

# Bluegen: Utilisation of Biorefinery Residues for Blue Hydrogen Production

## Hydrogen BECCS Innovation Programme: Phase 1

### Project closure report

Written by:

**Dr Martin J. Taylor** - University of Hull

Edited by:

**Dr Peter Hurst** – Biorenewables Development Centre

**Tobe Onwunaje** – Jesmond Engineering

**Dr Katie Chong** – Aston University

**Dr Kin Wai Cheah** – Teesside University



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## **Preface**

This report fulfils the requirements of the **Hydrogen BECCS Innovation Programme: Phase 1 Project closure report**.

**Lead:** University of Hull (UoH)

**Support:** Biorenewables Development Centre (BDC), Jesmond Engineering (JE), Aston University (AU) and Teesside University (TU)

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## Abstract

The Bluegen project's objective was to ascertain if sugar extracted biorefinery waste streams from locally abundant waste streams could be reformed into a solid fuel for hydrogen production. After hydrolysis using base (NaOH), C<sub>6</sub> and C<sub>5</sub> sugars were removed for valorisation, downstream leaving behind a lignin rich sludge. This material was post-treated via leaching (water washing) to remove alkali and alkaline earth metals and dried, followed by gasification at 950 °C (1% O<sub>2</sub>/N<sub>2</sub>) in a batch reactor (~0.3 g). Subject to base concentration and residence time in the Stage 1 process, the hydrogen yield (vol%) in the producer gas was found to vary between 7.63-27.95 vol% for barley straw derived sludges. For the case of wheat straw sludges, the hydrogen yield varied between 5.63-22.12 vol%, for both families of sludges the hydrogen yields far exceeded the performance of the parent barley and wheat straws by 85.15% and 47.97%, respectively. Scale up operations were initialised via the production of a detailed engineering design for a 1 kg demonstrator system, validated by Computation Fluid Dynamics (CFD). This system is designed as an addition to current operational digestion plants that extract sugars from waste, the resulting waste stream can be accommodated by the Bluegen technology for the sustainable production of H<sub>2</sub> while capturing CO<sub>2</sub> from the product stream *via* integrated BECCS. A Life Cycle Analysis of Phase 1 confirmed that a net-negative emission can be achieved with the proposed technologies when compared with an established and conventional hydrogen production method – steam methane reforming. It also concluded that the pre-treatment process can reduce the biomass feedstock demand and, in turn, the land use impacts by at least 50%. The techno-economic assessment concluded that the current proposed innovation has a positive profitability performance given by the positive NPV value of £104.77 million and desirable IRR of 35.27%. Where this method of hydrogen production was found to be substantially lower cost than current electrolyser alternatives.

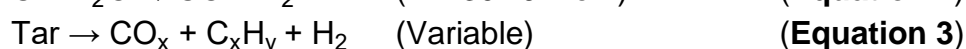
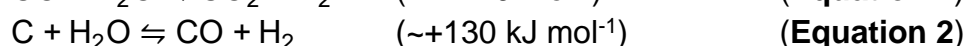
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## 1.0 Introduction

In a world of energy insecurity and energy poverty, we on a global effort attempt to continue decarbonisation efforts by seeking renewable energy, especially bio-renewables. Bio-renewables are materials generally derived from lignocellulosic origins, more recently the dominant focus has been on waste sources. Such materials can be the product of the food processing industries, agricultural waste streams and emerging biorefinery waste<sup>1-3</sup>. Lignocellulosic biomass waste is the growing option for the short-term substitution of traditional fossil based solid fuels, due to their high abundance and renewability, as well as low competition with food and feed markets, together with other forms of renewable energy true net carbon reductions (CO<sub>2</sub>) can take place and enable society to reach climate change mitigation targets as well as the ambitious net zero 2050. However, much like fossil residues before them, one cannot simply “plug and play”, the solid fuel must be pre-treated. This physical, chemical or physicochemical option can be such to reduce the overall material size (e.g. milling, grinding, sieving or drying), the removal of surface bound or soluble impurities (e.g. reduction in ash via leaching) or a combination approach where a material can be altered under harsh conditions to enable greater reactivity by expanding the pore structure or surface area for biochemical or thermochemical conversion<sup>4</sup>. However, the major problem with biorenewables is the same outcome as the use of solid fossil fuels such as coal, as they are carbon rich, when they are combusted/gasified they release CO<sub>x</sub>. Therefore, a sustainable approach to overcome this problem is to selectively promote the production of hydrogen (H<sub>2</sub>) from waste sources. Hydrogen is the pinnacle of low carbon fuels and has an energy density of ~60% higher than natural gas or bio-methane<sup>5</sup>. Therefore, by coupling bioenergy production processes with appropriate carbon capture and storage (BECCS), carbon dioxide can be removed from the produced gas feed post combustion/gasification of a fuel, pushing energy production into the realms of negative emissions. Although there are projected hydrogen production requirements of 512 Mt between 2030 and 2050 to reach Net zero 2050 targets<sup>6</sup>, much like net bioenergy production, there is no single best approach to produce enough sustainable hydrogen at the present technology readiness. Currently, there are vast global investments into electrolyzers that are steadily becoming more efficient, although their lifetimes still not level with more established technologies<sup>7,8</sup>. Electrolysis is a process where water separated into H<sub>2</sub> and O<sub>2</sub>, a rapid approach to hydrogen production but seriously hampered by cost due to high electrical demand<sup>9</sup>. Another approach is the decomposition of ammonia, a compressible liquid hydrogen carrier. Ammonia is highly corrosive and requires a large-scale process that remains unrefined since the 1900s that subjects feeds of N<sub>2</sub> and H<sub>2</sub> to high temperatures and pressure<sup>10</sup>. However, ammonia is an invaluable chemical for fertilisers, plastics and pharmaceuticals, in part detracting from its use as a bulk energy source. This does leave behind technologies such as methane pyrolysis which has been previously carried out using heterogenous catalysis and emerging technologies such as plasma assisted pyrolysis<sup>11</sup>. These systems often use natural gas and as a by-product generate a carbonaceous particulate carbon black material<sup>11</sup>. Although per kg considered as a cost-effective method of producing hydrogen, natural gas although abundant has a high carbon footprint is still a carbon intensive in terms of extracting (11.0–21.0 g CO<sub>2e</sub>/MJ<sub>LHV</sub>)<sup>12</sup>, although instability in Europe has led to natural gas shortages which will lead to higher net carbon emissions. This does leave behind the thermochemical conversion of lignocellulosic waste such as woody biomass as an option for sustainable

hydrogen production. With two choices available, pyrolysis and gasification, the focus is on gasification due to its greater concentration of gas phase product. Gasification utilises a critically dilute oxygen atmosphere (1-5 vol%) which does not fully oxidise the carbon in the way that combustion will (CO vs CO<sub>2</sub>)<sup>13</sup>. By doing so the produced gas mixture from gasification is denoted as syngas (synthetic gas) which generally contains CO, CO<sub>2</sub>, CH<sub>4</sub>, H<sub>2</sub> and trace short chain hydrocarbons. By coupling conventional gasification with either steam injection, catalysis or a combination of both will cause various reactions such as the water-gas shift (WGS) reaction (**Equation 1**), water-gas reaction (**Equation 2**), steam reforming of tar (**Equation 3**) and steam reforming of methane (**Equation 4**) will force the reaction to the right side, increasing the overall hydrogen yield, however some are more energy intensive than others<sup>14-17</sup>.



The variety of lignocellulosic biomass feedstocks is substantial. Each unique in their compositions of cellulose, hemicellulose, lignin and ash, these waste streams often suffer from high moisture and low bulk densities. Additionally, it can be considered that their individual component parts could be of greater value than simple combusting the material for energy. An example of this is the high value sugars that can be extracted from the cellulose fraction (hexose) and hemicellulose fraction (pentose) that can be fermented into various fine chemicals and liquid fuels. By doing so can leave behind a rich in lignin material that can be difficult to isolate and effectively utilise without high energy and or prolonged processing. As a result, lignin, the rugged polymer backbone of lignocellulosic biomass is often committed to waste and or classified as a low value material that has seen previous use in animal feed or as a component in adhesives<sup>18, 19</sup>. Lignin and specifically, lignin derived wastes hold a far greater stake in both the bioeconomy<sup>20</sup> and broader circular economy<sup>21</sup> that could display its true value in use in the emerging hydrogen economy<sup>22</sup> as a low cost and sustainable option to producing hydrogen not dependant on electrolysis, methane pyrolysis or the use of solid fossil fuels<sup>23</sup>. To enable this proposal, lignin rich biorefinery waste streams must be post-processed to increase their value by decreasing their overall ash content, often inflated by the impregnation of alkali or alkaline earth metals, sulphur or chlorine<sup>4, 24-26</sup>. It is well known that at scale, ash deposits lead to a wealth of reactor disruptions such as defluidisation for a fluidised bed reactor, corrosion or reactor hot spots, ash is also capable for driving product fluctuations downstream<sup>27-30</sup>. The latter is driven by the fact that ash can act catalytically for the various gasification reaction, especially Na and K for the WGS reaction (**Equation 1**), as discussed in previous work<sup>14, 31</sup>. Therefore, to ensure that an operator has full control over the gasification the process must accommodate means to drive down ash concentration and remove such elements to prevent undesired reaction, albeit stifle ones of benefit. This will also limit the chance of reactor slagging which will ultimately limit gasification production<sup>27</sup>, especially if reactive forming reactor bed adhesives such as sodium silicate (if using SiO<sub>2</sub> as a bed media in a fluidised bed configuration), often referred to as water glass, this will cause bed agglomeration by adhering particles together<sup>32</sup>. Similarly, Ca

present can reactively form calcium silicates or often calcium aluminosilicates, commonly referred to as slag<sup>33</sup>. Calcium is often rich in woody biomass feedstocks and will readily react with silica or aluminium containing quartz reactor beds. After successful removal of problematic ash components, a custom designed catalytic package can be employed to selectively drive specific gasification reactions, enhancing hydrogen yield.

## **2.0 Our approach**

For this project we present the effect of varying NaOH concentrations (0.2 M, 0.4 M and 1.0 M) on two abundant lignocellulosic biomass waste streams in the United Kingdom, barley straw and wheat straw. By increasing the base concentration, enhanced hydrolysis can take place to maximise the high value sugar removal (removal of cellulose and hemicellulose components), we will investigate if there is a correlated promotional effect for increasing hydrogen production from a lignin rich sludge during conventional gasification vs base hydrolysis concentration and residence time.

## **3.0 Methodology**

### **3.1 Feedstock production and post-treatment**

Barley straw and wheat straw grown locally was milled using a Retsch SM300 cutting mill fitted with a 1.00 mm screen. The 1.00 mm particles were pre-treated with varying concentrations of NaOH (0.2 M, 0.4 M and 1.0 M) (Fisher Scientific) across two residence times, 0.5 h and 1.0 h at 90 °C in a 10 L Universal Process Machine (RoboQbo 15-4). This was followed by drying at 105 °C in a Genlab OV/100/F/DTG oven overnight. The dried cake was then milled using a Retsch GM200 Grindomix Knife Mill at 4000 rpm for 1 min using the blunt edge of the blade, this was followed by sieving and separating using a Retsch AS200 Vibratory Sieve Shaker, reclaiming the 1.00-2.00 mm fraction. Each fraction feedstock was water washed (leached) in deionized water using a Heidolph Hei-Tec hotplate at 25 °C, mixing at 900 rpm for 24 h at a ratio of 10 g L<sup>-1</sup>. The temperature was monitored using a Pt1000 thermocouple based in the leachate. The leached feedstocks were separated from their leachates and dried under vacuo. This was followed by further drying in a Fisherbrand gravity convection oven for 24 h at 105 °C.

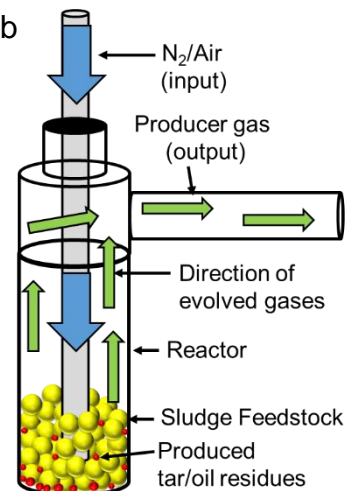
### **3.2 Feedstock characterization**

Proximate analysis was carried out using a LECO 701 thermogravimetric analyser at ~1.00 g scale where moisture, devolatilization, ash and higher heating value (HHV) were measured and calculated using **Equation 5**. The proximate analysis method used was as follows: ambient to 107°C at a rate of 3°C/min under nitrogen, holding for 15 min before heating from 107°C to 950°C at 5°C/min, holding for 7 min before cooling to 600°C. This was followed by an ashing phase in air from 600 °C to 750°C at 3°C/min, before cooling to ambient conditions. Fixed carbon was calculated by subtracting the final ash mass from the sample mass before combustion. Ultimate analysis of all feedstocks was acquired using a LECO Truspec CHN Combustion analyser using sample sizes of 50.00-60.00 mg. FTIR spectra were obtained using a Thermo Scientific Nicolet iS5 with a PIKE MIRacle single reflection horizontal ATR accessory. Scanning Electron Microscopy (SEM) images were acquired via a Zeiss EVO 60 instrument at 10<sup>-2</sup> Pa and an electron acceleration voltage of 20 kV. Powders were adhered to a coated conductive carbon tape and attached to the specimen holder. Bomb calorimetry was carried out on sample sizes between 0.80 and 1.00 g using a Parr 6200 Isoperibol calorimeter fitted with a Parr 1108P oxygen combustion vessel with an O<sub>2</sub> pressure of 450 psi. The full characterisation data for both

families of feedstocks is shown in **Annex 1, Table A1**. This clearly shows the effect of post processing leaching on the reduction of ash in the sludge derived feedstocks is in fact low than the untreated parent material, meaning that a substantial number of water-soluble contaminants (including Cl, Na and K) have been extracted and the subsequent moisture was driven down.

### 3.3 Gasification of sludges for hydrogen production

The gasification of the leached sludge feedstock was carried out in a lab scale, downdraft fixed-bed stainless steel, batch atmospheric reactor (**Figure 1**) under a controlled reactive atmosphere. Here, synthetic air (O<sub>2</sub> 20% and N<sub>2</sub> 80%) was diluted by a mass flow controller with nitrogen to achieve a 1% O<sub>2</sub> in N<sub>2</sub> mixture at a flow rate of 40 mL/min, corresponding to ~0.2 s of gas residence time. The gasifier was heated to 950 °C, measured by a K-type thermocouple positioned in the sample holder of the reactor. The heating rate was calculated to be approximately 50 °C/min for a total reaction time of 23.5 min, gas products were cleaned by a liquid tar trap (deionised water) and dried (SiO<sub>2</sub> gel, 70-230 mesh, Alfa Aesar) before storing in a 1 L Tedler bag and analysing offline using a Pollutek Gas 3000P analyser. The final product composition data was normalised by removing nitrogen and oxygen from the mixture. The reactor once the reaction had been completed was cooled to room temperature and cleaned in acetone (Fisher) to recover both the solid and liquid products from the reactor body and tubing. Once filtered from the char the tar/oil residues were separated via rotary evaporation and weighed.



**Figure 1 - Schematic of the lab scale downdraft gasification reactor at the University of Hull**

### 4.0 Testing – a road map for scale up

Thermochemical reactions such as gasification generate four products. The producer gas, a char (solid), bio-oil/tar (liquid) and residual ash. By minimizing side reactions and augmenting selectivity by pre-treating the sludge feedstocks, we were able to radially increase the gas yield the Bluegen process. Moreover, by investigating the role of base hydrolysis prior to leaching, we were able to demonstrate a road map for boosting sustainable hydrogen from a novel waste material. **Annex 2, Table A2** shows the reaction selectivities and gas phase product yields (vol%), graphically represented in **Annex 2.1, Figures A1-A3**, where **Figure A3** shows the variation in testing method to increase the performance of the gasification reaction, increasing both gas selectivity and hydrogen concentration. Method optimization for both the feedstock and reactor configuration has enabled Bluegen viability for scale up operations (Phase 2). See **Section 7** for a summary Technoeconomic Assessment of the Bluegen system moving into Phase 2.

### 5.0 Phase 2 Demonstrator Detailed Engineering Design

For complete detailed of the Bluegen Demonstrator system, please consult Deliverable 5.0 of the Phase 1 Bluegen project. For this report, a schematic overview is shown in **Figure 2**, a summary technical report is shown in **Annex 3**. A model of the proposed Bluegen gasifier is presented in **Annex 4, Figure A4** with subsequent CFD (computational fluid dynamics) analysis for both single and two phase is provided in **Annex 4.1, Figures A5-6**. The proposed process starts from the first storage hopper (housing sludge post hydrolysis), assuming the base hydrolysis has been completed as a pre-requisite, the produced sludge is conveyed to a mill for size reduction (1-2 mm). By emulating the reactor and downstream processing in the lab scale system, a comprehensive 1 kg system was designed. This design was outfitted with a tar removal system that as a temporary measure will use vegetable oil, the tar will mix with this and not separate as it would



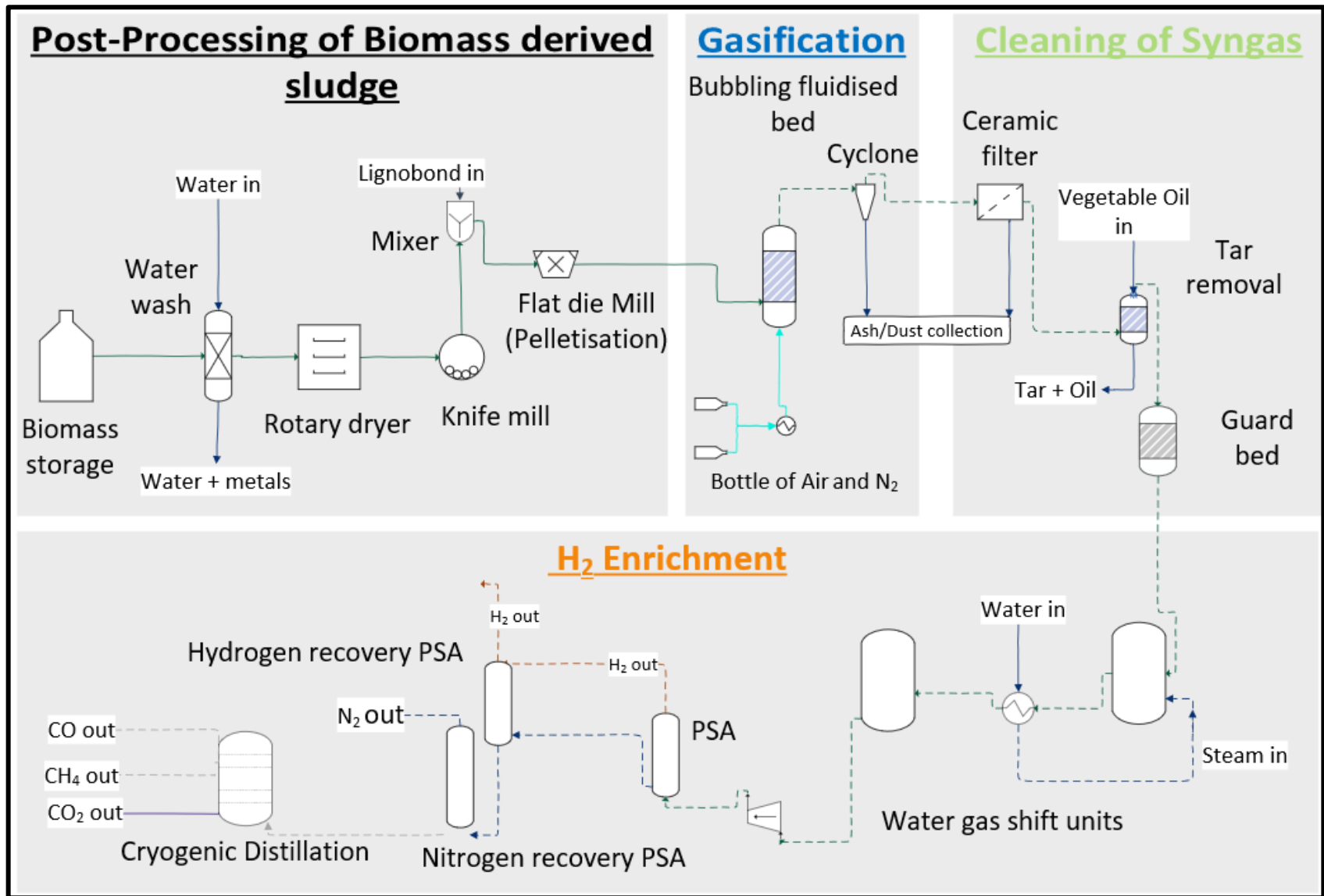


Figure 2: Process Flow Diagram of proposed Phase 2 Bluegen demonstrator system

in a water system. Phase 2 will develop this system further by incorporating a tar reforming catalyst either inside or post gasification to decompose the tar molecules into H<sub>2</sub> and valorised molecules that can be removed from the process as additional products. This will decrease the overall reactor footprint as only a guard bed would be installed between the ceramic filter and H<sub>2</sub> enhancement system. Further design details are shown in the technical summary report, **Annex 3**. The technical report provides a point by point approach to the overall engineering design, highlighting individual process elements and where possible recirculation system, specifically for water and other consumables. Additionally, **Annex (A)** provides a work break down structure for construction and continuous improvement of the designed demonstrator scale reactor. The Jesmond Engineering team will also work alongside the University of Hull and Biorenewables Development Centre to drive commercialisation and develop a stakeholder network, explained further in **Section 8**.

### **5.1 Phase 2 performance testing protocol**

To enable long-duration testing, the phase 2 system will operate a continuous flow, fluidized bed gasifier. This is where feedstock is pelletised and stored in a transient hopper as it is fed into the gasifier on a screw thread (**Annex 3**). The intended feedstock consumption rate for the Bluegen Demonstrator system (BG2) is 1 kg/h, this will allow for detailed analysis of the produced gas, as it is made via either online gas analysis using a gas chromatograph, outfitted with a thermal conductivity detector (GC-TCD) or by capturing in gas bags and then chromatography, sampling points before and after H<sub>2</sub> enhancement. Utilising a low, non-reactive ash (a substance that will not react with the bed media), we have projected a continuous operation window of at least two months (~1440 hours), subject to the ash removal system and availability of parent feedstock. Tar and oil residues will be sampled offline and analysed via gas chromatography mass spectrometry and the ash/dust will be investigated by powder x-ray diffraction, scanning electron microscopy and energy dispersive x-ray spectroscopy to investigate grain morphology and composition.

Before achieving the long performance testing, a number of stress tests will be carried out to optimize the demonstrator system. This will allow for troubleshooting, planning maintenance, assessing system leaks and enable us to map energy consumption, as mentioned in **Annex (A), WBS 5**. A larger aspect of the Phase 2 project will allocate a researcher from the University of Hull on the production and functionalization of biorenewable filter materials (modifying char produced in the Bluegen process) for water remediation, creating a closed system and prevent water contamination.

As part of the testing regime, feedstock quality and characteristics will be processed using large scale characterization equipment at the University of Hull. These instruments were used in Phase 1 and are designed for representative analysis allowing rapid parallel screening of multiple samples at ~1 g scale (thermogravimetric analysis) and ~100 mg for elemental analysis (CHN). Representative samples will also be taken from the process periodically (every 5 kg produced) for a full analysis including spectroscopies and microscopy, as completed in Phase 1. Gas samples will be also collected in gas bags and validated using a second GC-TCD at the University of Hull for results validation, especially for characterizing the removal of CO<sub>2</sub> from the producer gas after the cryogenic distillation

system where the gas feed will be compressed and passed through methanol for capture or a liquid amine system. Effective scrutiny of the feedstock (pre, post hydrolysis and post leaching) will govern the reaction selectivity (Phase 1) and overall gas yield. This variability will allow the team to adjust the demonstrator system accordingly to alter conditions (temperature, flow rate and or the addition of catalysts to drive **Equations 1-4** mentioned above) or process to maximise hydrogen production. The Phase 1 reaction only utilised a single thermocouple, the BG2 system will accommodate at least six thermocouples along the gasifier and further along the scrubber system to map condensation residues, as well as a series of pressure sensors and high capacity mass flow controllers for both the air and nitrogen inputs. As Phase 2 will operate a continuous production process, the produced H<sub>2</sub> will be measured using a water displacement set up where a volume per hour measurement can be recorded in accordance with the consumption of 1 kg of feedstock per hour. Preliminary reactor optimization work has already been carried out by using two phase CFD modelling, this has indicated a number of geometry modifications for the gasifier itself to maximise particulate extraction from the gas feed. Phase 2 will continue applying this level of investigation to the whole process, opposed to targeted pinch points in Phase 1. Alongside experimental performance testing in Phase 2, Jesmond aims to extensively CFD in order to address expected scale-up challenges. CFD is a branch of fluid mechanics that utilises 1D and 2D/3D numerical method and algorithms to simulate problems that involve thermo-fluid problems, including chemical reactions. It is a powerful tool used in many industries to analyse, optimise and verify the performance of equipment and production processes.

A number of appropriate CFD models will be created for the major elements of the proposed system and simulate various parts of the process. Jesmond will use the data collated from the experimental performance testing to validate the CFD models to ensure the simulation results represent those results observed in real-life. The validated CFD model will then be used to explore a range of operating envelopes, changes in geometry and variations of fluid properties. Simulation results will be actively used to inform decisions for future commercial scale-up such as material selection, practicality of commercial operation and optimisation of operating conditions.

A number of areas have been identified where CFD will be utilised during Phase 2 and envisages that the CFD studies will focus on:

1. Optimisation of the water-wash stirred tank geometry and impeller in order to reduce post-processing treatment time and power usage.
2. Comparison of the deionised water wash against various acidified water wash solutions to improve and optimise the leaching process and minimise ash content.
3. Thermal analysis of the rotary dryer system including water vapour recycling by heat exchanger to improve thermal performance and reduce moisture content.
4. Optimisation of the gasifier geometry to minimise issues such as bed amalgamation, and inefficient or non-uniform heating over the gasifier.
5. Simulation of the movement of the biomass particles within the fluidised bed in order to optimise the dynamic process of the biomass gasification.
6. A study focusing on the variation of air/fuel ratio to optimise gasifier fluidised bed temperatures.

7. An assessment of varying biomass compositions, in order to characterise and maximise H<sub>2</sub> production at different operating conditions.
8. Cyclone separator simulation to assess performance across a range of sand/ash particle diameters in order to minimise downstream transport of contaminants.
9. Comparison and analysis of the tar scrubber to explore if sludge feedstock may be utilised as an effective and less expensive packing material.
10. Thermal analysis of the water-gas shift heat exchangers in order to assess geometry effects and improve heat transfer.

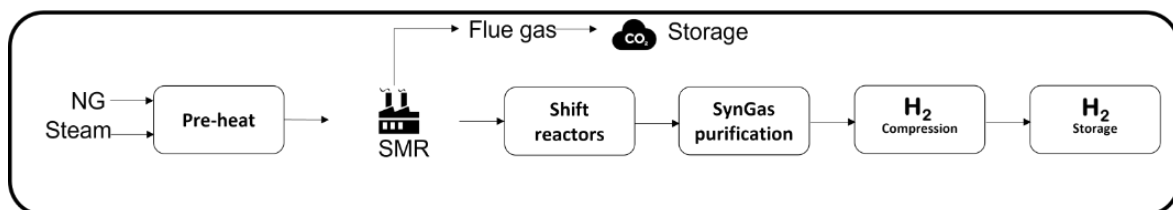
A holistic approach to the CFD analysis will be taken. Simulation results of increasing optimisation from a previous stage may also be fed into the next stage to further test and assess the effect of any downstream performance gains on the upstream processes.

## 6.0 Life Cycle Assessment of the Bluegen technology

### 6.1 Methodology

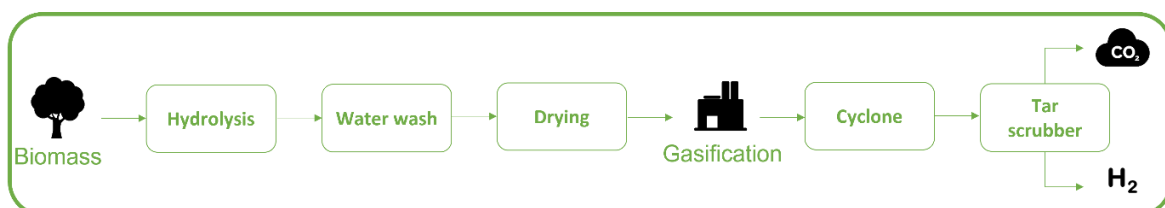
Following experimental work in WP1-3, a mass balance was produced and modelled using Aspen Plus simulation software, and a life cycle assessment was carried out to provide insights into the environmental impacts of renewable hydrogen production per the BEIS Hydrogen BECCS innovation.

A reference hydrogen production process is considered for comparison based on a higher TRL and assumed environmental impacts. The reference system chosen was hydrogen via steam methane reforming, **Figure 3**. Steam methane reforming (SMR) using natural gas is one of the most common methods to produce hydrogen. Natural gas is pre-treated and desulphurised to decompose the long-chain hydrocarbons into methane and syngas. The methane reacts with steam to produce hydrogen and carbon monoxide. The yield is further increased through a water-gas shift reaction, whereby the carbon monoxide reacts with water to produce hydrogen and carbon dioxide.



**Figure 3 - Steam methane reforming block diagram**

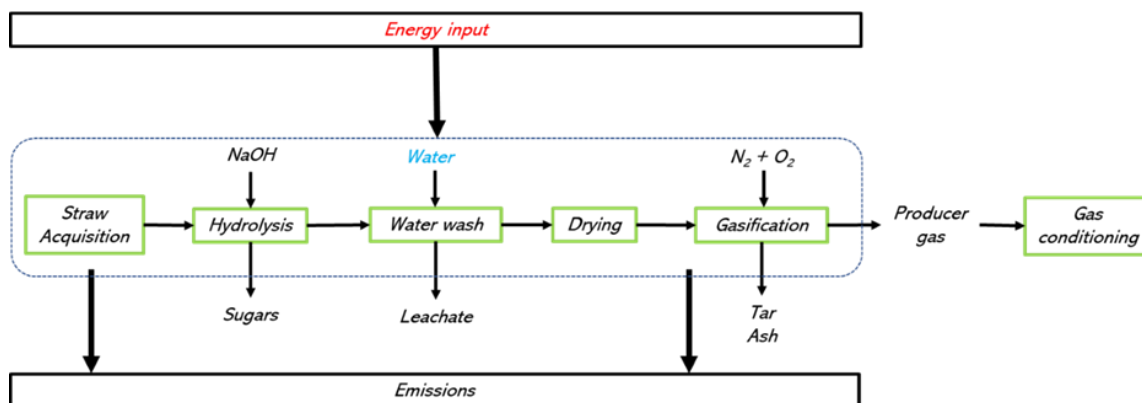
The Bluegen production process uses gasification, a thermochemical conversion technology, to convert pre-treated wheat and barley straws into syngas, **Figure 4**. In addition, the pre-treatment processes used varying concentrations of sodium hydroxide (NaOH) solutions to hydrolyse the feedstock to improve the hydrogen content downstream of the thermochemical conversion.



**Figure 4 - Bluegen block diagram**

For the feedstock, transport-related emissions for production and transport to site from the local area (inland Europe, 0.17tkm) are included. In addition, the energy demand for pre-

treatment and processing is included. The scope of the LCA study does not consider downstream of the gasifier or the multifunctional use of hydrogen within the project's current phase. However, it is accepted that the product's downstream technical performance and related emissions are identical. Solid and liquid effluents are not considered within the scope of this current phase as they are expected to undergo further post-processing downstream of the process (to be considered in Phase 2). The functional unit applied for this study is the production of 1 kilogram (SI: kg) of high-purity hydrogen (>99.9% v/v) available within the system (producer gas). Therefore, a gate-to-gate approach is adopted as the system boundary for this study (**Figure 5**).



**Figure 5 – The System boundary within the scope of the current assessment.**

## 6.2 Data inventory

Preliminary Aspen model simulations (**Annex 5, Figure A7**) validated feedstock characterisation and gas compositions obtained from WP1-3 experimental results to obtain material balances. In addition, the life cycle inventory (technosphere and biosphere) is obtained from the Ecoinvent v3.9 (cut-off) database via Brightway2; a python-based software.

The feedstock samples that produced the highest concentration of hydrogen following gasification were chosen for the analysis. In addition, samples from the leached wheat straw without pre-treatment were also used to compare the environmental impact (**Annex 5.1, Table A3**).

Biomass feedstock and raw materials are assumed to be produced and transported from close proximity to limit transport-related emissions. Solid and liquid effluents are not considered within the scope of this current phase as they are expected to undergo further post-processing downstream of the process (to be considered in Phase 2). Results show that the energy requirement is about 0.56kW per kilogram of biomass feedstock. It is also assumed that the energy is provided by grid electricity (standard UK grid mix).

The LCA followed ISO 14040/44 standard and was performed using the life cycle inventory (technosphere and biosphere) obtained from the Ecoinvent v3.9 (cut-off) database via Brightway2, a python-based open-source software. The resulting balance of CO<sub>2</sub> sinks (from biomass production, carbon capture) and sources (biomass treatment and conversion) will determine the net-negative emission potential of the system.

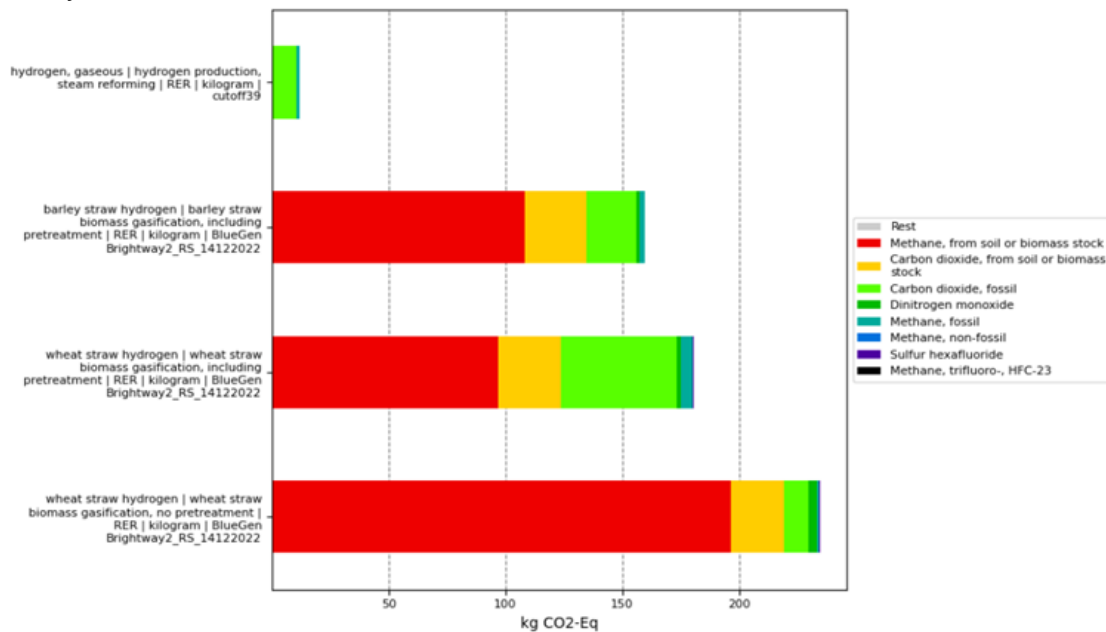
The impact assessment methodologies employed in this study are the CML v4.8, EF v3.1 category to assess the global warming impact, while the ReCiPe v1.03 methodology with

midpoint indicators to reduce the level of uncertainty is employed to assess the agricultural land occupation for the land use change study.

The impact assessment methodologies employed in this study are the CML v4.8, EF v3.1 and the IPCC v2021 to assess the global warming impact, while the ReCiPe v1.03 methodology with midpoint indicators to reduce the level of uncertainty is employed to assess the agricultural land occupation for the land use change study.

## 6.2 Results summary

A selection of the outputs from the analysis can be found in **Annex 6**. **Figure 6** shows the CO<sub>2</sub> emissions (CO<sub>2</sub>-eq) for three pre-treatment scenarios compared to conventional hydrogen via steam reforming, **Figure A8** shows the land use and **Figure A9** the Monte Carlo analysis.



**Figure 6 - CO<sub>2</sub> emissions (CO<sub>2</sub>-eq) for three pretreatment scenarios compared to conventional hydrogen via steam reforming**

## 6.3 LCA Key findings

Please see the full report (Deliverable 4.1) for a detailed results and discussion, including a more detailed sensitivity analysis.

1. Most emissions come from the methane component of the syngas after gasification. However, the methane will undergo post-processing in the reforming and shift processing which was not considered as part of this study. The resulting carbon oxides will be captured as biogenic carbon, so in the real system, these emissions will dramatically reduce
2. The production and logistics of NaOH also contribute significantly to anthropogenic emissions. Therefore, this is a key area for optimisation in Phase 2.
3. The land use change shows no significant variation as it is a function of the amount of biomass feedstock utilised.
4. Monte Carlo simulations reveal that pre-treated wheat straw has the most significant potential for optimisation.
5. Barley straw benefits from the smallest NaOH requirement to produce H<sub>2</sub>

Phase 2 will use these findings as stepping stones to produce a full LCA and sustainability analysis of the complete system, from cradle-to-grave. The LCA will quantify the environmental impact of all stages of the hydrogen lifecycle, from feedstock cultivation to end user. This will provide evidence of the technology's potential to help meet the UK's net zero targets. The sustainability analysis will include wider socio-political impacts and identify how the system matches with the UN Sustainable Development Goals, including factors such as job creation. This complete system analysis will enable the project team to identify the risks and benefits of the system, and use the data to carry out process optimisation as the project progresses.

## **7.0 Technology Economic Analysis of the Bluegen process**

A comprehensive techno-economic analysis was performed to determine whether the renewable hydrogen produced from this proposed technology is economically competitive with current grey hydrogen and green hydrogen production. This analysis also aims to evaluate the commercialization potential of the proposed state of art. As a whole, the project scope includes evaluating the economic viability of the proposed state-of-art technology, identifying the major cost drivers and potential cost reduction opportunities, and lastly determining the minimum selling price of renewable hydrogen produced from a biomass gasification plant operating in a 10-year timeframe.

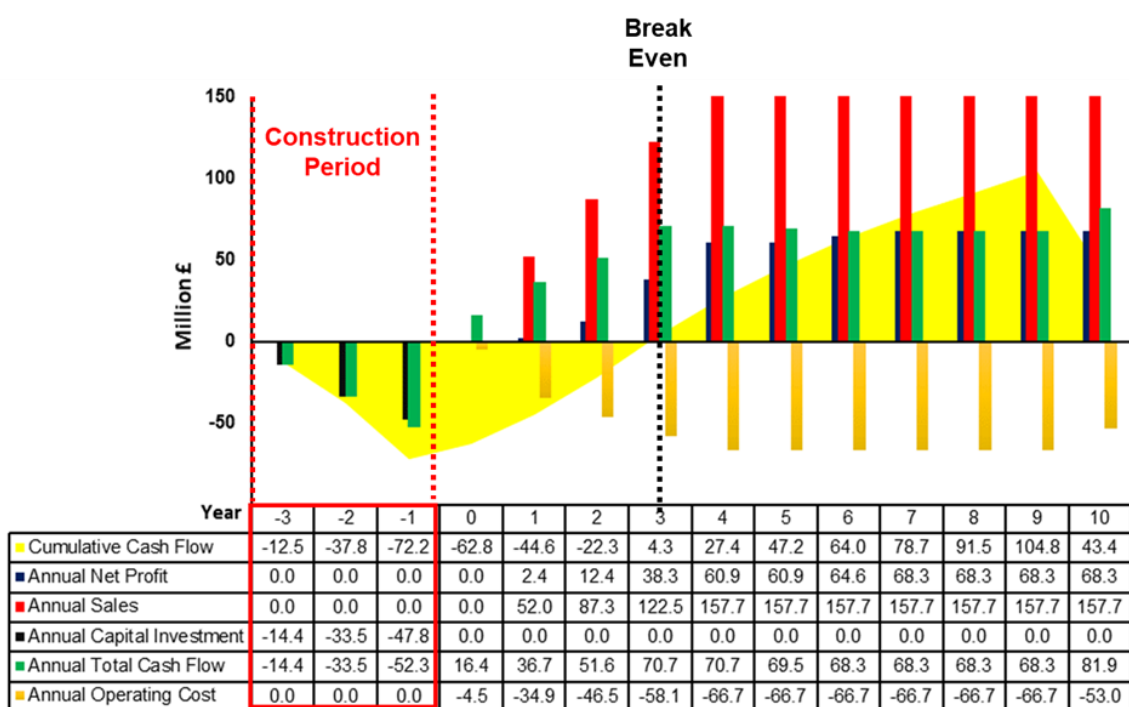
Based on the results of the techno-economic analysis (**Figure 7**), it is concluded that the proposed innovation offers a favourable ROI of 40.99% and IRR of 35.27% as compared to the minimum acceptable ROI and IRR (20-30%) for a typical industrial process investment. From the break-even profitability analysis, the pay-back period of this project is estimated to be about 3 years with a positive NPV performance of £104.77 million. Hence, this proposed innovation project is expected to be economically profitable for investment as it offers an annual net profits as high as £68.3 million on the assumption that all renewable H<sub>2</sub> gas produced is sold and distributed.

With the average price of grey H<sub>2</sub> gas produced from natural gas or methane ranges between £0.42–1.43/kg and the average leverised cost of green hydrogen gas derived from water electrolysis found in between £2.50–6.73/kg, the leverised cost of hydrogen produced from this project is found to be £1.89/kg at a MARR of 30%. Thus, it is evident the the hydrogen produced from this technology is economically competitive with green and grey hydrogen available in the renewable energy market. However, it is worth to point out that the current TEA analysis only focused on the upstream biomass pre-treatment and gasification processes. A more accurate and precise TEA analysis will be carried out in Phase 2 by including the downstream hydrogen purification (gas scrubbing system & pressure swing adsorbers) and carbon capture system. Also, the leverised cost of hydrogen cost is envisaged to be increased when the economic analysis is extended to the downstream processes including the product gas scrubbing/cleaning system and pressure swing adsorbers. However, the extent of the leverised cost increment is still unknown and could only be found if the TEA model includes the downstream hydrogen purification and carbon capture systems in Phase 2.

The sensitivity analysis showed that the total direct cost of this project and the H<sub>2</sub> yield have the largest influence on the IRR. For the raw material, the price of nitrogen demonstrated a significant impact on the IRR with more than a 5% change in the IRR.

Phase 2 will mitigate this by utilising a nitrogen generator alongside air compressor. The hydrogen yield was identified as one of the major cost drivers, this confirms and highlights an earlier comment that catalytic gasification would greatly improve hydrogen yield and enhance the hydrogen production capacity, which will eventually bring down the leverised cost to a significant extent under economies of scale.

Phase 2 would expand the current TEA and include supply chain and logistical analysis as well as carbon footprinting of Bluegen as it diversifies the number of potential feedstocks for sustainable hydrogen production. The TEA will also include a full energy analysis for the entire process, hot spots will be reevaluated as Phase 2 progresses so that less energy intensive options can be exploited, lowering cost.



**Figure 7 - Profitability analysis and overall cash flow diagram of Bluegen**

## 8.0 Pathways to commercialization

The solution provided by the Bluegen project is the development of a pre-treatment process that produces a biomass feedstock with a H<sub>2</sub> content, when gasified, that can be utilised for hydrogen production. Biomass for the process has been recovered from a biorefinery waste stream, reducing the amount of waste produced and creating additional revenue. The process contains heat integration, water recycling, regenerates scrubbing solvents and makes use of all produced gases within the process, producing N<sub>2</sub>, CH<sub>4</sub>, CO and CO<sub>2</sub>. The additional revenue streams this will generate within biorefinery activities will increase investor confidence in commercial ventures that help build a sustainable UK bioeconomy, enabling the UK to achieve its legal commitment to achieve Net Zero greenhouse gas emissions by 2050 while also reducing the reliance on petrochemical derived chemicals and fuels.

It is estimated that the global production of petrochemical polymers and chemicals is around 330 million tonnes per annum utilising well established technologies. To replace these products with bioderived sustainable alternatives will require significant investment



and rapid deployment. Petrochemical markets have been developed and operating for, in some cases, 50 plus years. For the bioeconomy to fully replace that market there will need to be a concerted and sustained effort to achieve this 50+ years of development within a much-shortened timeframe - most likely 10-15 years.

The International Energy Agency (IEA) Bioenergy Task 42 defines biorefining as “The sustainable processing of biomass into a spectrum of marketable products and energy” with spectrum being the key word - referring to multiple energy and non-energy products. The majority of biorefineries attract investment through production of one product be this either a fuel (bio-ethanol or bio-butanol) or chemicals. Biorefineries are presently still in their infancy and heavily rely on subsidised markets (Bio-fuels) or production of high value low volume chemicals (succinic acid) where they can compete as alternatives to well established petrochemical products. The main market barrier for bio-based products is their cost of production when compared to the petrochemical alternative especially when there is no clear performance advantage in changing materials. This is predominately driven by the majority of biorefineries focussed on one product stream and not utilising all product streams. Ultimately the profitability of the plant is determined by the cost of the waste streams which are often overlooked in the development process and the IEA has identified this as a technical barrier to the deployment of biorefineries.

Phase 1 of the Bluegen project has utilised biorefinery waste streams to produce hydrogen via gasification to offer an extra revenue stream with a primary focus on wet sludges produced via acid or basic pre-treatment sugar release technologies. Bluegen has demonstrated that hydrogen production from these biorefinery residues is indeed possible, and, in certain conditions, a higher concentration of hydrogen can be produced. Utilisation of the Bluegen innovation within a biorefinery will enable a spectrum of products to be produced sustainably from one feedstock.

In terms of the current target market, at present there are 14 biorefineries of differing size within the UK manufacturing chemicals and biofuels. This is significantly lower than France (44), Germany (78) and the Netherlands (36) and has only increased from 11 since 2017. For the UK to keep pace with our European neighbours and our own net zero targets it should be expected that the number of biorefineries would need to at least double in number by 2050 As described earlier a technical and financial barrier to this is the cost-effective utilisation of all streams produced from the process enabling the outputs of the biorefinery to be more cost competitive to petrochemical products. This can be seen in recent history in the UK with both Ensus and Vivergo shutting down production due to the volatility of the ethanol fuel market. They have reopened production with the introduction of E10 onto the market making the process more viable due to the higher volume of ethanol being permitted into the market. However, if the plants had a viable product stream from the solid residues it could have reduced the impact of the volatile ethanol market and ensured they remained open. The UK is not feedstock limited due to the scale of imported biomass into the country for energy generation resulting in the UK importing in the region of 5 million tonnes per annum. The Bluegen innovation offers a solution to provide an additional revenue stream to existing and new biorefineries. Enabling biorefineries to establish a second product stream will reduce the impact of a volatile main product market and the cost difference to the petrochemical alternatives.

Of the current 14 biorefineries, the majority are located within the region where the Bluegen partners are located. These include Wilton, Teesside where Ensus and NovaPangaea Technologies are operating plants to manufacture sugars from crop residues which are utilised to produce ethanol or high value chemicals. Ensus currently processes 1,000,000 tonnes of biomass a year to produce predominately 400,000 cubic metres of ethanol and 350,000 tonnes of Dried Distiller's Grains with Solubles (DDGS). In Hull, the Vivergo plant utilises 1.1 million tonnes of wheat straw to produce predominately 420,000 cubic metres of ethanol and 500,000 tonnes of DDGS. Equally, the plant could be retrofitted to flour processing plants or breweries, industries which produce a large volume of lignocellulosic bio-waste, which can be converted to H<sub>2</sub> for energy production. Energy produced could be exploited within the process, moving these energy intensive practices to green ones.

A commercial Bluegen plant would be utilise the solid DDGS fraction of the process as these currently have low value outputs. Any commercial plant would need to be designed to deal with a maximum annual output of between 350,000 and 500,000 tonnes to match the current industrial standard for the UK.

The project consortium believes the innovation at commercial scale would be best situated in Teesside and Hull due to the location of the existing biorefinery infrastructure and skills base. The project seeks to attach the process described in the engineering design near to or even on the same sites where the biomass waste is produced to reduce CO<sub>2</sub> production via transportation. Sites that will be targeted include farmland seeking a sustainable energy production method. The operation would also sit inside the Zero Carbon Humber and Net Zero Teesside clusters which both have aims to reduce industrial CO<sub>2</sub> emissions by 50%. Of significance to this project is the Hydrogen to Humber (H<sub>2</sub>H) Saltend project led by Equinor which is a significant low carbon hydrogen facility at the forefront of decarbonising the Humber region. In addition, Drax Power are developing Europe's largest decarbonisation project with the introduction of a BECCS solution which would generate negative emissions. The region is therefore already gearing itself towards being a leader in net zero innovation and deployment. The project consortium has been promoting the project to interested parties including Equinor (Humber), Drax Power (Drax, North Yorkshire), Binding Solutions (Wilton, Teesside) and NovaPangaea Technologies (Wilton, Teesside). Providing an outlet for the residues increases investor confidence by demonstrating that all products have a viable outlet realising the biorefinery as a more viable alternative to the crude oil refinery and enabling the UK to become a leader in this field. Consequently, the market for this innovation should increase as the number of biorefineries increases.

The development of an integrated process shows that H<sub>2</sub> production can be feasibly achieved from a biorefinery waste resource. The UK's industrial strategy is intertwined with its commitments to achieve Net Zero by 2050 and decarbonise energy intensive processes by providing an alternative energy source to fossil fuels in the form of H<sub>2</sub>. Hydrogen has an energy density of nearly 34 kWh of useable energy per kg which is superior to diesel, having roughly a third of this energy density. With continuous improvements to H<sub>2</sub> fuel cells, their use as fuel is closer than ever. The industry should therefore seek to move towards a means of supplying the amount of hydrogen necessary to convince

governments and industry leaders that the switch from fossil fuels can be made with as little disruption to the supply of energy as possible.

The UK's industrial strategy is built on five foundations (Ideas, People, Infrastructure, Business Environment, and Places) and the Bluegen project supports all five. The project is innovative in the way it seeks to integrate itself into existing processes and provide solutions to the issues that are currently experienced in biomass gasification. In addition to this, methods to integrate heat and recycle water to minimise waste further have also been detailed in the engineering design (**Annex 3**). With the scale up of the process, new jobs will be created so that safe operations can occur. This would provide 'Green Jobs' on a variety of levels from machine operators to engineers to specialists and would incentivise government and employers to be more invested in bridging skill gaps that the general labour force currently has as they would have an industry to work in by the time the Bluegen project moves to commercialisation. The technology and processes being developed directly target infrastructure by producing H<sub>2</sub> that can be used to support the UK's push towards a hydrogen economy, reducing CO<sub>2</sub> emissions and improving air quality. Hydrogen is best option in the push to decarbonise the economy because of its energy efficiency compared to non-renewable sources, producing only water vapour and heat. A purified H<sub>2</sub> stream can also be used in the UK's existing gas infrastructure and won't require changes/additions to houses such as solar panels or heat pumps. The ability to produce H<sub>2</sub> to the scale required to shift towards a H<sub>2</sub> economy would reduce energy costs and thus business costs, leaving more money for industry to spend on other aspects such as R&D, maintenance of equipment or increasing worker wages and boosting the economy and business environment. The project is based in the north of England, with project partners spread across Yorkshire, an area of the UK that comes under the scope of development of the Northern Powerhouse and levelling up strategies, which are government initiatives set up to provide boosts to regional economies in areas of the UK that previously have been underfunded or underdeveloped. By fostering innovation that benefits society in this region, it creates more reason for further development, in turn having a positive knock-on effect to local communities.

In phase two, the Bluegen team plan to innovate the water washing process, by enhancement with dilute nitric acid. The theory suggests that this may improve the leaching of metals in biomass and reduce the ash produced during gasification. Neutralisation using sodium hydroxide provides sodium nitrate, which is a fertiliser which can be used for the growth of biomass, introducing circularity to the process and either additional revenue or reduction of costs of reforming sludges.

The UK defines the Hydrogen BECCS process as generating hydrogen from biogenic feedstocks via gasification or other bioenergy conversion routes combined with carbon capture and storage. CO<sub>2</sub> will be captured via Cryogenic Distillation, which works on the premise that the CO<sub>2</sub> desublimation point is relatively high compared to the other gases present in syngas (H<sub>2</sub>, N<sub>2</sub>, CO, CH<sub>4</sub>). The gas stream is cooled to below the CO<sub>2</sub> desublimation point so that it solidifies while the other gases can be separated and utilised further up the column. CO<sub>2</sub> at this stage is at industrial grade and could be used for agricultural growth in greenhouses to speed up the rate of plant growth and eliminate pests – again targeting circularity. Another use could be as a coolant/refrigerant in various

parts of the process that require cooling e.g., the cooling of pellets following their production. Further processing to reach food grade (known as grade H = 99.9% purity) can be achieved by employing technology such as Vacuum Pressure Swing Adsorbers (VPSAs) and then be used in a brewery or for carbonated drinks - turning CO<sub>2</sub> into a revenue stream and once again promoting a Circular Economy.

The Phase 1 Bluegen project has demonstrated that biorefinery residues produce more hydrogen than if the untreated raw material was gasified. The utilisation of the residues provides the biorefinery with at least two products that have viable markets resulting in a more stable setup. The UK will have to move to a greener economy based on biogenic feedstocks further reducing the reliance on products/ fuels derived from petrochemical sources as part of the net zero targets. This should result in an increasing number of UK biorefineries who would be looking for investment and will be looking for certainty on returns. This would be achieved by offering multiple product streams which the Bluegen innovation provides through the production of hydrogen from biogenic sources.

The development of a Low Carbon production method for H<sub>2</sub> with CCUS offers the UK part of the solution to achieve net zero by 2050. To be able to state this, decision makers need to have viable options to pursue that have a realistic prospect of benefitting local economies and reducing CO<sub>2</sub> emissions. Biomass gasification has been a technology that provides a pathway to hydrogen production but saw issues with ash formation, bed amalgamation and unwanted reactions and tar production that caused clogging downstream. Bluegen has provided solutions to these issues and aims to further optimise the process to help bring about Net Zero in the UK by 2050.

### **8.1 Phase 1 commercialisation and moving forward**

In Phase 1, there was no formal commercialisation attempt, however, the team have generated a network of interested parties that will be invited among others to a series of planned stakeholder events in Phase 2. These events will be held at the BDC where a tour of the demonstrator process can be provided, along with technical information such as the LCA and TEA produced in Phase 1. Our aim is to hold a number of stakeholder events, an independent commercialisation officer will also be assigned through the BDC to direct these events and grow the stakeholder network. The planned events are shown in the BG2 project timeline (**Annex (B)**). By demonstrating the Bluegen technology at a small scale, we are able to align with CRI2 (commercial trials of the technology on a small scale) where we will also present our scale up design for developing on from 1 kg scale, unlocking CRI3. It is the team's belief that true commercialisation can only be achieved with physical evidence of the system, especially if private investors are to be attracted. As the BDC have a track record in working with biotechnology stakeholders and Jesmond Engineering have a history of working with engineering firms, the two will work from opposite sides to grow the network. The University of Hull will support both partners by presenting data and showcasing the Bluegen project and its wider applications.

### **9.0 Bluegen 2 – A H<sub>2</sub>-BECCS Demonstrator Project**

Due to its location to project partners and potentially interested stakeholders, available space and readily amenities, the Bluegen 2 demonstrator system (BG2) will be situated at the Biorenewables Development Centre (BDC) in York. The BDC have established a unit on the same innovation park to their other facilities and can provide the relevant gas,

power supply and foot print for the BG2 system to be developed. They also have skilled team to maintain the system in the form of a dedicated Technician and Lead Technologist. As the sludge production facilities is also present at the BDC, we can ensure the BG2 system is sustainable from the start where the feedstock can be made and delivered into the system without external transportation (cross country haulage).

### **9.1 The BG2 team – Project management**

The BG2 project team will consist of an unchanged team from Phase 1, however, subcontractors have been invited to become full partners on the project.

#### **University of Hull**

- Dr Martin J. Taylor – Lecturer in Chemical Engineering - Project Lead
- Dr Vicky Skoulou – Senior Lecturer in Chemical Engineering - Technical Manager
- Dr Carolina Font Palma – Lecturer in Engineering

#### **Biorenewables Development Centre**

- Dr Peter Hurst – Lead Technologist – Technical Manager
- Dr Mark Gronnow – Process Development Unit Leader
- Philip Lawless – Senior Technician

#### **Jesmond Engineering**

- Simon Walker – Technical Manager and Chief Engineer
- Tobe Onwunaje – Project Management Officer and Engineer
- Patrick Kelly – Design Engineer
- Dr Jason Dale – Senior Design Engineer

#### **Teesside University**

- Dr Kin Wai Cheah – Lecturer in Engineering – Technical Manager

#### **Aston University**

- Dr Katie Chong – Senior Lecturer in Chemical Engineering – Technical Manager

### **9.2.1 Project oversight and governance.**

The BG2 project will be led by Dr Martin Taylor, University of Hull. Tobe Onwunaje, Jesmond Engineering will assume the role of Project Management Officer to facilitate project governance in the form of KPI tracking, progress reporting, chairing progress meetings and assisting the lead on ensuring that deliverables are kept on track. By splitting project oversight across two partners, we can ensure that Phase 2 as a much larger project can be completed as smoothly and to the same quality as Phase 1 was. As the project is 4x as long and of much higher value, the number and scale of deliverables will be much larger. The assigned Technical Managers will control their own work packages and subsequent deliverables, this provides accountability for all partners. In the case the project lead not being available or away, Simon Walker, Jesmond Engineering and Dr Peter Hurst, BDC will jointly lead.

### **9.2.2 Reporting**

Following Phase 1, the same meeting and reporting regime will be continued. This will include a formal project “catch up”, every two weeks for 1 hour. This provides time for the Lead to feedback on any BEIS of Management Officer information and steer the project. The team then goes through each work package to speak of progress with the use of slides. These slides are retained with the meeting minutes for reflection.

### 9.3 Evolving from Phase 1

For the effective development and delivery of BG2 (Phase 2), the team will not only construct and operate the Bluegen Demonstrator system to produce sustainable H<sub>2</sub> from a variety of waste streams, Phase 1 highlighted key areas for innovation such as:

- Tar reforming catalytic systems for enhanced hydrogen yield.
  - Embedding a catalytic package that can operate **Equations 1-4** beneficially
- Augmenting Bluegen chars into effective water remediation devices, this will enable water screening and close the BG2 cycle, preventing water from being wasted or requiring sustained water supplies.
- Diversification of feedstocks, Phase 1 effectively used two feedstocks, Phase 2 would seek to substantially expand this scope to increase supply options and therefore hydrogen production.
- The use of dilute nitric acid (1-5%) in water for increasing metal removal during leaching, for the case of Na, generating a salt product that can be sold/exported as a fertilizer, subsequently giving back to the land.
- Supply chain and logistic analysis for the effective use of a variety of waste feedstocks – an expansion of the current TEA.
- A higher precision LCA and TEA, accommodating the whole process, feedstocks and pre-treatment options.
- A deeper CFD analysis to focus on the feedstock processing aspect of Phase 2

Core planned activities, as designated by individual work packages are presented in **Annex (B)** along with timeframes, expanded objectives and Phase 2 deliverables:

- **Work package 1** – Construct, Commission and Demonstrate BG2
  - Objective 1 – Source core gasifier as an off the shelf item
  - Objective 2 – Assemble BG2 and integrate the core modules (**Figure 2**)
  - Objective 3 – Leak and safety assessment of BG2
  - Objective 4 – Operate the gasifier, begin stress tests for H<sub>2</sub> production
  - Objective 5 – Sustained testing period, 1 kg/h feedstock consumption
  - Deliverable 1 – A log of energy consumption, feedstock usage, producer gas composition, CO<sub>2</sub> separated and quality of products
  - Deliverable 2 – A complete demonstrator process with technical report
- **Work package 2** – Continuous development of lab scale system for actionable data and operational parameters for BG2.
  - Objective 1 – Increase reactor capacity to 3 g and conduct gasification of Phase 1 samples, using the complete feedstock (full size range)
  - Objective 2 – Investigate the effect of low cost heterogenous catalysts on tar reforming reactions – removing the tar trap, increasing H<sub>2</sub> production
  - Objective 3 – Assess the effect of dilute acid (1-5% HNO<sub>3</sub>) in water washing and its effect on ash reduction across all feedstocks
  - Objective 4 – The implementation of Bluegen char products as water remediation devices – reducing water waste and closing the system.
  - Objective 5 – Feedstock diversification, investigate the applicability of a number of waste derived feedstocks as options for H<sub>2</sub> production with full feedstock characterisation.
  - Deliverable 1 – A brief report on the effect of acidified leaching on ash extraction.
  - Deliverable 2 – A manuscript on the use of improved gasification chars on water remediation
  - Deliverable 3 – A manuscript on the development of bifunctional catalysts for promoting H<sub>2</sub> production by reforming tars

- Deliverable 4 – A feedstock report on the application of various other locally sources biomass waste streams with gasification data
- **Work package 3** – Revision and continuous development and optimisation of the BG2 design with computational fluid dynamics.
  - Objective 1 – Individual module development as articulated in **Section 5.1**
    - Development of leaching system including geometry and impellor to reduce power and required leaching time, thermal analysis of the rotary drying system, optimising gasifier geometry to reduce non-uniform heat and mixing, enhancing the cyclone system to accommodate feedstocks of higher ash compositions.
  - Objective 2 – Continuous improvement of BG2 pinch points, optimisation of the demonstrator
  - Deliverable 1 – A full report on module development complete with both one phase and two phase CFD for lower cost and improving the run time of BG2 and its effect on H<sub>2</sub> yield.
- **Work package 4** – Expanded Life Cycle Analysis and Environmental Impact analysis of Bluegen
  - Objective 1 - Full LCA and sustainability analysis of the complete system, from cradle-to-grave
  - Objective 2 - Quantify the environmental impact of all stages of the hydrogen lifecycle, from feedstock cultivation to end user
  - Objective 3 – Investigation in socio-political impact and identification of how the system matches with the UN Sustainable Development Goals
  - Deliverable 1 – Carbon foot printing of sludge production and utilisation – are sludges a low carbon fuel source?
  - Deliverable 2 – A report on the socio-political impact of Bluegen
  - Deliverable 3 – A complete cradle-to-grave LCA of the Bluegen technology
- **Work package 5** – Expanded Techno-Economic Assessment and complete supply chain and logistics model
  - Objective 1 – A complete TEA analysis for the Bluegen process
  - Objective 2 – Energy Assessment of Bluegen, steering BG2 design for reducing consumption
  - Objective 3 – Supply chain and logistic analysis of Bluegen and potential sustainable feedstock options.
  - Deliverable 1 - A report on the energy consumption of Bluegen, indicating areas of impact for reduction
  - Deliverable 2 – A complete cradle-to-grave TEA of the Bluegen technology
  - Deliverable 3 – A full assessment of the Bluegen supply chain
- **Work package 6** – Commercialisation and stakeholder engagement
  - Objective 1 – Run planned stakeholder engagement events every six months to map interest and attract private investment.
  - Objective 2 – Liaise with stakeholders on the integration of Bluegen into their current waste utilisation process
  - Deliverable 1 – A report on stakeholder engagement after each event
  - Deliverable 2 – A commercialisation roadmap for progress post Phase 2

#### **9.4 Project Dissemination to the broader sector**

By using Phase 1 as a stepping stone and technology validation, Phase 2 will endeavour to disseminate findings and promote BG2 as a sustainable and viable option for the production of hydrogen from underutilized waste streams. This will include inviting industrial players to a series of planned Bluegen showcase events to be held at the University of Hull and Biorenewables Development Centre. To be held in Months 3, 6, 12

and 18 of Phase 2. This will allow the team to interact with the broader sector and link with potential stakeholders such as those mentioned in **Section 8** to establish a clear route to commercializing the Bluegen Technology.

### 9.5 Phase 2 - Project costing

Partner	Proposed costing	Reason
University of Hull	£900k	<ul style="list-style-type: none"> <li>Two full time postdoctoral researcher for two years (Inc. overheads, £320k)</li> <li>Project team labour (£25k)</li> <li>Research Assistant for one year (Inc. overheads, £60k)</li> <li>BG2 demonstrator system – bulk items (off the shelf), additional parts, components, heating equipment and onstream analysis (£437k)</li> <li>Project consumables (gases, chemicals, lab scale equipment parts, characterization services, £8k)</li> <li>Additional lab scale testing equipment (TGM, UV-Vis and Ion Chromatography, £50k)</li> </ul>
Biorenewables Development Centre	£500k	<ul style="list-style-type: none"> <li>Facility rental and amenities (rental of a nitrogen generator and air compressor over two years, £70k)</li> <li>Labour and overheads for a full-time technician and Lead technologist (£130k)</li> <li>BDC commercialization officer for two years (£70k)</li> <li>Sludge feedstock production throughout the project (£50k)</li> <li>Onsite testing of feedstock quality (£30k)</li> <li>Lab consumables (20k)</li> <li>BG2 development (£130k)</li> </ul>
Jesmond Engineering	£450k	<ul style="list-style-type: none"> <li>Project labour for full team (Inc. overheads, £163k)</li> <li>CFD software and HPC packs, £150k)</li> <li>Server and operating system (£20k)</li> <li>Aspen software (£100k)</li> <li>Computers for team (£2k)</li> <li>Rent and utilities (£15k)</li> </ul>
Aston University	£360k	<ul style="list-style-type: none"> <li>Two PDRA researchers (Inc. overheads, £320k)</li> <li>Project team time (Inc. overheads, £40k)</li> </ul>
Teesside University	£200k	<ul style="list-style-type: none"> <li>One PDRA (Inc. overheads, £160k)</li> <li>Project team time (Inc. overheads, £20k)</li> <li>Computer and software licenses (£20k)</li> </ul>

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## Annex 1 – Feedstock characterisation

**Table A1** – Proximate and ultimate analysis of 1-2 mm raw, leached and leached barley and wheat straw derived sludges, at three different NaOH concentrations and two hydrolysis residence times.

Feedstock	Time (min)	Moisture (wt%)	Volatile (wt%)	Fixed Carbon (wt%)	Ash (wt%)	HHV (MJ/kg)	C (wt%)	H (wt%)	N (wt%)	O (wt%)*	C/H ratio	C/N ratio	Calorific value (kJ/kg)	
<b>Barley Straw</b>	Raw	-	9.58	76.25	10.76	3.08	15.67	44.30	5.97	0.40	7.42	110.71	15.67	17.22
	Leached	-	5.06	83.60	10.41	0.88	16.71	47.30	6.15	0.10	7.69	460.25	16.71	19.96
	L 0.2 M NaOH	30	2.82	86.06	9.67	1.45	16.82	43.00	6.11	0.19	49.25	7.04	224.08	18.55
	L 0.2 M NaOH	60	1.36	83.99	9.96	4.70	16.58	45.30	6.71	0.03	43.26	6.75	1680.89	17.80
	L 0.4 M NaOH	30	3.76	83.76	9.65	2.93	16.45	45.40	6.81	0.17	44.69	6.67	259.81	17.45
	L 0.4 M NaOH	60	1.51	87.78	5.50	5.21	15.59	44.80	6.80	0.11	43.08	6.59	390.11	17.33
	L 1.0 M NaOH	30	1.96	84.50	10.94	2.59	17.02	44.60	6.72	N/D	46.24	6.64	-	16.98
	L 1.0 M NaOH	60	4.36	82.93	9.96	2.75	16.43	43.10	6.63	0.01	47.51	6.50	3243.04	17.17
<b>Wheat Straw</b>	Raw	-	8.98	76.24	10.96	3.48	15.73	43.80	6.27	0.22	6.99	198.23	15.73	16.90
	Leached	-	2.30	85.12	11.08	1.47	17.18	45.50	6.28	0.09	7.25	503.21	17.18	18.73
	L 0.2 M NaOH	30	2.11	85.72	10.44	1.73	17.04	46.20	6.51	N/D	45.56	7.10	-	19.01
	L 0.2 M NaOH	60	6.53	81.46	10.33	1.68	16.34	44.20	6.48	0.03	47.61	6.82	1308.47	17.01
	L 0.4 M NaOH	30	2.81	84.69	10.98	1.52	17.07	44.20	6.59	0.11	47.58	6.71	391.22	15.34
	L 0.4 M NaOH	60	2.52	85.31	10.74	1.44	17.09	46.50	6.89	N/D	45.29	6.75	-	18.08
	L 1.0 M NaOH	30	2.98	86.26	9.39	1.44	16.76	45.80	6.94	N/D	45.85	6.60	-	17.32
	L 1.0 M NaOH	60	1.51	86.74	10.24	1.51	17.13	44.20	6.61	N/D	47.86	6.69	-	17.25

L – Leached feedstock

HHV – Higher Heating Value, defined in equation 5

N/D – Not detectable

\*O (wt%) is calculated by the following equation  $O = 100 - [\text{ash}(\text{wt}\%) + C(\text{wt}\%) + N(\text{wt}\%) + H(\text{wt}\%)]$

$$\text{HHV} = (0.3536 (\text{FC})) + (0.1559(\text{VM})) - (0.0078(\text{ASH})) \quad (\text{Equation 5})$$

## Annex 2 – Laboratory scale testing

**Table A2** – Gasification reaction gas phase product mix (vol%) and overall reaction selectivity (wt%)

<b>Feedstock</b>	<b>CO (vol%)</b>	<b>CO<sub>2</sub> (vol%)</b>	<b>CH<sub>4</sub> (vol%)</b>	<b>C<sub>x</sub>H<sub>y</sub> (vol%)</b>	<b>H<sub>2</sub> (vol%)</b>	<b>Solid (wt%)</b>	<b>Liquid (wt%)</b>	<b>Gas (wt%)</b>
BS Leached Feedstock	44.15	39.26	10.43	2.02	4.15	17.84	32.33	49.83
BS 0.2 M NaOH 30 min	45.69	35.23	10.67	0.78	7.63	10.79	17.50	71.70
BS 0.2 M NaOH 60 min	41.17	30.00	8.09	0.85	19.89	7.66	17.03	75.31
BS 0.4 M NaOH 30 min	24.89	33.62	7.86	5.68	27.95	8.49	18.09	73.42
BS 0.4 M NaOH 60 min	49.69	28.44	7.19	2.50	12.19	10.73	8.86	80.41
BS 1.0 M NaOH 30 min	50.83	16.34	5.94	2.15	24.75	10.52	16.58	72.90
BS 1.0 M NaOH 60 min	42.83	32.35	6.80	2.21	15.81	12.01	14.17	73.82
WS Leached Feedstock	66.30	12.05	6.58	3.56	11.51	7.41	31.90	60.69
WS 0.2 M NaOH 30 min	32.86	51.64	7.75	2.11	5.63	37.60	18.87	43.53
WS 0.2 M NaOH 60 min	40.79	25.00	10.71	1.43	22.06	50.02	17.11	32.88
WS 0.4 M NaOH 30 min	40.60	28.68	9.95	1.57	19.20	10.80	17.08	72.12
WS 0.4 M NaOH 60 min	37.96	29.29	10.14	1.53	21.08	10.50	17.78	71.72
WS 1.0 M NaOH 30 min	41.44	26.82	8.33	1.29	22.12	11.59	16.70	71.71
WS 1.0 M NaOH 60 min	40.57	29.26	10.64	1.69	17.84	29.83	16.00	54.17

## Annex 2.1 – Laboratory scale testing – Graphical Analysis

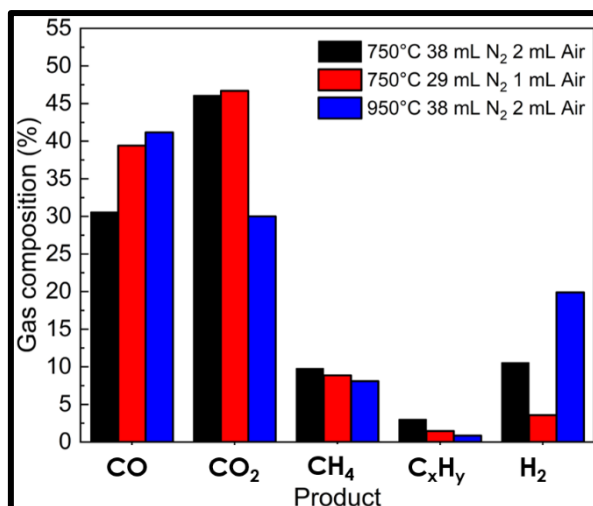


Figure A1: Gasification optimization, the effect of temperature and flow rate on the gasification of BS 0.2 M NaOH 30 min

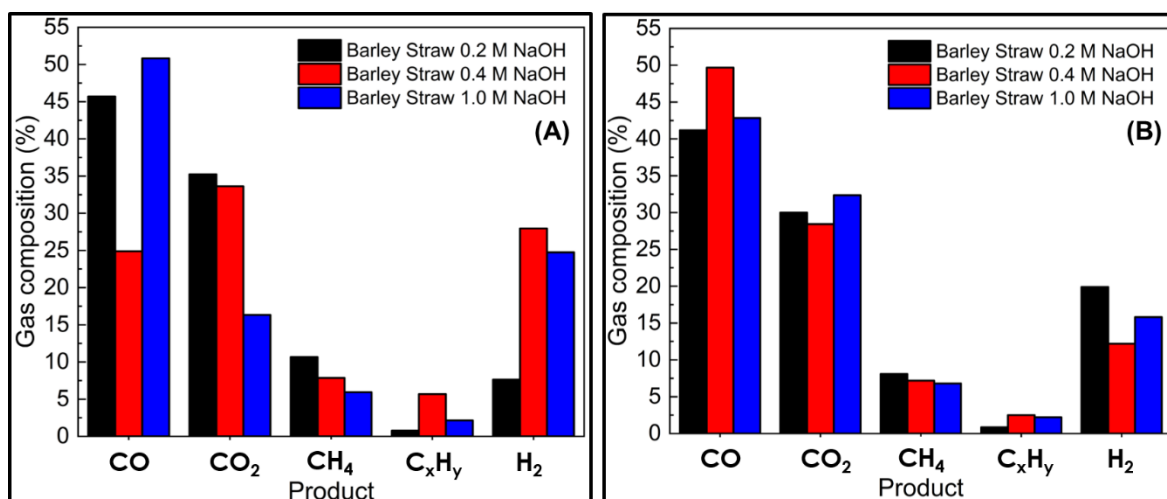


Figure A2: Gasification reaction product mix data for barley straw sludges (A) after 30 min hydrolysis and (B) after 60 min hydrolysis.

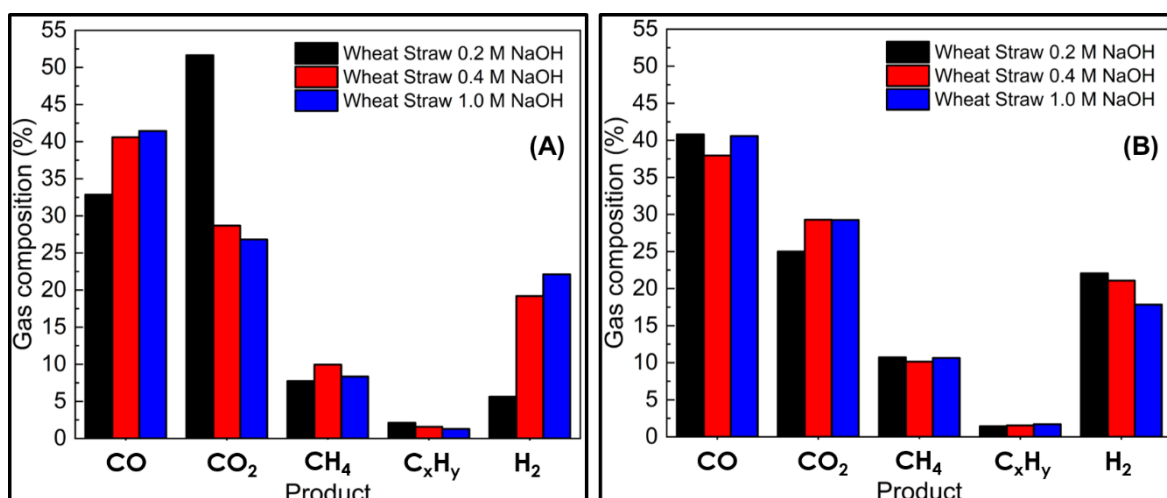


Figure A3: Gasification reaction product mix data for wheat straw sludges (A) after 30 min hydrolysis and (B) after 60 min hydrolysis.

### **Annex 3 – Detailed Engineering Design - Technical report**

The sludge is then brought to a stirred tank via a screw feeder. In the stirred tank, the waste stream is mixed with deionised water to achieve a  $10 \text{ g L}^{-1}$  ratio. The leaching tank stirring at 900 rpm to ensure water can diffuse into the waste and allow for solubilisation of the alkali and alkaline earth metals for a period of 2-3 h. Once this time has been reached, the sludge is omitted from the tank and pumped through into a filter, where the waste water and dissolved metals can be separated and the wet sludge waste is then passed through another screw feeder onto the next stage of the process.

Sludge is passed into the belt filter press after washing. The flow into the belt filter press is controlled via pinch valve as this prevents the system from being overwhelmed and allows for easier maintenance. Water pressed from the sludge is recycled elsewhere in the process. After the belt filter press, sludge is carried to an air rotary dryer via a screw feeder, chosen as it is effective at moving clumped material.

Sludge is passed through the rotary dryer, at  $60^\circ\text{C}$  to remove surface bound water on the sludge. Water vapour produced by the dryer is first passed through a cyclone separator to remove trace sludge residues. The removed particles are re-added to the sludge stream, where they continue on to densification. Water vapour produced from this process is cooled, stored and reintegrated back in the process. Dried sludge is now sent through a knife mill (blunt edge to limit size reduction) to break the biomass down into 1-2 mm majority particle size, keeping with the initial sizing regime. After the mill, the leached sludge is fed into a hopper before being sent into a mixer. This is done to help control the flow through the system. The sludge is mixed with LignoBond a lignin based commercial binding agent.

The sludge mixture is finally sent through a heated, flat die pellet mill ( $\sim 120^\circ\text{C}$ ) to convert loose sludge into a 10 mm pellet form and then immediately cooled in a heat exchanger to prevent break up. After cooling, pellets are periodically transferred into the gasifier by use of a rotary airlock valve to prevent air entering the gasifier and a screw feeder.

When Feedstock is dropped into the gasifier, the leached sludge is converted to syngas via gasification. The bed material is silica sand (quartz) and is fluidised by passing a gas mixture through it at a velocity that moves the sand particles upwards with a greater drag force (drag force is applied due to the velocity of the gas) than that which is applied to it from gravity.

When the syngas leaves the top of the gasifier it passes through a cyclone to remove any solid particles (ash and sand), this prevents potential clogging/damage to the system downstream and impure  $\text{H}_2$ . Sand and ash will be separated with a sieve separator where ash and sand are predicted to have a large enough size difference. Ash produced is stored in a hopper from which it can be sold off for other uses such as for aggregates. Sand is diverted back into the gasifier.

The system is continuously monitored by pressures sensors and thermocouples across the gasifier - this will assist in detecting any issues that may arise such as bed amalgamation, inefficient heating and to detect whether gasification conditions are being met. A furnace covers the upper portion of the gasifier to keep an even temperature profile and in conjuncture a Bubbling Fluidised Bed (BFB) is used.

Hot gas leaving the cyclone needs to be cooled down to increase energy density but kept above tar's dew point (200-250°C) so that tars do not cause clogging/fouling downstream. Syngas passes through a shell and tube heat exchanger where water is used as the coolant, and converted to saturated high-pressure steam after cooling syngas down. Cooled syngas is sent through a ceramic filter, where any residual ash is trapped and added to the collector. Ceramic filter candles are the most efficient method for particulate filtration. With all solid particulate has been removed, Syngas is sent on to be scrubbed of hydrocarbon-based tars.

A wet packed bed configuration is employed, utilising locally sourced vegetable oil (to be removed from the process once a tar reforming catalytic package has been developed), which flows down onto a bed of Iron Raschig rings in a random packing as this provides the best tar scrubbing efficiency and can easily be reproduced from lab scale to pilot scale and beyond. Oil, at 50 °C, is sprayed and flows down the scrubber, whilst gas enters from the bottom of the tower. Flow of oil and gas are counter-current to each other so the gas contacts as much oil as possible. Oil can be reused/regenerated which would make this a low cost, temporary option in comparison to water scrubbing methods.

The mass balance and subsequent experimental data have informed the decision to employ a High-temperature (HTS) and Low-temperature (LTS) Water-Gas shift configuration. Thermodynamic laws dictate that the WGS should be conducted at lower temperature to give a higher selectivity. However, lower temperatures inhibit kinetic rates and therefore more catalysts material would be required to achieve satisfactory CO conversion.

Now that CO has been partially converted, a relatively low process temperature can be used in order to fully convert CO. Syngas is sent through a heat exchanger to the lower the temperature for the LTS operating conditions. Steam for the HTS is produced in this heat exchanger.

LTS generally contain 30-33% copper (Cu or CuO) active species, with the rest consisting of aluminium and zinc oxides. LTS converts almost all remaining CO, with the process favouring a lower reaction temperature - shifting the equilibrium towards maximal H<sub>2</sub> production. Once the syngas has been passed through both reactors, it is sent to a condenser to cool the producer gas and remove water from the stream.

To separate H<sub>2</sub> from syngas, Pressure Swing Adsorbers (PSA) units will be used. This process makes use of H<sub>2</sub>'s volatility and affinity towards zeolites to produce a purified H<sub>2</sub> product stream. Firstly, water present in the stream is removed and the producer gas is compressed to between 10-50 bar, holding at constant temperature and sent into a dual reactor system that follows these four steps:

1. Adsorption: Impurities (gases excluding H<sub>2</sub>) are selectively adsorbed onto the PSA bed under pressure.
2. Depressurisation: Pressure lowered to just above atmospheric pressure so that the affinity of PSA bed lowered due to release of pressure from system so impurities can be released.

3. Regeneration: Adsorbent material is regenerated and the PSA bed is purged with H<sub>2</sub>. At this stage, the other vessel will begin its adsorption phase so the process can remain continuous.
4. Repressurisation: PSA bed is repressurised to original pressure to repeat the process and provide continuous H<sub>2</sub> generation.

H<sub>2</sub> is given off as a product stream while the off-gas stream is sent to further PSA units to recover any H<sub>2</sub> left in stream as well as N<sub>2</sub>, which can be compressed and potentially used as a coolant for CO<sub>2</sub> capture, storage and utilisation via Cryogenic distillation.

Cryogenic Distillation works on the premise that CO<sub>2</sub> has a relatively high boiling point in comparison to other gases present in syngas. Carbon dioxide has a liquefying point of -78.5 °C and the nearest gas that is present in the process stream is CH<sub>4</sub> at -162 °C, which means that desublimation of CO<sub>2</sub> can occur without affecting the rest of the gas stream. Gases entering into this process are compressed and require heat exchangers to cool down sufficiently for separation. Cooled & compressed gas mixture is sent to an expander, which causes a temperature drop and CO<sub>2</sub> will solidify. Remaining off-gases (besides any residual H<sub>2</sub>) have a liquefying temperature between -160-200 °C, enter the distillation column. Gases are cooled to separate different components in the order of N<sub>2</sub> (-196 °C), CO (-192 °C) and finally CH<sub>4</sub> (-162 °C). The higher the temperature, the lower it will come out of the column.

## Annex 4 – Phase 2 Demonstrator Bluegen Gasifier Design

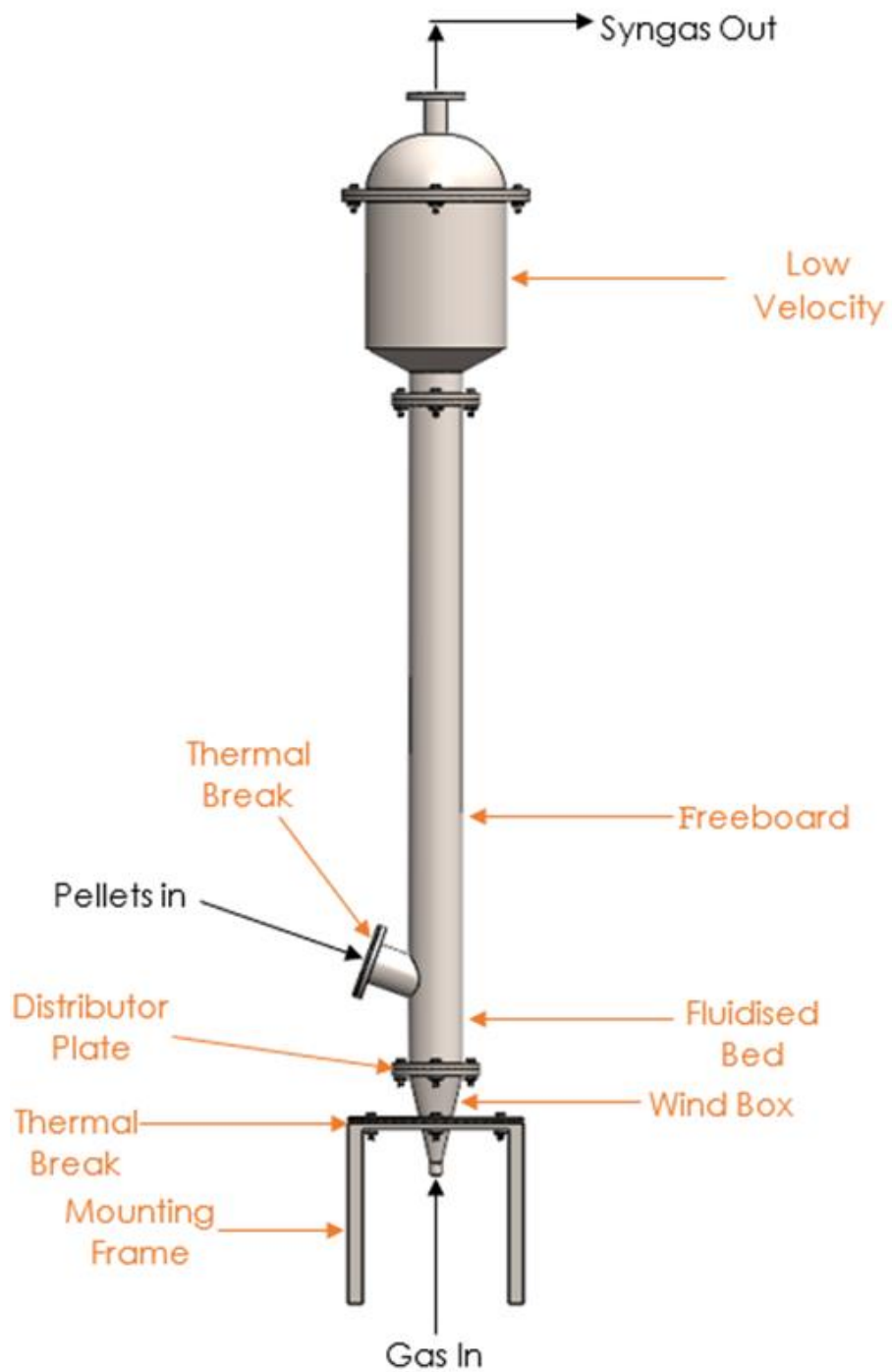


Figure A4: Gasifier reactor design to be integrated into BG2



Annex 4.1 – Phase 2 Demonstrator Bluegen Gasifier CFD analysis

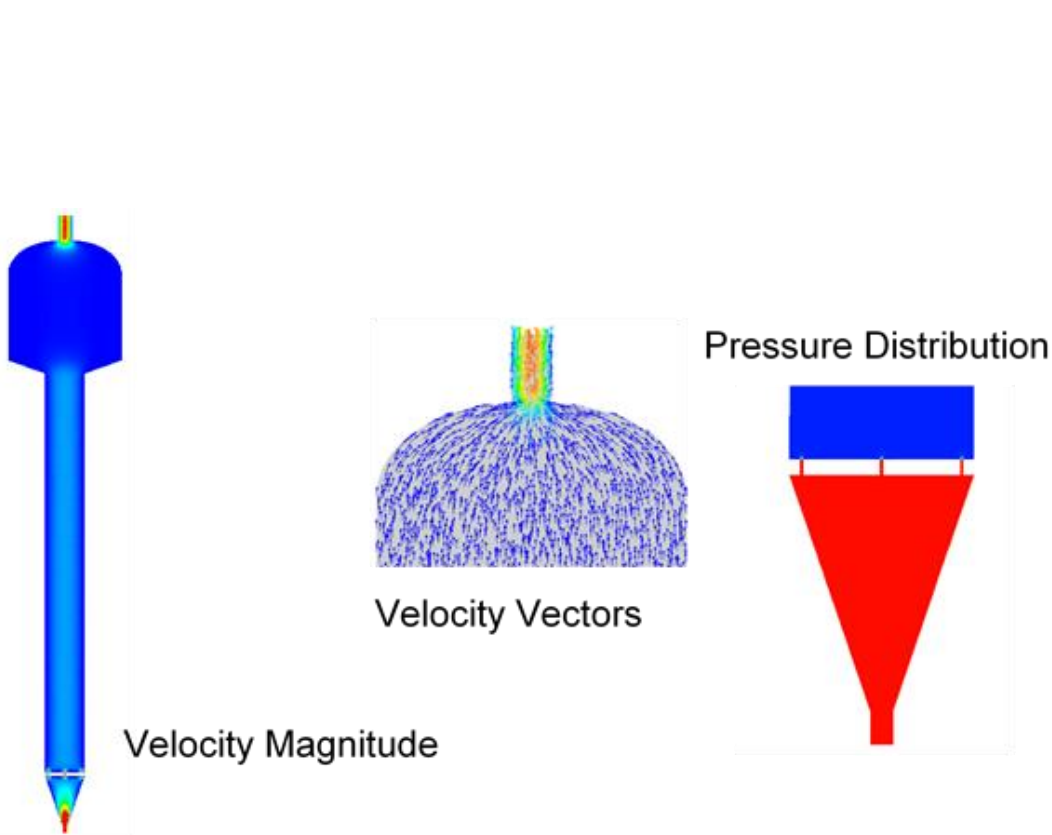


Figure A5: Single-phase CFD analysis of the proposed Gasifier

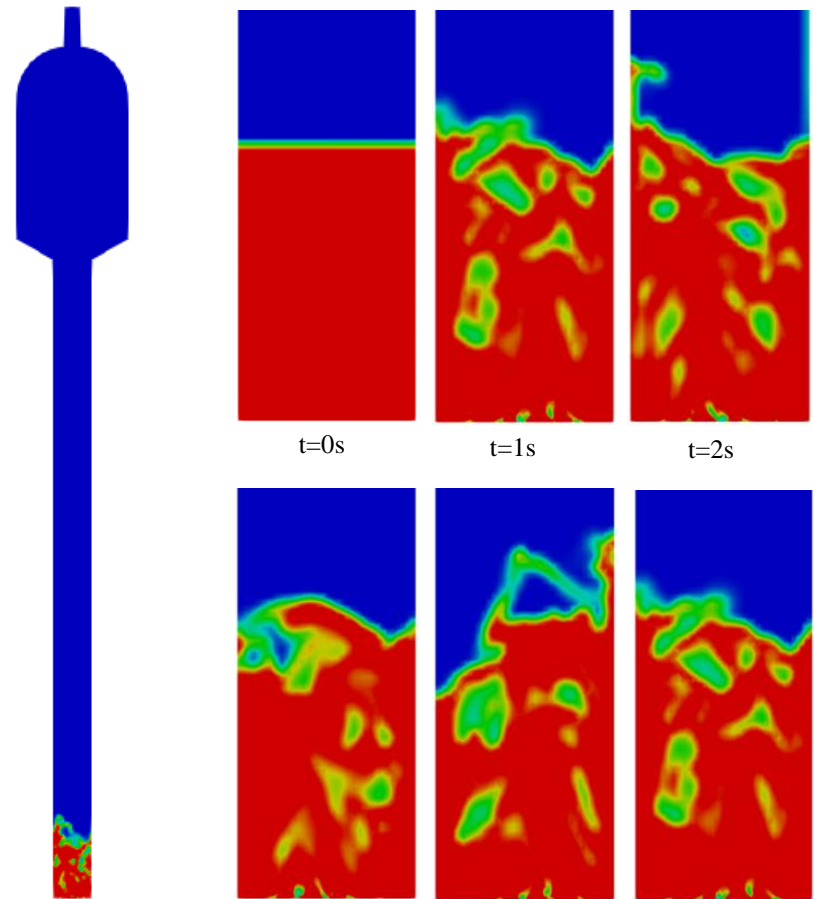


Figure A6: Two phase CFD analysis of the proposed Gasifier

## Annex 5.0 – LCA Aspen Simulation

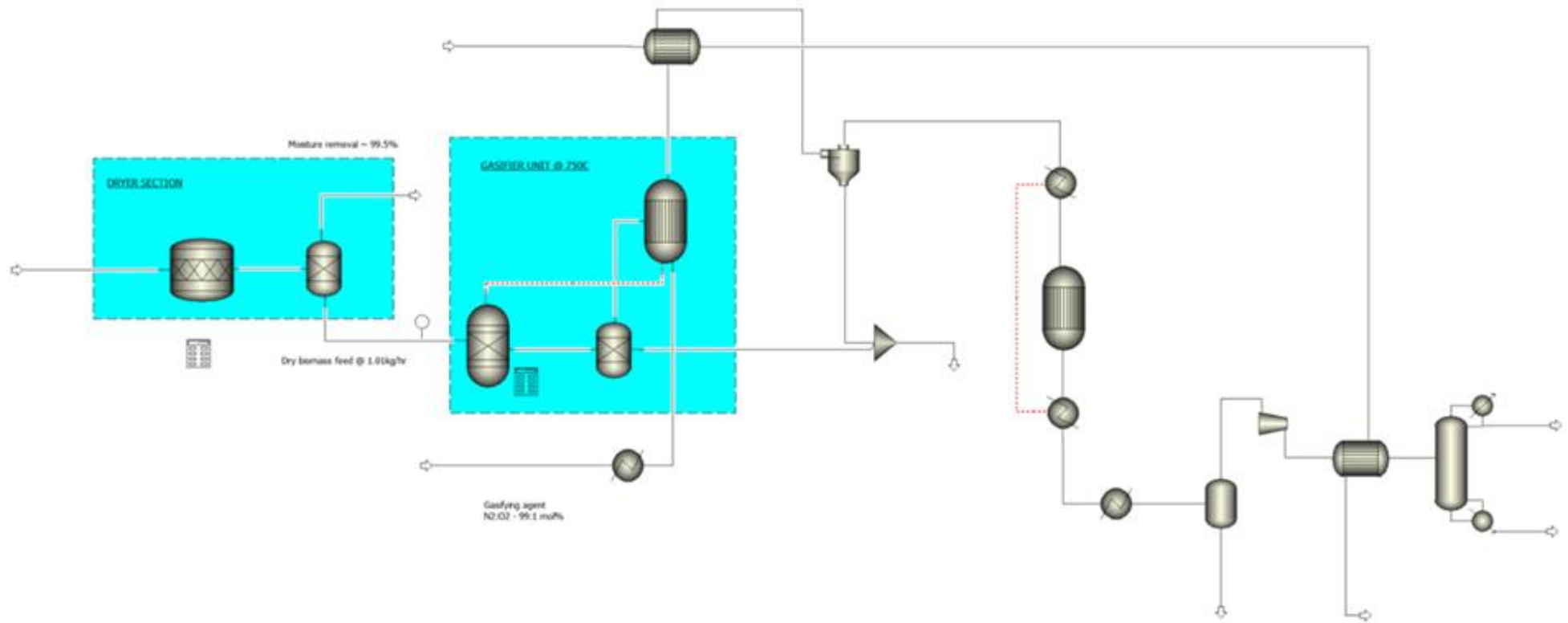


Figure A7 - Bluegen Aspen simulation

## Annex 5.1 – LCA Aspen Simulation

Table A3 – Feedstock data included into the LCA

Feedstock	NaOH (M)	CO (%)	CO <sub>2</sub> (%)	C <sub>n</sub> H <sub>m</sub> (%)	H <sub>2</sub> (%)	Gas (%)
Wheat	0	66.3	12.05	10.14	11.51	60.69
Wheat	1	41.44	26.82	9.62	22.12	71.71
Barley	0.4	24.89	33.62	13.54	27.95	73.42

## Annex 6 – A selection of the core LCA results

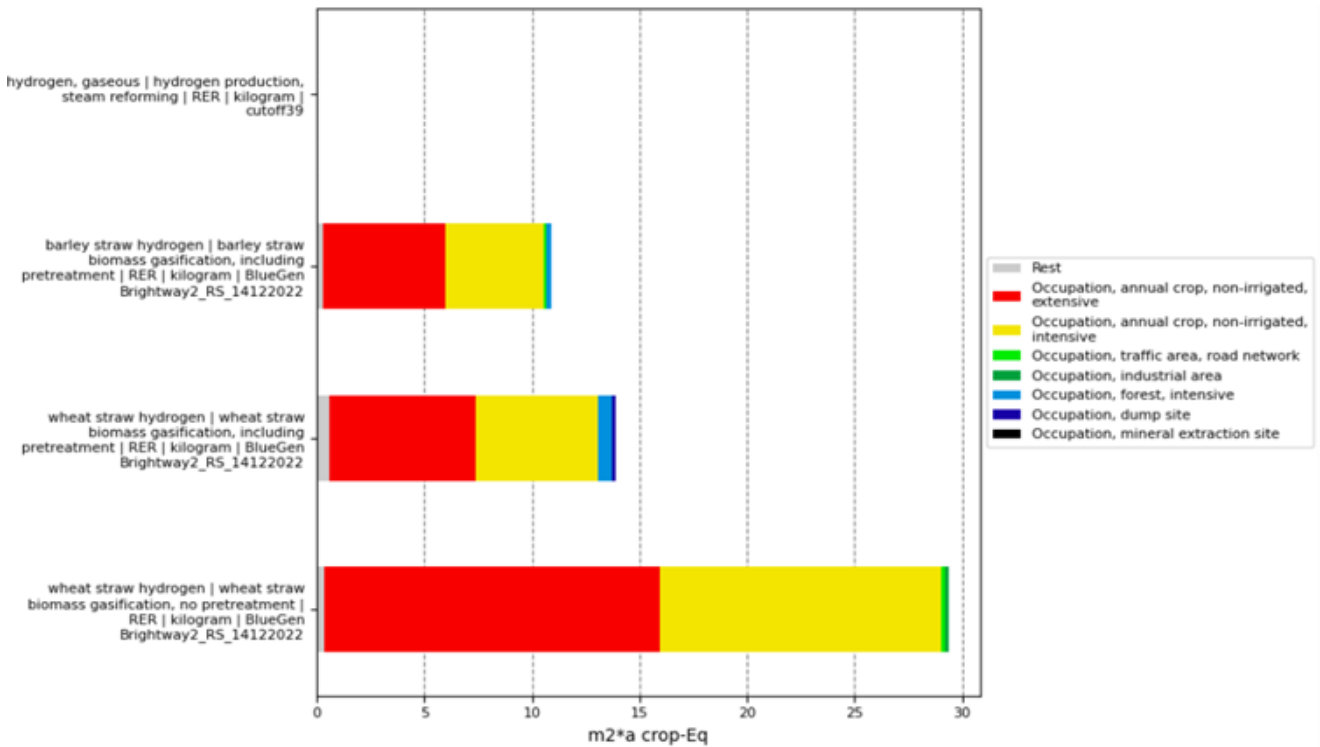


Figure A8 - Bluegen overall land use, considering the current feedstocks

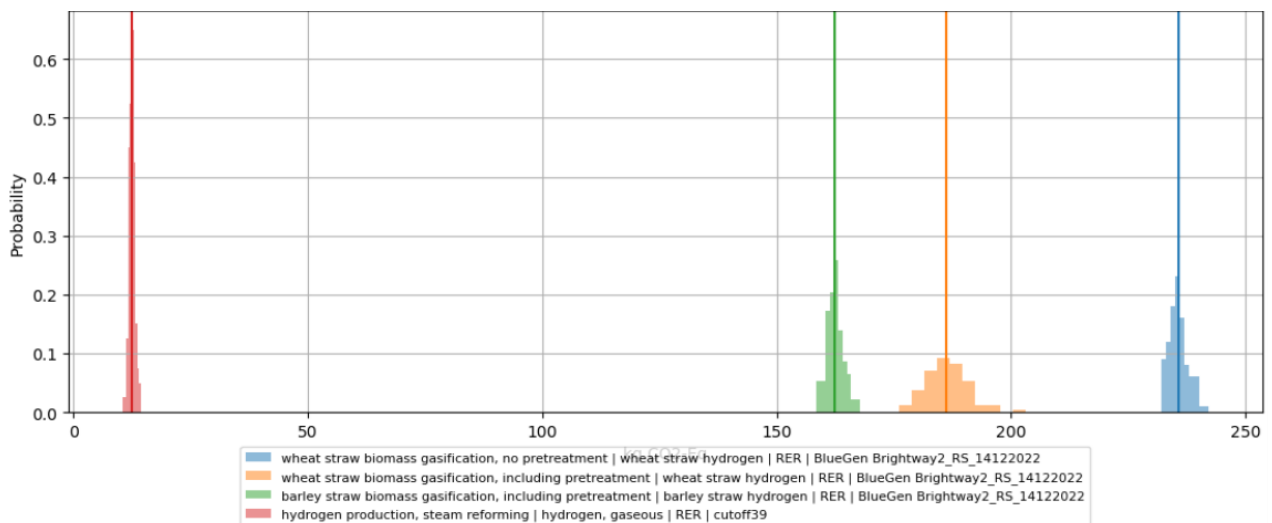
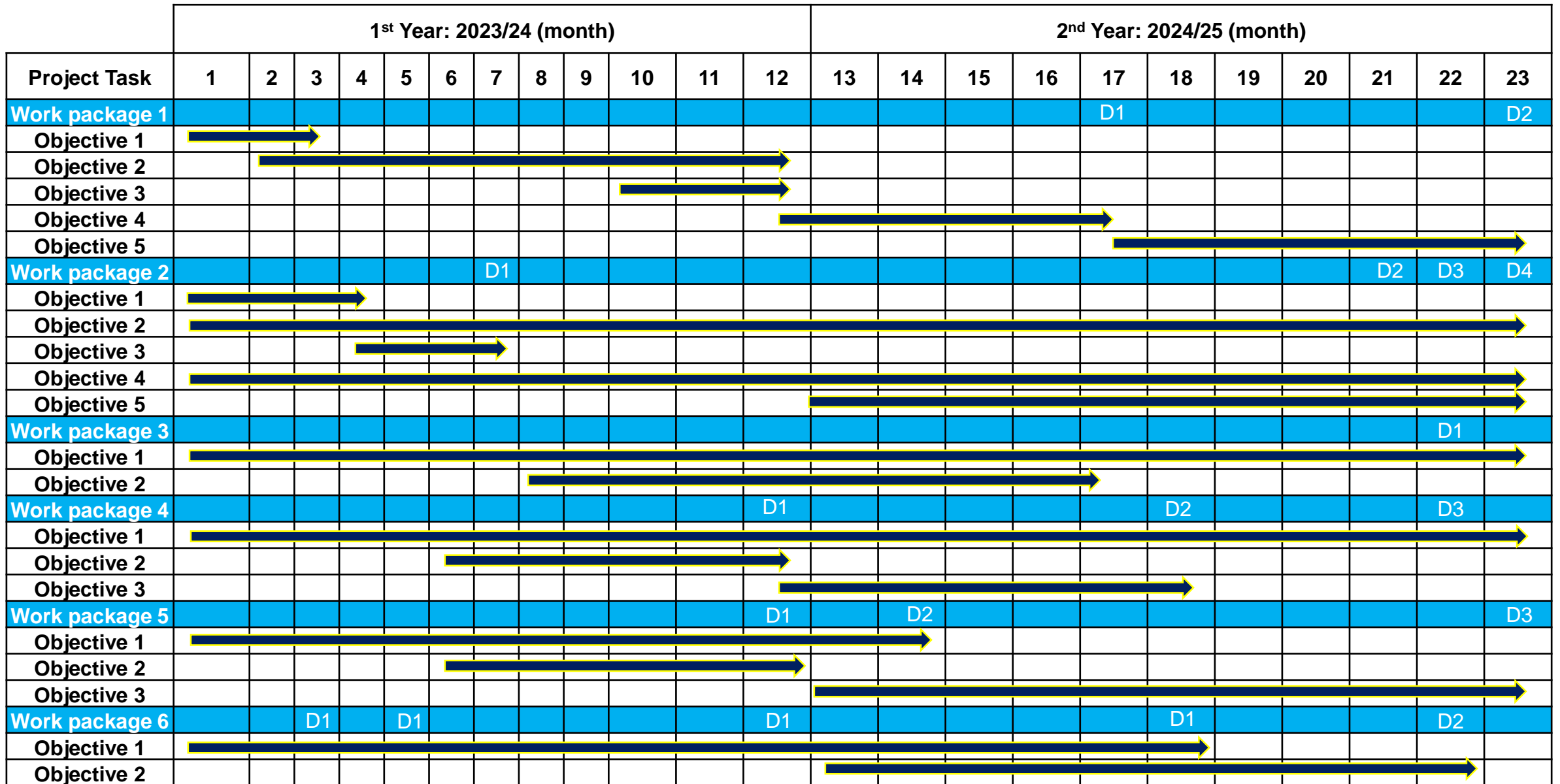


Figure A9 - Monte Carlo Analysis



# Annex (B) - Bluegen Phase 2 Timeline



D = Deliverable