier	t/h	341,300	1,831,000
Syngas output from reformer	t/h	242,100	1,364,000
Hydrogen yield	kg/odt	77	78
Hydrogen production	tpa	12,600	72,600

Model parameter	Units	Plant size 330,000 tpa	Plant size 1,000,000 tpa
Electricity consumption	MWe	15	82
Electricity consumption	MWh/year	107,100	604,500
Plant availability	%	85	85
Energy efficiency	%	44	40
Main consumable	tpa natural gas	130	836
Main consumable	tpa oxygen	65,900	372,000
Main consumable	tpa steam	314,000	817,800
Main consumable	tpa water	214,100	1,209,000
Main consumable	tpa chemicals	16,500	93,000
Key material output stream	tpa CO_2	248,400	1,424,500
Key material output stream	tpa flue gas	492,600	2,805,200
Key material output stream	tpa flue gas CO_2	55,000	288,000
Key material output stream	tpa bottom ash and char	716	5,600
Key material output stream	tpa effluent	231,000	1,302,000

The block flow diagrams for the modelled 330,000 tpa and 1,000,000 tpa Advanced Gasification Technology (AGT) **biomass to H_2** plants, can be found in Figure 2 and Figure 3, respectively within the original reference, on page 46.

The results from the model for the two waste plant sizes of 100,000 tpa and 550,000 tpa are presented in Table A.2.

Table A.2. Waste to H_2 process model

Model parameter	Units	Plant size 100,000 tpa	Plant size 550,000 tpa
Process streams	---	1	2
Feedstock throughput	t/h	13	74
Thermal input rate	MWth	36	199
Thermal input rate	MWh$_{th}$/year	268,100	1,481,800
Syngas output from gasifier	t/h	121,000	665,900
Syngas output from reformer	t/h	75,000	413,700
Hydrogen yield	kg/odt	67	69
Hydrogen production	tpa	3,900	22,000
Electricity consumption	MWe	5	29
Electricity consumption	MWh/year	37,800	208,100
Plant availability	%	85	85
Energy efficiency	%	38	39
Main consumables	tpa natural gas	235	1,295
Main consumables	tpa oxygen	29,100	160,000
Main consumables	tpa steam	70,500	387,700
Main consumables	tpa water	75,700	416,100
Main consumables	tpa chemicals	5,300	32,000

Model parameter	Units	Plant size 100,000 tpa	Plant size 550,000 tpa
Key material output streams	tpa CO_2	76,900	432,000
Key material output streams	tpa flue gas	152,500	850,700
Key material output streams	tpa flue gas CO_2	17,000	87,000
Key material output streams	tpa bottom ash and char	10,700	58,900
Key material output streams	tpa effluent	81,500	448,100

The block flow diagrams for the modelled 100,000 tpa and 550,000 tpa AGT **MSW to H_2** plants, can be found in Figure 4 and Figure 5 of the original reference, on page 50.