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Hydrogen BECCS Innovation Programme Phase 1

BIG-H_2 Phase 1 Final Report

H_2 production via Biomass gasification Integrated with innovative one step Gas shift reforming and separation (BIG-H_2)

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Contents

1. Executive Summary

The project focuses on maximising hydrogen production from biomass via gasification. A demonstration plant of up to 600 kW capacity will be designed. The innovative element of the demonstration is one step H_2 separation and CO to H_2 conversion. During the first phase a Front End Engineering Design (FEED) study was prepared. This will include feedstock selection, site selection, gasifier selection, and gas clean up, H_2 enhancement via Water Gas Shift (WGS) and H_2 separation by membrane and end use of product hydrogen. The design package will be used to fabricate and demonstrate the integrated plant in the second phase. Performance of the plant will be assessed for H_2 separation efficiency and H_2 quality to meet the end user requirements. Long term operation of the plant will be demonstrated to prove robustness, viability and stability. Scale up challenges will be identified and mitigation measures will be proposed. A commercialisation plan will be developed to identify end users, potential sites for commercial plants and viable plant capacity for maximising H_2 production and CO_2 capture.

2. Introduction

Pressure to generate clean energy is growing. Renewables have increased in recent years, but to deal with their intermittency, there is a need for other clean, reliable sources of energy for sustainability and security of supply. Hydrogen is an excellent potential candidate to fill this gap as a clean energy carrier. It has a range of applications to decarbonise heat/power/transport/industry, paving the way to achieve the UK Government's ambitions of net zero by 2050. Hydrogen can be produced via multiple techniques, such as electrolysis, steam methane reforming (SMR), auto-thermal reforming (ATR), partial oxidation and gasification. Most hydrogen is produced from fossil fuels, resulting in total emissions of ~830 $MtCO_2$/yr, corresponding to the combined CO_2 emissions of Indonesia and the UK. Biomass being considered as CO_2 neutral, can offer negative CO_2 emissions if used with CO_2 capture (BECCS). Biomass gasification with carbon capture offers the dual benefits of producing clean hydrogen and sequestering CO_2, offering net negative carbon emissions.

The main aim of the BIG--H_2 project is to demonstrate the application of next generation gas separation and upgrading technologies for producing cost- effective, low -carbon, clean hydrogen, through integration with a state -of -the -art gasifier. Syngas produced by the gasifier, after necessary clean-up (to remove tar, sulphur, particulates, etc.), will be fed to the innovative process intensified syngas upgrading and hydrogen separation unit (single step membrane and WGS), where it will be processed to produce hydrogen to the required standard.
During the first phase of the project, a feasibility study of the whole prototype has been carried out, covering the whole value chain of the process, including an analysis of biomass/bio-waste and a detailed review of different gasification technologies available on the market. The focus was on maximising hydrogen production and minimising impurities.
Front End Engineering Design (FEED) of the 600 kW prototype gasifier integrated with the gas upgrading/separation technology and carbon capture is performed, using techno economic analysis, leading to engineering, financial and development planning for the Phase 2 investment decision on the project to be made with a high degree of confidence. The design determined the costs (CAPEX/OPEX) associated with building the prototype, the economic viability and levelised cost of H_2, which can be compared to different means of generating hydrogen. The design also assessed issues relevant to reliability of the proposed BECCS- to -hydrogen solution. Furthermore, comprehensive process modelling verified the entire integrated design. Moreover, information on the route- to -market and insights into scalability of the technology has been assessed.

3. Hydrogen BECCS innovation Technical summary

The BIG-H_2 project consists of H_2 production via Biomass Gasification Integrated with innovative one-step water gas shift reforming and separation.

BIG-H_2 will investigate the integration of biomass/bio-waste gasification with innovative gas cleaning and membrane based separation, to produce a high purity (~99.97%) hydrogen stream. Additionally, when the hydrogen is separated from the rest of the syngas, this leaves another stream with a high CO_2 concentration (~25%), thus enabling carbon capture and storage.

This project, considering carbon capture, has the potential to deliver long-term net negative carbon emissions for a range of industry sectors when deployed at commercial scale.

The programme is divided into three themes, consisting of (i) engineering design; (ii) economics, sustainability and carbon impact; and (iii) demonstration, development and reporting. The project has reviewed different gasification technologies to determine the most appropriate method for this application, along with available and suitable biomass/bio-waste.

An integration study has ensured the efficient combination of all system components – including the gasifier, gas cleaning, gas separation membrane, gas upgrading (via water gas shift, WGS) and CO_2 capture. There are, however, certain limitations at demonstration scale.

The innovative development of a hydrogen membrane, combined with a novel WGS catalyst within the membrane tube offers a compact, versatile hydrogen production unit, resulting in a device capable of taking any syngas source and maximising hydrogen yield and selectivity. The novel feature here is that, under the optimised WGS equilibrium reaction conditions, as hydrogen is separated through the membrane from the reaction zone, the equilibrium is skewed to further promote the WGS reaction to increase conversion and maximise hydrogen yield. Hydrogen purities of up to 99.97% can be achieved under continuous operation, with long term stability testing to show no noticeable degradation or deactivation of either catalyst or membrane.

Assessments of the techno economics, potential product markets and overall sustainability (the latter using criteria such as plant carbon footprint, CO_2 captured/avoided, etc.) has been used to perofrm the overall initial front end engineering design (FEED) studies of the integrated system. Along with a variety of systems modelling and sensitivity analyses, these feasibility studies will identify a forward development plan to take into Phase 2. This will result in a demonstration plant that will ultimately prove the technology to be ready for further deployment to become a proven commercial technology that can be readily adopted for other real operational environments.

4. Deployment pathways

The BIG-H_2 partnership brings together leading multinational power companies, innovative SMEs and academic institutions with a shared plan to develop a BECCS-To-Hydrogen demonstration plant with novel gas separation technologies to reduce the cost of hydrogen production.

Although there are significant deployment challenges, current interest in the production of clean, low-cost, low-carbon hydrogen is of great importance to create genuine opportunities. Hydrogen can deliver deep emissions reductions in sectors otherwise hard to abate. H_2-BECCS via gasification and gas separation/cleaning has the potential to be transformative in hydrogen deployment to decarbonise industry/heat/transport. The knowledge from the demonstration plant will be used to further develop the concept that will ultimately prove the technology to be ready for further deployment to become a proven commercial technology that is able to be adopted for other real operational environments. This project will provide definitive data, engineering design, Life-cycle assessment (LCA) and implementation of novel gas separation technologies, providing assurance to prospective developers, unlocking commercial development.

This project has developed a plan to commercialise. BIG-H_2 capability addresses BEIS priorities to enable commercialisation and deployment of H_2-BECCS at scale to achieve negative emissions and hydrogen production targets, outlined in the UK's Sixth Carbon Budget. This will aid the move towards a hydrogen economy, reduce reliance on fossil fuels and thus help adapt the energy systems to be resilient.

5. Carbon Lifecycle Assessment of technology

Urbanomy has developed sustainability and carbon assessment of the technology. A framework for conducting the sustainability assessment, using various metrics inspired by 5 of the UN's Sustainable Development Goals is prepared. These metrics consider the price and production rate of the H_2, the approximate number of employment opportunities, as well as the impacts of the feedstock and waste products, which will depend on the disposal methods planned.

Through exploring potential hydrogen users, local value was demonstrated to industry indicating that the system could sustain this. The local needs also align with the trend for a mixture of high purity and pressure transport applications in the UK, indicating national value. It is also recommended that existing infrastructure be reused where possible, sustaining the heritage of the site. Low carbon hydrogen-producing technologies were assessed by LCOH, and the critical value of CCS to make the system cost-competitive was indicated. Next, the employment potential of the system was explored, suggesting additional social value that the system could provide. Lastly, an alternative heating source to the electrical boiler could be used to reduce the energy consumption, and wastewater could also be used to reduce water consumption.

The carbon assessment methodology is inspired by the Bilan Carbone method developed by the French Environment and Energy Management Agency (ADEME), and covers the perimeter of the feedstock purchase, to the emission or capture of the gases separated downstream. The study perimeter comprises the different mass and energy flows, as represented in Figure 1, which does not take into account:

- Distribution and use of the H_2 and CO_2: This is part of the scope 3 of the carbon assessment of the system, but as the detailed definition of the end users of these 2 outputs have not been done at this stage, it has been chosen not to include it in the scope.
- Construction work and EPC for the various assets: The detailed design of the system is not known at this stage and further progress in the engineering stage is required to be able to assess the impact of the construction phases.

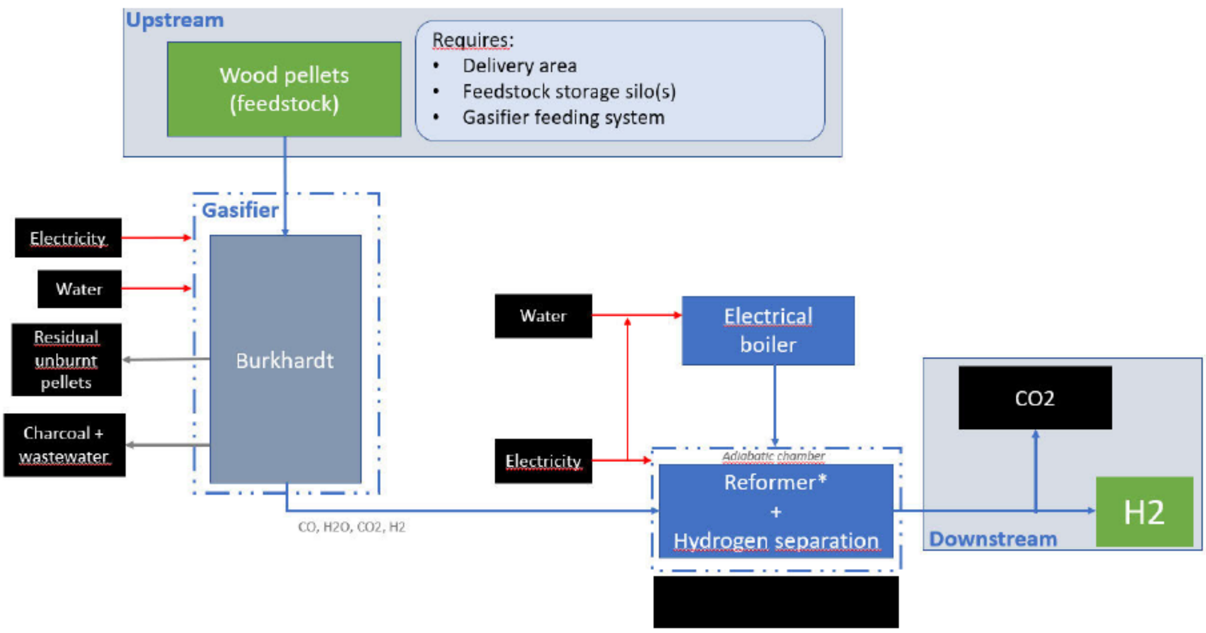

Figure 1: Diagram of the perimeter taken into account in the Carbon Assessment.

The estimated total emissions for the project are:

- Total CO_2 emissions : 464,478 kgCO_{2e} for one year or 7500 hours of operation.
- 7.37 $kgCO_{2e}/kg\ of\ H_2$.

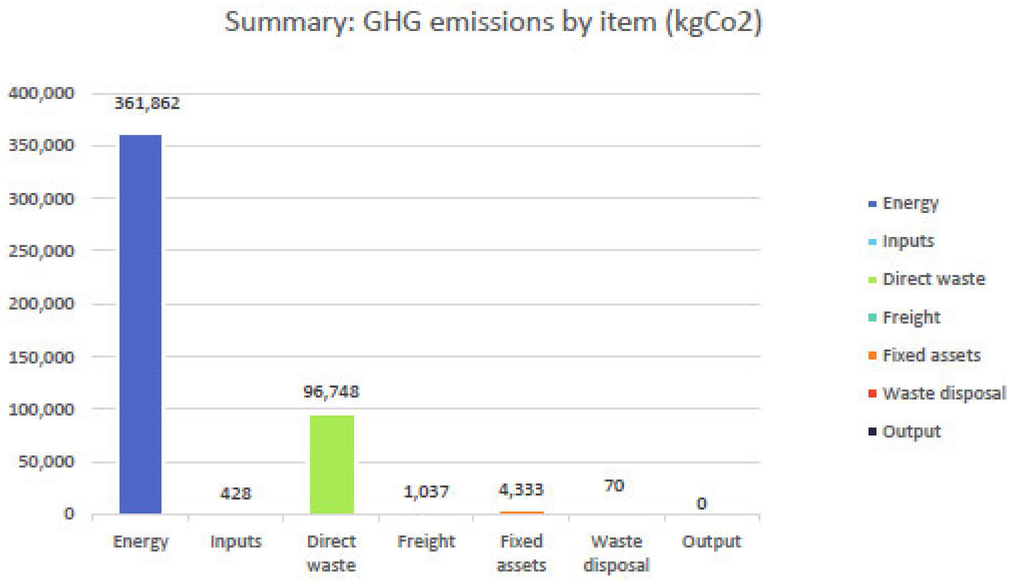

Figure 2: Breakdown of GHG emissions by item without CO_2 storage

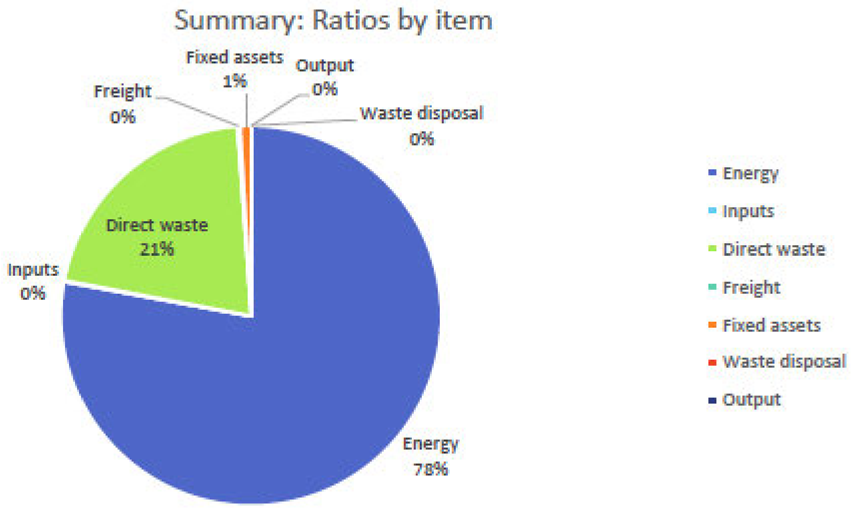

Figure 3: Breakdown of GHG emissions by item with CO_2 storage

In terms of emissions, the most significant item is energy. This item represents 78 % of the emissions. Its carbon footprint comes from the use of electricity for the different components of the project, which will be exposed later in the report. Concerning the output, the emissions related to it are equal to zero. The retentates coming out of the “reformer + H2 separation” are composed of: hydrogen (H2), carbon dioxide (CO2), methane (CH4) , steam (H2O), carbon monoxide (CO) and dinitrogen (N2). However, this assessment only counts the anthropic Kyoto Protocol GHGs CO2 and CH4. Furthermore, biogenic CO2 is not accounted for, which is the

case of the CO2 in the reformer since it comes from the combustion of the wood pellets in the gasifier.
Carbon capture is not part of the demonstration plant. However, considering CO2 in the retentate stream is captured and stored, there is potential to reduce CO2 emissions. The net CO2 emissions are calculated based on CO2 capture from the retentate stream to be -12.37 $kgCO_2/kgH_2$.There is further potential for reduction in CO2 emissions as product hydrogen in the above calculations is considered to be compressed to 200 bar which is not required for onsite use and compression to 30 bar is sufficient for distribution.Commercial scale will have further opportunities for reducing CO2 emissions due to better integration of utilities and larger scale.

6. Engineering Design

Engineering design of the overall integrated system has been prepared by EDF in the UK and the wider group. Feedstock and gasifier has been selected and reports have been submitted against the respective deliverables. There is some data available regarding domestic feedstock availability, considered in the outputs from WP3, both current and going forward over the lifespan of the plant to be purchased and used as part of Phase 2 (including beyond the end of the BEIS test programme - to approximately 20 years lifespan). In the short-term, availability of feedstock should not be an issue; however we note that the projections for potential future feedstock supplies over this timescale may be variable, with large differences often seen between the data estimations for maximum and minimum values regarding availability - leading to uncertainty in the future security of supplies. This will be considered and monitored as part of Phase 2. Moreover it is likely that the national landscape for biomass/bio-waste feedstocks will evolve rapidly with changing policy and demand growth.

The project has also taken into consideration the availability of equipment and external suppliers for the selection of the gasifier technology, which was the output of the technical review performed in WP1. Commercial small-scale gasifiers were taken into consideration due to their availability at the required capacity for the Phase 2 demonstration, and the Burkhardt design was selected. Wood pellets are the primary input for this system, a singular partially fluidized bed rising cocurrent reactor. There are two modular designs available, the V4.50 and V3.90 with wood pellet consumption rates of 40kg/h and 110kg/h, respectively (approximately 192kW and 528kW of feedstock input). Furthermore, the V4.50 is already installed at the TERC facilities, and it has the capability of producing 50kW of electricity and 110kW of thermal output. This existing relationship with the manufacturer could shortcut times and ease logistics while having a trustable manufacturer with many operating units in different countries, and direct operational experience from the project lead.

An engineering design package for the demonstration plant is prepared. The integrated set up includes::

- Biomass storage
- gasifier with feeding system
- Syngas clean up
- H_2 separation membrane with integrated WGS catalyst
- H_2 usage/storage

A visit has been made by consortium members to an EDF site to discuss and identify the options for biomass storage and plant installation.
Different options for the product H_2 are being considered including use in power production and compression and storage at 200 bar to allow easy transport via road.

System and components description

Wood pellets arrive at the process plant and are stored in silos, from where they are sent to the gasifier. As mentioned above, the system is composed of three main sections: biomass gasification, syngas cleaning, and syngas upgrading/hydrogen separation through the membrane unit. It is important to mention that each of these sections has different requirements in terms of feedstock and utilities. Therefore, the understanding of the physical and chemical phenomena that govern the performance of each section will determine the interaction between the components of the system and mandate the requirements of conditioning and cleaning units. A clearer description of the process, with the integration among the sections, as well as the boundaries of the process are represented in Figure 4:

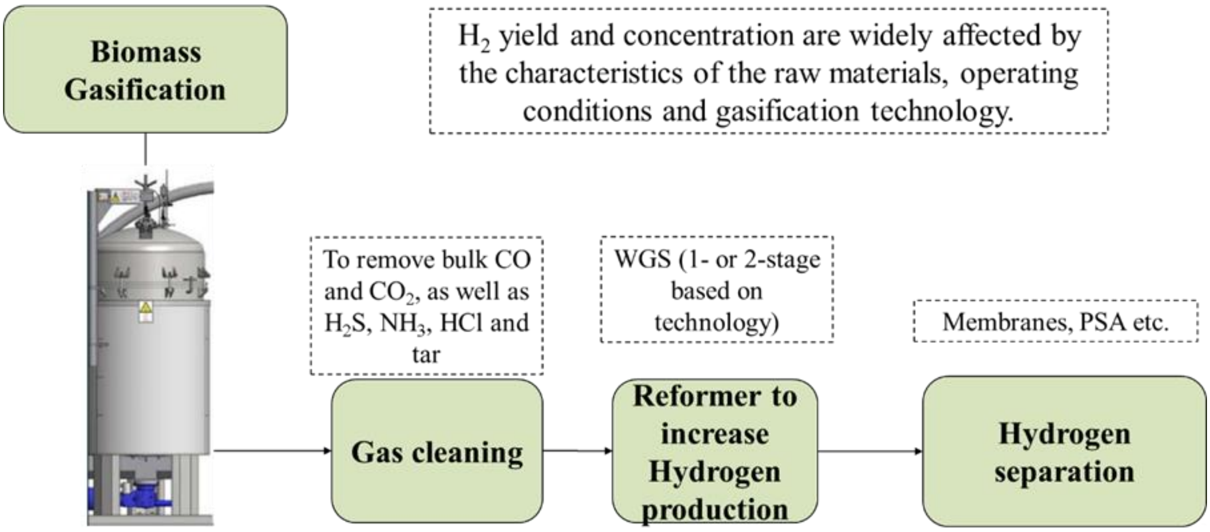

Figure 4: Biomass to hydrogen integrated process.

Biomass gasification: The Burkhardt gasifier, based on an ascending cocurrent gasification with stationary fluidized bed, is able to produce homogeneous high purity syngas. Ascending cocurrent gasification occurs in the reactor with a stationary fluidized bed. This means that the gasification occurs in a bottom-up air flow that is measured so that the pellets are swirled in certain zones without being carried out. All of this process is done autothermically, therefore, no additional heat source is needed. Some of the pellets are burned in the lower area of the fluidized bed, at the same time, the air supply is controlled so that combustion does not occur completely.

Syngas cleaning and conditioning: The gas cleaning option included in the module of the Burkhardt's gasifier, includes some cooling and filtering units. A jacket tube heat exchanger cools the gas from around 800 °C to 130 °C. At this point, approximately 75 kW of heat is extracted for heating purposes at around 95 °C. The gas is separated from solids in a gas filter with temperature-resistant bag filters after it has been cooled to 130 °C. Finally, in a gas cooler, the syngas is further cooled to approximately 80°C.

Membrane: At the moment, steam reforming followed by water-gas shift (WGS) reaction (Equation 1) is one of the main pathways for producing hydrogen. Because the WGS reaction is moderately exothermic, the equilibrium constant (Kp) decreases with increasing temperature and becomes thermodynamically limited at high temperatures. However, at high temperatures, the reaction kinetics are favoured, resulting in a high throughput of hydrogen production. In the industry, the reaction is carried out in two steps: a high temperature WGS reaction at 350°C -550°C with a Fe-Cr-based catalyst to quickly convert CO and a low-temperature shift reaction at 200°C -350°C with a $Cu/ZnO/Al_2O_3$ catalyst to achieve equilibrium conversion. Ni-based catalysts are being extensively researched for high-temperature WGS reactions in place of Fe-Cr catalysts, which are toxic due to the Cr content and pyrophoric in nature in their reduced state.

$$CO + H_2O \leftrightarrow CO_2 + H_2$$

(Equation 1)

Membrane reactors are a promising technology with substantial potential in thermodynamically constrained reactions such as hydrocarbon reforming, water gas shift, and esterification. Conversions in membrane reactors are higher than in conventional fixed bed reactors because one or more product species are removed from the reaction environment. They also offer various other benefits, including simple process design, lower operating temperatures, and equipment downsizing. Therefore, catalytic membrane reactor (CMR), a combination of membrane and catalytic reactor, is an alternative for multi-stage WGS process with CO_2 scrubbing. By selectively eliminating H_2 from the product stream during the reaction, a high temperature WGS process in a membrane reactor allows CO conversion to overcome thermodynamic equilibrium restrictions. Catalytic membrane reactors run at high temperatures benefit in the following ways: (1) they alter the thermodynamic equilibrium, (2) they produce high-quality hydrogen at a faster pace, and (3) they suppress methane generation. However, a highly permeable membrane with great selectivity is required for the production of high-quality hydrogen with increased throughput. In this sense, different membrane materials, supporting materials, catalysts, and configurations have been tested at various research facilities for enhanced syngas conversion and hydrogen selectivity, as well as hydrogen purification.

Mass and Energy performance

The mass and energy balance for the different units of the system have been taken into account for the design of the system. Most of the data was collected from the technology suppliers, and some of them were estimated under reasonable assumptions.

For the gasifier, the most important parameters are the composition of the syngas, in terms of the main components, as well as considering the main pollutants. Figure 5 shows the composition of the syngas as per information provided by the company Burkhardt. Table 1 depicts the pollutant contents expressed as ranges and maximum specifications.

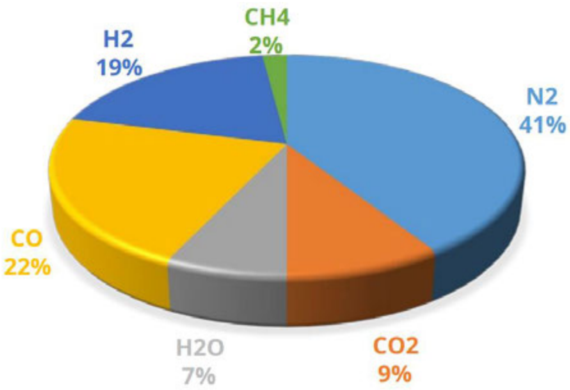

Figure 5: Average composition of the (moist) wood gas in volume units.

Table 1: Wood gas pollutant composition.

Name	[mg/Nm^3]
Benzene (C_6H_6)	300-400
Total BTEX	<1,000
Total PAH	<100
Total halogens	<5
Total sulphur	35
Dust	<10
Water vapour	40,000-60,000
Ammonia	145
Phenol	<10

Based on the performance of this gasifier, the membrane was sized resulting in the mass and energy performances shown in Figure 6. The resulting product is 8.4 kgH_2/h at 99.97% of purity, while at the same time a retentate stream is also produced. As presented in Table 2, as per configuration of the current system, the generated retentate gas contains 35% of N_2, as well as some traces of CO and CH_4. Retentate stream contains 1.7mol% of methane and heavier hydrocarbons. The retentate stream will be treated before emitting to the atmosphere. Different options have been discussed including flaring, thermal oxidiser, catalytic conversion etc. Nevertheless the H/Cs will be converted to CO_2 before emitting.

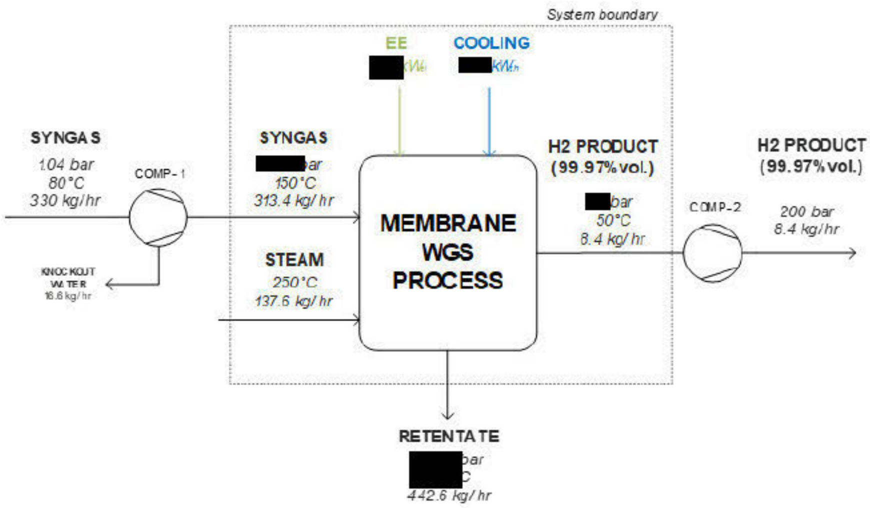

Figure 6: Mass and energy balance of the membrane system.

Table 2: Mass concentration membrane system.

STREAM TABLE						
	SYNGAS 1	**SYNGAS 2**	**STEAM**	**RETENTATE**	**MEM PRODUCT**	**FINAL PRODUCT**
Temperature [°C]	80	150	~250	[redacted]	50	~40
Pressure [bar]	1.04	[redacted]				200
Mass flowrate [kg/hr]	330	313.4	137.6	442.6	8.4	8.4
Molar flowrate [kmol/hr]	14	13.1	7.6	16.5	4.2	4.2
Molar composition (%)						
H_2	19.0	20.3	0.0	8.4	99.97	99.97
CO	22.0	23.5	0.0	0.9	0.015	0.015
CO_2	9.0	9.6	0.0	25.3	0.0	0.0
CH_4 (and C_{2+})	2.0	2.1	0.0	1.7	0.0	0.0
H_2O	7.0	0.5	100	28.9	0.0	0.0
N_2	41.0	43.9	0.0	34.7	0.015	0.015

7. Testing approach (Category 2: Gasification components Option 2)

Demonstration plant (600 kWth) will be built in the 2nd phase based on the Front End Engineering Design (FEED) prepared in the first phase. The demonstration plant will be commissioned followed by operation of the integrated setup at operational conditions. This will include:

- Demonstration of the gasifier to produce the desired syngas quality
- Demonstration of the gas clean up to achieve desired syngas quality suitable for the downstream gas separation system
- Demonstration of the H_2 separation (membrane + WGS catalyst) system
- Performance assessment for quality of product H_2 (>98%) and H_2 separation efficiency
- Performance assessment for CO_2 capture ready operation
- Demonstration of H_2 usage in power system or compression and storage for road transport to other hydrogen users in the region.
- Demonstration of the integrated set up at a wide range of operational conditions
- Optimisation of the integrated unit under realistic operational conditions for maximising H_2 production and lowest impact on resources
- Demonstration of the integrated set up for long term operation (1000+ hrs)
- Environmental impact assessment of the integrated system for water and energy use, emissions to atmosphere and waste generation
- Assessment of challenges related to scalability
- Comprehensive operational strategy

Performance of the demonstration plant will be assessed for H_2 separation efficiency and quality of product H_2 to achieve IGEM Hydrogen Gas Quality.

8. Project plan

The current plan is to install the demonstrator at the EDF West Burton A site. However, if there are issues at EDF, TERC site is being considered as a second option. The feasibility phase of this demonstration is completed and the demonstration phase is scheduled to start in March 2023, depending on the timescales of BEIS' selection process. This phase will last 2 years. The overall project scope will cover:

- Installation, commissioning, operation and decommissioning (if required) of the facility
- Bioenergy feedstock delivery to demonstration site and handling
- Operation of feedstock gasifier, gas cleaning and gas separation for 3 to 6-month trial period
- Preparation of hydrogen for end use
- Separation and processing of other gases
- Disposal and treatment of waste products

The demonstration facility will be based at West Burton A power station in Nottinghamshire. The coal fired power station is starting decommissioning in 2023 and has available land for a demonstration facility with road and rail connections on site.

At the same time, a comprehensive dissemination plan for publications in open access journals and international conferences and to a wider audience including relevant industrial sectors in particular is prepared. In order to maximise impact, there are key activities which the project team will undertake:

- Public events: Identifying and presenting at public engineering, scientific, industry and research events aligned with bioenergy, hydrogen, and carbon capture.
- Social media and consortium partner websites: Press announcements through LinkedIn and on company websites at launch of the project, at the end of phase 1. Further engagement with relevant public press websites.
- Technical papers: Publishing papers on the technology, the design and the project in relevant publicly available academic journals.
- Internal dissemination: The consortium will undertake engagement internally, continue to update the BEIS team and monitoring officer on progress of the project each month, and arrange site visits for the project and BEIS programme teams.

Showcasing the merits and opportunities when using gasification for BECCS, as well as highlighting risks and considerations that should be made with reference to future projects have been identified as key criteria for the consortium.

9. Commercialisation plan

Wider market engagement has been conducted in terms of contacting potential suppliers of the most relevant gasifiers, identified through the shortlisting process - a key outcome and deliverable from WP1. The conclusions from here are likely to inform the wider commercialisation plan for the integrated BECCS-hydrogen system (WP7/8) and the feedstock selection (WP3).

The final feedstock selected here may limit the number of plants that can be operated commercially (based on the indigenous supply and the demand from this and other applications), however the various suitable feedstocks that were shortlisted (and the potential flexibility of the gasification plants investigated) would enable a larger number of plants to become operational simultaneously if there were certain degrees of feedstock flexibility, fuel fungibility and diversification of supplies incorporated into their designs.

A comprehensive commercialisation plan has been developed, including;

- Role of the technology is achieving Net Zero
- Viable commercial scale of the technology to deliver maximum H_2 production and CO_2 removal
- possible options for commercial locations
- identification, size and nature of target market
- Hydrogen revenue
- Hydrogen costs of production (eg. BEIS modelling etc. and trial parameters) – subsidies reliant on low carbon hydrogen standard compliance
- Hydrogen market size (locally and UK scale)
- Wider energy system impact

10. UK and Wider Economic plan

The hydrogen economy has great potential to play a vital role in the global energy mix but has major challenges i.e. infrastructure for transport, distribution and storage, large scale hydrogen production, high LCOH, market uncertainties. The ability of UK providers of capital equipment and design, engineering, construction and project management services to capture a high proportion of the economic value of BECCS to hydrogen demonstration plant is key to realising the direct economic impacts of the project. The Big-H_2 will demonstrate the low cost H_2 production using innovative one step water gas shift and H_2 separation technologies. An economic plan will be presented to address the challenges and tackle the barriers to large scale deployment of the BECCS to H_2 plants in the UK and globally.

11. Labour and Skill availability:

As the energy dynamics are shifting from fossil fuels to green energy, capacity building in green industries is a key element. There is generally a skills shortage in the engineering industry. It takes time to train people where they can deliver the job to a high standard required. Without the skilled workforce it will be highly difficult to deliver the green economy and achieve net zero targets. Skill gaps in the relevant industries to contribute to a circular green economy and the requirements to equip people with key skills to fulfil future job requirements of the future green infrastructure particularly BECCS to hydrogen via gasification to achieve net zero is identified. Direct, indirect and induced employment potential was estimated as 2, 1, and 2, respectively. These include highly skilled jobs in construction, such as welders, pipe fitters, machine installers and technicians, with additional jobs across the supply chain and wider economy. Moreover, this development would benefit the Humber region by creating more employment and highly skilled jobs in a region with high unemployment rates, and also this development aligns with the targets of the Humber 2030 plan to stimulate a hydrogen economy and capture carbon.

12. Conclusions

Hydrogen production via biomass gasification has a great potential to contribute to achieve UK net zero targets. However, there are significant challenges which need to be addressed for large scale deployment. These include technological, supply chain and infrastructure. One of the main technical challenges is that syngas from a gasifier has a number of impurities. The level of impurities is dependent upon the type of gasifier and feedstock used. Nevertheless, cleaning the gas and separation of hydrogen with high efficiency and high purity is required for downstream processes such as compression, usage, storage etc. BIG-H_2 project is aimed at addressing these issues by demonstrating the technology in a 600 kW prototype demonstration plant using a single step water gas shift to maximise hydrogen production and membrane separation for high purity H_2 product reducing costs of producing hydrogen.

Additional annexes

Annex A: Bioenergy feedstocks

Ensuring a sustainable feedstock for gasification is essential, where sustainability indicators comprise of many environmental factors (e.g. carbon emissions, soil conservation, sustainable water use, biodiversity/natural capital, land use and air quality) and economic development, labour conditions and social aspects. However there are a number of other considerations that need to be taken into account when finalising feedstock selection – including feedstock availability (in this case, domestically-sourced – i.e. from the UK), fungibility, costs, pre-processing requirements, energy content, composition/contaminants and any competing uses.

Herein, a number of different biomass/biowaste types and species/products were considered based on these criteria, including: virgin woods, perennial energy crops, short rotation forestry/SRC, agricultural and forestry residues, recycled waste wood, municipal and commercial/industrial wastes (including that which has been processed to RDF/SRF) and wetland materials. Conventional food or feed crops, novel feedstocks and plastics were not considered. Table 1.1 summarises the information found for these various biomass and biowaste feedstocks for the different criteria, classifying them in the form of a traffic light system – greens for favourable outcomes discovered for the criteria, with amber and red indicating less satisfactory results.

Table 1.1: Traffic light summary of the different biomass and biowaste feedstocks considered against the assessment criteria. The numbers for fungibility indicate which fuels may be interchangeable to some degree – i.e. the woody fuels are grouped and the waste fuels are grouped.

FEEDSTOCK	SUSTAINABILITY/ ENVIRONMENTAL FACTORS	DOMESTIC SUPPLY	FEEDSTOCK AVAILABILITY	FUNGIBILITY	COSTS	PRE-PROCESSING	ENERGY CONTENT	COMPOSITION/ CONTAMINANTS	COMPETING USES/DEMAND
Virgin woods – chips				1					
Virgin woods – pellets				1					
Perennial energy crops									
Short rotation forestry – chips				1					
Short rotation forestry – pellets				1					
Forestry residues – chips				1					
Forestry residues – pellets				1					
Agricultural residues									
Higher grade waste wood				1					
Lower grade waste wood									
MSW				2					
CIW				2					
Waste-derived fuels: SRF/RDF									
Marine/wetland materials									

Based on the assessment of these feedstocks, a shortlist was selected, which comprises of materials under the following categories:

- short rotation forestry/coppice
- forestry residues
- higher grades of recycled waste wood
- waste-derived fuels: RDF and SRF

These were chosen for a variety of reasons. There are reasonable domestic supplies with good potential availability, as well as being generally quite high quality feedstocks in terms of their properties and characteristics, including reduced levels of contaminants compared to other feedstocks. Similarities between some of these feedstocks would also improve overall fungibility and fuel flexibility within the gasifier plant. Gasification trials and full scale operations have already been conducted with these fuels, improving confidence in their use for this application, particularly with the more mature gasification technologies that have been shortlisted as part of WP1 (analytical and technological engineering performance review of different gasification agents and technologies). Some degree of compromise will need to be made regarding feedstock selection however with regards to one or more of the key criteria, as none of the feedstocks are completely ideal. To accommodate a balance of feedstock properties, quality, availability and cost, the use of co-gasification – where two or more of these materials are used in combination – can be employed; there is also significant operational experience on this in the literature.

In addition to the conventional food/feed crops, novel feedstocks and plastics that were already eliminated from enquiries, a number of the other feedstocks considered were subsequently excluded from the selection process and did not make the shortlist, based on the findings of the assessments. The feedstocks that are not to be considered further are:

- lower grades of recycled waste wood
- agricultural residues
- municipal solid waste
- commercial/industrial waste streams
- wetland materials

The rationale for their exclusion often combined a variety of factors, such as high costs (in comparison to their quality), poor availability of domestic supplies, high levels/number of competing uses and poor quality of the feedstock, especially with regards to contaminants, which could pose numerous issues throughout the supply chain, as well as within the gasification and subsequent processes, in addition to any required licensing and permitting. These were often thought to be expressively prohibitive to their use for this application and were therefore disregarded from further investigation.

There were two types of remaining feedstock – perennial energy crops and virgin woods – that have not been explicitly eliminated from consideration, however, they are not deemed a priority, due to the range of challenges associated with them. Whilst there are a number of advantages to these, such as the high energy content and low levels of contamination, the issues with these included the major lack of domestic supplies, high numbers of competing uses, considerable associated costs and significant pre-processing requirements to make the material suitable to the gasification process. During the next phase of the investigation, these may be fully rejected as potential feedstocks or they may be considered further if there is potential to co-gasify these to mitigate some of the issues, through blending with, for example, much cheaper feedstocks.

Annex B: Gasifier technology selection

Few large-scale systems (>100 MWe) have successfully completed the demonstration stage and begun longer-term operation despite the fact that numerous gasifier designs have been developed over the past 20 years to produce syngas from biomass. Small-scale developments (70 kWe to 3MWe) have had greater success. Moreover, modularity and low tar content of the syngas produced in these units can be regarded as additional benefits of these technologies. On the other hand, while lowering the nitrogen content of the syngas product has frequently been taken into account when designing gasifiers, small-scale gasifiers cannot support the use of oxygen to do so, and allothermal designs increase system complexity and cost. Furthermore, small scale gasifiers do not have much flexibility in terms of the feedstock that could be treated.

Different from large-scale commercial gasifiers, several small-scale gasifiers are available in the market. The reliability of their offered technologies could be reflected by the fact that up to 2019 more than 1100 installations have been constructed. Most of the small-scale gasifiers base their designs on the traditional fixed bed technology, with specific design characteristics that can overcome the limitations of the conventional architecture. Table B.1 presents a non-exhaustive list of these medium/small scale designs, which have been chosen because they are commercially available, and can withstand long runs and continuous operation.

Table B.1: Non-exhaustive commercial small-scale gasifier list.

Gasifier Producer	Peculiarities	Advantages	Disadvantages	Grid Feeding Plants
Ankur Scientific Energy Technologies Pvt. Ltd.	Extensive syngas treatment and conditioning system	High biomass flexibility	Tarry condensate disposal	8

Burkhart GmbH	Updraft fluidised bed reactor fuelled with pellet	High number (more than 200) of installations, therefore presumed high reliability	Limited feedstock flexibility (A1 EnPlus Pellets)	200
Costruzione Motori Diesel CMD s.p.a.	Double stage syngas filtering	High biomass flexibility	N/A	8
ESPE s.r.l.	Compact design, high integration with auxiliaries	High temperature tar cracking	High-quality fuel required	18
Fröling GmbH	Containerized and indoor systems installation	High wood to electricity efficiency	N/A	5
Glock-ökoenergie GmbH	Patented filtering system	Above average fuel flexibility and efficiency	N/A	13
GRESCO Power Solution GmbH	Vegetable oil scrubber	High nominal capacity (up to 500 kW)	High-quality fuel required	N/A
Holz Energie UK	High temperature filtering system	Robust design, no tar condensation	High-quality fuel required	120
Kuntschar Energieerzeugung GmbH	Patented gasification reactor	Catalytic tar cracking, no tar condensation	High-quality fuel required	N/A

LiPRO Energy GmbH	Double stage gasification reactor	Simple gas filtering architecture	Required biomass low in fine particles	9
RESET s.r.l.	Final stage biomass filter	Above average biomass flexibility	N/A	19
Spanner Re2 GmbH	External char combustor	>700 existing grid-connected plants	High-quality fuel required	700
Stadtwerke Rosenheim GmbH	Double stage updraft gasification reactor	Simple filtering stage	N/A	2
Syncraft GmbH	Double stage gasification (1 reactor for pyrolysis and 1 for gasification)	High biomass flexibility	Power plant complexity	6
Urbas Energietechnik GmbH	Filtering system with ceramic candles and Ca(OH)2 injection	Robust design and no tar condensation	High-quality fuel required	27
Volter Oy	Containerized and indoor systems possibility	High-performance patented reactor, simple filtration system	Low Power output	20
Xylowatt	Double stage patented	High capacity ranges	Tarry condensate	6

	gasifier		disposal	

Overall conclusions and recommendations

- Despite their suitability for hydrogen production, fluidised bed gasifiers are developed for large-scale applications. Small-scale gasifiers have shown successful long term operation, with economic advantage over large scale systems. However, available designs have been conceived for CHP.
- Fixed bed gasifiers are the preferred choice for small-scale gasification. Updraft and downdraft gasifiers are simple and low-cost. However, updraft-produced syngas contains between 10-20% of tar, while downdraft syngas has less than 0.1%. Drawbacks include: difficult process control, limited scalability, low feedstock flexibility, and high nitrogen content (air gasification).
- Enhanced gasifier designs have improved characteristics compared to the ‘traditional’ fixed bed reactor, in order to overcome limitations. An example of an innovative design is the ‘partially fluidised bed rising cocurrent reactor’, such as the Burkhardt gasifier.
- Since the main objective of the integrated process is to evaluate the integration of the membrane unit, small-scale gasifiers are preferred over advanced designs since they are commercially proven and well-established technologies. However, this report includes the technologies that could be adopted for a scale up of the integrated system.
- Burkhardt technology can be commissioned in a short period of time, and the technology has been proven at the TERC facilities.
- Burkhardt is a well-known manufacturer for European and UK markets, complying with their standards of quality.
- Fuel flexibility is challenging, however different syngas compositions can be synthesised to test the performance of the catalytic membrane under different conditions.