Department for Business, Energy & Industrial Strategy

Cranfield University

Bio-hydrogen Produced by Enhanced Reforming (Bio-HyPER) Feasibility Study

Phase 1 Final Report

Project reference: H2BECCS107

A collaboration between:

Cranfield University · HELICAL ENERGY · Petrofac · GTI ENERGY solutions that transform · BIOENERGY INFRASTRUCTURE GROUP · OrigenPower

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Report for

Department for Business, Energy & Industrial Strategy (BEIS)
1 Victoria Street
London, SW1H 0ET

1. Executive Summary and Bio-HyPER Project Overview

Bio-HyPER is a collaboration between Cranfield University (lead), GTI Energy, Helical Energy, Petrofac, Bioenergy Infrastructure Group, and Origen, looking to demonstrate a state-of-the-art novel hydrogen BECCS process.

The project consisted of a feasibility study on the production of biomass-derived hydrogen with carbon capture and storage with a net negative CO_2 footprint. This feasibility study assessed the potential for integrating advanced gasification technologies with the HyPER pilot plant based at Cranfield University. The HyPER pilot plant utilises the sorption enhanced reforming (SER) process and is based on a technology developed by GTI Energy called Compact Hydrogen Generator. HyPER[1] is a multi-phase programme and has been supported by the Department for Business, Energy & Industrial Strategy (BEIS) since 2019 under the Low Carbon Hydrogen Supply programmes.

The Bio-HyPER feasibility study performed and highlighted:

- A detailed full-scale techno-economic assessment and carbon assessment of a representative Bio-HyPER process plant ensured the hydrogen product would achieve the UK's low carbon hydrogen standard and assist with reducing the levelised cost of hydrogen (LCOH) production and improve efficiencies associated with hydrogen BECCS technologies.
- Extensive modelling, design, and engineering around the components and modifications required for the HyPER pilot plant so that it would be suitable to operate with a syngas feedstock and manage contaminant concentrations effectively.
- This engineering and modelling conducted has set the project team up for Phase 2 which would advance the TRL of the novel SER biohydrogen conversion technology, which is inherently integrated with CCS.
- A market assessment of the process products (H_2, CO_2, heat and power, and limestone) and routes to commercialisation of the technology has been performed.

Within this project a levelised cost of hydrogen was determined within this project to be £5.58/kg-H_2 (£142/MWh HHV H_2) with an associated net CO_2e removed per H_2 generated to be -21 kgCO_2e/kg-H_2 (-179 gCO_2e/MJ-H_2) thereby confirming this hydrogen would achieve the UK's low carbon hydrogen standard and assist the UK in meeting the low carbon hydrogen production rates and net zero by 2050.

Overall, the project has been very successful in its delivery and has demonstrated a clear pathway for achieving a net-negative CO_2 impact hydrogen, which has the potential to be rapidly deployed across the UK to deliver on the UK's Net Zero and 10 GW of H_2 by 2030 targets. Initial commercialisation and deployment discussions are beginning and will be supported by testing data obtained during Phase 2, if successful in our application.

[1] https://hyperh2.co.uk/

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2. Introduction to Bio-HyPER

Bio-HyPER is a collaboration between Cranfield University, GTI Energy, Helical Energy, Petrofac, Bioenergy Infrastructure Group, and Origen, looking to demonstrate a state-of-the-art novel hydrogen BECCS process. The project was funded by the Hydrogen BECCS Innovation Programme which forms part of BEIS' £1 billion Net Zero Innovation Portfolio, which aims to accelerate the commercialisation of innovative clean energy technologies and processes through the 2020s and 2030s.

The overall objective of the Hydrogen BECCS Innovation Programme is to support development of technologies which will enable the commercialisation and deployment of Hydrogen BECCS at scale to achieve negative emission and hydrogen production targets as outlined in the UK's Sixth Carbon Budget covering greenhouse gas emissions for the period 2033-2037.

The Hydrogen BECCS innovation programme has been split into two phases. Phase 1 supported 22 projects to scope and develop a feasible prototype demonstration project to be run in Phase 2. Phase 2 will select the most promising projects from Phase 1 and support the proposed physical demonstration of their innovation. This Bio-HyPER project report relates to Phase 1.

The project consisted of a feasibility study on the production of biomass-derived hydrogen with carbon capture and storage. This feasibility study assessed the potential for integrating syngas representative of that produced within advanced gasification technologies with the HyPER project pilot plant based at Cranfield University. The HyPER pilot plant utilises the sorption enhanced reforming process and is based on a technology developed by GTI Energy called the Compact Hydrogen Generator. Bio-HyPER is a parallel technology development to HyPER and considers a different pathway for commercialisation and would be utilised in a different segment of industry.

2.1. Project WP overview

The feasibility study was broken down into four main technical work packages and had outputs associated with each WP:

WP #	Title	Overview	Key outputs
1	Market assessment and commercialisation plan	This WP evaluated the markets of each of the products of the process (H_2, CO_2, heat and power, and limestone) to identify key steps to commercialisation of the sorption enhanced reforming (SER) technology utilising a biogenic feed within the UK and beyond.	• Report on technology and product market assessment & UK commercialisation pathway
2	Process synthesis and integration	This WP sought to understand the key process differences between a natural gas and syngas feed system. We performed rigorous process modelling to understand what were the key changes that would need to be made to the pilot plant equipment which informed the work in the subsequent WP.	• Shortlist of advanced gasification technologies with engineering options • Report on syngas clean up connected to selected gasification technologies • Detailed process modelling of the pilot plant to inform the engineering design • Report on reforming catalyst evaluation
3	Engineering design and costing of pilot plant modifications	This WP aimed to understand the cost and implementation strategy for the changes to the HyPER pilot plant to enable it to operate with a syngas feedstock to enable the testing within Phase 2 of Bio-HyPER.	• Engineering drawings, equipment lists, and related documentation for the pilot plant modifications • HAZID/ENVID report • Cost estimate and bill of materials (AACE Class 2) • Standard operating procedure
4	Techno-economic and environmental assessment of a full-scale Bio-HyPER	This WP investigated the techno-economics and initial engineering for a full-scale version of Bio-HyPER.	• Full-scale plant techno-economic feasibility study report (AACE Class 4) • Environmental assessment report

2.2. Achievements

The project has been managed effectively by Cranfield University and has completed on time and to budget.

The key achievements of this project are:

- A design and specification of the key equipment required to modify the HyPER pilot plant to be suitable to utilise a representative syngas feed and operate as the Bio-HyPER plant.
- A safety, environmental, and financial assessment of the modified design informing a potential Phase 2 project. This work will directly inform and guide our application for (and work within) Phase 2 and has reduced the amount of work required to be undertaken during Phase 2.
- Detailed modelling of the Bio-HyPER plant informing the design.
- An evaluation of the literature to inform catalyst development for Bio-HyPER.
- Review and assessment of the potential markets and likely off takers for the technology, H_2, CO_2, heat, and sorbent.
- A full-scale assessment of the Bio-HyPER system considering techno-economics and environmental emissions.
- An expected commercialised levelised cost of hydrogen of £5.58/kg-H_2 (£142/MWh HHV H_2) but could be as low as £3.91/kg-H_2. This very cost is competitive considering the existing technologies and doesn't yet account for carbon cost savings a business would make by avoiding the release of CO_2.
- Calculated the associated net CO_2e removed per H_2 generated to be -21 kgCO_2e/kg-H_2 (-179 gCO_2e/MJ-H_2) thereby confirming this hydrogen would achieve the UK's low carbon hydrogen standard and assist the UK in meeting the low carbon hydrogen production rates and net zero by 2050.
- The public understanding via this report and the other dissemination activities noted below.

One of our key engagement events was at the Hydrogen and Fuel Cell Showcase held at Cranfield University on 20th September 2022. Around 300 people from across industry and academia came to Cranfield University to understand progress and aims of the Bio-HyPER project and visit the future Bio-HyPER pilot plant. The organisational representatives also engaged in a presentation and the project stall at the event. This activity was in line with creating and widening our supplier network and establishing links and developing skill sets in the UK to support local economic growth and business creation.

The Bio-HyPER project was featured in a dedicated article in POWER magazine[2] and NCUB[3] and an article is due to released soon by IChemE TCE magazine to highlight the project. A general press release about the project from Cranfield University[4] has also been posted online. The project was highlighted by the HyPER project's twitter account and website too.

[2] https://www.powermag.com/the-future-of-sustainable-energy-production-hinges-on-hydrogen/
[3] https://www.ncub.co.uk/insight/hydrogen-a-fuel-for-the-future/
[4] https://www.cranfield.ac.uk/press/news-2022/cranfield-awarded-funding-to-research-clean-hydrogen-generation-from-biomass

3. Technical and scientific basis to Bio-HyPER

3.1. Sorption enhanced reforming for clean hydrogen

The sorbent enhanced reforming process utilises a high temperature CO_2 capture material (i.e. CaO – lime) to remove CO_2 from the process gas which shifts the equilibrium position of the entire reactor to favour the production of more H_2 (and CO_2 – captured by the sorbent). The set of equations that occur are presented within Table 1 below.

Equation 1 is the standard overall steam methane reforming reaction which includes the water gas shift reaction (Equation 3). Equation 2 is the carbonation of the CO_2 sorbent removing CO_2 from the syngas. Equation 4 is the overall sorbent enhanced reforming process. Equation 5 is the reverse of the carbonation step, called calcination.

The use of syngas offers a unique benefit of the sorbent enhanced process as syngas has a much higher oxidised carbon content (i.e. more CO and CO_2 than CH_4), this means less reforming (Equation 1) is required and more water gas shift and carbonation occur (Equations 2 and 3) which are both exothermic reactions. The result is a highly exothermic process with significant amounts of high-grade heat generated, which can be collected and utilised to run a steam cycle.

Table 1. Process chemistry Sorbent Enhanced Reforming (SER).

Reactions and enthalpies	
$CH_4 + 2H_2O + 168.2\ kJ/mol \rightarrow 4H_2 + CO_2$	(1)
$CaO + CO_2 \rightarrow CaCO_3 + 178\ kJ/mol$	(2)
$CO + H_2O \rightarrow CO_2 + H_2 + 42\ kJ/mol$	(3)
$\mathbf{CH_4 + 2H_2O + CaO \rightarrow 4H_2 + CaCO_3}$ $\mathbf{\Delta \mathit{H} = -9.8\ kJ/mol}$	(4)
$CaCO_3 + 178\ kJ/mol \rightarrow CaO + CO_2$	(5)

Two main reactors are required for the SER process, they include a reformer/carbonator and a calciner (Figure 1). For a syngas feed heat is removed from the reformer/carbonator where the catalytic reactions take place. Solids (lime/limestone) are circulated between the two reactors using fluidised/entrained flow reactors.

The calcium looping process (equations 2 and 5) has been demonstrated in a 1.7 MWth facility in Spain and is being considered at multiple cement plants to decarbonise their operations. The steam methane reforming process is a commercially operating process. The combination of both reaction systems in one plant is being demonstrated within the HyPER project. This Bio-HyPER project focusses on the use of a biogenic syngas feed.

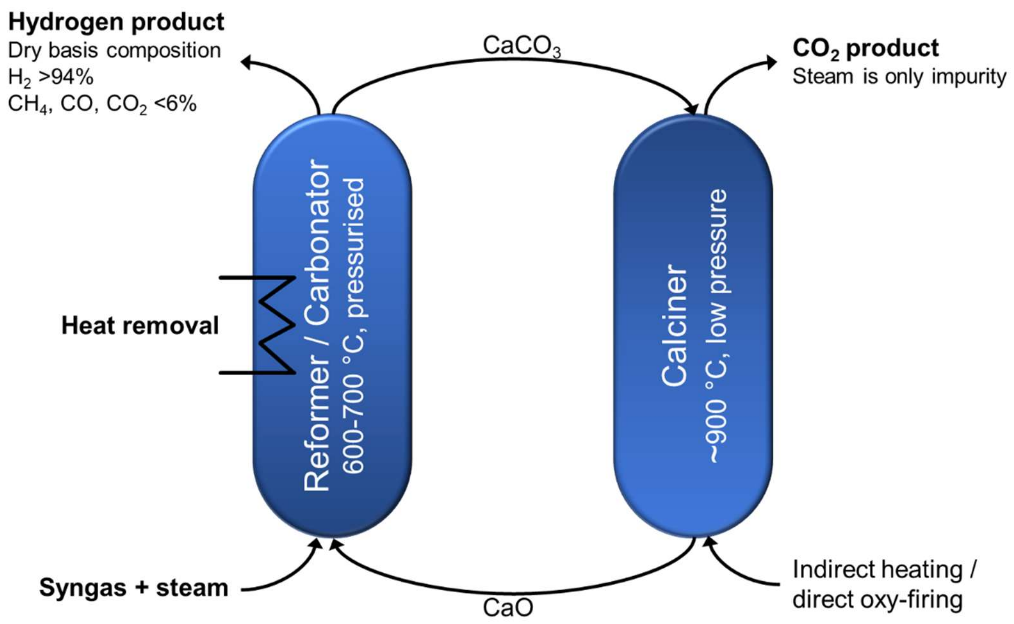

Figure 1. Process overview of sorbent enhanced reforming of syngas.

In the SER process, when natural gas is used as a feedstock, the overall heat balance of reforming and carbonation processes is approximately adiabatic, thus, no additional heat is generated. On the other hand, and the key advantage of utilising a syngas feedstock, when gasified biomass syngas is used as a feedstock, the exothermic carbonation reaction is dominant as the CO_2:CH_4 ratio is higher. This results in generating a significant amount of high-grade heat at 600-700 °C, which can be recovered and used for heat integration or power generation in a steam cycle. The generated heat is a function of CO/CO_2 contents in syngas mixture, which depends on the composition of biomass feedstock. A schematic of the HyPER/Bio-HyPER pilot plant is shown in Figure 2.

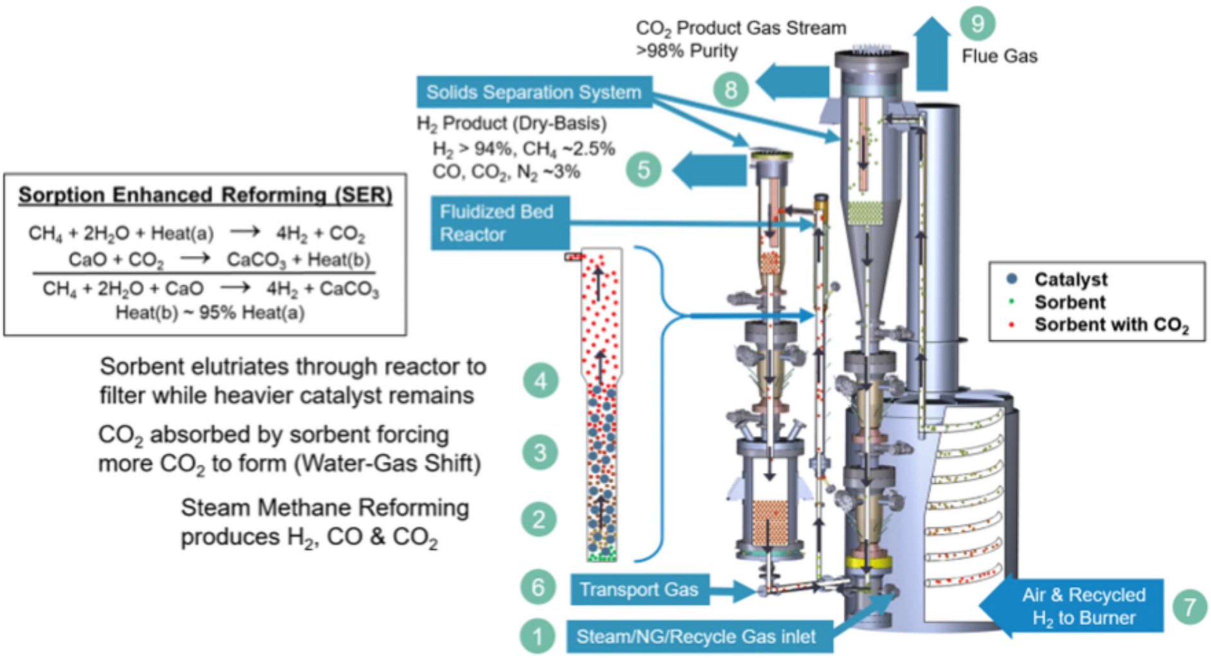

Figure 2. A schematic of the sorption enhanced reforming process when utilising methane as a feedstock (simplified from syngas), shown in a schematic of the HyPER/Bio-HyPER pilot plant located at Cranfield University.

3.2. How this innovation supports H_2 BECCS commercialisation

Low carbon hydrogen will be critical for meeting the UK's legally binding commitment to achieve net zero by 2050, and hydrogen generated via bioenergy has the potential to deliver negative emissions required to offset emissions from hard to decarbonise sectors. The innovation demonstrated within this project is that of a novel high temperature looping process which directly integrates CO_2 capture within the process and thus achieves a high efficiency and lower levelised cost of hydrogen. This process is called sorption enhanced reforming and has been developed by project partner GTI Energy for a natural gas feedstock within their Compact Hydrogen Generator technology.

This project's key innovation is to take the advantages of utilising a low carbon biogenic feedstock and convert it not only into hydrogen but also a valuable grade of CO_2 (suitable for market) as well as a high exergy heat steam. There is also potentially value to be had from the spent CO_2 sorbent as well, this is essentially limestone which could enter the feed for cement production.

This project involved key stakeholders in the UK market and are in key positions to exploit and commercially deploy the technology rapidly and at scale on advanced gasifiers.

4. Cost analysis and comparison of Bio-HyPER

The calculated levelised cost of hydrogen (LCOH) of a full scale (59 MW) FOAK plant is £5.58/kg-H_2 (£142/MWh HHV H_2, in 2022) with a range of £3.91/kg-H_2 and £8.37/kg-H_2 (based on the limits of the AACE Class 4 estimate).

This cost is competitive to competing H_2 production technologies as it doesn't account for any savings made by carbon credits for sequestering the CO_2 or the avoided cost of not emitting CO_2. The real value being demonstrated here is if a company/government was considering offsetting emissions to achieve net zero, then in many cases Bio-HyPER would be more economical compared to utilising direct air capture or other Greenhouse gas removal technologies and would produce value from its H_2 and heat products. Of course, it should be noted that locational and policy factors will play a part in any decisions made.

The LCOH presented here cannot be directly compared with that in the H_2 production cost report produced for BEIS in 2021 as there are several key differences in the baseline metrics applied, which make the H_2 product produced by Bio-HyPER appear to be more expensive compared to those in the report but are also more accurate. The differences include:

- We applied a bottom-up approach, identifying all equipment costs and industry best estimates for scaling factors, produced by project partner, and multinational EPC organisation, Petrofac and working to AACE cost estimation standards, whereas BEIS appear to have used a literature review methodology.
- A contingency was applied in our costs.
- The plant lifetime was assumed to be 25 years as opposed to BEIS utilising 40 years.
- Carbon price/credits were not accounted for in our calculations.
- This cost is for a first of a kind (FOAK) plant.
- We assumed compression of the H_2 and CO_2 up to 80 bar.
- We applied a different discount rate to BEIS.

5. Carbon assessment of Bio-HyPER

5.1. Carbon assessment for a full-scale plant

The key metric for this carbon assessment is to quantify the net CO_2e emitted per unit of H_2 generated, but other environmental aspects were also described and quantified (where possible) including emissions, effluents, solid waste, and eco/human toxicity.

The work conducted in this project has demonstrated the process will achieve a 100% CO_2 capture rate from syngas production, this will be captured and sequestered. The H_2 stream will be fed through a hydrogen purification package to meet the H_2 purity spec required, with this H_2 being routed to compression and export and the side product CO_2 routed towards compression and export.

The scale of the commercially operating plant was assumed to be commensurate with the small-scale plant capacity mentioned in the BEIS Summary Report of Advanced Gasification Technologies - Review and Benchmarking. This is equivalent to 59 MW or 13,000 tonnes per annum H_2 production equivalent from the facility. Accounting for about 93% availability, this results in a commercial scale capacity for the plant at 40 tonnes per day of net negative hydrogen product. Feedstock rate will be commensurate with this scale of Biohydrogen production.

The planned capacity of 40 tonnes per day of H_2 at 93% availability will generate 13.6 ktonnes of H_2 per year. Annual CO_2 removal would be approximately 291 ktonnes leading to CO_2 footprint of -21.4 kgCO_2e/kg-H_2 (-178.6 gCO_2e/MJ-H_2).

5.2. Other considerations

Within this report and the project, we have considered the choice of feedstock to be a biomass pellet adhering to the composition BEIS Summary Report of Advanced Gasification Technologies - Review and Benchmarking. There are of course uncertainties associated with biomass availability depending on the location of the plant's deployment and variability over a year/season. These variabilities will lead to variability in the performance of the plant, however, this deviation from the baseline is not expected to be significant and would be within the plants standard error margin.

As per BEIS guidance, there are net positive emissions related to handling the biomass feedstock from production to the consumption site. These are specified by DEFRA as part of 'GHG Conversion Factors for Company Reporting' for 2021[5]. These emissions factors contain values for N_2O and CH_4 emissions (which are not absorbed during growth) and have been added to the other emissions sources. Associated with this there is uncertainty associated with the direct and indirect land use changes due to the growth of the biomass.

Considering the CO_2 transport and storage, it has been assumed within this project that the CO_2 enters a local network pipeline, and this is the boundary limit of the plant, but it is expected this CO_2 is stored/utilised such that the CO_2 is permanently prevented from entering the atmosphere. Fugitive emissions and emissions related to those within Scope 2 and 3 were not considered as part of this project.

[5] https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2021

6. Detailed engineering design for Bio-HyPER

6.1. Phase 1

6.1.1. Overview

The Bio-HyPER project is a parallel development to the current HyPER project and will utilise the 1 MW pilot plant constructed originally for the HyPER project. Bio-HyPER will be designed to assess the performance of the sorption enhanced reforming (SER) technology with a syngas feed. To enable the rapid testing of multiple different syngas feed compositions and ensure operability, synthetically produced clean syngas will be utilised instead of coupling the SER with a gasifier directly.

The basis of the design is driven by ASPEN simulations of the Bio-HyPER process, with the intention that the operating constraints of the existing steam and feed systems, as well as the calcium looping system, are retained. The engineering design is therefore limited to the modifications necessary to store, convey and control a range of synthetically generated syngas blends, made by including varying proportions of H_2, CO, CO_2, C_2H_4 and C_2H_6 components into a mixer, that will be injected into the existing feed circuit upstream of the reactor. The other modifications to the plant will feature a new air-cooling system to manage the exothermic reaction inside the reactor when utilising certain syngas feedstocks.

The feasibility study has demonstrated that no new or high-risk technologies are required to facilitate the modifications of the plant for Bio-HyPER. Existing off-the-shelf technologies can therefore be used, alleviating any technical risks in sourcing, or developing new technologies to accommodate Bio-HyPER.

6.1.2. Design Conditions

The Bio-HyPER operating conditions are based on satisfying the requirements defined by the ASPEN modelling, with four variables influencing the design of the plant modifications.

- Reactor pressure levels — 3 off: at 4 bara, 11 bara and 17 bara
- Reactor temperature — from 400 to 700 °C
- Molar Steam:Carbon ratio — Fixed at 3:1
- Reactor feedstock composition — See Table 2

The reactor pressure and temperature fall within the design envelope of the proposed SER, however a feedstock composition range has been developed to reflect the expected synthetic clean syngas compositions from most advanced gasification technology (oxy-steam gasifier), the baseline is illustrated in Table 2. The design of the gas injection system is based on the below range of gases being blended together.

Table 2. Syngas composition operating baseline.

Gas	Composition	
H_2	41.0	mol%
CO_2	20.0	mol%
CO	26.0	mol%
CH_4	10.0	mol%
C_2H_4	2.0	mol%
C_2H_6	1.0	mol%

6.1.3. Plant description

The Bio-HyPER plant description will only focus on the additions necessary to convert the existing HyPER plant to accommodate a range of syngas blends as the feedstock. The plant modifications can be broken down into the following packages.

Gas injection comprising of:

- Gas storage
- Gas conditioning
- Gas blending
- Gas heating
- Gas injection

The simplified flow diagram (Figure 3) illustrates the process used to allow the synthetically-produced clean syngas to blend into the existing plant upstream of the reactor.

Figure 3. Simplified Bio-HyPER Gas injection flow diagram.

The high-pressure gas storage will comprise dedicated pure gas cylinders each holding one of H_2, CO, CO_2, C_2H_4 and C_2H_6. Natural gas/CH_4 will be sourced from the existing natural gas site feed. The larger storage vessels can be sourced from BOC or can be designed and manufactured to suit the plant requirements. Each storage vessel can be of double-wall design, where required, and will be fitted with safety relief and pressure regulation valves. The pure gas released from each storage vessel will be individually piped to its own dedicated gas conditioning package, where the final flow and pressure adjustment will be carried out using conventional valve control technologies.

The mass flow of each of the gases will be controlled from the plant PLC to match the targeted composition (set-point). This gas conditioning step allows the individual gases to be blended in a common gas mixing unit. The output from the mass flow meters will be summated and sent to the existing steam:carbon ratio controller to maintain the required ratio of 3:1. A modification of the existing steam:carbon ratio control's algorithm will be necessary to accommodate the additional flow I/O from these mass flow controllers.

The blended synthetic clean syngas then passes to a gas fired heater to preheat the gas. The blended gas will be injected into the steam/methane piping using a new piping injection manifold. The controlled mixed gas blend then picks up the required amount of CaO sorbent and flows into the reactor to carry out the reforming and carbonation steps. The gases and $CaCO_3$ sorbent exiting the reactor then pass through the existing gas-solid separator after which the gases will be analysed for composition and conversion efficiency. The $CaCO_3$ will flow into the existing calciner and return to the reformer/carbonator in the form of CaO, ready to absorb CO_2 again.

6.1.4. Plant layout

The plant footprint and utilisation of the available plot space is retained, with only a small amount of new equipment needing to be integrated in the existing HyPER facility. There are two primary drivers that define the plant layout:

a) Physical constraints of the existing facility, and
b) HSE gas cylinder storage guidelines for the safe storage of flammable and oxidising gases.

All HSE guidelines have been applied to locate the storage vessels on site in a safe position, and it is anticipated that specialist advice will be sought during Phase 2 to validate that the vessels are appropriately positioned and that any further safeguards needed are applied.

A floor mounted forced draft blower will be used to provide the necessary cooling air to the SER. The cooling air fan will be located beneath and within the footprint of the existing vessel's support structure. A small, blended gas heater is also introduced to pre-heat the synthetic gas from the gas storage vessels / cylinders. A detailed civils and structural interface review is anticipated to be required to confirm any additional loads on civils and structures, this will be carried out during Phase 2.

6.2. Phase 1 Feasibility engineering activities

Within Phase 1 the engineering has been divided into Process, Mechanical, Piping, Electrical, Controls and HSE categories. The engineering activities undertaken during Phase 1 of the H_2 BECCS programme provide the avenue to commence the detailed design engineering activities outlined in the next section.

6.3. Phase 2 Detailed engineering activities

The below engineering management process flowchart outlines the sequence of steps (Figure 4) to be followed throughout Phase 2 of the H_2 BECCS program for Bio-HyPER.

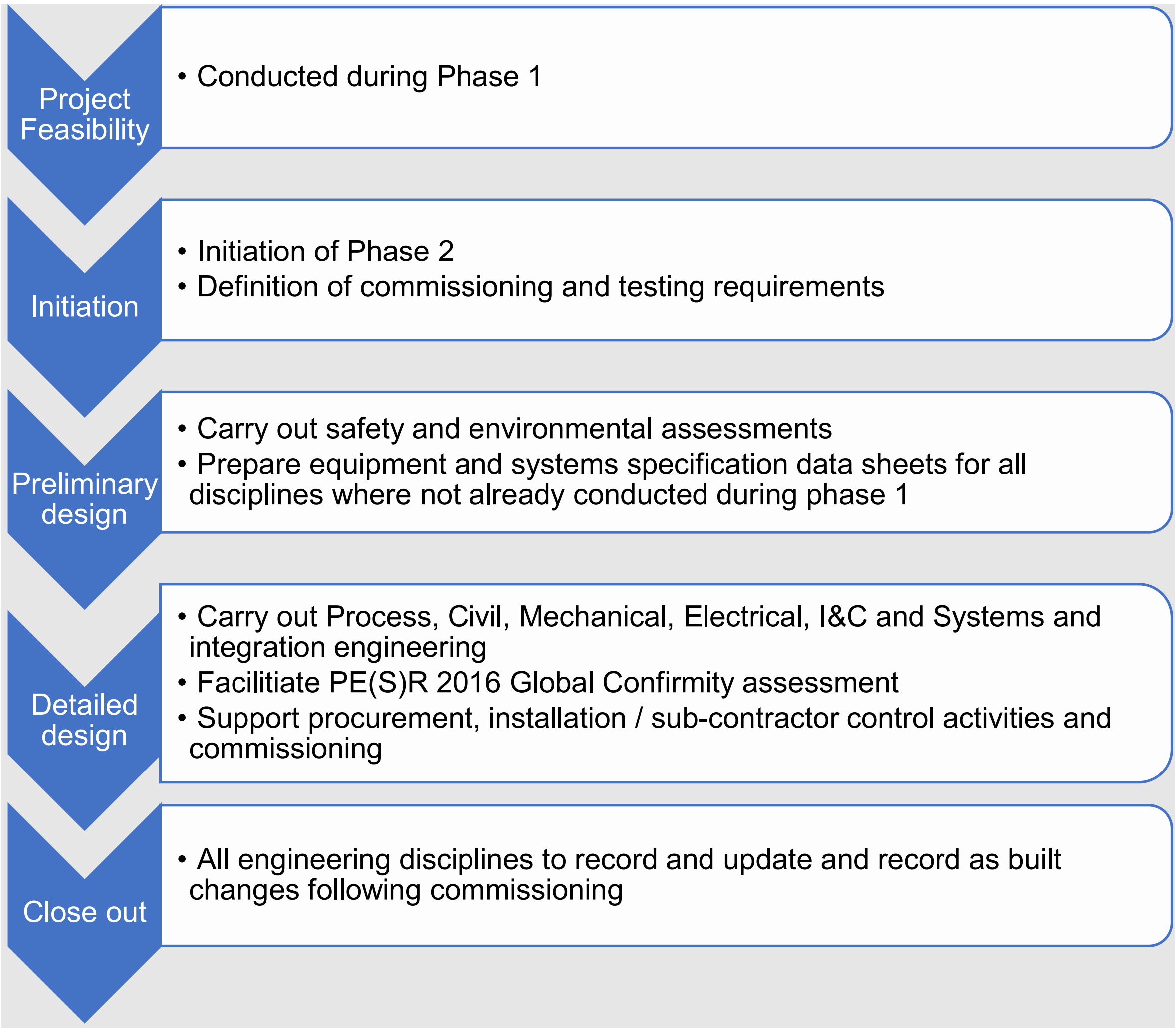

Figure 4. Phase 2 Engineering Management flow chart.

7. Testing plans for Phase 2

The testing plan for Phase 2 has the following objectives:

1. To demonstrate the technology's performance with a biogenic feedstock and the integrated heat production
2. Assess the commercial viability of the technology
3. To provide data to adjust/validate the Bio-Hyper model developed in Aspen Plus
4. To understand the impact of the parameters, such as the syngas composition, reforming pressure, and sorbent lifetime (linked to coking potential) on the process performance.

It should be noted that the compounds C_2H_4 and C_2H_6 will be present to represent the light tars expected to be produced from an advanced gasifier. Heavier tars and metals are being considered for incorporation as well to simulate alternative gasifier types but are not currently worked into the testing programme because within Phase 1 we have identified the most suitable gasifier type to be an advanced oxy-steam gasifier which has very low quantities of heavy tars.

These syngas compositions will be carried out at 4 bara and during day length tests. The effect of operating pressure parameter will be assessed at three levels, 4 bara, 11 bara and 17 bara, using one syngas composition, again in day length tests. The impact of the operation time on the process performance will also be studied over long time periods of operation to provide data on the process's reliability.

During all the tests, the following output measurements will be assessed: reaction performance, conversion efficiency, H_2 yield and purity, CO_2 capture rate, impurities such as tars and operability, and distribution of temperature and heat release.

To provide data for the techno-economic assessment of the process, the input utilities, such as synthetic syngas, sorbent, water, air and natural gas will be recorded. Besides the utilities, the process downtime has also an impact on the techno-economic performance of the process.

8. Project plan for Phase 2

8.1. How and where the Hydrogen BECCS solution will be demonstrated

The Bio-HyPER technology design, procurement, construction, commissioning, and testing will be completed at Cranfield University.

Within Phase 2 the project team will demonstrate the SER process at a MW scale in the existing HyPER pilot plant modified to use a representative syngas feed. We will utilise gas mixing capabilities to simulate various syngas compositions and potentially tars collected from a Bio-HyPER project partner's gasifier site. This will ensure the syngas feed is representative of real syngas from a gasifier but allows for greater control in operation and the ability to study a range of gasifier syngas compositions, furthermore it reduces the cost and complexity of the project.

The key activities to be performed within Bio-HyPER Phase 2 are:

1. To finalise the engineering of the reactor, and then construct and install it.
2. Install the new gas mixing system, including: 1) bottled gas for permanent gases, 2) additional pipelines, valves, and instrumentation, 3) tar vaporisation, 4) control system modification and retraining.
3. Measure and analyse the heat flows and sorbent recirculation rates required to achieve optimal hydrogen yield and consistent performance.
4. Develop the reformulated catalysts and test within the reactor to evaluate H_2 production, tar cracking and coke formation.
5. Several hundreds of operating hours with various syngas feed compositions to characterise the performance of the SER process. The testing programme will be defined within Phase 1.
6. To update the process models using test data to validate and provide integrity to the outputs and ensure ability to meet H_2 standards.
7. Refine the techno-economic case and the market opportunities within the UK.
8. To disseminate the results of the project via a public report and present the project at relevant industrial and academic conferences (including the IEA HTSLCN meeting). The HyPER website will also be modified to showcase the Bio-HyPER project alongside the HyPER project. A separate twitter account will also be generated for wide reaching impact and engagement.

There will be minimal work required for site preparation and a lifetime assessment will be conducted during the facility requirement review to ensure the reliability of some components used on the HyPER Phase 2 pilot plant for this demonstration phase. The engineering documentation prepared in the feasibility study will be used to develop the requirements for the Phase 2 demonstration, will provide the basis for the constructability development of the Bio-HyPER plant. Procurement activities will involve some suppliers engaged for the HyPER Phase 2 project where requirements were adequately met, and effective relationships established.

Construction and procurement activities will be conducted in parallel to adequately manage longer-lead item delivery within reasonable timelines. We will conduct a series of hazard elimination reviews to ensure that any construction and retrofitting risks are identified and plans put in place to mitigate or eliminate them. Phase 2 will also validate the proposed performance and operability of the Bio-HyPER plant. The preliminary detailed engineering design and the HAZID / ENVID study report will be developed, and a HAZOP workshop conducted before the design is finalised.

The commissioning and testing phase will involve testing campaigns, while using varied operational parameters to validate the operability of different components and lead up to the demonstration of the overall system functionality. Test results will be recorded, and proposed outputs used to validate the modelling.

8.2. Timelines for deliverables

Bio-HyPER Phase 2 H_2 BECCS project will have five phases. The project phases and timelines are presented in Figure 5 below.

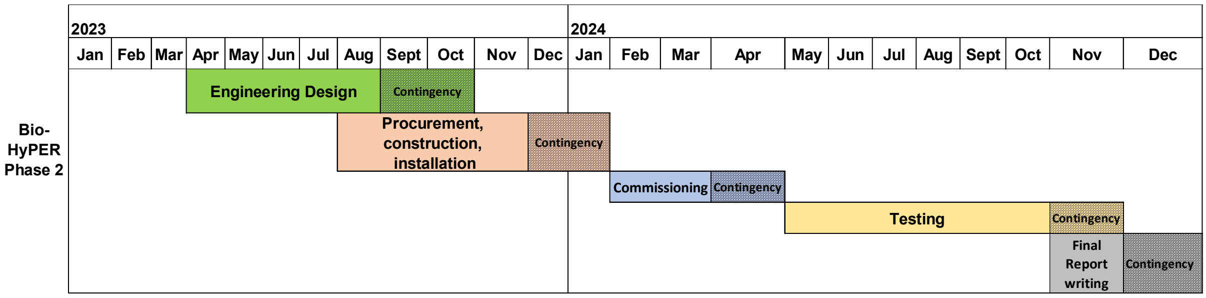

Figure 5. Bio-HyPER Phase 2 summary project plan.

8.3. Risks and risk management

The risk register is presented as an attached document. In the initiation phase of the project, the risk management plan will be developed and included in the project management plan, this will then be updated on a weekly basis throughout the project.

8.4. Project oversight and governance

The project will be led by Cranfield University and a steering committee/group was appointed to oversee the project delivery and governance. Throughout the duration of the project, the schedule and cost performance indices (SPI and CPI) will be used to track delivery performance and direct actions to proactively address any anticipated variances. WPs will be led by specific partners, with support from others in the consortium, aligned so that technical expertise is fully utilised.

Representatives from a range of industrial end users will be invited to join the Industrial Advisory Board (IAB), which ensured that progress and developments within the project are aligned with technical and market requirements.

8.5. Plans for disseminating the demonstration results and key learnings to relevant industry sectors

There are existing plans in place to disseminate the demonstration results and key learnings from this project including: IEAGHG 9th HTSLCN Meeting 14-15th March 2023, 4th UK CCUS & Hydrogen Decarbonisation Summit: Projects & Innovation. Stakeholder engagement, dissemination and knowledge transfer activities will be built upon from the activities engaged in Phase 1.

The project will continue to engage with organisations within our supply chain, as we have throughout previous HyPER Phases so far. These activities will continue growing UK jobs and skills in this sector. These networks and established links and skill sets in the UK will be vitally useful as we develop the first commercially operating facility. We have utilised suppliers who have expressed interest in supporting the development of the technology, e.g., by making improvements based on the pilot operation, thus building the knowledge and supply chain for future scales of operation.

The integration of gasification with SER will inevitably lead to new market opportunities and product development within the UK to address our supply chain needs, which would not occur without BEIS's investment. The technology development in this project will also support bringing new processes to market i.e., calcium and chemical looping. As a part of the project, we will record the number of business interactions and commercial engagements and report the value to the UK created back to BEIS.

9. Commercialisation

9.1. Overview

The Bio-HyPER is a H_2 BECCS process and is based on the core process of Sorbent Enhanced Reforming with inherent CO_2 capture in conjunction with Advanced Gasification Technologies to provide low-cost negative-carbon hydrogen production from biomass feedstock.

In the commercialisation pathway, it was identified that the key initial markets for the combined advanced gasifiers for the Bio-HyPER technology is new build gasifier projects in the UK. Although there is potential for retrofitting existing gasifier projects, it is thought that the high level of modification of these plants would be cost-prohibitive when compared to the cost of completely rebuilding these plants as new projects. The majority of the existing gasifiers are designed with air gasification for the end purpose of generating electrical power. These plants are extremely inefficient, converting biomass with efficiencies ranging from 20-30%. There are others that produce heat and power and others that just produce heat, both of which can be highly efficient (>80%) if all the heat is used. As many of the existing gasifier plants will have an end of life between 2025 to 2035 due to the expiry of ROCs and are unlikely to be profitable at the low levels of efficiency and likely carbon capture legislation costs. This is therefore the value proposition and potential market opportunity for the Bio-HyPER process. Key markets for the different products were shown within the Route to Market assessment report and are summarised in Figure 6.

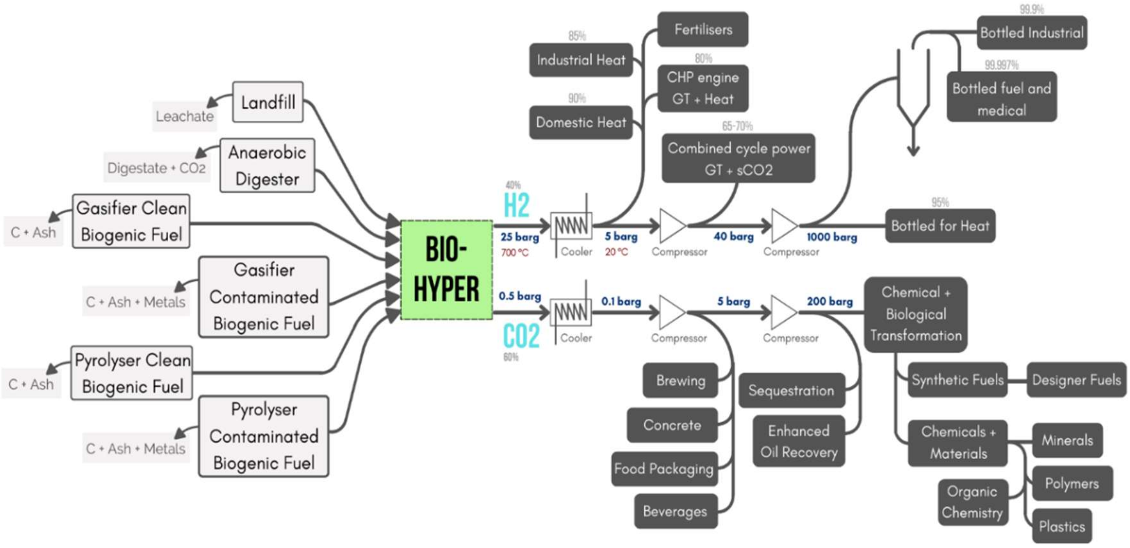

Figure 6. Routes to market for some of the main products.

It is expected the route to commercialisation will be tied closely to the HyPER / compact hydrogen generator technology development and commercialisation as they are both similar. There may actually be a more rapid take up of this Bio-HyPER process configuration technology as the net-negative CO_2 emissions and cost of CO_2 avoided could make better economic sense in some particular locations.

The pathway for achieving the commercialisation of the technology will be to engage in commercial partnerships with interested parties and scale from there utilising their support. Those companies could be partners involved in the Bio-HyPER project or those involved in the commercialisation of the HyPER process configuration.

Deployment scale is expected to achieve a 5-10 MW Bio-HyPER plant in operation by 2030 thereby contributing towards the low carbon hydrogen targets of 2030 (10 GW). Beyond 2030 the scale of deployment would be rapid as the technology is deployed more widely and on multiple plants in the UK, each one contributing towards achieving net zero by 2050.