UNIVERSITY OF LEEDS

H2BOOST REPORT

Hydrogen BECCS Innovation Programme: Phase 1 Project closure report

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Preface

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

Lead: University of Leeds (UoL)

Support: Biorenewables Development Centre (BDC), Greenthread Ltd, NNFCC and aardvarkem

Acknowledgements

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Section 1: Introduction

The H2Boost project aims to produce biohydrogen using dark fermentation (DF) from biomass that will undergo pretreatment with advanced oxidation methods. H2Boost comprises a multi-stage process, comprising biogenic feedstock pre-treatment, dark fermentation (DF) to produce biohydrogen with downstream processes for CO_2 capture, storage and use (CCSU). H2Boost will integrate with Anaerobic Digestion (AD) facilities to provide improved AD feedstock, increase biomethane and maximise the CCSU potential through use of the AD digestate as a nutrient feedstock for the CCSU stage. This project's innovation is an integrated system with additional separate innovations at each stage.

The project audited, and mapped underutilised and reliable supplies of feedstocks for production of hydrogen and material were secured for laboratory trials to test feasibility of the process. Various operational conditions (e.g. residency time) assed the effect of pre-treatment on material digestibility and the gas outputs. Through the sequencing approaches, the H2-producing microbes were identified and quantified. The analysis of DF microbial community provided insight into microbial responses to the operational conditions. The downstream processing technologies for the resulting gases (H_2, CO_2) and digestate were reviewed and integrated with microalgal technology. A high value microalgal product could find multiple market applications with high value products such as biofertiliser, biofuel and dietary protein. The H2Boost process was reviewed under techno-economic and carbon life cycle analysis to determine its commercial viability. Detailed engineering design and cost of commercialization was also evaluated.

Phase 1 delivered a feedstock assessment of materials considered suitable and available within England, for use in the H2Boost system. This also included feedstocks currently being used by a variety of AD facilities across England (Fig 1.). The approach to mapping is well understood and has been used for other projects. The aim was to determine overall quantities, accessibility and associated geographical distribution. Feedstocks fulfilling these criteria were located predominantly in the East of England, Yorkshire & the Humber, the East Midlands and the Southeast. Samples of feedstocks were obtained for assessment, and included household food waste, forestry waste, paper, verge grass, poultry litter and feathers, and following initial experiments, pea starch.

Co-location with existing AD mitigates some feedstock procurement risks, which can accelerate deployment but in some cases may lead to reduced scope of feedstock selection.

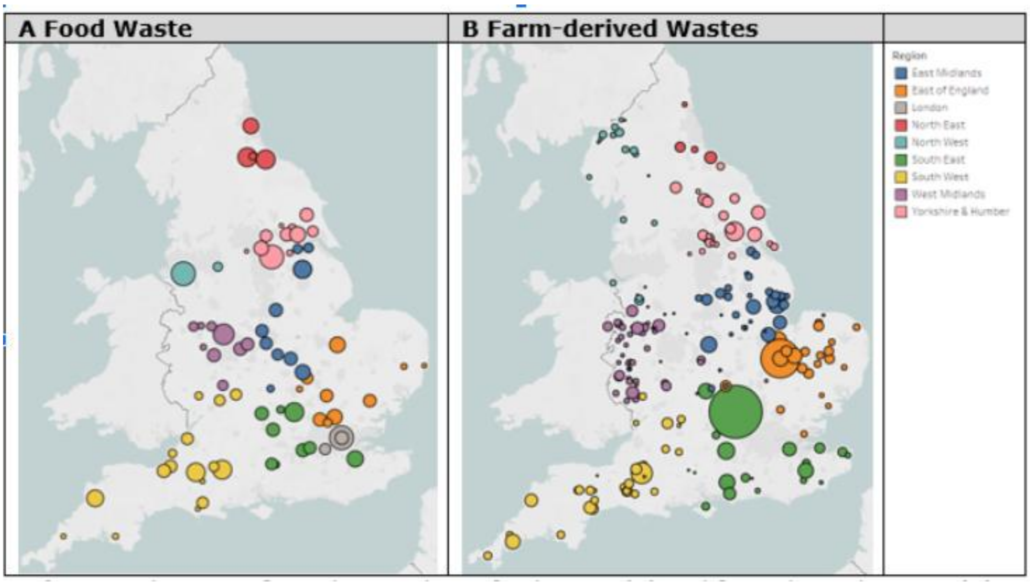

Figure 1 Location Of AD Plants

Fig 1: Location of AD plants utilising food waste (A) and farm-derived wastes (B). The relative size of each bubble is a visual representation of the volumes of waste type handled per year.

Feedstock preparation using the BioBooster system is a novel process, which applies extreme force and a specific chemical process to reduce feedstock particle size. This includes breaking down biological structures to create more accessible sugars for processes such as AD and DF. Use of BioBooster to prepare different feedstocks requires optimisation for DF including material loading and treatment intensity, as well as scale-up engineering. Feedstocks were also pre-treated using a lignocellulose degrading enzyme, both separately and in combination with the BioBooster system.

DF for hydrogen production is a novel application of existing fermentation engineering. The process requires an inoculum enriched for hydrogen producing microbes that can be obtained from AD digestate by inhibition or inactivation of methanogens. Phase 1 of the H2Boost Project assessed differing feedstocks and feedstock preparations, each subject to inoculum treatment, resulting in hydrogen production with a range of performances (high and low hydrogen yields) supporting the principle of hydrogen production, even under un-optimised process.

Microbial profiling of the mixed microbial inocula and DF microbiomes was analysed by amplicon (16S SSU ribosomal RNA) sequencing. This provided assessment of inocula pre-treatment success for methanogen inactivation and has started to inform optimisation conditions for higher performing hydrogen generation. In Phase 1 we showed that microbiomes of DF bioreactors are highly complex and diverse, dominated by members of families *Clostridiaceae, Bacillaceae* and *Lactobacillaceae* - well-recognized contributors to DF microbiomes. Lower hydrogen yields were accompanied by high lactic acid bacteria levels, presumably causing a build-up of lactic acid, leading to a pH drop which negatively impacted on hydrogen producing bacteria. Optimization and management of the inoculum microbial community will be refined during Phase 2.

Enzymes with known lignocellulose degrading capability have been tested to assess their potential to improve hydrogen yield and to understand residence time in terms of production. Early positive results are directing study to achieve improvements with other related existing and novel enzymes. Isolation of these novel enzymes is a specialist area but a known process. However, in-house production at scale for pilot, demonstration and commercial plant will require some scale-up consideration, allowing cost and technology control to be maintained over enzyme supply.

The DF process produces principally H_2 and CO_2 and standard techniques are available to separate the hydrogen. In this case, to meet the requirement of a fuel cell transport fuel, a 99.99 vol% pure hydrogen is required, which can be achieved using Pressure Swing Adsorption (PSA) technology. A further process stage to compress the product hydrogen to 350bar for supply into heavy goods vehicles is to be included. PSA, hydrogen compression, storage tanks and transport vehicle tank filling engineering are specialist technical requirements but commercially available.

The co-product of PSA in this case is CO_2 with traces of H_2, which has potentially beneficial applications, including use; to enhance methanation in AD; or as a carbon source to grow photosynthetic microorganisms including microalgae. Algae production comprises utilising the liquid fraction of process digestate (nutrient source), CO_2/H_2 gas mix arising from the H2Boost PSA stage and CO_2 rich flue gases from the co-located AD plant CHP unit (biomethane feedstock). This novel system approach maximises the opportunity to sequester CO_2 and will involve a specialist commercial partner with photosynthetic biomass production capability for Phase 2, accelerating delivery and reducing scale-up risk, Fig 2.

Figure 2 Algae CCSU System

The H2Boost project will use organic waste as feedstock and hence, it is structured to integrate with AD plants to meet waste management targets. In addition, energy demand for the H2Boost project can be satisfied with the supply of electricity from the

AD CHP system, using biomethane as fuel feedstock. The targeted enhancement in biomethane yield will deliver a net gain after delivery of internal energy demand.

Phase 1 of this project has delivered hydrogen yields in line with the high end of performance expectations (Habashy *et al*., 2021; DOI: 10.1016/j.tibtech.2021.04.001) for an unoptimised system. For example, household food waste yielded an average of 80 L H_2 / kg volatile solids through unoptimised DF. The use of microalgae for biological carbon uptake delivered harvested algal biomass with 50-55% carbon content at a rate of 125g/m3 day, which is in line with assumptions used in project mass balance and LCA.

For Hydrogen BECCS commercialisation, the H2Boost system is initially targeting co-location of processing equipment with AD facilities processing food wastes. The food waste processing AD facilities are typically the largest scale sites and in sum consume the greatest proportion of AD feedstock in England. 15.8 Mt per annum total over 358 facilities of which 101 are municipal, commercial and industrial waste users consuming around 10 Mt per annum of waste. 77 facilities process food waste with an average scale of 47kt per annum (128t per day) input (https://www.virtualthymeregion.com/maps). Phase 2 will optimise the H2Boost system for co-location with AD with initial feedstock input testing to utilise an existing food waste AD plant of a similar scale to average. This approach provides an accelerated delivery pathway for Hydrogen BECCS at commercial scale. Further optimisation for other identified hydrogen yielding feedstocks, will provide confirmatory operational assessment for co-location with more operational AD systems and potential for new standalone projects, providing further potential for Hydrogen BECCS delivery.

Each 128t per day AD facility would deliver around 197 kg H_2 per day, and with the algae CCSU, would deliver in the order of 8.5t per day of CO_2 capture, based on Phase 1 findings. In a commercial system there would be lower in-service operational performance, which will be explored during phase 2.

Additional biomethane production in the form of increased yield and biogas quality is expected from the provision of an AD-ready feedstock from DF (high VFA content) and injection of a CO_2/H_2 mix from the PSA unit. 50% increase is the aim for the technologies tested.

Economic assessments for Phase 1 assumed no policy incentives, to determine the baseline financial capacity of H2Boost. The project demonstrates potential for good financial performance but may need to explore the, now available, government support for bio-hydrogen to achieve investor acceptance of this first of a kind (FOAK) asset. Phase 2 will provide evidence of potential for improvements to this case.

Phase 2 refinements, including performance trials, will secure operating data to support mitigations available for asset integration risks.

Section 2: Carbon Life Cycle Assessment

This multi-step integrated process combines novel pre-treatment processes with a novel dark fermentation process to produce hydrogen, the by-products of which feed into a conventional anaerobic digestion system producing biomethane that can be used to generate heat and power for the system as a whole and export surplus biomethane to the grid. The process therefore generates both hydrogen and biomethane as energy outputs and provides synergistic opportunities for exploitation of the carbon contained in organic waste feedstocks to deliver low carbon outputs. Such a system also offers several opportunities for carbon capture in concentrated forms from tail gases from both hydrogen and biomethane upgrading operations (where CO_2 is the main co-product) and from less concentrated flue gas streams (the CHP system linked to the AD process). These streams can be captured via geological sequestration or as tested in Phase 1, on a lower energy basis via capture via algal biomass, with opportunities for circular production of biomass as a supplementary primary feedstock input.

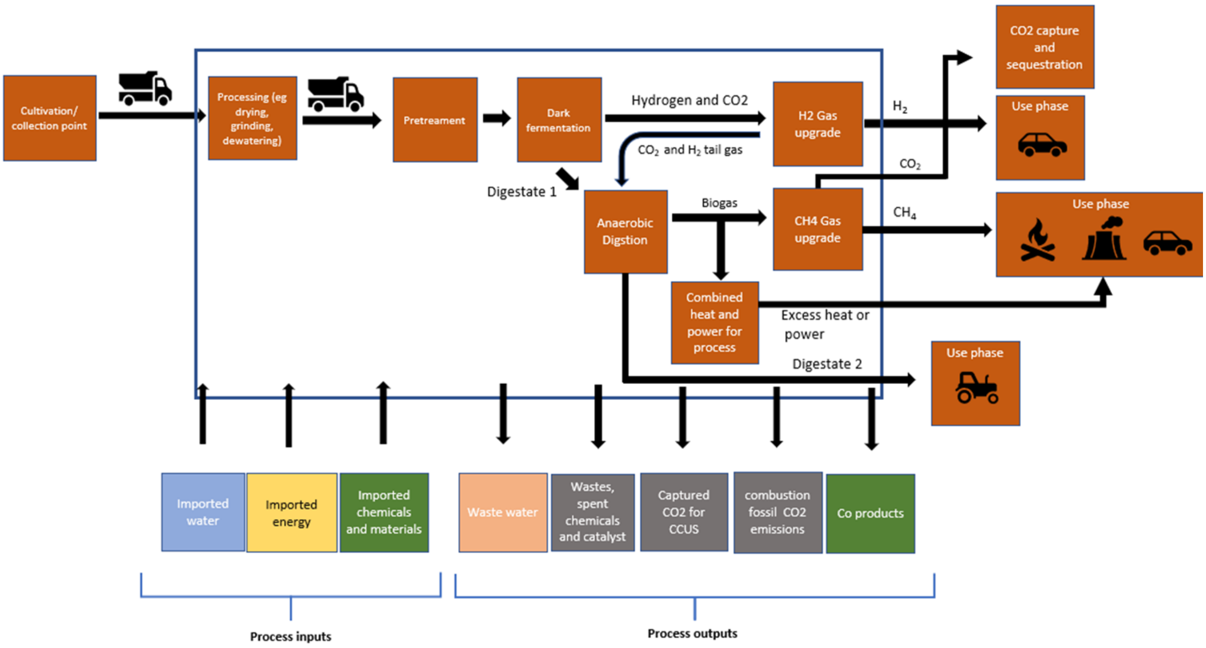

Figure 3 Integrated process supply chain for dark fermentation and AD and main process flows within the scope (blue box) of the analysis

A ‘well to tank’ GHG assessment was used to examine the GHG impacts of organic waste-derived biohydrogen and biomethane production, both separately and as an integrated process. Material flows and energy balances were modelled for the system focussing on the impacts of producing 1kg of H_2 for use in transport applications. Data collation was based on literature values, assumptions drawing on existing knowledge of systems and feedstock performance amended with laboratory findings from the project where available. All upstream emissions in each case were allocated to the energetic product in question and not allocated to digestate outputs and exchanges. The mass balance model was optimised such that internal biomethane use was optimised to just deliver against the internal heat demand, which results in a small net power import demand. The main input to all processes is electrical power. It was assumed that net grid input was applied proportionately to each process requiring power input.

In the absence of carbon capture the dark fermentation process can deliver compressed hydrogen suited to use in transport at a base GHG emissions index of around **1.6kgCO_2/kg H_2** in combination with anaerobic digestion. Where sources of CO2 were also captured from hydrogen upgrading, this delivered **net GHG impacts of -6.7 kgCO_2/kg H_2.** Where CO2 was captured from biomethane upgrading this delivered **net impacts of -1.4 kgCO_2/kg CH_4.**

Allocating all the savings to hydrogen alone delivered GHG savings of **-21kg of CO_2 per kg of hydrogen produced,** Annex 1.

Most hydrogen is currently produced from steam methane reforming (SMR) of natural gas which delivers hydrogen with net positive GHG emissions ranging from 7.4 to 11.1 kgCO_2/kg H_2. This can be reduced to 1.2 to 3.9 with industrial carbon capture technologies. Green hydrogen from electrolysis also delivers hydrogen with a net GHG positive emission of around 1 kgCO_2/kgH_2 or less.

H2Boost therefore has the potential to deliver very low carbon hydrogen to levels much lower than that seen with technologies currently moving towards initial stages of commercial deployment.

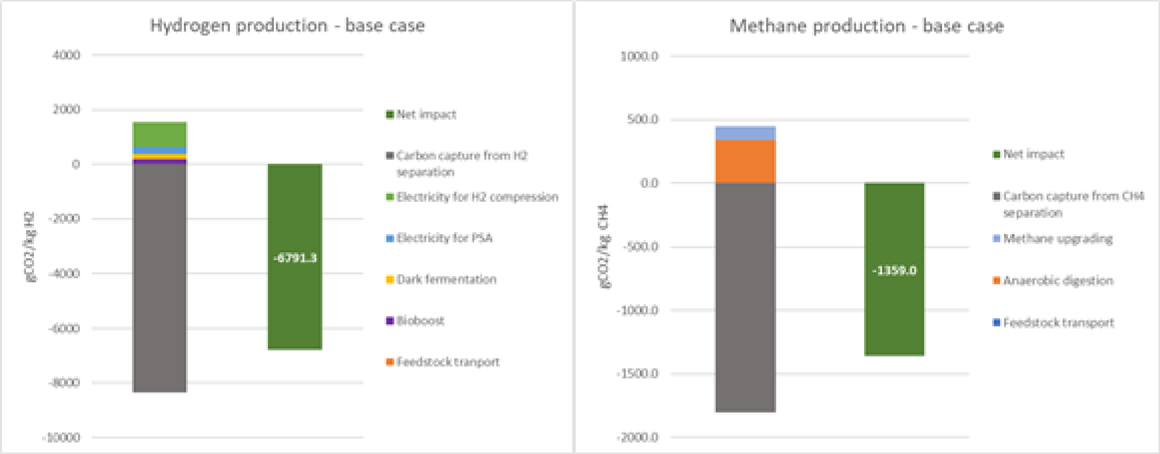

Figure 4Actual and net GHG impacts of hydrogen and biomethane co-production in the H2Boost system

The feedstocks of interest for the H2Boost technology are primarily organic residues (mixed food waste for the base case), which means their production does not have to comply with regulatory or compliance sustainability requirements. Any lignocellulosic residues (agricultural and forest) or crop feedstocks to be considered for use in future would have to comply with criteria to ensure legal harvesting, forest regeneration and maintenance of soil carbon. For instance, any crop residues (excluding processing residues) would have to comply with soil carbon criteria (to ensure soil carbon levels are maintained) and land criteria (to ensure these are not sourced from areas of high biodiversity).

Phase 1 identified a range of feedstocks available in significant quantities which could be considered but some materials, such as straw, have existing competing demands and these will not be progressed to Phase 2 of technology commercialisation. In most cases, feedstock contracting strategy will be as important as conversion to hydrogen, which is a key work package for Phase 2.

No virgin crop feedstocks are being considered for use with the proposed process in the continuing phases of this development (based on an existing food waste AD processing facility) so there are no direct or indirect land use change considerations which primarily affect use of virgin soya and palm products.

Section 3: Detailed Engineering Design

Phase 1 findings and hydrogen outputs are promising with clear optimisation potential. The initial stages of scale-up comprise DF optimisation at lab (0.5L) and bench (10L) scales, which also includes preparation of inoculum for the larger scale trials (pilot scale). The first significant scale-up will be to a pilot system comprising: 80L DF and 800L AD, inclusion of biological carbon sequestration using microalgae for CCSU and use of a single full scale BioBooster feedstock preparation module (1m^3/hr max treatment rate). The integrated operation will be optimised to inform process conditions and final design for a larger demonstration system capable of accepting 15 t per day feedstock input capacity. In particular, startup and running conditions along with an optimisation programme will be finalised at the 80L DF scale.

Engineering designs have been completed for the pilot and demonstration plants. The pilot scale plant will be based at the Biorenewables Development Centre, taking advantage of the co-located biotechnology resources and capabilities. A design and feasibility study have been completed for the demonstration plant, which considers a specific operational AD site in North Yorkshire. The demonstrator design comprises process design, layout and site integration including initial HAZOP stage.

The design approach has considered the processing stages activities with scaling and optimisation to be based on Phase 1 laboratory and research findings to be further informed by Phase 2 lab scale activities which utilise flexible arrangements for testing feedstocks and process conditions at the Biorenewables Development Centre. The DF stage testing will comprise multiple batch 0.5 L gas-tight, stirred digestion vessels, connected to evolved gas volumetric measurement systems, from which samples will be taken for gas composition analysis by gas chromatography (GC). Inocula will be prepared by heat-treatment of AD digestate using a standard lab autoclave, and will be characterised by DNA sequencing using third-party analysis. DF vessels will be fed using feedstock pre-treated by a lab-scale BioBooster system and/or enzymes. Enzyme pretreatment will be carried out at enzyme-specific temperatures in stirred reaction vessels. Sugar profiling of pre-treated feedstock will be by HPLC; other feedstock and digestate characterisation will be via Hach spectrophotometric analysis.

Following initial optimisation at 0.5L scale, 10L gas tight, stirred DF systems will be used to assess feedstock loading, feeding rates, etc., in a semi-continuous process at bench scale. Evolved gas composition analysis will be in-line or via sampling and GC analysis. Inocula and feedstocks will be prepared as above. DF residues will be tested for biomethane potential using 0.5L digestion vessels, and gas volume and composition assessed as above.

DF residues from 10L digestions will be used as the inoculum for 80L DF activities (pilot scale). Feedstock will be enzyme treated, and/or using a single full scale BioBooster treatment module.

As the next stage of demonstration, the pilot scale installation will be installed, allowing rapid trials with a wide range of feedstocks. An 80L DF digester was selected and the design developed will enable off site construction, including housing of the digester within a standard 20ft ISO container. The design concept has feedstock being prepared separately, with treatments selected to match these physical properties. Within the process container, all pumping pre-treatment will be performed by a 1m^3/hr BioBooster unit, monitoring and measurement will occur, with the DF digestate being passed forwards to an adjoining 800L AD unit from which final digestate will be discharged to an adjoining external vessel for transport to other facilities or disposal.

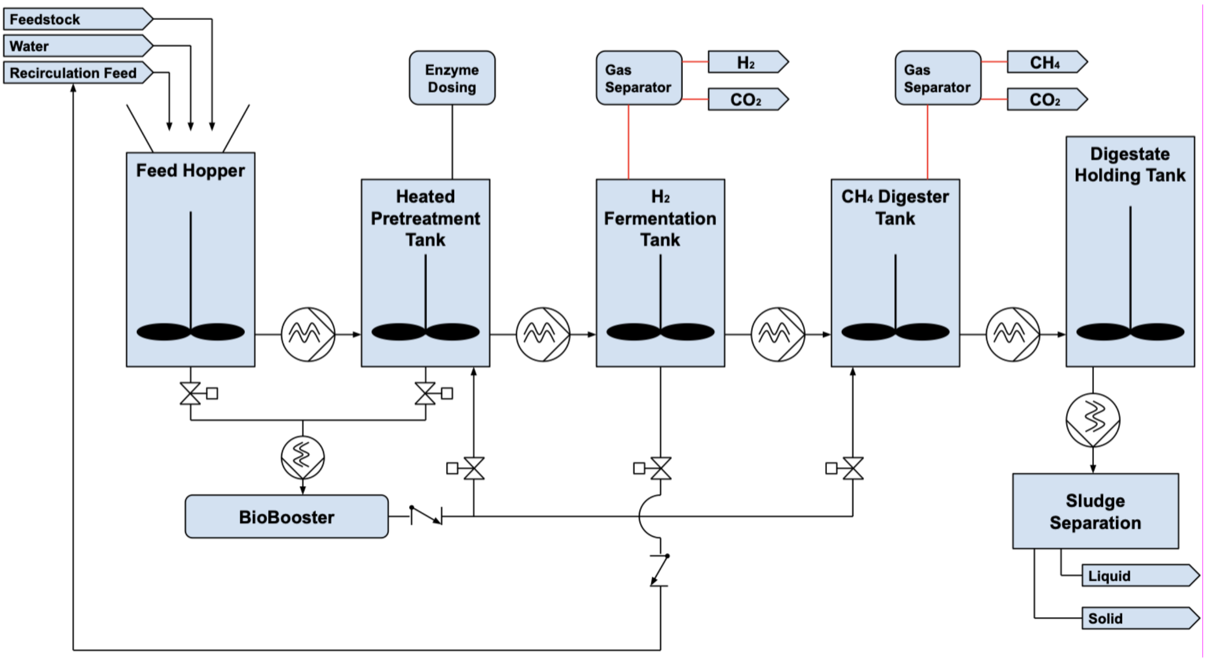

Figure 5 Pilot Plant Process Flow

The demonstration plant design (Fig 5) encompasses the process flow, control and instrumentation designs, equipment list, civil/structural design requirements and modifications required. In addition, the outline mechanical specifications for key equipment have been identified and required safety studies undertaken. This design has provided an estimation of the capital cost for the demonstrator plant, along with operational costs.

The H2Boost Phase 2 engineering designs, delivery and operations costs are within the Phase 2 budget constraints. The Phase 2 programme is shown at Annex 2 and associated risks are considered within the risk and mitigations plan at Annex 3.

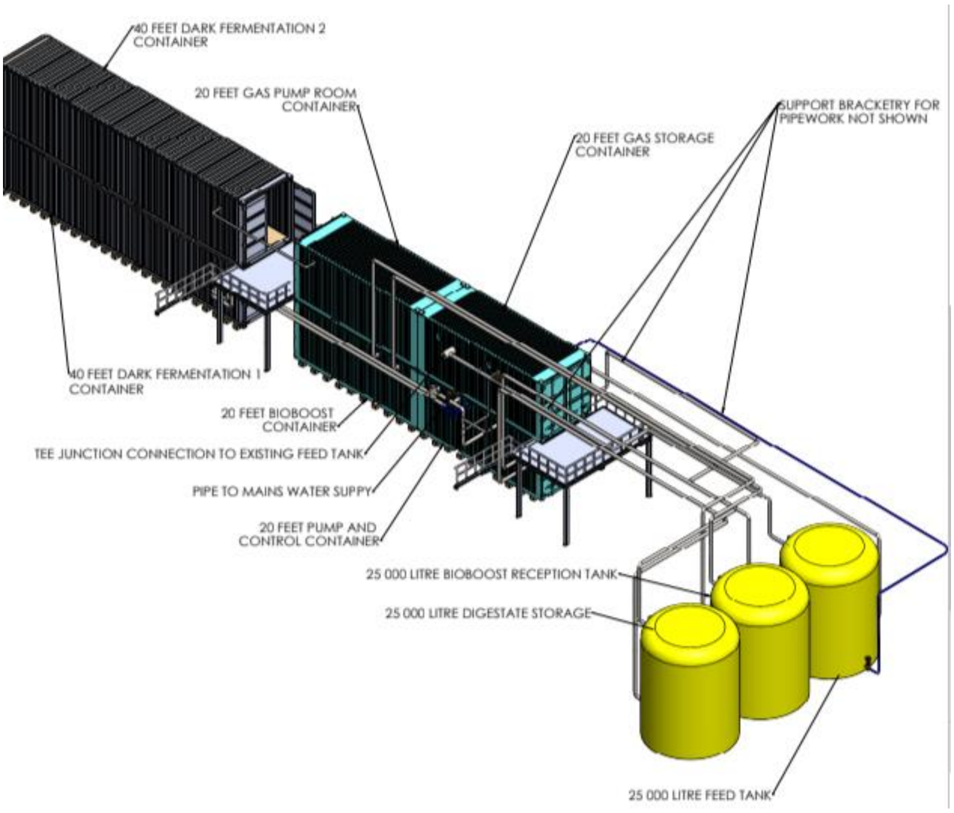

Figure 6 demonstrator Proposed Plant Layout

Section 4: Testing the Innovation

The Phase 1 trials demonstrated the capacity to produce biohydrogen at lab scale from a range of waste streams, including mixed household food waste, paper waste and pea starch, although it is clear that the process requires optimisation to maximise biohydrogen yield. This will be the focus of the initial trials in Phase 2. Areas such as feedstock pre-treatment (process intensity and solids loading) and the use of potentially novel enzymes will be tested in dark fermentation (DF) using multiple 0.5L batch vessels to advance optimisation of feedstock preparation. Running alongside will be the preparation of optimised inocula corresponding to feedstock type.

These pre-treated feedstocks and processes will then be transferred to 10L semi-continuous DF scale to optimise feeding rates during a continuous process, as well as assessing the impact of sparging during DF. Analysis of the microbiology of the systems will allow us to determine the robustness of the inocula throughout the process and how they refine over extended semi-continuous DF runs.

The residues remaining from DF at 10L scale will be used for two purposes: assessment of subsequent biomethane generation, and as the inoculum for the 80L semi-continuous DF vessels.

Assessment of the biomethane potential of DF residues at 0.5L and 10L scale will be carried out by co-digestion with feedstocks and digestate from the partnering AD plant, to mimic as closely as possible the impact that the addition of DF residues may have to their system at demonstration scale. This is an important de-risking step and an assessment of any beneficial or problematic impact will be made, resulting in an evaluation of the maximum amount of DF residue transfer possible to the partnering AD plant's AD vessels. This information will be confirmed during the larger scale trials at 80L DF into 800L AD.

Carbon dioxide capture using biological processes was tested in Phase 1, where 2L photobioreactors (PBRs) were used to assess the potential performance of green microalgae for biological carbon uptake. In Phase 2, bench scale (2L PBRs) units will also be used to define process conditions under a more realistic scenario (non-axenic conditions) using digestate liquor (nutrient source) and CO2 (carbon source). Several 2L PBRs will operate in batches using strains of Chlamydomonas and Cyanobacteria to identify biomass growth kinetics and carbon uptake rates. In each test, the liquid in the PBRs will be characterised over time for organic matter (COD - Chemical Oxygen Demand and C), nutrient (N and P), alkalinity and biomass (Volatile Suspended Solids; C, N and P) content; pH, temperature, Dissolved Oxygen and Redox potential (ORP) will be monitored over time. Results will be processed to calculate biomass growth and carbon uptake kinetics and inform the development and calibration of a numerical model to predict the performance of PBRs under continuous flow conditions. Predicted conditions will be validated at the same bench scale, where 2L PBRs will operate under continuous flow conditions to define key operational criteria including: CO2 saturation in digestate liquor, photoperiod, hydraulic retention times, cell retention time, digestate dilution and biomass (carbon) production rates. The validated computer-based model will be used for the design of a pilot-scale 200L photobioreactor for biological carbon capture using photosynthetic microorganisms.

At pilot scale, the 200L PBR will be fed with the digestate liquor from the 800L anaerobic digester and tested over a one-year period to assess seasonal variations and performance. At this scale, feedstock pretreatment, DF, AD and CCSU will be assembled for the first time. Designing capacity flexibility between stages enables operational turnup and turndown to determine the highest yielding operational conditions.

Phase 2 scale up to 80L DF will require feedstock procurement, supply and on-site safe handling to provide the input materials for optimisation. The process will require appropriate permits and licences including planning permission, environmental permit and waste handling and management licences.

The Phase 2 project budget and programme include the cost of securing permits, licences, material procurement and handling, along with capital, maintenance and operation costs. The cost of relatively small quantities required for initial 80L scale-up will reflect the special order requirements of the project and be higher than typical market rates for materials. For this procurement, a target feedstock specification will be established for each material to represent the market qualities available. Project partners are exploring inclusion of a feedstock supplier, which will be one of; a waste management company, a local authority or specialist trader.

The Phase 2 demonstration unit has been designed to complement an existing AD plant where feedstock procurement and compliance will be a role for the plant operator. The demonstration plant will use a proportion of total plant feed (c.20%).

Phase 2 demonstration scale co-location with an existing AD plant will reduce programme risk associated with requirements for feedstock procurement, licences and consents. Generation of hydrogen via DF as an integral part of existing AD facilities minimises risks relating to the development of a new site, feedstock supply, permits, consents and licences. The demonstration plant will provide data to support pilot and lab scale results using operational aspects for the scale-up process.

The prospective AD site partner is also exploring conversion of their existing diesel fuelled HGV fleet to use alternative fuels including biohydrogen, which would offer H2Boost a direct sight to a prospective hydrogen customer and a site specific ‘well to tank’ GHG assessment.

Phase 2 Programme

Feedstock Preparation

BioBooster technology is designed to impact key barriers common to wet digestion processes; their relatively low processing capacity, high operating costs and low hydrogen yields. Phase 1 testing demonstrated areas and feedstocks where BioBooster, using unoptimized operating conditions, delivered enhanced hydrogen yield. Process condition optimisation to achieve elevated hydrogen yield across a wider range of feedstock and subsequent AD methane yields, with increased rates of generation, will be explored further during Phase 2.

At each step in the scale-up during Phase 2, feedstock pretreatment using the BioBooster will be optimised to maximise biohydrogen production and increase digestion rates in DF and AD, establishing a library of process settings for tested feedstocks. This will include optimising co-treatment protocols with yield enhancing enzymes.

Optimising operating conditions to reduce feedstock viscosity whilst maintaining production enhancement aims will lead to energy reduction in pumping and mixing within digester systems. This will also provide evidence for elimination of other less efficient feedstock pre-treatment processes. Other effects will be examined, including, reduction in final digestate solids, process foaming and feedstock condition effects on plant availability more generally.

Existing and novel enzymes: The ability to release sugars and nutrients for microbial growth and biohydrogen production during DF is crucial to the success of the process. The enzyme used during Phase 1 (supplied by Verdant Biotech) will be used as a baseline in Phase 2 and compared with other commercially available hydrolytic enzymes, such as those supplied by Novozyme or Creative Enzymes, as well as novel enzymes identified by the University of York. Research led by Professor Neil Bruce *et al* in the Centre for Novel Agricultural Products has identified lignocellulose-degrading microbial communities from which novel enzymes are being identified (bit.ly/3FPwNBY; bit.ly/3WjSW2l). The BDC has experience in producing such enzymes and can produce batches at scale if considered useful for the larger scale work in Phase 2.

Dark fermentation: An important aspect of successful DF is the preparation of suitable inocula, matched as closely as possible to the main feedstocks under assessment. The development/optimisation strategy will build on Phase 1 activities, which confirmed that pre-treatment of the inoculum is essential for high biohydrogen yields. Methane production is a frequent concern in DF systems due to the presence of methanogens in the inoculum. In Phase 2, we will optimise reduction of the methanogen load in the inoculum to enrich hydrogen producing bacteria. Inocula pre-treatment approaches will include aeration, freezing, thawing, heat, and ultraviolet irradiation, in addition to acclimatising the inoculum to the feedstock. High throughput sequencing and performance at lab-scale (0.5 L reactors) will measure the abundance and activity of methanogens and hydrogen producers, and the optimal inocula will be preserved and used for seeding DF bioreactors.

An initial assessment of pre-treatment success and co-digestion potential will be carried out using multiple 0.5L vessels using a matrix approach. As trials move to 10L scale and upwards, we will assess feedstock loading and feeding rates in a semi-continuous process, to evaluate residence time vs H_2 production, building in scale with feedstock pretreatment activities. Outputs such as hydrogen, methane, carbon dioxide and VFA intermediates will be measured, as well as total organic carbon, total nitrogen, ammonia and phosphate levels.

High throughput sequencing during DF runs will link the dynamics of the microbial consortium with hydrogen yields, informing on any imbalance or potential for improving yields. Knowledge and learning from these lab to 80 L-scale activities will inform processes at demonstration scale at the partnering AD site.

Anaerobic digestion: Running alongside DF optimisation activities will be the evaluation of residual DF material in anaerobic digestion. Since residence times are anticipated to be short for DF (3 - 5 days), residual material contains valuable resources representing suitable feedstock for AD. Trials at lab to 80L DF scale will include a subsequent 800L AD step using the DF residue as a supplement with the partner AD plant's own feedstock and digestate. This will establish any potential impact on anticipated biomethane production and advise on feeding rates and incorporation at demonstration scale. Outputs such as methane, carbon dioxide and VFA intermediates will be measured, as well as total organic carbon, total nitrogen, ammonia and phosphate levels.

Gas separation: Out of the technologies reviewed in Phase 1 for the biohydrogen produced by 'bio-boosted' dark fermentation and the CO_2 generated as its by-product, only Pressure Swing Adsorption are commercially mature enough and able to deliver the required purity of 99.99 vol% H_2 for its use in zero emissions transport (PEMFC based), while at the same time being compatible with the CHP-equipped AD plant facilities already in place. PSA also claims the highest H_2 recoveries for this purity of product (ca. 80%). PSA off gas from the H_2 produced by dark fermentation will therefore contain CO_2 but also ca. 20% of the total H_2 produced. This presents an opportunity for various integration options of carbon utilisation to be explored in Phase 2 with a view to provide more favourable Life Cycle GHG emissions than the scenarios explored thus far in Phase 1. For instance, H_2/CO_2 PSA off gas mix can be used as methanation supplement and feed for bacterial growth in the local AD plant, As the local AD plant to which H2Boost will integrate is already equipped with biogas clean-up, (this removes all impurities apart from CH_4 and CO_2), followed by upgrading (CO_2 separation from the CH_4), and also features an internal combustion engine based combined heat and power (CHP) unit, another opportunity for further CO_2 utilisation is in the form of post-combustion technology, applied to the flue gases generated by the CHP unit. The CO_2 captured post CHP would be used to stimulate biomass growth and enhanced metabolism in the proposed CCSU unit based on the use of photosynthetic micro-organims. An alternative integration option of the off-gas from the PSA unit servicing the DF unit will be to use it directly in the CHP unit as a hythane fuel, where the CO_2 in the gas mixture can be used to lower the combustion temperature and act as a low NOx measure (similar to exhaust gas recirculation) necessary to counterbalance the NOx enhancing effects of the high temperature hydrogen combustion. Alternatively, the CO2/H2 mix from PSA can be injected in the AD reactor to boost methane production.

Best use of the high purity H_2 product from H2Boost is expected to be its compression to 350 Bar, and storage in cylinders for downstream use in mobile PEMFC applications closest to the plant, but alternative scenarios of the H_2 use will be explored further in Phase 2 by use of process modelling and LCA.

Section 5: Project Planning

Project management (including project team and key suppliers)
Phase 2 of H2Boost project will see the team expand from Phase1. All partners and subcontractors will add value to the project through their expertise and/or facilities.

H2Boost Phase 2 will be led by Associate Professor Dr Miller Alonso Camargo-Valero, at the University of Leeds (UoL), with his research team. Dr Camargo-Valero is water@leeds Associate Professor of BioResource Systems and leads the BioResource Systems Research group at Leeds. UoL will lead the project and bring their expertise and facilities in DF, biohydrogen biomethane and algal carbon uptake to the project. The BDC will bring its expertise and facilities in AD and microbial optimisation, spatial mapping and will again manage the project. The University of York will provide expertise in enzyme development and AD research through Professor Neil Bruce and Professor James Chong. Greenthread has developed the BioBooster, an innovative technology which will be tested and optimised for hydrogen production through dark fermentation in this project. aardvarkem bring their expertise in the design, development and build of commercial plants. Their expertise in the designing and delivering of AD and energy facilities is essential to the project. NNFCC and consultant Chris Corner (CM90 Ltd) will again provide the LCA and TEA expertise throughout the project to ensure H2Boost is delivering a sustainable and realistic option to produce Hydrogen and capture carbon. For Phase 2 a larger scale plant is required to demonstrate the commercial viability of the project. The team is in discussions with a commercial AD provider to provide the location for the demonstration plant.

Timelines for deliverables.
Phase 2 Programme is shown at Annex 2 and outlines the staged approach to building capacity against a programme of process and feedstock testing, optimisation and enhancements. The H2Boost Phase 2 has been broken down into clear work packages starting with functional laboratory testing at 10L scale, where the results from Phase 1 will be optimised further and continuous testing will begin. This then will inform further functional continuous testing at the 800L AD scale. Once this has been optimised and proven, the performance testing will take place at the demonstration scale. This will run continuously for over 1000 hours. Work packages 6 and 7, will run alongside all of the optimising and testing work packages, delivering a comprehensive commercial strategy.

Risks and risk management.
Project risks have been identified and reviewed as Technical, Commercial, Financial, Regulatory, Health Safety & Environmental. Phase 2 project comprises a sequence of scale up optimisation steps which together carry a programme risk which in turn affects all risk areas. A full risk table is available in Annex 3.

Quality assurance.
All partners have a comprehensive and considered approach to quality assurance. This includes, but is not limited to, the following: Standard Operating Procedures covering equipment use and processes, and comprehensive risk assessment and COSHH, DSEAR etc. In addition, the health and safety requirements of processes are reviewed after any modifications. Equipment is maintained appropriately and calibrated, and standards are used where applicable (e.g. for chemical identification or quantification). Processes are reviewed for compliance with the Environment Agency, local authorities etc, as applicable, and permits sought when required. Data is captured and stored securely, with backup systems in place, and shared between project partners under a confidentiality agreement. Financial claims are supported with detailed evidence, timesheets, invoices and receipts. The engineering project management will follow the established processes and procedures by the engineering supply companies.

Project oversight and governance.
The H2Boost project will build on the successful Phase 1 BEIS SBRI funded project. The University of Leeds will lead the project, with their expertise in Hydrogen and Carbon Capture. The BDC will again provide the project management across the whole project, liaising with the consortium partners and subcontractors throughout. The project will hold monthly meetings internally and with BEIS. There will also be work package sub groups established to manage the various work packages.

Reporting
H2Boost will report monthly to BEIS and the monitoring officer to ensure BEIS are informed and updated on progress of the project and on the deliverables and finances. We will produce a detailed quarterly report for BEIS. There will also be an annual site visit by BEIS. The team will also produce interim and final reports for all the work packages, under a BEIS approved project plan. There will be weekly technical calls to discuss the progress of each of the work packages and monthly meetings to assess the overall progress of the project and ensure the timescales and milestones are being met. The project manager and PI will work closely together to ensure the smooth running and successful delivery of the project.

Disseminating results and key learnings
Towards the end of the project, there will be a dissemination event to the AD industry and relevant industries. The successful results of the project will be made available on the University of Leeds and BDC websites under the project page. Interaction with BioVale AD Special Interest Group and the Biomass Biorefinery Network (BBNet) will

provide a dissemination route. They host frequent events for their memberships so could host the proposed dissemination activities. There will also be outreach opportunities through the BDC outreach centre and training will be available to address the skills gap.

Section 6: Target Markets

Hydrogen

Global hydrogen demand of c. 91m tpa, is satisfied to c. 99% with production from non-renewable sources, as of end of 2022. Production principally uses fossil origin methane which is reformed and converted mainly into ammonia and methanol. Hydrogen produced by electrolysis or from bio-feedstocks is attracting significant investment to displace fossil origin materials and to support its use in fuel cells for transport applications. With fossil based hydrogen pricing at around $2-4/kg and renewable hydrogen currently with costs above $6/kg there are value based commercial challenges to overcome with users. To overcome this, while technology develops, UK Government support for hydrogen is in place via its Low Carbon Hydrogen Business Model contracts.

The UK Government is supporting development of local supply chains for zero emission Hydrogen to be used in vehicles, typically heavier where an advantage exists versus battery technology. The UK Government’s Hydrogen Strategy projects annual demand for hydrogen in transport applications of around 6TWh (152kt) by 2030, 20-45TWh (0.5m-1.1m t) and around 140TWh (3.5mt) by 2050. H2Boost is configured to supply into the emerging and growing demand projection.

Carbon Capture and CO2 Market

The H2Boost project produces biogenic carbon dioxide (bio-CO_2) during hydrogen production and at the associated AD energy unit using *in situ*-generated biogas as renewable fuel. A carbon capture element for the CO_2 arising from hydrogen and energy production is integrated within the H2Boost process. This unit uses photosynthetic microorganisms able to take up inorganic carbon (CO_2) and convert it into biomass (biological carbon capture). For carbon sequestration purposes, the resulting biomass can be stabilised with lime (Calcium hydroxide - Ca(OH)2)), which is added to raise the pH of the biomass to 12 for 2 hours; then, the pH is subsequently maintained at more than 11.5 for 22 hours. This option provides a safe route for carbon sequestration as any potential release of CO_2 afterwards can be rapidly transformed into calcium carbonate. Stabilised biomass can be permanently stored in abandoned limestone quarries or used as a raw material in other industries (i.e. sewage sludge stabilised with lime has been used for producing cement clinker, with a net reduction in carbon emissions by 38.5% to 51.7% - Ping et al., 2020).

However, there are additional opportunities arising from the production of nutrient rich biomass (aprox. 50% C; 10% N; 1% P), as the global supply of industrial fertilisers is now facing pressing challenges related to their dependency on fossil fuels (nitrogen fertiliser production) and access to finite raw materials (phosphate rock for P fertiliser production). The production of fertilisers from alternative raw materials (nutrient rich biomass) is a viable option to help achieve net zero targets in the UK’s agriculture sector.

The system is to be designed to capture in the order of 8.5t CO_2 per day (3,100t per annum) at each H2Boost co-located AD project. With carbon markets evolving on a more global basis as demonstrated by the formation of the G7 Carbon Club (12 Dec 2022), with a secretariat to be held jointly by OECD and IEA, this has ambitious goals of aligning carbon metrics, policies and setting a global minimum carbon price. With this alignment, securing carbon capture will be increasingly valuable in the future, whether financially in the form of accessible traded certificates or as contribution to the overall national and global aims for net zero.

Section 7: Commercialisation

The technology is aiming initially to co-locate with existing AD plants, the average operational scale for a food waste AD unit is around 130t per day feedstock input rate. The right-size H2Boost system would accept all feedstock and process through the H2Boost system, ahead of DF digestate supply to the co-located AD plant, taking up to 100% of the total plant input, with a target to exceed this by up to 50%.

The Phase 2 pilot and demonstration plant size selection is based on the pathway to achieving full commercial scale at the equivalent scale to a large AD facility. An AD facility consuming 150t per day of feedstock is the co-location prospect for Phase 2 and which will provide 10% of its feedstock (15t per day) to the H2Boost demonstration plant. This will demonstrate operational performance within a commercial scale environment. Further scale-up to commercial operational size does not represent significant engineering change. Confirmation of operational performance and acceptable economic case during Phase 2 is expected to lead to deployment of the technology at industry scale which will require a deployment of a first full commercial scale plant.

Application of H2Boost alongside existing AD plants, including the BECCS, is designed to produce hydrogen with a net zero emission factor. This is in line with the UK Government’s legally binding goals to achieve net-zero by 2050 and in this case to supply hydrogen which is transport fuel ready.

The Low Carbon Hydrogen Business Model (LCHBM) includes support for biobased hydrogen. Phase 1 feasibility has taken a market-oriented approach, based on a noincentive assessment. Indicative returns, assessed during TEA and Feasibility work, are supportive of funding but securing First Of A Kind (FOAK) investment would benefit from LCHBM to accelerate initial deployment.

The H2Boost project has engaged with the University of Leeds Commercialisation Team during Phase 1 of the project to inform development of the robust strategy for IP management and commercialisation. The Commercialisation Team is responsible for working with academics from across the University to identify and evaluate intellectual property (IP) arising from research activities that have commercial potential. Leeds has experience across the complete commercial landscape with a portfolio of over 35 active spin out companies, completing over 300 new licences per annum and has over 500 patents and patent applications under management. Furthermore, Leeds is one of the three founder universities of Northern Gritstone, one of Europe's largest university focused investment companies, who work closely with the university to support the development of IP-rich spinouts.

We will continue to work with all project partners to ensure that suitable arrangements are in place for accessing background IP and provide a framework for the future use of arising IP. The agreements will clearly define ownership of arising IP based on intellectual and financial input into the work.

The collaborative partners will each be contributing background IP into the project and the current proposed route to effectively package these contributions is the creation of a Special Purpose Vehicle (SPV) to act as the IP holding. Background IP from each party along with any IP arising from the project will be assigned or a licence granted to the SPV to allow it to act as the sole licence holder for the complete process. The use of an SPV offers a mechanism to manage contributions across a range of partners and provides a single entity with the capability of licensing the full technology package to a third party, or to parties in the existing consortium. With support from the University's Commercialisation Team we will engage with all parties in the project to define the principles of the SPV at an early stage to ensure IP can be exploited to the benefit of each party.

The H2Boost system is a fully integrated process which will produce hydrogen whilst capturing the CO_2. The system goes from initial feedstock, through pretreatment processing, dark fermentation, AD and carbon capture with algae. It will produce quality hydrogen for use in transport, fuel cells or injecting into the grid. 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 is in Annex 4.

The H2Boost system shows good potential for commercialisation and an integrated Hydrogen BECCS system is aligned with the UK Government's net zero policies.

Annex 1
Carbon Life Cycle Assessment

Net impact of 1kg of Hydrogen production on GHG emissions from H2 Boost system

	Output (kg) ***normalised to 1kg of H2 output from system***	**Net CO2 impact gCO2/unit**	**Total GHG impacts (gCO2 per kg H2 output)**
Hydrogen production	1	-6791	-6791
Methane to grid	8.36	-1359	-11366
Other associated GHG savings (CHP flue gas)			-2903
overall CO2 impact			-21061
overall CO2 captured (kgCO2)			-21.06

Annex 2
H2-Boost Phase 2, May 2023- March 2025

Month

Work Package	Task	Deliverable	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	21	22	23
WP 1	**WP 1 - Laboratory Development**																								
1.1	Feedstock pretreatment optimisation - BioBoost: loadings, intensity etc.	D.1.1 pretreatment optimisation	🟩	🟩	🟩	🟩	🟩	🟩																	
1.2	Feedstock pretreatment - (novel) enzymes	D1.2 development of optimal enzyme	🟩	🟩	🟩	🟩	🟩	🟩				🟩	🟩												
1.3	Feedstock mixture testing	D1.3 Optimisation of feedstock			🟩	🟩	🟩	🟩																	
1.4	innoculum development (sequence the enriched incula before seeding the reactors)	D1.4 Innoculum development	🟩	🟩	🟩	🟩	🟩	🟩				🟩	🟩	🟩	🟩										
1.5	full characterisation of feedstocks before and after pretreatments (give a more targeted approach), using DNA sequencing	D1.5 Characterisation of feedstock	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩										
1.6	feedstock fermentation conditions optimisation (0.5 L)	D1.6 fermentation optimisation			🟩	🟩	🟩	🟩																	
1.7	monitor metabolites (VFA, ethanol)	D1.7 optimisation of metabolites			🟩	🟩	🟩	🟩																	

1.8	Development of algae CCS and CCS testing	D1.8 development of CCS					🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩										
1.9	trial sparging with co2 and n2 to produce more H2 from feedstock	D1.9 optimisation of H2 production					🟩	🟩	🟩	🟩	🟩														
WP 2	**WP2 - Continuous functional Testing 10L and 800L**																								
2.1	Feedstock requirements defined and procured	D2.1 Trials have suitable feedstock available			🟩	🟩	🟩	🟩																	
2.2	conversion from batch DF testing to continuous	D2.2 Successful continuous trials						🟩	🟩	🟩	🟩														
2.3	10 L continuous dark fermentation	D2.3 Successful 10L dark fermentation trials with feedstock						🟩	🟩	🟩	🟩														
2.4	optimisation of parameters, inc. sparging	D2.4 Optimisation of parameters						🟩	🟩	🟩	🟩														
2.5	optimisation of feeding rates	D2.5 Optimisation of feeding rates						🟩	🟩	🟩	🟩														
2.6	Production of novel enzymes	D2.6 Mass production of novel enzymes						🟩	🟩	🟩	🟩														
2.7	800L continuous system trial	D2.7 Successful 800L continuous system trial						🟩	🟩																
WP3	**WP 3 - Engineering Build**																								
3.1	Development of 80L system (into 800L AD)	D3.1 Build of 800L system at BDC	🟩	🟩	🟩	🟩	🟩	🟩																	
3.2	Permissions, Permits & Licenses	D3.2 Secure 80L/800L	🟩	🟩	🟩	🟩																			

		Permission, Permits and Licenses (R&D scale)	🟩	🟩	🟩	🟩																			
3.3	Testing BDC site	D3.3 Test equipment						🟩	🟩																
3.4	Development of commercial AD site	D3.4 Build of full system at AD Site		🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩												
3.5	Permissions, Permits & Licenses	D3.5 Secure amendments to include in existing site permits			🟩	🟩	🟩	🟩	🟩	🟩	🟩														
3.6	Testing of AD site	D3.6 Test AD site											🟩	🟩											
WP 4	**WP 4 - 800L trials**																								
4.1	Run trials in 80L system (into 800L AD)	D4.1 Complete trials with different feedstocks and pretreatments to optimise results							🟩	🟩	🟩	🟩	🟩	🟩	🟩										
4.2	Optimise Performance Testing	D4.2 Develop and optimise the system										🟩	🟩	🟩	🟩										
WP 5	**WP 5 - Demonstration Scale testing**																								
5.1	Commercial AD trials	D5.1 Complete trials following WP 4												🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩		
5.2	Optimise Performance Testing	D5.2 Develop and optimise the system																			🟩	🟩	🟩		
WP 6	**WP 6 - Sustainability Development**																								
6.1	Commercialisation strategy development	D6.1 Agree terms for commercialisation	🟩	🟩	🟩										🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩

		and develop clear strategy	🟩	🟩	🟩										🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
6.2	SPV established	D6.2 Establish an SPV to commercialise H2-Boost																🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
6.3	LCA	D6.3 Develop an LCA for the project						🟩	🟩	🟩				🟩	🟩	🟩					🟩	🟩	🟩	🟩	🟩
6.4	TEA	D6.4 Develop an TEA for the project																			🟩	🟩	🟩	🟩	🟩
6.5	Business Plan	D6.5 Develop a Business Plan for delivery of commercialisation for the project	🟩	🟩	🟩	🟩					🟩			🟩	🟩	🟩				🟩	🟩	🟩	🟩	🟩	🟩
6.6	Policy Environment	D6.6 Engagement with policy drivers																			🟩	🟩	🟩	🟩	🟩
6.7	Market engagement and testing (H2, Feedstock, Algae)	D6.7 Stakeholder engagement with the hydrogen and AD communities					🟩	🟩	🟩								🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
6.8	Feedstock - business connections	D6.8 Stakeholder engagement with feedstock suppliers						🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩
6.9	Dissemination	D6.9 Events and press releases on the projects developments							🟩	🟩							🟩	🟩					🟩	🟩	🟩
WP7	**WP 7 - Project Management**																								
7.1	Project Management	D7.1 Monthly and quarterly reports	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩	🟩

Annex 3 H2-Boost Phase 2 Risk Management

Risk	**Overall Risk Rating (Likelihood x Impact) High, Medium, Low**	**Mitigation actions**	**Residual risk rating after mitigation High, Medium, Low**
TECHNICAL			
Failure of partners to secure Phase 2 funding	High	Thorough discussion of Phase 2 project plan, collaboration agreement and long-term commercialisation strategy has started and will continue throughout project.	Medium
Detailed final design engineering	Medium	Early requirements for all aspects of the project delivery. Focus on scope of work to ensure all items below, including functional performance are covered.	Low
Plant integration (commercial site co-location) does meet the interface risk and operating site requirements	High	Minimise plant interfaces with material flow control to enable holding H2Boost alongside direct operations without direct impacts. The planned 80L scale up optimisation to provide operational performance data enabling integration option to be progressed.	Medium
Engineering Supply & Construction	High	Secure appropriate contracts for provision (EPC, EPCM)	Medium
Programme (Design, Supply Chains, Services, Permits, Construction, Resourcing, Operations, Testing, Scale-up stages)	High	Project management resources provided for technical, engineering, construction, and BEIS interface. Identify all critical path items and ensure resources and actions directed for early completion and resolution.	Medium
Operational stability for performance test	Medium	Define and adopt system test approaches including, for example, longer run-times well ahead of the performance test	Low

Target additional methane yield not demonstrated	Medium	Assess whether H2boost can operate commercially on a standalone basis?	Low
COMMERCIAL			
Breach of project confidentiality breaching/jeopardising IP	Medium	Confidentiality Agreements in place. IP and commercialisation reviewed as part of project management meetings as standing item	Low
Unfavourable process economics and return to stakeholders	High	Materials and facility costs are well-characterised so these and transport logistics and crop-material availability will be quantified.	Medium
Commercial risk	Low	The commercial strategy is being discussed and agreed up front	Low
Failure to engage with relevant stakeholders	Low	BDC is a member of several programmes that directly engage with the AD community and partners include industry leaders..	Low
FINANCIAL			
Phase 2 funding	High	Phase 2 planning and discussions are under way.	Medium
Control over subcontractors in Phase 2	Medium	Project partners will agree and contractually engage subcontractors and service providers where necessary. Timescales and deliverables from these providers will be agreed in advance and progress monitored weekly.	Low
Failure to spend Phase 1 budget	Low	The budget of Phase 1 is being closely monitored and assessed throughout the project	Low
Programme falls out of line with BEIS requirements (reporting, progress achieved and financial)	Low	Ensure robust project management strategy is in place, regular monthly project partner meetings held, claims processed accurately before deadlines, regular interaction with Monitoring Officer.	Low
REGULATORY			
Complex and/or lengthy regulatory compliance registration for Phase 2 trials	High	Phase 2 planning underway. One partner has extensive experience in regulatory compliance Secure additional services of specialist provider(s)	Medium
HEALTH AND SAFETY			
Health and Safety issues	Low	All partners are established labs and businesses meeting the HSE requirements	Low
HAZOP/HAZID/DSEAR	Medium	H&S central to design, construction and operational management approach	Low

Annex 4
H2Boost Phase 1 assumptions.

This Phase 1 feasibility study was designed to test assumptions including;

- Hydrogen generation from dark fermentation (DF) using a range of low value biomass feedstocks including pre-processing using BioBooster technology and additional treatment to focus microbial communities to those with hydrogen producing capability.
- The principle of hydrogen separation to a suitable equality for use in fuel cell heavy good vehicles was assumed as included
- Potential for additional methane yield which would be available from use of DF digestate as anaerobic digestion feedstock.
- Carbon capture using CO2 in the tail gases arising for hydrogen separation, and CO2 from the exhaust stream arising from co-located biomethane CHP. The method for capture would be via algae consuming nutrients in the digestate arisings and CO2, both passing through an algae reactor.
- Life-Cycle Assessment would support assumptions for whole system CO2 savings.

The research, measurements, analysis and research approaches using the study provided data for supporting testing assumptions made to the extent noted here.

- Hydrogen was produced for the range of feedstocks tested to varying degrees with food waste, paper waste and pea starch demonstrating the highest yields. In these feedstocks, sufficient hydrogen production [lab vs theory] was demonstrated to support a baseline financial case and consider scale-up for process optimisation. This will include a switch for batch operation to a continuous running system allowing closer examination of; operating conditions for pre-processing, DF conditions, and examination of improved enzymes.
- The DF gases produced would be suitable for the hydrogen separation technologies examined, including Pressure Swing Absorption, suitable for fuel cell use. This will be fully tested during phase 2 using PSA separation and hydrogen feed to a fuel cell.
- Potential for additional biomethane yield was examined briefly in later stages of the study with a range of positive results although additional optimisation trial will be required to conclusively confirm the principle.
- The principle of algae growth using CO2 waste streams and digestate feedstock was supported but trials will be required to confirm yield potential.
- LCA modelling using best literature limits supports the CO2 reduction and associated TEA and Feasibility, using lab and operation limits at reduced hydrogen performance also confirmed high levels of CO2 sequestration.