Department for
Business, Energy
& Industrial Strategy

Hydrogen BECCS Phase 1

Category 3 - Novel biohydrogen technologies

Redacted Report (Public)

Hydrogen from Cyanobacteria - a biological route to zero-carbon or carbon-negative hydrogen

January 2023

17Cicada Ltd
University of Nottingham

1 Contents

2 TECHNICAL DESCRIPTION OF PHASE 1 PROJECT

2.1 Overview and Objectives

17Cicada is a UK-based start-up/university spin out company, incorporated in May 2021. The company was established to exploit the cyanobacterial strains being developed in Samantha Bryan's research group at the University of Nottingham (UoN).

In Phase 1 of the H2 BECCS project we used cyanobacteria for the biological production of hydrogen (H_2). Cyanobacteria are photosynthetic organisms that use light energy and carbon dioxide (CO_2) as a carbon source under ambient conditions offering a low energy, zero/negative carbon approach for the direct production of H_2 from solar energy. Since CO_2 is the major feedstock for cyanobacteria, this approach has the potential to complement other H_2 production methods and associated carbon capture and storage (CCS) technologies as an integrated solution in the wider H_2 supply chain. Indeed, cyanobacteria offer a low-cost, potentially highly scalable way to sequester large quantities CO_2 while converting the carbon feedstock into next-generation products for energy.

In Phase 1, we implemented a strain engineering strategy to develop novel cyanobacterial strains with increased H_2 production rates for commercial deployment. We utilised lab scale reactors (0.25 to 1L volume) for the initial strain development work: the best performing strains where then evaluated in Varicon Aqua Phyco-Lift systems at 12L and 140L scale, demonstrating the production of hydrogen at TRL 6. Photobioreactors from Varicon Aqua offer a competitive edge and allowed us to develop optimised conditions for the photosynthetic fermentation of our novel engineered strains.

A rigorous technoeconomic analysis (TEA) model was created to assess the financial feasibility of the proposed renewable H_2 production process and inform process development. A robust life-cycle analysis (LCA) will reveal any hotspots in terms of our environmental impact as we strive to achieve net-zero and beyond. The TEA will support the development of reactor designs and allow costings and planning for the Phase 2 demonstration, while the LCA will be carried out during Phase 2.

Our approach is to develop a cyanobacteria strain and bioreactor configuration that can produce H_2 at commercial scale, a first of its kind process, in the UK and globally. These UK advances in sustainable H_2 production will have both national and global deployment capability, representing a first in class demonstration of decarbonisation through resource circularity in the manufacturing (steelworks; batteries) and energy sectors. Our approach is highly disruptive to fossil fuel, natural gas and other incumbent technologies that produce energy from primary resources; moreover, we propose a low-energy, highly circular alternative to water electrolysis which could significantly reduce the burden of clean energy required to deploy H_2 solutions.

Our research will frame and catalyse further knowledge exchange, given that the anticipated global reduction in carbon intensity aligns with (1) UK legislation on attaining net zero carbon emissions by 2050, and (2) the UK's Clean Growth Grand Challenge. We align with UN Sustainable Development Goals: 7 (Affordable and Clean Energy), 9 (Industry, Innovation, and Infrastructure), 11 (Sustainable Cities and Communities) and 13 (Climate Action).

2.1.1 Phase 1 Project Plan

The work packages and deliverables for the project are described in detail in the Results sections below. Note that references are included in the individual deliverables reports collated in Appendix 2: they are not repeated in the text of this report. A log of assumptions made when conducting the feasibility study, along with an assessment of the impact that gaps in the data may have on the viability of the Hydrogen BECCS innovation, can be found in Appendix 1.

2.2 Results

2.2.1 Work Package 1: Project Management

The aim of this was package was to manage project progress, decision making, budgeting, and reporting. Deliverables assigned to this work package were:

2.2.1.1 Quarterly BEIS progress reports

Completed for Q1, this report for Q2

2.2.1.2 Draft Final Report

Completed and submitted to BEIS on Dec 13th 2022

2.2.1.3 NZPI KPIs Project Start

Completed

2.2.1.4 NZPI KPIs Project Close

Completed

2.2.2 Work Package 2: Strain Engineering

Led by Dr Samantha Bryan, the team at the UoN work with the model cyanobacterial strain *Synechocystis* sp. PCC 6803 (PCC 6803). This is a well studied organism for potential industrial biotechnology application. Proof of concept H_2 production by PCC 6803 has previously been established and validated in UoN labs (TRL 4). However, H_2 production rates were too low to be economically viable.

Photobiological H_2 metabolism in cyanobacteria presents two major challenges to overcome:

- Firstly, H_2 production is catalysed by a bidirectional [NiFe] hydrogenase (Hox) which reversibly oxidises molecular H_2 . Therefore, as a redox system, hydrogenase activity is limited by electron supply.
- Secondly, Hox activity is inhibited by oxygen - a major by-product of the photosynthetic pathway.

[text and figures redacted]

2.2.2.1 [text redacted]

[text and figures redacted]

2.2.2.2 Text redacted]

[text and figures redacted]

2.2.2.3 [text redacted]

[text and figures redacted].

2.2.3 Work Package 3: Fermentation Studies

Led by Professor Alex Conradie (UoN), the main aims of this work package were to:

- Scale up fermentation from Lab scale<1L) to 12L then 140L (D3.1)
- Establish online H_2 detection methods (D3.2)
- Evaluate Biomass Accumulation with WT strains Optimise Fermentation (D3.3)
- Optimise Fermentation media with mutant strains (D3.4)
- Demonstrate H_2 production from a 140L Pilot photobioreactor (D3.5)

We evaluated commercially available photobioreactors supplied by the leading manufacturer in the field, Varicon-Aqua. We utilised both the 12L and 140L Phyco-Lift Photobioreactors from Varicon-Aqua, which consist of a series of interlinked bubble columns. Scaling up is achieved by increasing the height resulting in narrower columns with a reduced width: height ratio to avoid 'shading'. Increasing the height (VS the width) of the bioreactor also allows for more efficient land use, with reduced associated CapEx costs for an equivalent bioreactor capacity. Multiple columns can be

chained together to increase scale in a modular, 'daisy chain' fashion with culture media and gases (feedstock CO_2) circulated between columns in a continuous process for eventual product harvesting (e.g., O_2, H_2). This modular approach also facilitates efficient maintenance and operations, reducing potential downtime of the overall process. Thus, if there is an issue with one module within the system, this can be slotted out and easily replaced with another module without disruption to the operation of other modules.

2.2.3.1 Reactor Validation and Optimisation (D3.1)

The aims of deliverable 3.1 were to validate fermentation in Laboratory bioreactors at 5-10L scale, and to adapt the 140L Varicon Aqua photobioreactors to ensure suitability for hydrogen generation.

We experienced unexpected delays in delivery of Varicon Aqua PBRs (12L and 140L). We expected to have these within a month of project start, but in fact they were badly delayed: we took delivery of the 10L system on 7th October, and 140L in mid-November. This necessitated a major rescheduling of work package 3, particularly Task 3.1 (Reactor validation and optimisation 5L and 150L) and Task 3.3 (Fermentation studies on wild type bacteria): these required access to the PBRs to be completed. Both tasks and their associated deliverables were pushed back from Q1 into Q2 because of this problem. We also put in place contingency plans, fabricating 4 smaller PBRs (0.25L scale) to allow us to do some preliminary work in Q1. These issues were addressed in Major Change Request #2.

The results are described in detail in the Technical Reports for Deliverable 3.1 (Reactor Validation and Optimisation – see Appendix 2): highlights from this report are shown below. This report demonstrates validation of fermentation at both 5-10L and 140L scale. Both systems were commissioned using bacterial strain 11901 **[text redacted]**, a fast-growing marine strain of cyanobacteria, which can reach high cell densities and was utilised as a risk mitigation strategy. Growth and H_2 productivity were assessed in both batch and continuous mode. **[text redacted]** will be performed at large scale in January 2023 as part of deliverable 3.5.

2.2.3.2 Establish continuous H2 detection methods (D3.2)

Continuous H_2 detection was implemented using a Raman Laser Gas Analyser. H_2 is considered as an extremely explosive gas, a long run using a commercial high precision special mix of 40% H_2 mixture was therefore considered not safe by the technical team. A short detection of highly concentrated H_2 was assessed instead to establish a base line.

The results are described in detail in the Technical Reports for Deliverable 3.2 (H_2 detection – see Appendix 2): highlights from this report are described below. Using the Raman setup above, we were able to successfully detect H_2 using a commercially available control gas mixture. Unfortunately, we were unable to detect H_2 from 11901, because H_2 production is linked to dark fermentation and was below the detection limit for the instrument: instead we used gas chromatography with a thermal conductivity detector (GC-TCD) (see Technical Reports for Deliverable 3.4, Appendix 2).

2.2.3.3 Fermentation studies on WT- evaluate biomass accumulation (D3.3)

The aim of this stage was to study biomass accumulation, cultivation parameters and media composition utilising the wild-type (WT) strain to define baseline growth conditions, which would then be modified for subsequent mutant strains as required. The results are described in detail in the Technical Reports for Deliverable 3.3 (Fermentation studies on WT – see Appendix 2): highlights from this report are shown below.

Time constraints and delays impacted severely on our efforts to complete Deliverable 3.3. In the first instance, we decided to attempt optimisation of cultivation conditions on a mutant PCC6803 **[text redacted]**, rather than the WT strain. Given the delayed delivery of the Varicon Aqua photobioreactor (see D3.1) time constrains would not allow for the both the WT and the mutant strain to be evaluated. Therefore, we decided to focus on the mutant strain as we felt that data acquired from this would be more valuable.

Our initial attempts at cultivation (Oct 25th to Nov 7th) revealed a fault in the (new) photobioreactor that caused light intensity to be too high, leading to photobleaching and subsequent death of the culture (despite efforts to revive the culture). The intended light intensity selected mirrored the intensity utilised in the competitive fermentation selection, hence the rationale behind the selection. The second attempt saw a reduction in in light intensity and **[text redacted]** PBR to maintain selective pressure on the strain (Nov 11 – Nov 14: informed by D2.3). The addition **[text redacted]**

Despite both attempts being unsuccessful, we learned a lot about the operation of the reactor, due to time constraints, we moved straight into the scale up phase (D3.5) from the middle of Nov, without making further efforts to optimise cultivation conditions.

2.2.3.4 Fermentation Media optimisation (D3.4)

The aim of deliverable 3.4 was to collect base data on the WT strain (cultivation conditions and media screen). The results are described in detail in the Technical Reports for Deliverable 3.4 (Fermentation Media optimisation – see Appendix 2): highlights from this report are shown below.

As with deliverable 3.3 (above), owing to time constraints due to the late delivery of the Varicon Aqua Photobioreactors, it was decided to focus on the mutant strains rather than the WT strain, as originally proposed, given there wasn't sufficient time to test both.

This work was done in the 5-10L Varicon Aqua Photobioreactor (PBR) using 2 different mutant strains of cyanobacteria: **[text redacted]**.

Subsequent growth of **[text redacted]** in the PBR at 10L scale **[text redacted]**.

In this deliverable, we assessed 11901**[text redacted]** at 140L scale. **[text redacted]**. At this critical junction we felt that it was essential to meet the deliverable and evaluate a strain at 140L scale. Therefore, we chose to use 11901**[text redacted]**.

Several conditions were evaluated during the growth of 11901 **[text redacted]**, these included dark adaptation and photoautotrophic growth. We were unable to detect H_2 in continuous mode with the Raman, however, by switching to batch and shutting off the flow of gas into the PBR for a period of 8 hrs we were able to collect H_2 gas from the vessel for analysis via GC-LTD. We were able to detect small amounts of H_2, but only following dark adaptation. H_2 production was much lower than expected, furthermore productivity was reduced compared to the small-scale analysis. This is probably due to suboptimal growth conditions, given the heating was switched off for the 8hr period along with the gas.

2.2.3.5 Lab-scale demonstrator runs at 140L on best performing strain (D3,5)

The results are described in detail in the Technical Reports for Deliverable 3.5 (Lab-scale demonstrator runs at 140L – see Appendix 2): highlights from this report are shown below.

The delivery of the 140L system was severely delayed, which meant that the initial commission could not be performed on the WT strain as originally envisaged and detailed in the deliverable. To meet to milestone, we proceeded to run a mutant strain 11901 **[text redacted]**, in the 140L reactor. This strain had already been validated at 12L scale and mutant 10 was contaminated leaving PCC11901 **[text redacted]** as the only viable option to complete the deliverable. Given the valuable information we could gain with a 140L run we proceeded with this option.

We made two runs on the 140L photobioreactor in Dec 2022, and a further 2 attempts in Jan 2023 (as part of the project extension granted in CR04). The January 2023 runs were sadly blighted by contamination. However, the December runs did yield data in both batch and continuous mode. Hydrogen was generated following dark adaptation: this is the first reported example of H_2 production at 140L scale in a cyanobacteria.

2.2.4 Work Package 4: Feasibility Reporting

The aim of this work package was to conduct a rigorous technoeconomic analysis (TEA) model to assess the financial feasibility of the proposed renewable H_2 production process and inform process development. This will support the development of reactor designs and allow costings and feasibility planning for the Phase 2 demonstration.

2.2.4.1 Technoeconomic analysis report (D4.1)

The results are described in detail in the Technical Reports for Deliverable 4.1 (technoeconomic analysis report – see Appendix 2): highlights from this report are shown below.

The TEA conducted in Phase 1 was made with the following assumptions:

Assumption 1: The TEA model is based on a multi-acre photobioreactor (PBR) installation producing an average of 36 tonnes H2 /day (post-phase 2 of BEIS project). This is significantly larger than the post-phase 2 installation considered in the original application, at 0.5 tonnes H2 /day. The decision to switch to a larger installation was driven by refining our primary commercial focus to steel plants. According to McKinsey, a small steel mill producing 2 million tons of steel per annum would require

144,000 tonnes of H2 per annum, or @400 tonnes per day. The proposed 36 tonnes H2 /day bio- H2 installation would contribute approx. 10% of the total steel plant demand (noting that seasonal light variations mean the H2 production figures will be lower in the winter and higher in the summer), significantly greening the process.

Assumption 2: Compares the following three systems: 1) **[text redacted]** (requires modifications to commercially available systems; 2) helical tubular system (commercially available); 3) flat panel system (commercially available)

Assumption 3: Any biological H_2 system is likely to need a secondary product to be cost viable. We have assumed the sale of biomass as a co-product for animal feed

The TEA demonstrates that the **[text redacted]** system remains the cheapest by a significant margin: **[text redacted]**.

Our original proposal focussed on novel in-house designed flat panel PBR systems, for which the Varicon Aqua systems were a commercially available analogue. According to our TEA, to make this option competitive, we would need to increase H_2 productivity vs **[text redacted]** and decrease CAPEX costs. We have a proposed design (see the Technical Reports for Deliverable 4.1 (Technoeconomic analysis report –in Appendix 2, and section 4.1 below) which we believe will significantly reduce CAPEX, but we have not included it in the TEA because it is unproven.

We propose to test both the **[text redacted]** and our novel flat panel designs in Phase 2 at the 1,000L scale, with a view to obtaining more refined data on the novel flat panel design to rule it in or out of future development of the technology.

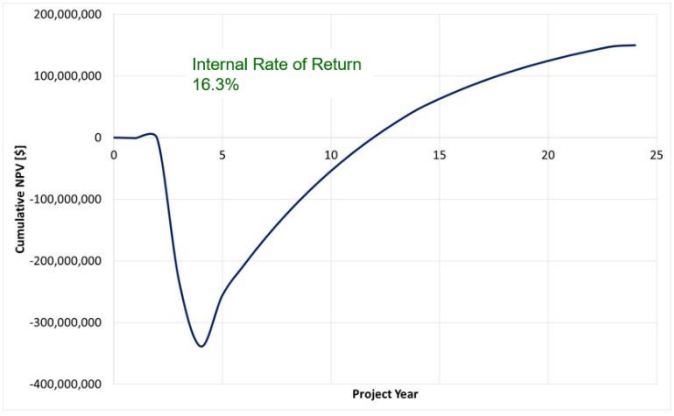
2.2.4.2 Reactor designs and costings (D4.2)

The results are described in detail in the Technical Reports for Deliverable 4.1 (Reactor designs and costings – see Appendix 2): since this is described in detail in section 4 below, no further information will be provided here.

2.2.4.3 Feasibility report (D4.3)

The capital estimation for the **[text redacted]** is described in the Technical Reports for Deliverable 4.3 (technoeconomic analysis report – see Appendix 2): highlights from this report are shown below.

The total capital investment for a **[text redacted]** producing 12.6 (ktonne H2)/yr was estimated at $474MM. Further estimates were made for fixed and variable operating costs. The three cost models were combined into a comprehensive investment analysis, summarised by the below cumulative Net Present Value (NPV) figure. Payback occurs in approximate year 12 of the project life, attaining a NPV of ~$160MM from the sale of H_2 and animal feed. The internal rate of return for the investment was calculated as 16.3%.



Given the uncertain associated with conceptual stage techno-economic assessment, a Monte Carlo simulation was undertaken for 90 scenarios randomised within the uncertainty bounds for e.g., capital cost estimation. The resulting discrete probability histogram can be used to determine a

cumulative probability curve, which shows that given the uncertainty bounds, there is a 70% likelihood that the NPV will be greater than $20MM. Negative NPV outcomes thus have an approximately 30% probability of being realised.

2.2.5 Work Package 5 Innovation Management, Dissemination and Exploitation

The aim of this work package was to monitor competitors and the market to ensure full exploitation of project outputs. IP protection of reactor design in progress but to be modified as required depending on project outcomes. Protection of the strains and the overall process will also be considered. Dissemination and communication activities to highlight project outputs and engage investors and end users.

2.2.5.1 Updated business plan (D5.1)

The 17Cicada Business plan is attached – see Appendix 3

2.2.5.2 Dissemination plan and communication materials (D5.2)

The results are described in detail in the Technical Reports for Deliverable 5.2 (Dissemination plan and communication materials – see Appendix 2): highlights from this report are shown below.

[text redacted].

With this in mind, we have not yet published any papers around the work done in phase 1, and our public presentations have been limited in scope to avoid any premature public disclosures that would invalidate a patent application.

2.2.5.3 Preparation for Phase 2 (D5.3)

This is described in detail in sections 4,5 and 6 below

2.3 Conclusions

The project was achieved the following milestones;

- Cyanobacterial strain producing hydrogen continuously in the light – the first time this had been reported, and a major achievement in the production of bio-hydrogen.
- Hydrogen production detected at fermentation scale of 140L.
- **[text redacted].**
- **[text redacted].**
- Technoeconomic analysis completed to guide further development.

3 LIFE CYCLE ASSESSMENT OF PHASE 1 PROJECT

No life cycle analysis was performed during this study, nor was it part of our project proposal: It was envisaged as part of our Phase 2 project.

4 PHASE 2 – Engineering Design

4.1 Concept

The TEA conducted in Phase 1 compared **[text redacted]** (requires modifications to commercially available systems) vs helical tubular (commercially available) vs flat panel (commercially available), and concluded that, of those systems, **[text redacted]** systems were the best option for post-Phase 2 (see section 2.2.4.1 above).

Our original proposal focussed on novel in-house designed flat panel PBR systems; this was not included in the TEA because it is unproven design, which we felt was inappropriate to include given the (revised) scale of the proposed system (50 tonnes H_2 /day).

[text redacted]. Therefore, we would like to compare the 2 proposed designs in Phase 2 at the 1,000L scale.

4.2 [Text Redacted]

[text and figures redacted].

The cost of developing this sytem is estimated at £179,00 as a one-off single installation in Phase 2. In Phase 2, we plan to sub-contract Varicon aqua to develop the design, construct and install the 1,000 L system.

Once the design is proven, we estimate the production cost of a 1,000L installation to be £30,974 (see D4.2 scale up reactor design and costings for Phase 2 demonstration report, Appendix 2).

4.3 [Text Redacted]

[text redacted].

The cost of developing this sytem is estimated at £129,00 as a one-off single installation in Phase 2. We have not calculated the production costs of the proven design.

5 PHASE 2 - Testing Plan

Light, carbon and mineral nutrient supply, temperature, and pH are the main variables liable to limit photosynthetic cyanobacterial growth and thus reduce the productivity of cultivation systems (assuming there is no predatory contamination). We note that Phase 2 **[text redacted]**, which will likely result in new problems and challenges not encountered on a laboratory scale, i.e., contamination and insufficient light supply.

5.1 Functional testing

Functional testing will monitor the following parameters:

- H_2 production and quality (including HAZOP assessment)
- Biomass/Chlorophyll A gain (CO_2 fixed)
- Feedstock consumption (CO_2, inorganic nutrients, water)
- Light intensity, availability, and light/dark frequency
- Mixing/aeration rate (minimise shear stress/cell damage)
- Energy consumption
- Emissions and waste outputs

Testing will be performed in steady state conditions during continuous fermentation, and parameters will be monitored continuously and plotted against time to show variations. Functional testing will be performed both before and after long duration performance testing.

For the scalability of photobioreactors, an appropriate setting between various factors must be struck, such as light intensity, , light distribution, hydrodynamics, and environment (nutrients, pH, and temperature). Light availability for each cell is often the most important factor for scaling up in photobioreactors.

5.2 Performance testing

Performance testing will monitor all the above parameters, and additionally:

- H_2 and CO_2 gas leaks (HAZOP assessment)
- Equipment and component duty cycles and failures
- Heating/cooling requirements
- Photobioreactor turn-over frequency and time
- Operating hours and downtime due to planned and unplanned maintenance
- Maintenance and staffing requirements
- Consumables costs

We have allowed 3 months for performance testing (~1,500 hours). Comparison of monitored parameters for the two different photobioreactors proposed for Phase 2 **[text redacted]** will guide CAPEX and OPEX improvements to both, as well as demonstrating the relative balance between H_2 production and CO_2 fixation. This data will determine the best photobioreactor solution to use post-Phase 2.

6 PHASE 2 - Project Plan

6.1 Timelines for deliverables.

[text redacted]

Building on the parameters established in Phase1, in Phase 2 two large-scale (@1,000L) commercial pilot photobioreactors **[text redacted]** will be built and operated (TRL7). This is intended to showcase our technology and help us to sell/license to domestic and international markets.

A preliminary Budget has been prepared for Phase 2, as follows:

Total Labour Costs, exc Overheads (48%): £760,470

Total Overhead Costs (28%): £158,762

Total Material Costs (8%):£69,000

Total Capital Equipment Costs (9%): £42,000

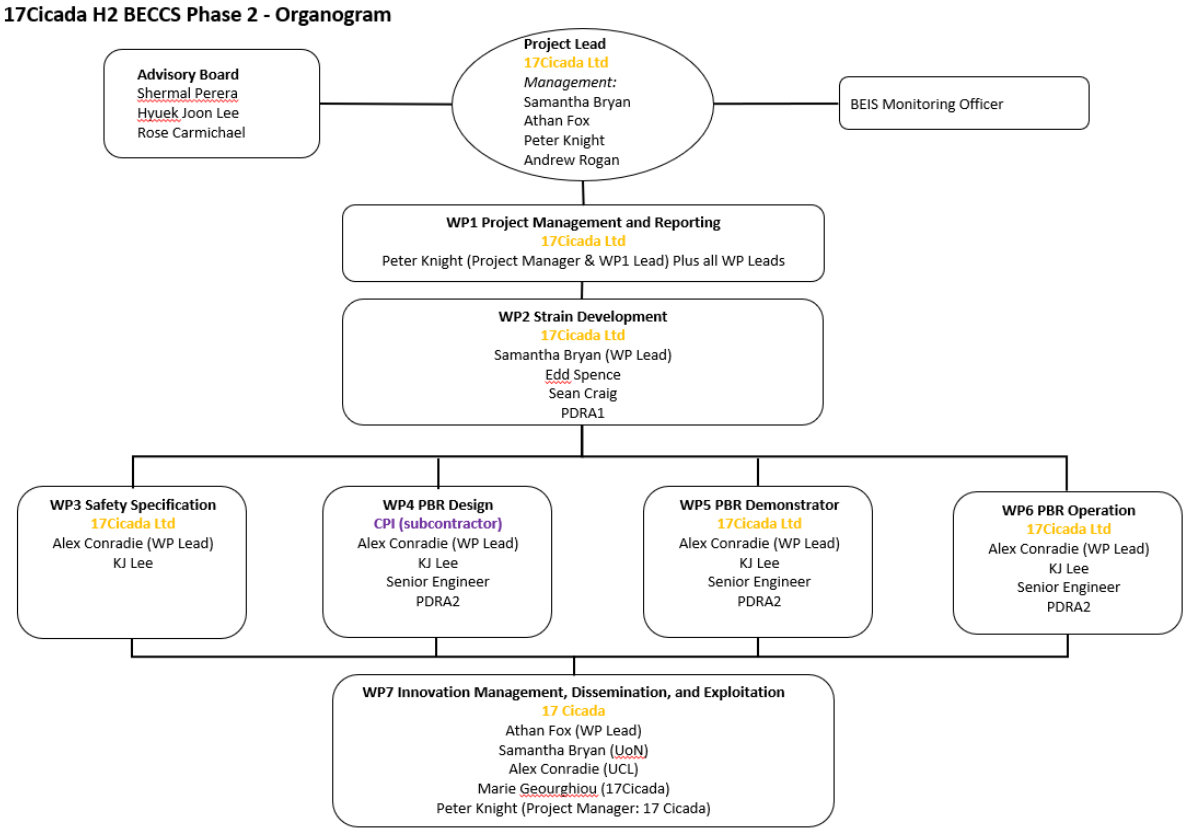
Total Sub Contract Costs (7%): £336,300

Total Travel & Subsistence Costs (1%) £25,150

Total Project Costs: £1,391,781

6.2 Project management (including project team and key suppliers).

The Phase 2 organogram is shown below, and bio's of team members are detailed in Appendix 6.



6.3 Risks and risk management.

See separate Risk Register (Appendix 7). A collaboration agreement will be put in place between UoN and 17Cicada covering IPR, governance arrangements and dispute resolution. The team are experienced in collaborative research. We have a strong working relationship and track record developed over previous and ongoing projects. The project will be managed in accordance with PMBOK principles, including:

- Fortnightly reviews;
- Risks management via risk register;
- Sufficient contingency incorporated into all WP's; (iv) KPIs/deliverables/milestones to measure success; (v) WP leaders will manage resources and deviations.

Work has been carefully planned and is considered achievable within the timescales/budget proposed.

6.4 Quality assurance.

In April 2022, BEIS published the Low Carbon Hydrogen Standard, setting a maximum threshold for greenhouse gas emissions allowed in the production process for H_2 to be considered low carbon. It will require H_2 producers – including 17Cicada - to meet a greenhouse gas emissions intensity of 20g CO2e/MJLHV of produced H_2 or less for it to be considered low carbon, as well as to calculate their greenhouse gas emissions up to the point of production. Further requirements include accounting for the emissions associated with meeting a theoretical minimum pressure level of 3MPa, as well as a theoretical minimum purity of 99.9% by volume at the production plant gate, in the emissions calculations.

The standard also requires producers to meet additional requirements for the use of biogenic inputs, where relevant and as appropriate for the feedstock source and classification, demonstrating compliance with the land, soil carbon and forest criteria; satisfy the minimum waste and residue requirement; and report on estimated indirect land-use change greenhouse gas emissions.

These parameters will be measured either in-house or via third party analytical companies. This is in addition to standard Quality Assurance measure which include management of the quality of raw materials, assemblies, products and components, services related to production, and management, production, and inspection processes.

6.5 Project oversight and governance.

High level insights from the External Advisory Board will help to steer the commercial and technical aspects of the project in alignment with future market developments. Board members are as follows:

Dr Shermal Perera (Nigeria/Malaysia). Highly accomplished biotech CEO. Founded Bioven EuropeLtd. Owner/operator biofuel industry

Dr Hyuek Joon Lee (South Korea). Biotech superstar who served as Executive Vice President at Cellatoz Therapeutics, Inc and ILJIN Group.

Ms Rose Carmichael (USA). Visionary Electrical Engineer and Chief Financial Officer who co-Founded Siemens Capital.

6.6 Reporting plans.

Led by experienced project manager Peter Knight who will: ensure that the project meets the quality, time, and cost requirements; identify risks (ISO31000 risk management standard-risk matrix; manage project spend (LibreProject, Xero online accounting software); action finance/progress reports to BEIS; and provide commercial/dissemination management. Dependencies and milestones monitored against Gantt chart, Risk Register and work package detail.

6.7 Disseminating results and key learnings to relevant industry sectors.

17Cicada is developing dissemination strategies/actions to raise awareness and enable knowledge transfer among public and private sector. Communication materials to support these activities will also be produced.

Information and results will be disseminated through:

- 17Cicada website and social media channels (e.g., LinkedIn)
- Publications in high impact journals (dependent on status of patent applications, which will be prioritised)
- Attendance at (International) conferences and trade events (e.g., Conference National ISPP, AlgaeUK NIBB meetings)
- Engagement with networks (e.g., BBSRC Networks in Industrial Biotechnology and Bioenergy)
- Selected stakeholders will be invited to view lab scale demonstrations.

KNOWLEDGE EXCHANGE KPIs: MONITORING SOCIAL IMPACT

- 2000 users engaged with social media channels?

- 2-3 workshops/events to showcase the project and results, targeting 50-100 attendees.
- Communication materials (flyer/presentation/video).

6.8 Any other relevant material to demonstrate good practice in project delivery

As a bio-based process, there is a significant reduction in environmental impacts compared to other industrial processes:

Greenhouse gas emissions (GHG): Our approach offers a truly transformative opportunity to meet the UK's net zero target through circular biorefineries. The Royal Society report on greenhouse gas removal (2018) projected that after ambitious UK decarbonisation, net CO_2 emissions of 130 million tonnes per year would remain in 2050. GHG-intensive transport, heat and power emissions dominate this scenario, comprising 40% of these difficult to decarbonise emissions. Green H_2 from cyanobacteria, generated utilising only light energy and water, whilst capturing CO_2 and utilising renewable electricity offers a considerable opportunity to counterbalance these persistent CO_2 emissions.

Energy demand: Biological fermentation processes operate at ambient temperatures (35 to 45^{o}C. Our process will operate at 30^{o}C presenting a significantly lower energy demand compared to H_2 production via steam methane reforming or electrolysis, both energy intensive processes requiring operational temperatures of 700-1000 ^{o}C. Furthermore, we will utilise renewable electricity.

Land Impacts: Bioreactor approach avoids the need for land/water harvesting allowing greater control over the process. The flat panel bioreactor design also uses height to scale reducing the potential land required, 1 hectare per 200m3, 1 process operator per 25 hectares for fermentation. Coupling to other industrial processes means existing industrial sites will be targeted. For the **[text redacted]** design, brownfield sites can be used avoiding the need for greenfield.

Water demand: Cyanobacteria are halotolerant and can survive and grow in saltwater (seawater). Furthermore, cyanobacteria can utilise wastewater including agricultural runoff, sewage/municipal and mixed waters mitigating the need for fresh water. Water can also be recirculated in the bioreactor.

Water quality Impact: Cyanobacteria have already been shown to effectively decontaminate agricultural runoff contaminated with different types of pesticides commonly used for various crops. We have successfully demonstrated the removal of nitrates, phosphates, and pesticides from wastewater from rice cultivation (Castellanos-Estupiñan et al., 2022). Enabling the treatment of wastewater for optimal discharge, and the bioconversion of the pollutants toH_2.

Air quality Impact: Cyanobacteria convert CO_2 to H_2 ; therefore, our process will reduce GHG emissions improving air quality, furthermore our strains can also utilise both SOx and NOx, groups of gases that are mainly formed during the combustion of fossil fuels. Both are harmful to human health.

Biodiversity Impact: Our approach will not encroach on precious natural habitats being located at established steel operating plants and brown field sites, our impact on biodiversity will be minimal.

Improved resource efficiency: Biorefinery approach allows for further productivity, including 2,3 Butanediol, which can be utilised as a coating product in the steel industry. Omega threes for health applications and through the recovery of spent cyanobacteria for use as a biofertilizer or animal feedstock.

7 PHASE 2 - Commercial Plan

7.1 Target market for the innovation detailing its size and nature.

We have focussed our commercial plan on two opportunities: systems for the steel industry, and systems for energy.

7.1.1 Systems for Steel Industry

We have continued our dialogue with Celsa, a multinational European steel manufacturer with interests in decarbonising their processes. Celsa uses electric arc furnace (EAF) technology to produce steel for construction and automotive applications. The EAF process can be decarbonised by using H_2 as a reducing agent. In fact, Volvo's recent initiative to produce a vehicle from zero-carbon steel shows that the foundation industries are pivoting to H_2 and the EAF process. Our competitors, who manufacture H_2 via electrolysis and/or treatment of waste (municipal solid waste and plastics, for example) require expensive thermolysis or thermo-catalytic processes. 17Cicada's technology is unique in that it utilises CO_2 as a feedstock - this enables a more environmentally benign and catalyst-free pathway to zero-carbon metallurgy.

Celsa remains interested in the 17C H2 BECCS technology if we can de-risk it by successful scale-up in Q2 and Phase 2. Celsa have offered advice and expertise to evaluate the zero-carbon steel opportunity during Phase 2. In addition, we have recently opened a dialogue with Tata steel, who have expressed an interest in our H2 BECCS Technology including for piloting at one of their UK sites. Tata Steel Europe have commented publicly *the question is not whether hydrogen will play a role, but when and under what condition*, and forecast the availability of large-scale H_2 use in the steel industry from approximately 2040.

Green hydrogen's role would only be assured if it can be provided "competitively" at around USD $2/kg, which would contribute to the overall production cost of green steel rising by 15-20% to around USD $100/tonne. This would be recouped via green premiums on decarbonised steel

7.1.2 Systems for energy,

17Cicada is evaluating a ground-breaking concept in partnership with Star Scientific, based in Australia. The idea is to produce H_2 from CO_2, and to feed the H_2 into a mini–Star Scientific reactor which would generate heat of approximately 1,000 to 1,500^{o}C. The heat can be used to power an industrial process; to heat up homes (including off-grid); or to generate electricity (which is the classic application of the Star Scientific system).

Star Scientific has developed a ground-breaking technology for the utilisation of hydrogen. The system comprises a catalytic surface which oxidises hydrogen (to produce water), generating up to 1,500 degrees C of heat in less than 60 seconds from exposure to hydrogen. The technology integrates into the existing grid - by replacing coal as the heat source, everything downstream from the heat exchanger remains the same. HERO, the tradename of the catalyst developed by Star Scientific, is therefore in direct competition with coal – it is designed to produce heat and to replace heat-from-coal when it comes to production of electricity. Star Scientific's largest investor, Monume LLC, has expressed an interest in using our hydrogen to power Star Scientific's technology, and 17Cicada remains in ongoing discussions with Star.

The global H_2 Generation Market was valued at USD £160 BN in 2022 and is forecast to reach USD $264BN by 2027 (CAGR 10.5%). The Market is driven by a shift towards clean energy generation as well as H_2 fuel cell vehicles. The market can by split into portable and on site, with the latter

particularly relevant to 17Cicada's technology. The on-site segment is likely to hold significant market share soon as industry benefits from its cost-effective nature and operational benefits.

7.1.3 Wider market engagement

We are engaging with VCs and stakeholders in the H_2 space so we can understand the market forces and trajectories which are affecting this industry. Our conversations with Soffinova, Fly VC, Compound VC, Black Peak Capital and more have provided us with insights in terms of the reasons VCs are investing in the H_2 space. Many of these VCs have indicated that a shift away from storage and distribution of H_2 is interesting - particularly if the H_2 can used to manufacture key chemicals (like ammonia) or heat and electricity. We are also engaging with companies which have innovative storage and transportation solutions for H_2 (such as Proton Technologies based in Canada). By engaging with Proton and other similar companies, we are hoping to understand where the storage and transportation of H_2 could be economically sound and attractive from an investment point-of-view, and how we could pivot towards supplying H_2 in this space if the need or opportunity ever arises. For the time being, storage and transportation of H_2 are not relevant in our commercial plan, but we consider it important to stay up-to-speed with developments to understand the wider market perspective.

7.2 The intended scale and deployment locations of your innovation

No specific sites have been identified in Phase 1 for deployment of the planned 1,000L photobioreactors in Phase 2: this task is and was always envisaged as being a component part of Phase 2 (see Phase 2 Gantt chart, Appendix 5). As outlined above (section 7.1), we have active dialogues with both steel producers and energy producers who are interested in the technology. Our primary goal is to deploy the photobioreactors in steel plants operated by Celsa and/or Tata steel.

7.3 How the innovation will be commercially deployed at scale beyond Phase 2

to deliver maximum biohydrogen production and biogenic carbon removal, and how this aligns with the UK Government's legal commitment to achieve Net Zero greenhouse gas emissions by 2050.

As described in the Phase 1 technoeconomic analysis (see section 2.2.4.1), post-Phase 2 we plan to deploy a photobioreactor plant producing 38 tonne/day of H_2, sufficient to provide approx. 10% of the H_2 needs of a small steel plant. This greenifying of steel production aligns with the UK Government's Net Zero strategy as outlined below.

In the April 2022 British Energy Security Strategy, the UK Government doubled its 5GW production capacity target to 10GW, with at least half of this coming from electrolyticH_2. The Government also published updates to the Hydrogen Strategy in July and December 2022, which re-affirmed this commitment and set out the Government's aim to have up to 1GW of electrolytic H_2 and up to 1GW of carbon capture, usage, and storage (CCUS)-enabled H_2 operational or in construction by 2025. In December 2022 the Government announced £25 million in funding to accelerate the deployment of H_2 from bioenergy with carbon capture and storage (H2 BECCS), paving the way for a negative emissions opportunity such as the system being developed by 17Cicada.

7.4 Integration with and benefit to the Hydrogen BECCS process.

As outlined above, our proposed photobioreactors are a negative emission technology that is a good fit with the UK Government's H2 BECCS initiative. Reaching the UK's target of net zero greenhouse gas emissions by 2050 means every aspect of the economy must reduce its carbon footprint as close to zero as possible.

But some carbon-intensive industries such as aviation and agriculture will likely always produce residual emissions. The need to counteract the remaining emissions of industries such as these make negative emissions an essential part of reaching net zero by 2050, according to a report by The Energy Systems Catapult.

As well as counteracting remaining emissions, however, H2 BECCS can also help to decarbonise other industries by enabling the growth of a different low carbon fuel:H_2. Our approach also offers an additional value proposition for industry through improved resource efficiency. Carbon capture and utilization from flue gases generated by industrial processes provide the CO_2 feedstock required for our photobioreactors in a resource recycling/reuse loop. The resulting H_2 can then be used to power industrial processes to offset emissions.

A joint Royal Society and Royal Academy of Engineering Greenhouse Gas Removal report, includes research into BECCS, DACCS and other forms of negative emissions in its list of key actions for the UK to reach net zero.