CATAGEN

H2BECCS105 – CATAGEN Phase 1 Feasibility Study Public Version

CATAGEN LIMITED

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Disclosure

The BECCS Innovation Programme funding has facilitated the technological advancement of the technology described in this report. Through the funding, a Bio-Hydrogen from waste biomass production approach has been evaluated, which showed promising results. Due to commercial sensitivities, this report has been extensively redacted, and as such does not reflect the true value or extent of the funded R&D activities. For queries around the extent of work complete please contact:

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CATAGEN beyond now

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1. Introduction

As the worldwide supplies of oil, gas and coal continue to be depleted, whilst having the effect of producing harmful greenhouse gases such as carbon dioxide, the desire and need to switch to an alternative renewable and sustainable energy economy is growing rapidly. Hydrogen will have a significant part to play in this transition away from fossil-fuels, because hydrogen is capable of producing energy without direct carbon emissions, as water is the only by-product. This is especially true of hydrogen produced from renewable energy sources, such as electrolysis or biomass sources due to the low carbon intensity in its production.

The UK government has stated its intention to produce 10 GW of low carbon hydrogen by 2030, in its Energy Security Strategy with at least half of this is to be generated from electrolysis. To achieve this ambitious goal, as current low carbon hydrogen capacity is less than 5 MW, significant growth will be required, not just in electrolysis but alternative hydrogen production methods as well.

The use of waste biomass as a potential feedstock for the renewable production of hydrogen presents a significant opportunity. An underutilised waste biomass stream that arises as a result of a renewable energy production process can currently be purchased at a relatively low price point but whose energy potential is significant. The current demand for this waste product falls short of the overall production rate, thereby presenting an opportunity for utilisation in energy production. As the demand for renewable energy will increase, to strive towards a net-zero economy, this overproduction of the waste biomass is set to increase. Therefore, an opportunity to utilise a waste by-product of a renewable energy process that is capable of producing hydrogen would be a valuable avenue for exploration of feasibility.

The control of greenhouse gas emissions during energy production is another prominent challenge facing the energy sector today. Carbon capture, storage and utilisation (CCUS) will be required in several renewable energy technologies. As the production of hydrogen from waste biomass will generate carbon dioxide, to make this process a viable long-term hydrogen production technology, a robust CCUS technology is required.

1.1. Literature Review

The first main deliverables of this Phase 1 project were the completion of in-depth literature reviews on the chosen process, for both hydrogen production and the capturing, storage and utilisation of carbon dioxide, with approximately 75 papers being reviewed. This included the investigation into alternative mechanisms of hydrogen production from biomass sources, such as methane pyrolysis, biomass gasification, dark fermentation, direct and indirect bio-photolysis and photo fermentation.

These literature reviews were utilised to inform the prototype build for the production of bio-hydrogen and the capturing of carbon dioxide, whilst also providing Catagen with an understanding of the current technical readiness of the processes and where best value could be added to progress this technical readiness.

The primary challenges of the feasibility of these technologies that were identified as part of the Phase 1 project are:

- Pre-treatment of reactants and products to improve overall process efficiency
- Supplying the energy demand required for the process in an environmentally and economically friendly way
- Achieving a low energy cost relative to the amount of bio-hydrogen produced
- Evaluating several different carbon capture system designs.

2. This Solution

Our proposed system's primary aim is to be a sustainable source of bio-hydrogen by utilising a biomass feedstock arising as a waste product from a renewable energy production process. The objective of Phase 1 was to design and build a system capable of efficiently harnessing the biomass feedstock to create a hydrogen product, enhance this hydrogen production through secondary reactions and then successfully separate out the bio-carbon dioxide by-product from the hydrogen stream. This prototype would then undergo a regime of extensive testing to provide insight into the feasibility of long-term hydrogen production and carbon capture and identify areas that require further investigation in a Phase 2 project.

During the Phase 1 feasibility study, the hydrogen production and carbon capture systems were investigated separately, to maximise the resources available within the project and allow for individualised testing to take place, without having to rely on the other processes operation. The hydrogen production from the waste biomass source was successfully achieved, seeing high levels of hydrogen production and biomass conversion, whilst the carbon capture system successfully was able to strip the carbon dioxide from a product gas stream and release as required.

The results of this research shows significant potential for long-term hydrogen production and has identified key areas for optimising hydrogen production efficiency and long-term operation, providing a starting point for further investigation and modification in Phase 2.

3. Experimental Results and Conclusions of Phase 1 Project

The experimental regime for hydrogen production and carbon capture during the Phase 1 project aimed to show that the processes can operate in isolation, confirm the literature findings, whilst also learning out the intricacies of the process beyond the information that was attainable from the literature review.

To achieve these goals, both systems had an experimental plan developed to better understand the operational considerations of optimising performance and to understand the chemical properties of the biomass feedstock and carbon dioxide, and the material compatibility considerations and to prevent or reduce unwanted side reactions.

Overall, the hydrogen production experimental plan conducted at Catagen was successful in demonstrating that the formation of hydrogen from a biomass feedstock and the capturing of carbon dioxide as expected and added additional learning regarding the optimal operating conditions. Hydrogen production achieve a peak of 0.888 kg/hour. This demonstrated the core feasibility of being able to produce hydrogen from a biomass feedstock in large quantities.

The capturing of carbon dioxide experimental plan conducted at Catagen also successfully demonstrated that the capturing of carbon dioxide from the product gas stream can be achieved, observing near total removal of carbon dioxide and its subsequent release as a concentrated gas, thus proving its core feasibility.

4. Design of Demonstration Project for Phase 2

Globally, the International Environmental Agency (IEA) estimates that the current demand for 70 Mt of hydrogen will grow to over 200 Mt by 2030 with the majority of this growth coming from carbon neutral and carbon zero sources such as electrolysis and bio-hydrogen production. This further emphasises the need for innovative solutions that can increase the generation capacity of hydrogen that will further develop hydrogen economies at scale, a role that this technology is ideally placed to play.

Within the demonstration project, the aim is to build a demonstrator system which would have much more capability to produce hydrogen than the Phase 1 prototype. Efficiency gains would be implemented to improve the cost effectiveness, such as the use of waste heat recovery. As the system is a thermal and chemical process, offsetting the thermal energy required has a significant impact on the hydrogen and carbon dioxide production cost. Renewable energy will also be used to power the demonstrator to generate these products.

The development of the demonstration project for the CATAGEN bio-hydrogen generator has four main aims:

1. The technology works at pilot scale in an optimised setup that allows the technology to be commercially viable
2. The process can be integrated into existing infrastructure/industry
3. The solution can generate and purify bio-hydrogen at a cost that is competitive or cheaper than current alternative solutions
4. The solution can generate and purify bio-carbon dioxide at a cost that is competitive or cheaper than current alternative solutions

To do this, engagement with potential consortia partners has already begun to identify ideal collaborators and the optimal way to demonstrate the feasibility of the technology. This will also enable investigation of how the technology can be optimised.

The purpose of this section was to ascertain an early design schematic for a demonstration scale reactor, required for Phase 2. Understanding this as early as possible is critical due the Phase 2 project framework. This work allows the Phase 2 work packages surrounding reactor design to gain a head start in their works and optimises the decision processes surrounding the demonstrator.

Early in the project, a thorough literature review was conducted to better understand the intricacies of the technology. This initially informed the design of the basic prototype reactors, but some of the information gathered was not implementable into the Phase 1 project due to its constraints, such as budget and timeframe of implementation. As well as these lessons, learnings from the experimental campaign conducted at CATAGEN were also implemented into the Phase 2 design. Various aspects of the technology were modelled to understand where the largest efficiency gains could be made, and these were used as key aspects that had to be included in the Phase 2 design.

The outcome of this work was an initial, complex schematic for a Phase 2 bio-hydrogen production reactor. It incorporates processes from the Phase 1 experimental campaign and proposed processes that are deemed necessary to make this technology feasible. It also provides an early estimation of footprint, utility requirement and a bill of materials that would be required, which subsequently allows for estimated total project costs to be calculated. The proposed demonstration project will cost in the region of £4.6 million. This has been estimated based on the proposed design and prior experience in reactor builds (both in and outside of H2BECCS105). Knowing this ahead of time streamlines the Phase 2 demonstrator design and allows for the demonstrator build to occur more quickly. The approximate breakdown of costs are given in Section 5, with the majority of these associated with the build, operation and analysis of the demonstrator.

5. Phase 2 project description

The proposed Phase 2 demonstration described in Section 4 should be delivered from May 2023 through March 2025. The project comprises design, build, demonstration and analysis activities, which are proposed to be complete at CATAGEN's Belfast base in a Net-Zero demonstration area. The selection of CATAGEN headquarters as a host location for the technology demonstrator (rather than a 3rd party renewable generation site for instance), was driven by risk mitigation given the relatively short project duration.

To deliver the proposed project, a team comprising a mix of existing CATAGEN employees (including those who completed the Phase 1 project), along with experienced hires in areas such as manufacturing engineering and material science, and new supporting roles will be assembled. The proposed team comprises 23 total employees, with a full-time equivalency of 15 FTEs. The CATAGEN Senior Leadership Team are experienced in delivering R&D projects, with employees in post for key project oversight roles. Additionally, key technical resource from the Phase 1 project is carried over, providing continuity and specific experience in bio-hydrogen production from an engineering and control software development point of view. The team structure along with CATAGEN project best practice and procedures are designed to facilitate successful project delivery. This includes an internal reporting and dissemination structure, where key stakeholders are kept abreast of relevant information, financial reporting and tracking, H&S policies and oversight, technical sign-off and QA etc.

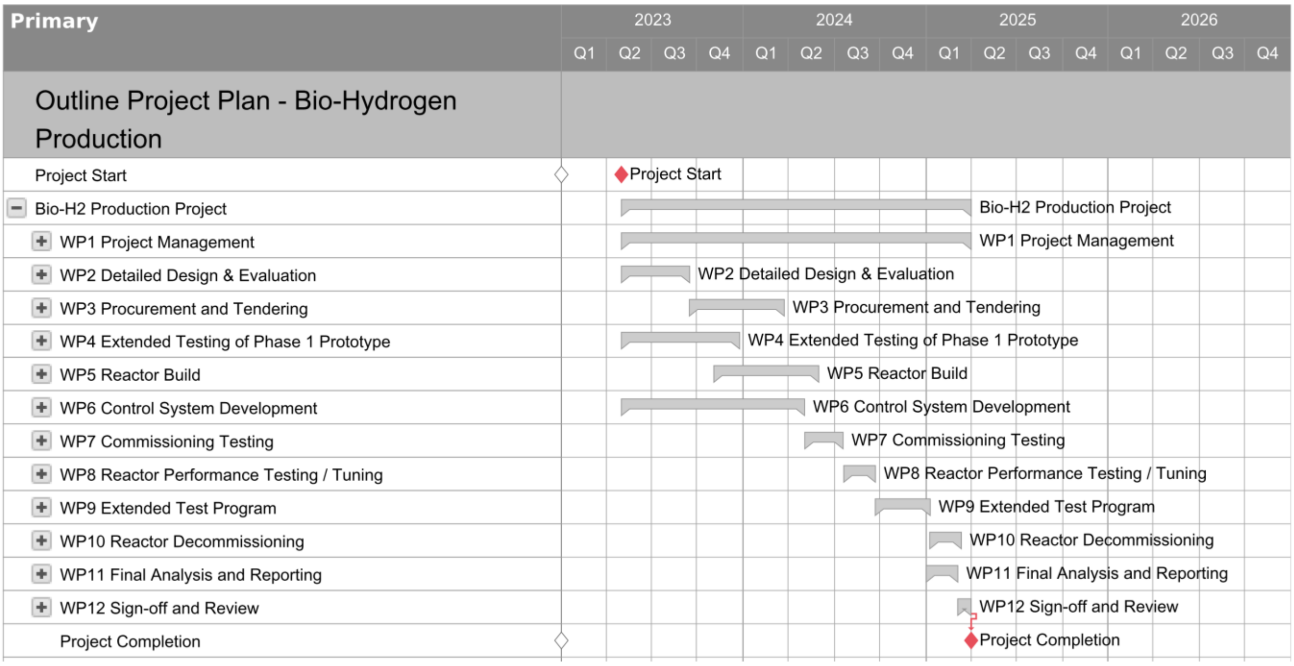

Figure 1 - Outline Phase 2 Project plan

To assess the progress and success of the project, a total of 12 work packages, with 30 deliverables, 8 milestones and several stage gate points are proposed. The initial activities focus on reactor design, following on from the Phase 1 project. It is necessary for these activities to be complete early in the project due to supply chain challenges, with a target completion date of mid-September in year 1. During this period, the control system for the demonstration reactor will also be developed. This allows for a level of maturity in the control software necessary for safe 24/7 operation, and therefore the necessary running time to assess the potential performance of the system. The timeframe allowed for this development is 12 months, which will include virtual testing and simulation for preliminary validation and verification.

The design activities are followed by procurement, with planned receipt of all components and materials by March 2024. Once the necessary materials are received, the reactor build will be complete. Initial steps for site preparation etc. will be complete prior to this, with overall completion of the build scheduled for the end of May 2024.

Following the design and build activities, the project will enter a circa two month reactor commissioning phase, testing for functionality and safety, with a late July 24 completion. Once safe reactor operation has been established, the project enters the demonstration phase, with operation from July 24 through to January 25. During this time the testing plan outlined in section 6 will be complete. The project will then conclude with final analysis and write-up, along with decommissioning of the reactor by the end of March 2025.

Completion of the milestones above is contingent upon project risks being sufficiently mitigated. There are a broad range of risk factors for delivery of the proposed project, including: supply chain issues which are as challenging as ever in 2022, resourcing the project teams, and more technical risks such as the durability of the reactor. The key risk to project delivery is in the procurement of components and materials, with potential challenges in availability and lead time. As with the Phase 1 project, this will be front of mind when designing the equipment, with a work package dedicated to procurement. Additionally, external support with specific supply chain experience will be utilised to de-risk. In general, risks will be assessed continuously at weekly team meetings, with updates to risk ratings and mitigatory steps required as and when necessary.

Considering finally the project costs estimated for Phase 2, the completion of the activities above is expected to total £4.6 million, with a cost breakdown as shown below. The values in this table have been rounded for ease of display. The largest contributing factor to the project cost is labour and associated overheads. The Phase 1 project was successfully delivered with a low headcount, however, to deliver on the larger scale Phase 2 project an increased headcount is required (as touched on above). The increased headcount would allow for more thorough engineering design, optimisation of material and subcontract costs, greater insight from testing results, bespoke build of a safety and control system to allow maximum flexibility among others. Another key factor in the overall project costs is material expenditure for reactor build. This covers raw material for subsequent manufacturing and fabrication, to expensive gas phase separation equipment. These material costs would be driven down over time by manufacturing scale up and the economies of scale associated with this, along with system and component optimisation.

Category	% Cost
Labour & Overheads	42.6%
Material	33.3%
Subcontract Labour	19.1%
Other (PPE, tools, software licencing, travel, shipment etc)	4.0%
Total	100%

6. Phase 2 Demonstration Performance Testing

During the testing of the Phase 2 demonstration project, there will be a variety of factors that will require consideration for the long term technical success of a bio-hydrogen generation system. A regime of testing will be required, looking at the operating conditions to ensure that not only are the desired hydrogen production rates achieved, but that the system operates efficiently, optimising the energy requirements, ensure a degree of flexibility for variation within the biomass feedstock and that the quality of the gaseous product is at the required level.

Short functional tests at specified test conditions will be utilised to determine each set of operating conditions and how the variations effect the system's performance on hydrogen production rates and quality and gas purification.

Long-duration testing will be required to develop a complete understanding of the long term operation of the system, how to maintain the system to ensure sustainable and reliable operation and any cumulative performance-reducing effects have on the system and how they can be managed, reduced or removed from the process. These tests will help build a better understanding of the process and be fed into the next generation design and set realistic expectations for a potential future commercial system.

7. Commercialisation

Due to this expected uptake in demand for hydrogen and the lack of hydrogen production capacity to meet it, fossil-based hydrogen with carbon capture and storage is expected to fill this gap. This is not ideal as it relies on finite, carbon intensive, resources. Bio-hydrogen production from waste biomass sources creates a sustainable production pathway for hydrogen.

Engagement with potential consortia partners has already begun to identify ideal collaborators and the optimal way to demonstrate feasibility of the technology. This will also enable investigation of how the technology can be best optimised to meet end user needs across a range of different industries.

Proving the ability of the system to generate the quantities of bio-hydrogen and bio-carbon dioxide predicted is a key milestone in demonstrating the viability of the technology as this will form the basis of the value proposition of the technology. This relies on the efficient use of intermittent renewable energy to power the system (such as wind, solar, and geothermal) to produce much greater quantities of hydrogen for the same electrical power input as green hydrogen generation. This, as well as the quality of the bio-carbon dioxide produced, are key factors in development of the potential applications and ultimately value proposition of the technology.

The thermochemical nature of the system also presents an interesting interaction with intermittent renewable energy sources such as solar and wind. The high thermal inertia of the system allows for a more adaptive and flexible response to variations in power input than traditional low and zero carbon hydrogen generation technology (such as electrolysers) can achieve. This allows for more optimal use of the electricity generated by these renewable sources and engagement with potential renewable energy consortia members has proposed how to quantify this potential improved compatibility.

These value proposition must also account for the large scale of the processes that the technology is likely to be co-located with. The size of wind farms has increased to GW scale installations, and industrial energy users demand GW of power for everyday operation of plant. This means the Catagen system needs to be able to scale up to match the size of these systems, something that the technology is better positioned to do than traditional electrolysis or battery technology. This is due to the underlying fundamental unit that the technology is based on. Most renewable technologies such as battery, electrolyser, and fuel cells scale up linearly due to the fundamental unit of the system being the individual cell size. The Catagen system, however, has a fundamental unit based on pipe diameter. This means that the system scales up in a quadratic fashion due to the relationship between circular diameter and area (e.g., doubling the pipe diameter increases the area of the pipe by a factor of 4), which is a more favourable scale up curve than a linear progression, which reduces the CAPEX per throughput of the system as the size increases, similar to traditional engineering of industrial units.

The production of bio-carbon dioxide also presents other routes to market, particularly as a way to reduce embodied emissions in products where caron dioxide is needed. The bio-carbon dioxide produced from this system would not require some of the expensive after-treatments that fossil derived carbon dioxide does such as desulphurisation. The cost savings from removal and full optimisation of bio-carbon dioxide production need to be properly assessed within the next stage of this project but may present ways to further reduce the cost of bio-carbon dioxide when compared to fossil derived alternative. This would aid in the displacement of fossil fuel-derived carbon dioxide from the market and assisting in the achievement of net-zero gas emissions by 2050.

The waste biomass presents a cheap, readily available source which arises from a renewable energy technology. It supplies both hydrogen and carbon for use in the bio-hydrogen reactor that enables a reduced LCOH compared to electrolysis and a sustainable alternative to SMR technology, while creating a use for this waste product. This creates a circular model of operation that is firmly rooted in the fast carbon cycle due to the biomass removing carbon dioxide from the air for photosynthesis and this carbon dioxide evolving from the bio-hydrogen reactor as a secondary product.

As Catagen's bio-hydrogen process utilises a waste product from a renewable energy production process, it does not have a direct impact on land use, or the emissions associated with land use. It will simply process a waste product for bio-hydrogen production. One potential impact that this system may have been that if the renewable energy production process has a viable outlet for its primary waste product, it may result in an increase in an appetite for increasing this renewable energy production. However, how much of this would be down to the viable disposal of waste biomass and the primary driver of decarbonising the transport sector as part of the overall net-zero strategy is very difficult to determine or quantify.

These several use cases demonstrate the flexibility of the Catagen system to integrate with both existing industrial processes and emerging developments in the renewable energy sector and so highlight the potential of the technology to rapidly deploy across many of the largest industries around the globe.

8. Route to Market Assessment

The Catagen bio-hydrogen generator will require several significant steps to progress through CRL development; pilot scale demonstration, business model(s) development and application optimisation, MRL development and business model validation.

The progression to reach these steps has already begun during Phase 1 with the development of the system, as well as basic market awareness and value propositions being developed in parallel with the technology. Further progression of CRL will be dependent on deployment of the pilot device with input from a consortium partner to fully align the technology with the market as well as optimisation of the technology to meet end user demands.

This will prove the technology viability with a 'beachhead' customer and allow for refinement of financial models and technology optimisation. As well as this, the development of the system MRL will be necessary to ensure that the market demand for this technology is met and the scale of production is appropriate for the market.

As this system offers bio-hydrogen as a product, an energy vector, the total addressable market for this technology is incredibly large; with market potential across all areas of the energy sector including as an alternative to fossil fuels. The main barrier to this market is the ability of systems to utilise hydrogen as a fuel source.

Hydrogen has been present in natural gas pipelines for decades. In this situation it was considered a 'impurity' of the gasification of coal as it reduced the energy content of the gas mixture (town gas) and caused premature wear of some components at high concentrations.

This presents an emerging route to market in modern energy systems of displacing use of natural gas in the gas network by replacing some of the gas content with hydrogen. It is estimated that approximately 20% of the total gas content by volume could be replaced with hydrogen without detrimental effects on the transmission network or existing boiler systems. But due to the lower energy content of hydrogen gas per unit volume compared to natural gas due to its lower density, this 20% vol addition represents only 7% of the energy content of the gas.

It is estimated that approximately 4 times the volume of hydrogen gas would be necessary to produce the same energy content as natural gas. This route to market is currently being explored mainly in the UK and other parts of Europe where there is a large dependency on gas networks for industry and domestic heating and as such represents a potential route to market and export opportunity for the Catagen technology as a supplier of this bio-hydrogen.

There are several categories of job creation associated with the deployment and successful commercialisation of this technology:

- Direct Technology Development and Manufacture
- Technology Support and Deployment
- Synergistic Sector Growth

These three categories represent a range of roles including:

- Mechanical, Chemical and Electrical Engineering
- Manufacturing and Deployment Logistics Crew
- Welding, Plumbing and Maintenance Crew
- Sales, Marketing and Administrative Support roles
- Wider sector growth roles e.g., increased demand for renewable energy jobs and transmission network roles

In addition, the potential for bio-hydrogen production assists in the decarbonisation of many industries. This can help to future proof jobs in areas such as public transport, construction and power generation by offering a net zero alternative to entire industries currently dependent on the use of fossil fuels. The impact of this technology could be globally significant in aiding in the creation of a hydrogen-based world energy system and can aid in ensuring the sustainability of jobs across a multitude of businesses.

Through the development of bio-hydrogen production there is also the opportunity to reduce the carbon emissions of industries such as the aviation industry (currently responsible for 8% of UK transport emissions annually) as well as the public and private mobility sector by adoption of FCEV vehicles such as buses and passenger vehicles. This net zero solution can help ensure these vital industries do not further contribute to human induced warming and also presents an alternative way to harvest renewable energy from intermittent sources such as wind and solar by 'locking up' the excess wind in chemical form, further increasing the viability of intermittent renewable assets as part of the wider energy network. This technology also creates the opportunity to vastly increase supplies of hydrogen, which could help accelerate adoption of hydrogen as an energy source, increasing the rate that decarbonisation occurs at by ensuring supply for users to demand.

9. Dissemination

Ongoing dissemination activities have occurred in parallel to technology development throughout the project lifespan. These activities have included individual and group site visits for stakeholders including: government (national, regional, and local level), supply chain partners, potential customers and consortium members. Additionally, CATAGEN staff have attended a range of events to raise public and industry awareness of the project and obtain independent feedback concerning the suitability of the technology for different market segments and industries.

10. Conclusions

The goal of this Phase 1 study was to determine the feasibility of developing new capabilities and technologies to combine with known flow-through gas reactor test technology to yield a production machine and process for high efficiency bio-hydrogen production and capture and store bio-carbon dioxide generated in the process. Whilst different hydrogen production methods were assessed, one technology was selected for further development based on a number of criteria.

A Phase 1 prototype was built, commissioned and tested with the goal of ascertaining a better understanding of the technology. The testing proved that the reactor could be used to yield hydrogen and separate out the carbon dioxide. The experiments completed at CATAGEN have provided a greater understanding for the intricacies of the technology and have informed the design of a Phase 2 reactor.

Alongside the practical elements of Phase 1, modelling activities were completed to understand what further R&D activities would be required to reduce the cost of hydrogen produced from a demonstrator. CATAGEN were able to highlight the key problems that require solving, with some potential solutions identified that require further research.

The potential efficiency gains identified in Phase 1, allow levelized costs to be calculated which demonstrate that CATAGEN technology has the potential to produce low cost and low carbon emitting hydrogen.

Overall, the Phase 1 H2BECCS105 project has successfully demonstrated that through further R&D activities, a low-cost bio-hydrogen production reactor and carbon capture system is feasible. This has been demonstrated through:

1. The testing of the Phase 1 prototype reactor proved hydrogen can be made via this process.
2. The testing of the Phase 1 prototype system proved carbon dioxide can be captured and separated from the product gas stream via this process.
3. The modelling deliverables that establish, by targeting specific issues, significant efficiency gains can be made that reduce the overall cost of hydrogen production.
4. Evaluating potential partnerships that can add value to the system that will decrease the energy cost of hydrogen.