Department for Energy Security & Net Zero

H2Boost

Hydrogen BECCS Phase 2 Final Report

March 2025

Biorenewables Development Centre

University of Leeds

aardvark environment matters

ab agri

CM90

The Bioeconomy Consultants NNFCC

Maltings organic treatment

Cyanocapture Scalable carbon capture technology

QUBE renewables

Ramboll

The Department for Energy Security and Net Zero provides dedicated leadership focused on delivering security of energy supply, ensuring properly functioning markets, greater energy efficiency and seizing the opportunities of net zero to lead the world in new green industries.

The project “H2Boost” is part of the Department’s £1 billion Net Zero Innovation Portfolio which provides funding for low-carbon technologies and systems and aims to decrease the costs of decarbonisation helping enable the UK to end its contribution to climate change

Preface

This report fulfils the requirements of the Hydrogen BECCS Innovation Programme: Phase 2 Project closure report.

Lead: Biorenewables Development Centre

Support: University of Leeds, AardvarkEM, AB Agri Ltd, CM90 Ltd, CyanoCapture, NNFCC, The Maltings Organic Treatment Ltd, Qube Renewables, Ramboll UK Ltd

Acknowledgements

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Executive summary

The H2Boost project was originally developed to use underutilised bio-wastes to produce low carbon hydrogen (H_2) and carbon capture and storage (CCS) for the UK transport sector, aligning with the UK ambition of reaching net zero by 2050. The system integrated dark fermentation (DF) anaerobic digestion (AD) and microbial CCS using photobioreactors (PBRs) to produce algae/cyanobacteria utilising CO_2 arising from DF and nutrients from the AD digestate produced, Figure 1.

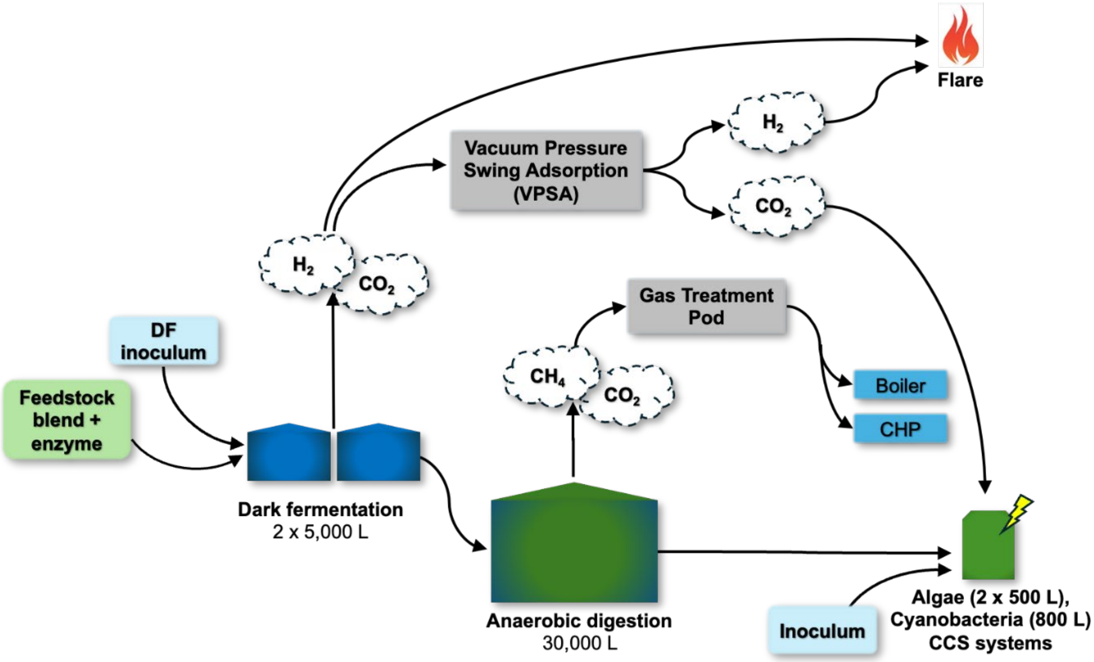

Figure 1. Schematic of the H2Boost Phase 2 system

The project combined academic and industrial partners with expertise in feedstock pre-treatment, microbiology and fermentation, CCS, technoeconomic and life cycle analysis (TEA, LCA), plant design, engineering, planning, regulatory compliance, and health & safety. Within 21-months, a H2Boost demonstration system was designed, installed, commissioned, and ran continuously for 54 days (1,296 h), produced 57.6 m^3 of H_2 and converted 18.98 kg of carbon in the form of algae/cyanobacteria, Table 1. Activities were delivered on time and on budget.

Further optimisation is required to commercialise H2Boost as an integrated solution. LCA determined that CCS using PBRs does not provide the required negative CO_2 emissions for H2Boost to be deployed in the UK, since they are more appropriate in brighter/warmer climates at their current stage of technology development. The system configuration with the best overall emissions performance is DF+AD, with emissions for H_2 generation at around 14.98 gCO_2eq/MJ_{LHV}. Based on CO_2 purified from DF biogas and captured, including estimated emissions associated its capture and geological storage, additional carbon savings of c.218 gCO_2eq/MJ_{LHV} of H_2 are possible, giving net H_2 emissions of -202 gCO_2eq/MJ_{LHV}.

DF reactions were curtailed by acid build up. Acid removal/reduction, coupled with identified feedstock/nutrient requirements, indicated up to a 6-fold performance increase is possible, and required, before full deployment.

Table 1. Demonstrator performance

Project Parameter	Performance Trial (Average/Overall)
Feedstock used by DF (15.2%$_{dm}$ 13.5%$_{vs}$ basis)	52,409 L (971 L /day)
H_2 Biogas produced	245.8 Nm^3 (5.9 Nm^3/day) (19.7% H_2: 80.8%CO_2)
H_2 produced	57.6 Nm^3 (1.1 Nm^3/day)
CO_2 produced (DF)	198.6 Nm^3 (4.8 Nm^3/day)
H_2 Purity	Variable up to 89.4%
H_2 Yield	3.46 Nm^3/t_{dm} 3.90 Nm^3/t_{vs}*
Algae produced CO_{2e} basis, conversion efficiency	3.98kgCO_{2e}, 67 %
Cyanobacteria produced CO_{2e} basis, conversion efficiency	15kgCO_{2e}, 48.7 %

*t_{dm} = tonne of dry matter, t_{VS} = tonne of volatile solids

A commercial scale DF concept was developed**,** based on commercial H_2 compression equipment, with a minimum flow of 10 kg/hr H_2, leading to a 43 kt/yr feedstock requirement, yielding c.80 t/yr H_2, rising to 240 t/yr H_2 (11GWh$_{HHV}$ / 1.4MW$_{HHV}$ capacity) with process improvements. Levelised Cost of Hydrogen (LCOH) for H2Boost for the demonstration plant was £633/kg (16.1k/MWh), which is projected to reduce to £156/kg (£3.9k/MWh) in 5 years with an improved process and plant, and to £7.01/kg (£178/MWh) for a commercial deployment, based on DF with shared allocations for AD and geological CO_2 store.

Potentially competing H_2 production technologies were considered, including proton exchange membrane electrolysis, a favoured low emission H_2 technology in the UK and internationally, with varying LCOH values ($3.56-$11.96/kg.) At £7.01/kg H_2 for H2Boost at commercial scale, with further reduction potential, the technology should be progressed to enable deployment.

Supply chain study suggests potential for scale of up to 90 kt/yr feedstock, yielding >482 t H_2/yr (19GWh$_{HHV}$ / c.2.4MW$_{HHV}$) with further cost reduction and return improvement possible, supporting full integration with an AD system and inclusion of CCS. The commercial scale design for DF alone could achieve unlevered returns of c.10.4 % (H_2 price of £9.49/kg (HAR1 strike price)). As a new integrated system, H2Boost started at a low TRL, but progressed for all processes, Table 2.

Table 2. Technology readiness levels of H2Boost

Process	Project start TRL	Project end TRL
DF	TRL 3	TRL 6
AD	TRL 9	TRL 9
PBR for CCS	TRL 1	TRL 3

Further demonstration scale operations are needed to improve the process, requiring funding to construct and operate a mid-scale reference plant and the development of a technology package to take to market. H2Boost will then be an attractive proposition for investors.

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Glossary

Aardvark	AardvarkEM
AD	Anaerobic digestion
AFDW	Ash-free dry weight
AFEX	Ammonia fibre expansion
ARC	Archaea (a microbial group)
A+ macronutrient mix	KCl, $CaCl_2$, $Na_2EDTA.2H_2O$
BBM-3N	Bold Basal Medium with three times the nitrogen
BDC	Biorenewables Development Centre
BECCS	Bioenergy with carbon capture and storage
BEIS	Department for Business Energy and Industrial Strategy
Bio-CO_2	Biogenic carbon dioxide
CapEx	Capital expenditure
CC	CyanoCapture
CCS or CCUS	Carbon capture and storage or carbon capture, utilisation and storage
CDM	Construction Design and Management
CFD	Contracts for difference
CHP	Combined heat and power
CLU	Certificate of Lawful Use
C:N	Carbon-to-nitrogen ratio
CO_2	Carbon dioxide
COD	Chemical oxygen demand
DESNZ	Department for Energy Security and Net Zero
DF	Dark fermentation
dm	Dry matter
DSEAR	Dangerous Substances and Explosive Atmospheres Regulations
EA	Environment Agency
EoW	End of Waste
FIT	Feed-In Tariffs
FOS/TAC ratio	Ratio of volatile fatty acids (FOS) to total alkalinity (TAC)
GGSS	Green Gas Support Scheme
GHG	Greenhouse gas
H_2	Hydrogen
HAR	Hydrogen allocation rounds
HAZID	Hazard Identification
HAZOP	Hazard and Operability Study
HHV	Higher heating value
H_2KPO_4	Monopotassium phosphate
HPB	Hydrogen-producing bacteria
HRT	Hydraulic retention time
H_2S	Hydrogen sulphate
HSB	Hydrogen-scavenging bacteria
HSBM	Hydrogen Production Business Model
HSE	Health safety & environment
ICE	Internal combustion engine

ICP-MS	Inductively coupled plasma mass spectrometry
IEA	International Energy Agency
I-PBRs	Inoculum photobioreactors
IRR	Internal rate of return
LCA	Life Cycle Analysis
LCHA	Low Carbon Hydrogen Agreement
LCHBM	Low Carbon Hydrogen Business Model
LCHS	Low Carbon Hydrogen Standard
LCOH	Levelised Cost of Hydrogen
LEP	Local Enforcement Position
LHV	Lower heating value
MBT	Methanobacteriales
MCU	Methanoculleus
MM	Minimal medium
NaCl	Salt
Nm^3	Normal metres cubed
N:P	Nitrogen-to-phosphorus ratio
NPV	Net present value
OD	Optical density
OD:AFDW	Ratio of optical density to ash free dry weight
OE	Owner’s Engineer
Opex	Operating expenditure
PBR	Photobioreactor
PD	Principal Designer
P&IDs	Piping and instrumentation diagrams
PRVs	Pressure reducing valves
PT	Performance testing
QMP	Quality Management Plan
QP	Quality Protocols
qPCR	Quantitative polymerase chain reaction
Qube	Qube Renewables
RAE	Royal Academy of Engineering
RFs	Resource frameworks
rRNA	Non-coding ribosomal ribonucleic acid
RS	The Royal Society
RTC	Renewable Thermal Collaborative
RTFCs	Renewable Transport Fuel Certificates
RTFO	Renewables Transport Fuel Obligation
SAF	Sustainable Aviation Fuel
SCADA	Supervisory Control and Data Acquisition
SMR	Steam Methane Reforming
SOPs	Standard operating procedures
Spirulina	*Arthrospira platensis*
TEA	Technoeconomic Assessment
The Maltings	The Maltings Organic Treatment Ltd
Tris-HCl buffer	Tris-hydrochloride buffer
TRL	Technology Readiness Level
UKCA	UK Conformity Assessed

UoL	University of Leeds
VFA	Volatile Fatty Acids
VPSA	Vacuum Pressure Swing Adsorption system
VS	Volatile solids
Waste codes	A categorisation of waste types using the European Waste Catalogue1 system

1 Project background

This project formed Phase 2 of a two-part Hydrogen BECCS Innovation Programme, part of the DESNZ Net Zero Innovation Portfolio. The project consortium had previously undertaken a Phase 1 multi-stage project, funded by BEIS, which laid the groundwork for Phase 2 by assessing the feasibility of an integrated H_2-BECCS demonstration scale system to meet Net Zero ambitions.

Phase 1 was led by the University of Leeds and brought together a new consortium. Initial focus was on the geographical location, accessibility and forecasted availability of high volume, underutilised feedstocks across England. Samples of feedstocks were obtained for assessment, including household food waste, forestry waste, paper, verge grass, poultry litter and feathers. Feedstock pre-treatment trials included the use of enzymes, particularly for lignocellulosic-rich feedstocks. A process was developed for DF inoculum preparation, enabling laboratory scale DF and AD trials accompanied by microbial profiling.

Yields of H_2 were in line with performance expectations[1] for an unoptimised system, for example 80 L H_2/kg volatile solids (VS) from household food waste. The use of microalgae for biological carbon uptake delivered harvested algal biomass with 50-55 % carbon content at a rate of 125 g/m^3/day, demonstrating the potential of an integrated H_2 BECCS system utilising organic wastes processed by microbial systems.

Initial TEA and LCA studies determined the baseline financial capacity of the H2Boost system and showed that it had the potential to deliver very low carbon H_2 to levels much lower than that seen with technologies currently moving towards initial stages of commercial deployment.

Phase 1 also identified areas requiring further evaluation, development and optimisation, which became the basis of the Phase 2 project. While laboratory scale processes had demonstrated the feasibility of an integrated, microbial process for H_2 production and CCS, certain practicalities needed to be optimised at scale in order to demonstrate commercial viability of the system. This included feedstock blending and pre-treatment, inoculum preparation for DF and microalgae culture, the use of a H_2 upgrading system (only possible at scale), plus an assessment of site-wide energy inputs, outputs and product yields to enable the development of substantial TEA and LCA studies, and generation of the commercialisation plan. An initial engineering design was, developed and a suitable location identified for hosting demonstration scale activities.

1.1 Consortium information

The H2Boost project was based in North Yorkshire, with the consortium comprising two project partners and eight experienced subcontractors based around the country. The consortium brought experience in research, knowledge transfer, industry engagement, commercialisation and economic assessment expertise, along with extensive networks of contacts across the AD and H_2 supply chain. Each was subcontracted to the lead and brought clearly defined areas of expertise, with specific objectives to deliver (Table 3).

Table 3. H2Boost consortium members

Consortium member	Organisation size	Role within H2Boost Phase 2
Biorenewables Development Centre (BDC)	26 employees	Project lead: Project management, DF development and optimisation, AD, DF inoculum preparation, molecular tool development, technology transfer to demonstration scale
University of Leeds (UoL)	9,151 employees	Project partner: Carbon capture with algae, H_2 expertise
The Maltings Organic Treatment Ltd (The Maltings)	48 employees	Subcontract: Site location, utility supply, security and operation of the demonstration scale plant
Qube Renewables (Qube)	8 employees	Subcontract: Design and build of the demonstration scale plant
AardvarkEM (Aardvark)	25 employees	Subcontract: Planning, permitting and enabling works
NNFCC	14 employees	Subcontract: Life cycle analysis
ABAgri	1,321 employees	Subcontract: Additional testing of AD and DF digestates
CM90	2 employees	Subcontract: Technoeconomic assessment, supply chain, commercialisation
CyanoCapture (CC)	13 employees	Subcontract: Carbon capture using cyanobacteria
Ramboll UK Ltd (Ramboll)	1,543 employees	Subcontract: CDM Advisor, Engineering Project Management, HAZOP, DSEAR

2 Project overview

2.1 Description of the project

H2Boost Phase 2 brought together an extended consortium of partners and subcontractors (as given in Table 3) to design, build, commission and operate a demonstration scale plant for the microbial production of H_2 and CH_4 via DF and AD, respectively, and CCS via growth of microalgae and cyanobacteria using DF-generated CO_2 and AD digestate. Figure 2 shows a schematic of the overall process.

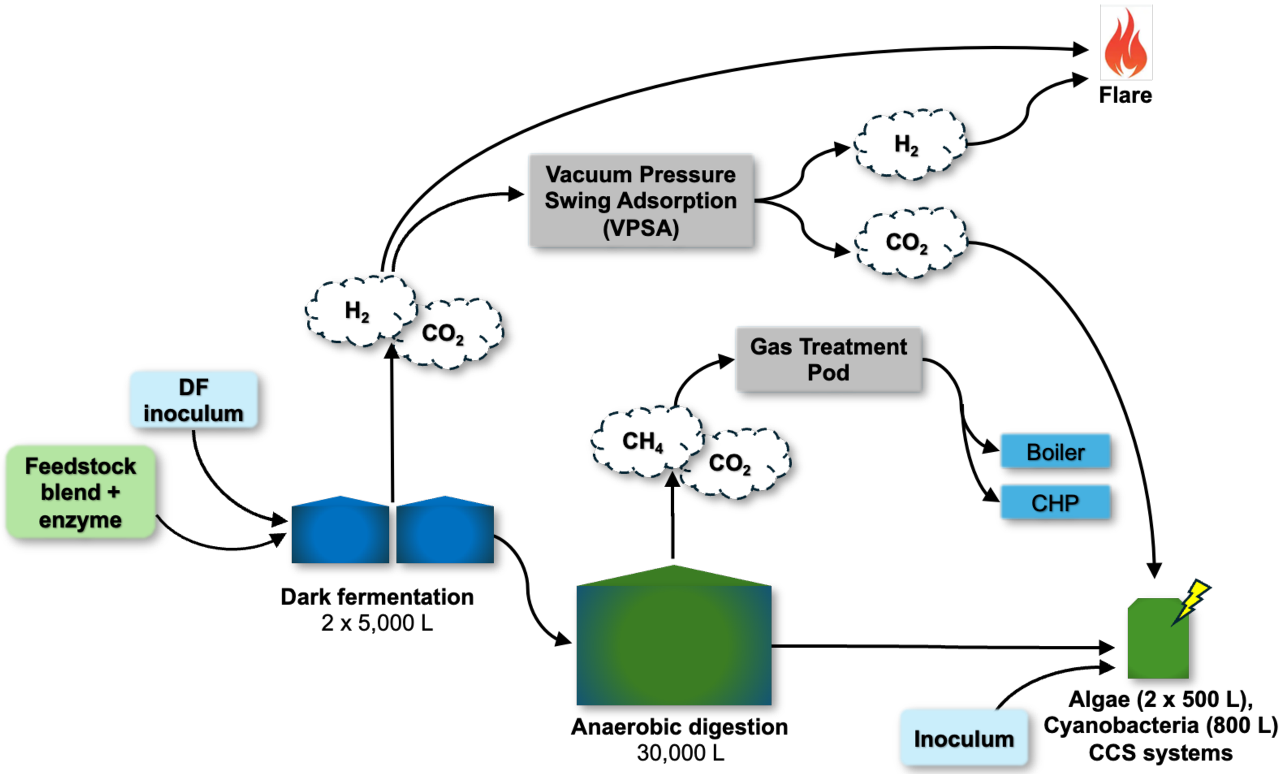

Figure 2. Schematic of the overall H2Boost Phase 2 system.

The preliminary engineering design developed in Phase 1 was updated to encompass the activities shown in Figure 2 for Phase 2, with planning and permitting undertaken to enable siting and operation at The Maltings, where the feedstock blend was prepared. The equipment build ran alongside HAZID and HAZOP, with commissioning leading into functional and performance testing of the system.

H_2 was produced using DF, a process comprising an inoculum (AD digestate treated to remove CH_4-producing microbes) and a feedstock blend supplemented with a lignocellulosic-degrading enzyme. H_2 was either flared as a H_2 dominant syngas or upgraded via a vacuum pressure swing adsorption system (VPSA) and then flared, since it was not possible to compress and store the upgraded H_2 within Phase 2. DF residues were then fed to an AD vessel, pre-seeded with farm waste AD digestate, or to an external storage tank. AD digestate was separated into liquid and solid fractions, with the liquid fraction being used to supplement growth within the algal/cyanobacterial CCS systems, which also captured CO_2. CH_4 produced from the AD vessel was used to fuel the boiler and CHP system to provide hot water/heating to the DF and AD vessels.

More comprehensive LCA and TEA were undertaken in Phase 2, using data drawn from laboratory and demonstration scale activities. Levelised cost of hydrogen modelling and a review of the commercial viability of the H2Boost system were prepared, including a comparison with competing H_2 production technologies.

2.2 Project aims and objectives

Biomass utilisation and bioenergy are critical planks of the strategy to defossilise and reinvigorate UK industry. On an island where biomass supply is limited, resource efficiency demands that the best use is made of available feedstocks in a sustainable process that eliminates avoidable waste and carbon emissions to the atmosphere.

H2Boost Phase 2 drew together a consortium of expertise from across the biological, process, and engineering sciences, as well as TEA and LCA expertise, and built on work undertaken in the Phase 1 project to evaluate the feasibility and commercial potential of an integrated H_2 production-CCS system at demonstration scale. The project's innovation was an integrated, demonstration scale system with additional separate innovations at each stage. Laboratory scale work ran throughout the Phase 2 project to direct and develop the demonstration scale activities.

The overarching project aim of producing H_2 through DF and capturing carbon at demonstration scale was broken down into the following objectives:

- development of a feedstock blend from underutilised, low value waste streams and byproducts from a range of industries
- design and build of a multistage, integrated demonstration scale plant comprising DF inoculum preparation, feedstock blend and supply, DF (Hydraulic Retention Time (HRT) of 2-5 days) integrated with AD (HRT of 21-38 days) and CCS (microalgae and cyanobacteria), H_2 upgrading to produce fuel-cell input quality H_2, for example for a proton exchange membrane fuel cell, and all associated monitoring and HAZID/HAZOP requirements
- obtaining planning and permitting associated with the demonstration scale activities
- optimisation of pretreatment conditions (enzymes) to increase H_2 and CH_4 yields and reduce HRT in AD
- development of a scalable DF inoculum production process
- separation of CO_2 capable of export to remote CCS to enable microalgae/cyanobacteria growth with an associated CO_2 production capture rate > 70 %
- demonstration of the integrated system across a 1,000 h testing period, with a target of the H_2 yield potential rising from 80 mL H_2/g biomass (95.9 mL H_2/g volatile solid) to 138 mL H_2/g biomass (165 mL H_2/g volatile solid), being ~23 m^3 (2 kg) per day rising to 42 m^3 (3.8 kg) per day, and associated CO_2 at ~29 kg per day rising to 55 kg per day
- acquisition of plant performance data informing TEA, LCA and commercial design options, including capex, opex (costs, reliability) and yield performance projections for an investment case

2.3 Schedule and deliverables

H2Boost Phase 2 ran from July 2023 to March 2025. The project team managed a tight schedule with parallel activities, multiple sites and competing priorities while still completing design, build, optimisation, performance testing, reporting and project closure within the contract end date. A detailed project plan outlining the proposed timescale of the project was developed and continuously monitored and updated, ensuring the consortium was on track to deliver the demonstration scale activities (Figure 3).

Due to the tight timescale of the project, several work packages ran in parallel. For example, the engineering design of the demonstration plant was an early output, which resulted in a design being developed and built before laboratory work optimising the process had begun. Work packages (WPs) 1 and 3, therefore, ran in parallel, with laboratory scale work, plant design and some build all being undertaken simultaneously. This resulted in design/build changes being required further into the project, once laboratory data was analysed.

The Phase 2 demonstration scale plant was manufactured off-site by Qube, CC and UoL, or leased from third parties. Plant was moved to The Maltings site between April and July 2024, where it was commissioned before functional testing took place.

To ensure the performance testing of a minimum of 1,000 hours took place before the end of November 2024, the continuous/performance testing phase had to start before the various biological systems (AD, DF and CCS systems) were optimised and mature.

H2Boost Project Plan	July 2023 to March 2025	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8
WP1- Lab Scale Optimisation	Optimisation of inoculum production, feedstocks, pretreatments, H_2 production and algal/Cyanobacteria								
WP2- Continuous Testing	Continuous functional testing and optimisation: feedstock pretreatment, DF and AD								
WP3- Engineering Build	Planning and permitting, design, procurement, commissioning and building of the demonstration plant, CDM requirements								
WP4- Demonstration scale testing	Full demonstration scale: functional and performance testing								
WP5- Supply chains and market	Supply chain assessment and market engagement								
WP6- Sustainability	Development of commercial strategy, the TEA and LCA								
WP7- Project Management	Project management, including engineering project management								

Figure 3. Work packages of H2Boost Phase 2

2.4 Financial information

DESNZ initially awarded H2Boost Phase 2 a total of £4,967,149.48. After six months, there was a change in the pretreatment scope following initial test results and the scope was reduced, which resulted in the budget being reduced to £4,763,209.96. The project actual spend remained within budget, with the project being delivered within the original timeframe.

3 Process and engineering design

The H2Boost project integrated feedstock development and DF inoculum preparation through DF, AD, H_2 separation and clean-up, and CCS, Figure 4. System processes were developed and optimised in the laboratory, along with H_2 and CO_2 upgrading and capture.

3.1 DF inoculum preparation

DF inoculum was prepared from AD digestate, containing a diverse microbial population able to break down organic materials to produce CH_4 and CO_2. One component of the microbial consortium were methanogens, which convert small compounds into CH_4. Methanogens also utilise H_2 to produce CH_4, effectively fixing H_2 produced in DF, preventing accumulation in the H_2 biogas. High temperature treatment was used to destroy methanogens in the inoculum while retaining a consortium of microbes capable of feedstock break down and H_2 production.

Laboratory work identified that digestate from wastewater treatment produced the highest volume of H_2 during batch DF experiments. As this digestate is also widely available from several plants across the country it was the preferred inoculum source. Trials were carried out at 60 L scale to determine which treatment conditions produced inoculum with the greatest H_2 yield potential. This then informed the engineering design and build.

3.2 Feedstock & preparation

The development of the optimised feedstock to produce H_2 was critical to the project. Batch DF (0.6 L scale) was used to screen underutilised feedstocks/waste streams available at The Maltings and develop a bespoke feedstock blend for demonstration scale activities. Commercially available enzymes, including cellulases, were screened in laboratory trials for their capacity to increase H_2 yields from DF. Enzymes were added directly to DF vessels at their maximum recommended inclusion rates. An enzyme cocktail targeting cellulose and hemicellulose was selected for inclusion at demonstration scale.

The final blend used throughout laboratory and demonstration scale work comprised:

- waste from lozenge manufacture (7 % w/w)
- soft drinks effluent (76 % w/w)
- paper dust residues from paper recycling process (7 % w/w)
- meat effluent (10 % w/w)
- commercial enzyme cocktail (625 mL/m^3)

3.3 Dark fermentation

Laboratory scale DF trials were carried out to determine process elements such as operating temperature, feedstock pre-heating optimisation, feeding rate and alternative nitrogen sources. These evaluations fed into demonstration scale process optimisation. At demonstration scale, DF vessel mixing, feedstock volumes, DF inoculum preparation and operational temperature were varied in order to maximise H_2 production.

3.4 Anaerobic digestion

DF residues and the feedstock blend were fed to the AD tank to produce CH_4 and CO_2 at demonstration scale, since DF residues have been shown to increase the CH_4 yield from AD. [2] The CH_4 rich biogas was then transferred to a gas storage bladder after H_2S removal. The gas was then utilised in either the boiler or CHP to generate heat for the site. The resulting digestate, between 1-2 % TS, was then passed through a 10 mm screen to remove solids from the liquid, and the liquid was stored ready for CCS via microalgae or cyanobacteria cultivation.

3.5 Carbon capture

CCS was carried out by utilising CO_2 created during DF for microalgal and cyanobacterial growth. This innovative approach focused on utilising the liquid fraction of digestate alongside the waste CO_2 gas stream to produce a sustainable culture medium for algal or cyanobacteria growth.

3.5.1 Microalgae cultivation

The CO_2 enriched digestate liquid was used as a growth medium in PBRs to produce microalgae. The resulting algal biomass containing carbon (~50%), nitrogen (~10%) and phosphorus (~1%), not only mitigates climate impacts by capturing CO_2 via photosynthesis but also opens new possibilities for carbon sequestration via biochar production and carbon and nutrient reutilisation in products such as biofuels, biofertiliser and animal feed.

3.5.2 Cyanobacteria cultivation

Similarly to microalgal cultivation, the cyanobacterial PBR system was designed to transform raw inputs such as CO_2, water, and nutrients from digestate liquid into valuable biomass. Initial cultures were grown in the laboratory ahead of inoculating the 15 L inoculum preparation system, before transfer to the 800 L tubular PBR system.

Operation of the 800 L PBR involved digestate-based medium or low concentration nutrient media with controlled heating and lighting. Both media types were infused with CO_2 waste from the DF H_2 biogas. Once the cyanobacteria reached a certain density of cells, the culture was harvested, and the biomass transported off-site for concentration through flocculation (~6% volume concentration) using an organic flocculant, chitosan. The biomass was separated through centrifugation, before drying and milling into a stable product containing 40–50% captured carbon by weight.

3.6 Vacuum pressure swing adsorption

Vacuum Pressure Swing Adsorption (VPSA) was used to purify H_2 in the DF biogas using a combination of pressure and adsorbent material operated cyclically. The CO_2 and other impurities in the biogas were trapped in the adsorbent under low feed pressure, while the H_2 passed through into a purified product stream. The VPSA then swung to vacuum conditions to release the CO_2 and impurities into a separate CO_2-rich waste gas stream. The VPSA was capable of upgrading the H_2 to a purity of >99.99%.

3.7 Engineering approach

Development of the H2Boost Phase 2 demonstration scale plant followed approved engineering processes that met the requirements of Construction Design & Management Regulations 2015[3] (CDM), including defined roles for the parties in the project. This integrated with the evolution of a design concept which advanced to final designs, including HSE, generating a comprehensive approach to ensure the safety and compliance of the H2Boost project.

3.8 Engineering design

The engineering design was completed by three consortium members: Qube, CC and UoL. Qube was responsible for design and build of the DF and AD vessels, with the wrap around gas integration, material storage and flow, and data collection. The two CCS systems were designed to fix the CO_2 separated from DF biogas: CC designed the cyanobacterial CCS system, while the algal CCS system was designed by UoL. The main components of the demonstration scale plant are shown in the process flow diagram, Figure 4.

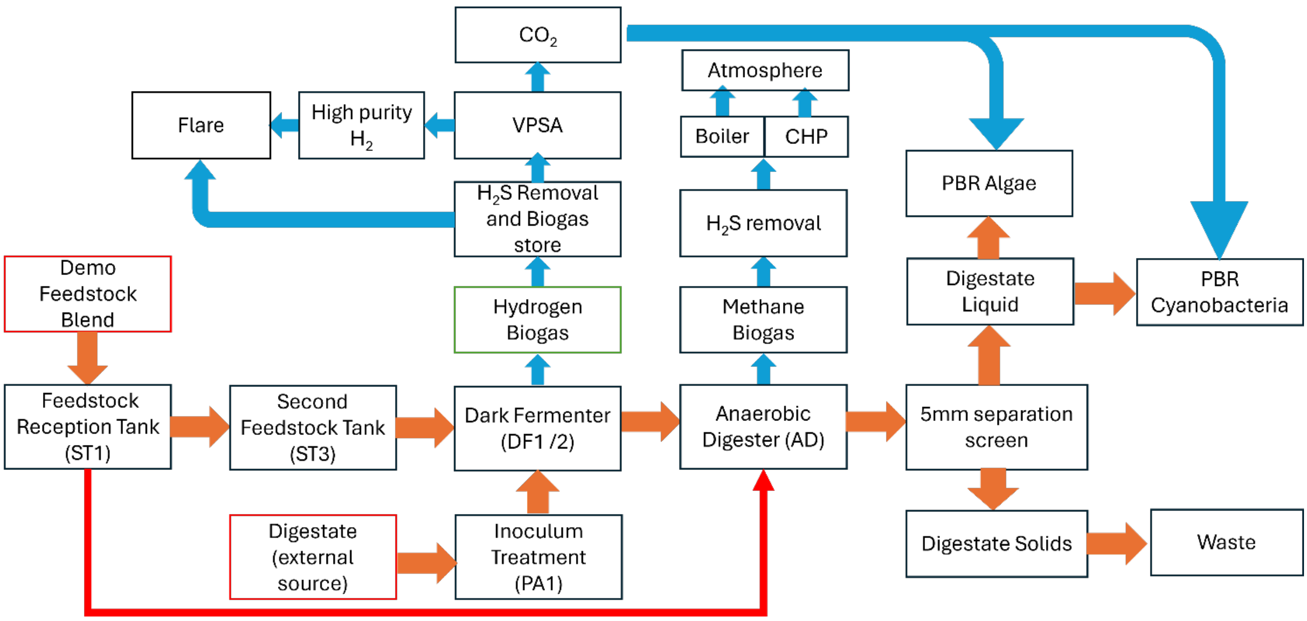

Figure 4. Process flow of demonstration plant

Orange arrows indicate material flow, blue arrows indicate gas flow, and the red arrow denotes an alternative route which was utilised in the trial.

The initial design of the demonstration scale plant was based on learnings and data from Phase 1 of the project, resulting in changes were made to the design and build as Phase 2 progressed and laboratory findings were evaluated between the laboratory and engineering design teams. The demonstration scale system was designed to be housed in modular, containerised units, providing a compact, scalable solution. A brief description of the main elements of the demonstration plant is given in Table 4 below

Changes occurred throughout the demonstration phase. Some were process changes, such as feed rate increases/decreases while there were also equipment changes e.g. upgrading the heating system. The process changes were carried out based on the analysed data coming from the plant daily, with the H_2 content in the DF biogas being a main parameter used. Process changes were discussed with the relevant team members at the demonstration site. Equipment changes were raised with the engineering team for discussion. Once a solution had been found, this was checked against the HAZOP before being implemented.

3.9 Engineering project management

A project Quality Management Plan (QMP) was developed. The QMP paid particular attention to the planning and implementation of the key areas including engineering design, procurement, off-site manufacturing, on-site installation, legal and regulatory compliance, equipment and whole plant UK Conformity Assessed (UKCA) marking, system completions and turn over packages, pre-commissioning and commissioning and final handover to operations.

3.10 Design reviews

Design reviews were undertaken for each of the equipment suppliers to the project. The purpose of the design review process was to review the engineering designs prepared by the suppliers to ensure compliance and compatibility to an integrated system. An engineering gap assessment was also undertaken to provide an initial assessment of the maturity of participating suppliers' engineering documentation and identify gaps in the design. An Interface Management Document was prepared to manage the interfaces between packages, identify gaps in the planned design, and provide support to ensure clear interface points and an integrated design. This plan relates to the creation of Integrated Standard Operating Procedures (SOPs) and Integrated P&IDs.

Table 4. Summary table detailing the design of the main elements of the Phase 2 demonstration scale plant and any changes made throughout the project

System phase	System component	Component information and changes required
Initial design	ST1	5,000L tank for feedstock storage, entry to DF and AD vessels, with level sensors & turbine stirring.
	PA1	500 L stainless steel tank. Temperature control was via a water jacket capable of cooling to <20°C, or heating to ~90°C. Probes within the vessel monitored temperature and level.
	DF1 & 2	The DF system comprised two cuboid 5.1 m³ stainless steel tanks, which could be operated individually. The tanks were heated via internal heating coils in the sides of each vessel. There was a motorised stirring paddle, and vessels were monitored by pressure sensors, level sensors and temperature sensors. The design of DF 1 & 2 was based on Qube's existing design for modular AD tanks (see next section), with a stainless steel to reduce the risk of fugitive H_2 emissions.
	AD1	The AD tank was created within a shipping container sealed to be gas and watertight. The working volume was 31,000 L with a head space of approximately 4 m^3 including pressure & level sensors and temperature probe. The system was heated via internal heating coils in the middle of the vessel with an operating range of 37-43 °C. There were two mechanical agitators and a biogas agitator.
	VPSA	VPSA separated H_2 from the DF-biogas using a combination of pressure and adsorbent material (zeolite) operated cyclically. CO_2 and other biogas impurities were trapped in the adsorbent under low feed pressure, while the H_2 passed through into a purified product stream. The VPSA then swung to vacuum conditions to release the CO_2 and impurities into a separate CO_2 rich waste gas stream.
	Flare	Safe flaring operation to handle the H_2 produced.
	Gas management	Including gas composition and volume analysis, H_2S removal via activated carbon, gas storage and utilisation via boiler/CHP to provide heat to the plant, and CO_2 rich waste gas delivered to PBRs.
	CCS algae	Clarification tank and a 1 m³ tank for CO_2 bubbling to decolour the AD digestate and allow light to reach the photosynthetic algae. The digestate was then saturated with CO_2. Two 500 L PBRs operated in parallel to cultivate algae, each having peristaltic pumps and an LED lighting system. A second clarification step separated algal cells from the growth medium by gravity or using flocculant.
	CCS cyanobacteria	Consisting of 15 L inoculum preparation PBRs and one 800 L main PBR for cyanobacteria cultivation. PBR controls included pH control via CO_2 injections, light intensity controls and heating systems.
	PA1 vessel upgraded	Results of inoculum preparation at laboratory scale demonstrated that a temperature of 120 °C was required to sufficiently remove methanogens from the DF inoculum. A cross-contamination risk from methanogens present in the digestate used to prepare DF inoculum was identified via pipework to the rest of site, requiring pipework changes.

System phase	System component	Component information and changes required
	CCS algae	Peristaltic pumps did not give high enough flow rate (below 1 L/min)
Final design changes	PA1	New vessel sourced: a 500 L stirred, pressure vessel capable of reaching 120 °C was installed to produce DF inoculum. The system included temperature, pressure and level probes. The upgraded PA1 also required a generator and boiler to create steam for the heated vessel jacket.
	ST3	New vessel introduced. ST3 was used as a secondary feedstock store and had the capability to cool inoculum from 80 °C to <20 °C. Previously PA1.
	CCS algae	Peristaltic pumps changed to integrated submersible pumps, increasing flow to 116L/min.
Changes during operation	PA1	Process temperature reduced to prevent over-processing of microbial consortium.
	ST3	ST3 was used as a feedstock heating vessel to counter the sub-optimal temperatures observed in the DF vessel.
	DF1 & 2	Tanks struggled to heat to the desired 45 °C operating temperature when ambient temperatures dropped, requiring heating system upgrades and further pipe insulation. Recirculation was used to stir the units more efficiently, by closing the valves to and from the DF units and activating a pump to move DF residue around the system - effectively creating a loop. This mixed the materials well; however, it could only be carried out manually in between feeds.
	AD1	Positioning of pressure sensor led to inaccurate level readings, resulted in sensor being moved. The feeding system did not allow for differing feed between the DF and AD tanks. An alteration was made to the pipework to allow DF residues to selectively bypass the AD tank. A separate 100 L blend tank was utilised to feed the AD tank alternative feedstock to the DF vessel.
	VPSA	Software/running parameter changes were made to optimise upgrading.
	Gas management	A larger air generator was added to meet the increased demands of mixing in the DF and AD tanks.
	CCS algae	Extra LED lights to increase light intensity. 3 x more 50 L PBRs as further experimental vessels
	CCS cyanobacteria	Additional power source was arranged from the site to power the heaters in the container as power supply overloading issue was experienced on site. Contamination control measures were introduced in the 800 L PBR by adjusting pH below the optimal set point to overcome contaminant growth and promote the growth of cyanobacteria. Varying concentrations of AD effluents were tested in 4x 15L PBRs on site as these PBRs are quite similar in operation with the 800 L PBR

3.11 Site

The H2Boost demonstration plant was located at The Maltings Organics Treatment Centre at South Milford, North Yorkshire, (Figure Figure). The Maltings plant is one of the largest food waste processing sites in the UK and receives a wide range of foods, beverages and other organic wastes. The site prepares feedstock for AD plants on an industrial scale so was able to provide the feedstock for H2Boost, to the specification required for the project. A discreet area of land on the site was ringfenced for H2Boost, between the main Maltings site and the adjacent AB Agri AD site.

Name	Reference	Description
H_2 Processing	A	20 ft standard container
Gas Bladder	B	20 ft standard container
Canopy Area	C	canopy over items of plant, including CHP boiler
Control Container	D	20ft standard container
Dark Fermenter	E	20 ft HiCube (3m) container
Pasteuriser	F	20 ft HiCube (3m) container
Anaerobic Digester	G	40ft standard container
Carbon Capture	H + I	2 x 30ft containers
Feedstock and water tank	J	5m3 Enduramax tank and blend tank
Site Office	K	Site office
H_2 Flare	L	3.8 m flare (6.4m total)
Rundown Screen	M	Separator screen and liquor store

Figure 5. A map and layout of the H2Boost demonstration site

3.12 Consenting, permitting and regulatory

3.12.1 Planning permission

A review of the extant planning consents at the Maltings concluded that the current Certificate of Lawful Use (CLU) for the site would cover the activities to be undertaken within the demonstration project. This was submitted on 1 October 2023. However, after further consultation, a full planning permission application was required. Full planning permission was received for the demonstration project on 19 December 2024.

3.12.2 Environmental permit

The Maltings site held an environmental permit from the EA for waste activities, but this did not include activities to be undertaken in the trials. The EA confirmed that a specific permit was not required, and a Local Enforcement Position (LEP) letter should be suitable for the activities envisaged. A submission was made on the 3 June 2024.

The LEP letter was issued by the EA to The Maltings in good time for the trials to commence, on 14 August 2024. The EA officer received regular updates from the Site Operator and visited the site during the trials.

3.13 Oversight (HSE, PD, CDM, HAZOP)

Ramboll were appointed as Owners Engineer (OE), to the Client, BDC and appointed as the CDM Advisor, responsible for:

- providing CDM advice to the client and other stake holders
- producing a Pre-Construction Information document
- reviewing the Principal Contractors Construction Phase Plan for suitability

This also encompassed the delivery of HAZOP/HAZID and DSEAR processes.

A HAZID report was prepared to summarise the outcomes of the HAZID workshop.

Key findings included:

- identification of 52 hazards and operability issues, with corresponding actions
- critical hazards primarily related to loss of containment of flammable gases and ignition risks
- consideration of H_2S gas release impacts on operator safety, necessitating personal gas detector monitors
- concerns about flammable gases in the CO_2 feed stream and CO_2 column, particularly regarding mixing with air
- highlighting design review needs, especially for flammability issues in the CO_2 feed stream within the CC process

An integrated process Standard Operation Protocol and P&IDs were developed, to cover the commissioning, running and decommissioning of the elements of the H2Boost demonstration scale plant, to integrate the designs from the individual contractors.

3.14 Procurement & build

The equipment including the AD, DF, inoculum preparation, feedstock tank, mixer and carbon capture facilities were fabricated specifically for the project and leased to H2Boost. The VPSA unit was leased for the duration of the project. The system was managed and data recorded on a SCADA system. Following the design sign off, the fabrication of the DF and AD elements started in October 2023 at Qube's factory. The carbon capture units were bespoke built during November to April before being delivered to site.

3.15 Approach to tests

Regular testing plans were designed for the feedstock, DF inoculum, DF and AD liquid phases, and the CCS units. By closely monitoring the whole system, the H2Boost team was able to adapt the system when necessary to ensure the smooth running of the plant. Demonstration site activities were dynamic, and decisions regarding process change or running parameters were made between the relevant members of the team in response to analysis results and observations. Table 5 below shows the analysis that informed daily decision or was used to produce the LCA and TEA.

Table 5. Main analysis used at the plant to determine daily operations and feed into LCA and TEA

	Process point	**Analysis**	**Use**
Success measures	DF biogas	H_2 %, CO_2 %	These measures were used daily to drive decisions around process changes. E.g. if the H_2 % had dropped, an addition of DF inoculum would have been considered.
	AD biogas	CH_4 %, CO_2 %	
	DF biogas	Volume produced	
	AD biogas	Volume produced	
	Feedstock entry	Volume in	This data was used to inform the TEA and LCA findings.
	Feedstock entry	DM, VS	
	CCS algae	Carbon captured, biomass produced	
	CCS cyanobacteria	Carbon captured, biomass produced	
Daily running parameters	AD tank	FOS/TAC ratio	The FOS/TAC ratio informed onsite AD feed rate plans.
	DF inoculum	Lab test for H_2 potential, qPCR and DNA sequencing	These tests were used to ensure the inoculum produced had a sufficient decrease in methanogens and produced H_2 during small scale DF.
	DF tank	Carbon:nitrogen ratio	C:N target was 140:1 but due to variability in feedstock this had to be monitored closely.
	AD digestate	Phosphate levels	The PBR media required phosphate; if not present in the digestate, it was added in.

	Process point	Analysis	Use
	CCS algae	Nitrogen: phosphorous ratio	Optimal ratio was 1:10 and was maintained by addition of monopotassium phosphate
	CCS algae	pH and alkalinity	This was analysed in treated AD digestate prior to cultivation to ensure target CO_2 solubilisation had occurred
	CCS cyanobacteria	pH & Temperature	pH and temperature were used to determine the optimal growth conditions for cultivation, and whether more CO_2 and heating are needed to be added.
	CCS cyanobacteria	Optical density	Used to determine when cells should be harvested and when nutrient input was required.
	CCS cyanobacteria	CO_2 flow rate	Input measured with mass flow controllers and used to calculate carbon capture efficiency

4 Project technical findings

4.1 Lab scale optimisation

Laboratory activities were undertaken throughout Phase 2 to feed into the design of the demonstration scale plant and to ensure the most productive feedstock, inoculum and algae/cyanobacteria were developed. The main elements are summarised in Table 6.

Table 6. Summary of main laboratory scale activities during H2Boost Phase 2

Activity/process	Impact
Molecular tool development and 16S rRNA sequencing	Provided the ability to track success of DF inoculum preparation process, and health of DF and AD vessels.
Development of a scalable DF inoculum preparation process	Impacted on demonstration scale engineering design; requirement for upgraded treatment vessel.
Feedstock pretreatment	Impacted on demonstration scale processes; commercial enzyme cocktail incorporated into feedstock blend; enzyme loading determined.
Feedstock screening	Enabled identification of feedstocks/waste streams which promoted or restricted H_2 production. Development of demonstration scale feedstock blend.
DF trials	Impacted on demonstration scale processes. Feeding rate for DF determined. Yield of 548 mL H_2/g VS demonstrated with paper waste. 60-70 % H_2 potential demonstrated in continuous DF using feedstock blend. Assessment of DF residues into AD undertaken.
Algal CCS development	Algal strains were screened against different digestate batches; best performing strain identified. CCS demonstrated: saturation of 50 % digestate liquid with CO_2 promoted a 62.5 % increase in CO_2 capture; 8 g CO_2 captured in a 2 L PBR over 4 days.
Cyanobacterial CCS development	Cyanobacterial strains were screened against different digestate batches: best performing strain identified, but low tolerance to AD residue was noted. Development of a minimal medium (MM) recipe as an alternative to AD digestate. MM with AD digestate was used at 15 L scale whilst MM alone was used at the 800 L scale. CCS demonstrated: pH-controlled CO_2 injections at pH 9 set point; 47 g CO_2 captured in 15 L PBR in 7 days.

4.2 Demonstration scale

The overall aim of demonstration scale activities was to determine whether the H2Boost process could be scaled up and to examine the technoeconomic and commercial viability of the system. Carrying out H_2 production and CCS at demonstration scale via DF, AD, and algal and cyanobacterial cultivation not only verified the potential of H2Boost but gave invaluable insights on how to improve the process and plant design. Following installation and commissioning of equipment at The Maltings, activities were divided into functional testing and performance testing. Functional testing allowed an evaluation of equipment performance and associated processes, enabling adjustment where necessary. The performance testing phase linked all parts of the H2Boost platform and enabled assessment of the integrated system.

4.3 Functional testing 1

4.3.1 Functional testing of the AD vessel, AD1

AD1 was seeded with digestate from an AD system fed with pig slurry and crop residues, and initial feeding with the demonstration scale feedstock blend followed a ramp-up plan to enable the microbial consortium to become accustomed to the new feedstock. Regular over-/under-feeding and the resulting high FOS/TAC ratios meant that feeding was often interrupted. Adjustments were made to the positioning of sensors and the automated feeding system deactivated, so that automatic vessel filling based on tank levels would not occur.

4.3.2 Functional testing of PA1

Methodology transfer from laboratory scale to demonstration scale for DF inoculum preparation resulted in initial over-processing of the AD digestate used to prepare the inoculum, due to the longer cooling times (and hence increased treatment intensity) of PA1 compared to the AFEX vessel used at laboratory scale. Revised processing times and temperatures resulted in successful DF inoculum preparation using 500 L batches of material in PA1. Success measures for the inoculum production were H_2 production, reduced methanogen levels, and viable cells.

4.3.3 Functional testing of the DF vessel, DF1

After seeding DF1 with 5.2T of DF inoculum, feeding with the feedstock blend commenced immediately at 800 L/day - by comparison, at a much higher rate than typically used for AD vessel initiation. This high initial feed rate was based on laboratory data which had shown that high initial feeding rates promoted high biogas volumes and H_2 content. The operating temperature and stirring frequency were adjusted to maximise H_2 output.

4.3.4 Functional testing of algal CCS system

Functional testing of the algal CCS system identified several required modifications prior to performance testing. These included replacement of peristaltic pumps with submersible pumps for algal culture mixing, increasing the pumping capacity from 1 L/min to 116 L/min and improving mixing. Light intensity was also increased from 25-47 μmol/m^2/s to 1,500-2,000 μmol/m^2/s at the PBR walls, which promoted algal growth. AD digestate liquid was found to be prone to variable solids content levels, requiring flocculation and settling to reduce turbidity and promote light penetration. The optimal dose of flocculant (aluminium sulphate) was determined to be 2.3 g/L for 50 % digestate liquid (4.5 g/L for 100 % digestate liquid). However, flocculation also reduced the concentration of phosphorous needed for algal growth, leading to an imbalance in the nitrogen-to-phosphorous (N:P) ratio in the treated digestate. Final N:P mass ratios ranged from 1:13 to 1:409, with the highest values observed near the optimal flocculant dose. Subsequently, phosphorous was added to the digestate liquid to maintain the optimum N:P ratio of 1:10 and was supplemented in the form of monopotassium phosphate (H_2KPO_4), with a final phosphorous concentration of 4 mg/L (8.78 g of H_2KPO_4 per 500 L photobioreactor.

4.3.5 Functional testing of cyanobacteria CCS system

The 800 L PBR system was operated under controlled conditions using purified CO_2 and nutrient medium and the best performing cyanobacterial strain (*C. aponinum* UTEX 3222) in laboratory testing. This provided data for cyanobacterial growth under standardised conditions for the demonstration scale equipment. A full 7-day cultivation was completed using 45 L cyanobacterium inoculum raised in 15 L flat panel bag reactors, in an operational volume of 775 L within the PBR. Overall, the functional testing was successful, with steady pH and temperature maintained and all systems operating correctly in readiness for the performance testing.

4.4 Performance testing

H2Boost Phase 2 started performance testing on 8 October 2024 and ran continuously until 30 November 2024, a total of 54 days, 1296 hours**.**

4.4.1 Production of H_2

A total of 57.6 m^3 H_2 was produced over the performance testing phase, at an average of 3.90 m^3/t_{VS}. H_2-containing biogas from DF1 was upgraded using the VPSA system, producing H_2 at up to 89.4 % purity.

DF1 and AD1 were monitored daily to understand their response to being fed with the feedstock blend and obtain a baseline profile (biogas volumes, composition, digestate profiles etc) prior to introducing DF residues into AD1.

The introduction of DF residues into AD1 caused a marked change in CH_4 production, with initial CH_4 yields increasing shortly afterwards, also accompanied by a rise in FOS/TAC ratio, denoting vessel instability. While this showed short term potential for increasing CH_4 production, it is suspected that the acidic nature/high volatile fatty acid (VFA) content of the DF residue was inhibitory to the microbial consortium in AD1. This necessitated a change in DF residue routing, and a bypass system was established to enable diversion of DF residue to storage rather than into AD1.

High VFA levels were also thought to be inhibitory to the H_2 production process in DF1. A review of literature suggested that high concentrations of VFAs are inhibitory to microbial processes and, therefore, impact on H_2 production[5]. As well as the perturbation of AD1, this may also explain the batch-like nature of the DF vessel, which typically showed rapid H_2 production accompanied by a decrease in pH and accumulation of VFAs. H_2 production was then observed to decrease until fresh DF inoculum was added. Future demonstration scale activities and commercial use should integrate a VFA removal system with DF1, for example electrodialysis**.** It is anticipated that this would improve H_2 production and AD vessel stability when fed with DF residues.

Concentrations of trace elements were seen to fluctuate in the DF tank during operation. The highest concentration of trace elements was observed after reseeding the DF tank with inoculum on the 12 November. This also coincided with peak H_2 production. Literature review shows a large number of trace elements are capable of improving reactor performance and increasing H_2 yield, however higher concentrations can become toxic and inhibit fermentation. Future scale up would include more frequent monitoring of the concentration of trace elements being added to the reactor, ideally adding a steady stream of trace elements through the inoculum.

4.4.2 Algae CCS

Performance testing of the algae CCS system comprised seven cultivation cycles of microalgae in a 500 L PBR. In the first three cycles, two PBRs operated in parallel: one used CO_2-unsaturated clarified AD digestate liquid, while the other utilised clarified digestate liquid saturated with CO_2. This setup aimed to differentiate between the carbon captured from the atmosphere during standard microalgae cultivation and the additional carbon sequestered due to the prior CO_2 solubilisation step. Clarified digestate was transferred to a 1.2 m^3 tank equipped with gas diffusers at the bottom for CO_2 saturation. Digestate liquid concentrations in the bubbling tank ranged from 9% to 53%. It was necessary to use bottled CO_2 for digestate liquid CO_2 saturation, as the VPSA unit on-site had not yet achieved continuous CO_2 production.

Initial alkalinity varied across trials, influenced by both the different dilution levels and changes in the composition of the digestate liquid. The results showed that CO_2 was being solubilised in the digestate liquid, with differences in the final alkalinity between trials being attributed to three key factors: variability in the digestate composition and resulting differences in initial alkalinity, the digestate concentration in the tank, and the working volume of the saturation tank.

At a constant working volume of 500 L, higher AD concentrations required more CO_2 to achieve similar final alkalinity levels. Additionally, larger working volumes necessitated higher CO_2 input.

4.4.3 Cyanobacteria CCS

Over the performance testing period, seven cycles of cyanobacteria growth and harvesting were completed (Figure 6). Daily growth was monitored using optical density measurement at 730 nm. Based upon OD:AFDW measurement, this equated to 1 OD: 0.21 g/L biomass and 1 OD: 0.42 g CO_2/L as carbon captured. This ratio was used to predict the biomass quantity produced at each harvest. The culture was harvested semi-continuously (on a weekly basis) when OD_{730} reached between 12-15. Volumes of 240-440 L were harvested at a time to reduce optical density by 25-50%. This method was used so that the culture was harvested in the growth phase and was able to return to its peak (12-15 OD) in under 7 days, preventing both a lag or a stationary phase.

During cycles 2 and 3, system downtime was required, due to a minor leak from the PBR which required repair, and a power overload caused by increased energy consumption from the heaters when ambient temperatures were low, respectively. These downtimes correlated with reduced growth and, due to the stagnation, biofilm had developed on the walls of the PBR tubes. At the end of cycle 3, the full 800 L volume was therefore harvested, followed by a cleaning cycle and reinoculation with fresh inoculum being maintained in 15 L PBRs.

Throughout the performance testing, MM was added after the PBR had been partially harvested and was being diluted with water. The MM was added in low doses based upon being sufficient to reach a target OD_{730} of 14. During cycles 6 and 7, there were plateaus followed by growth which were a result of providing a dose of nutrients to the system, indicating that one or more nutrients had become limited during this time.

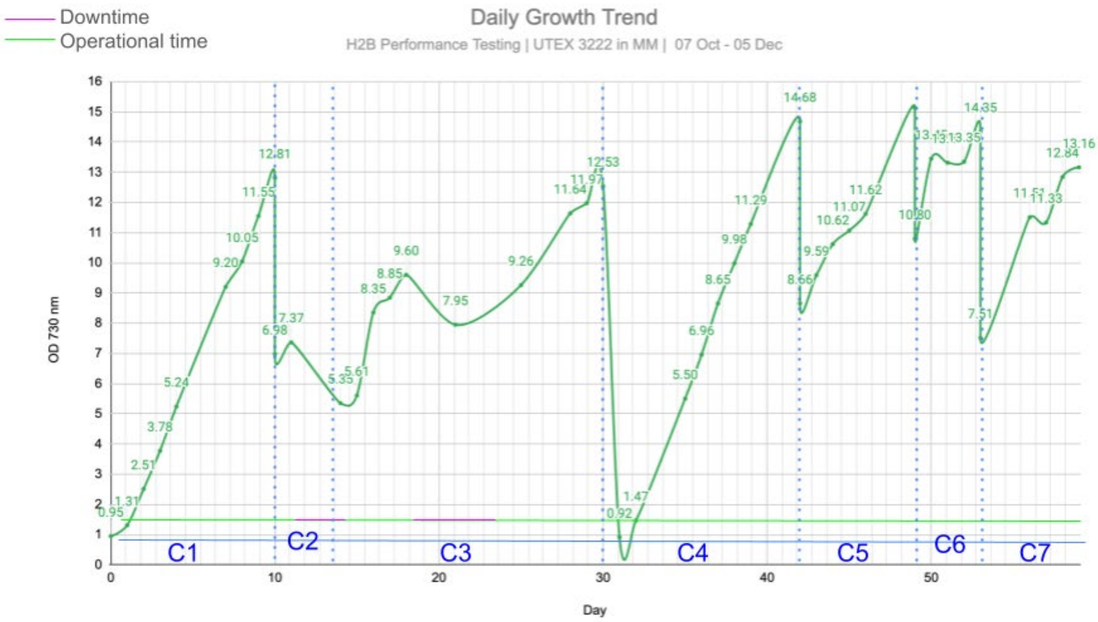

Figure 6. Growth of *C. aponium* UTEX 3222 measured by optical density

Each cycle is defined as a period of growth followed by full or partial harvesting of the culture volume (vertical dotted line). C = cycle.

4.5 Functional testing 2

4.5.1 DF and AD systems

Late in the performance phase, AD1 was fed a more traditional AD feedstock. Optimal AD feedstocks have a C:N ratio of 20-30, containing substantially more nitrogen than those required for DF. A food waste mix, created by The Maltings, was used to feed AD1 and continued throughout the functional testing phase, with a view to optimising AD1 in the hope that better tolerance to DF residues could be established. Small volumes of DF residue were fed to AD1 towards the end of functional testing, with little impact on AD1 CH_4 production. As demonstration scale testing had to be drawn to a close shortly after this, it is not possible to determine whether any longer effect might have been observed.

In the functional testing phase, cold weather arrived, and this presented a challenge to deliver sufficient heat to the DF vessels. In addition, the DF tank in use, DF1, developed a slow leak, potentially due to the acid levels within DF1 residue reacting with the sealing compound used on the vessel. Material was therefore transferred from DF1 to the previously unused DF2. However, sufficient stirring was not possible in DF2, and the feedstock kept settling. The alternative pumped recirculation was a manual activity which could only be used periodically. As a result, very little biogas was being produced, and the

H_2 composition was low. The decision was made to end the demonstration trial at this point due to these issues.

4.5.2 Algae CCS

The functional test was run for 7 days and aimed to replicate one of the performance testing cycles (e.g., using similar digestate concentration, similar CO_2 bubbling conditions, and approximately the same volume of algal inoculum). Despite best efforts to replicate, the conditions were different due to different digestate compositions, which affected microalgal growth and carbon capture as well as CO_2 solubilisation efficiency, which may also have been influenced by different ambient temperatures as well.

The functional test resulted in lower biomass productivity compared to the selected performance test cycle (0.20 vs. 0.32 g DW/L d) and lower CO_2 solubilisation efficiency (6% vs. 19.6%). The lower solubilisation efficiency in the functional test was due to the use of a larger digestate volume (twice as much as in the performance test trial). Consequently, the overall carbon capture efficiency was also lower during functional testing (4.3% vs. 7.8%). This was not out of line with the variability witnessed during different cultivation cycles in performance testing, therefore, not an indication of decay of equipment performance. No decay was observed in the performance of the crucial parts of the carbon capture unit, such as gas diffusers, mixing pumps, lights, settling tanks, and photobioreactors.

4.5.3 Cyanobacteria CCS

No system issues were identified in this period except for biofouling and sedimentation seen inside of the tubes. This had a negative impact on light penetration but could not be removed between the end of performance testing and start of functional testing.

4.6 Summary performance

The demonstration plant ran for 54 days (c. 1,296) hours operating, with material balances given in Table 7.

Table 7. Demonstration plant performance

Project Parameter	Performance Trial (Average/Overall)
Feedstock used by DF (15.2%$_{dm}$ 13.5%$_{vs}$ basis)	52,409 L (971 L /day)
H_2 Biogas produced	245.8 Nm^3 (4.55 Nm^3/day) (19.7% H_2: 80.8%CO_2)
H_2 produced	57.6 Nm^3 (1.1 Nm^3/day)
CO_2 produced (DF)	198.6 Nm^3 (3.68 Nm^3/day)
H_2 Purity	Variable up to 89.4%
H_2 Yield	3.46 Nm^3/t$_{dm}$ 3.90 Nm^3/t$_{vs*}$
Algae produced CO_{2e} basis	3.98 kgCO_{2e}
Conversion Efficiency	67%
Cyanobacteria produced CO_{2e} basis	15 kgCO_{2e}
Conversion Efficiency	48.7%

*t$_{dm}$ = tonne of dry matter, t$_{VS}$ = tonne of volatile solids

Table 8, below, details the design basis throughputs and actual values achieved.

Table 8. Demonstrator engineering design basis and performance

	Design Basis	**Trial Performance (best period)**
Dark Fermentation	(1,000hrs)	(6 days)
Feedstock input L/day	1,433 (8 $\%_{dm}$)	500 (15.2 $\%_{dm}$ 13.5 $\%_{vs}$)
Feedstock input kt/yr	0.48	0.17
H_2 Biogas Nm^3/hr	2.36	0.51
H_2:CO_2 mix %volume	35:65	34.3:64.1
H_2 Volume (post VPSA) Nm^3/hr (80 % recovery)	0.66	0.245
H_2 Yield $Nm^3/t_{dm\ or\ vs}$	55_{dm} 63.2_{vs}	55.8_{dm} 62.8_{vs}
H_2 Purity %	>95	89.4
H_2 Production kg (MWh_{HHV})	59.4 (2.31)*	2.3 (0.089)*
CO_2 Volume Nm^3/hr	1.53	0.329
CO_2 Generation kg	2,818*	87.3*
Anaerobic Digestion	(1,000hrs)	(12 days/DF digestate)
Feedstock input L/day	1,350 (8 $\%_{dm}$)	150 (7.79 $\%_{dm}$)
CH_4 Biogas Nm^3/day	348.5	40.91
CH_4:CO_2 mix % volume	60:40	59.1:42.0
CH_4 Volume Nm^3/hr	8.7	1.01
CH_4 Production kg (MWh_{HHV})	5,811 (89.5)*	194 (3.0)*
CO_2 Volume Nm^3/hr	5.8	0.72
CO_2 Generation kg	10,683*	382*
CCS	(1,000hrs)	(1,000hrs)
Productivity g/L/day	0.2 - 1.75	0.2635
Aerial Productivity $g/m^2/day$	12 – 50	31.52
Biomass Recovery %	80 - 90	60.7
Digestate inclusion %	< 5.0	0.25 – 3.0
CO_2 conversion efficiency %	80	48.66
CO_{2e} converted kg	-	15*
Electricity Usage kWh/kg biomass	28	485.4
Water Use kg/kg biomass	Unconfirmed	294.3

*During performance trial period

**Annual based on 8,000 hours

5 Greenhouse gas life cycle analysis & influences

The lifecycle analysis (LCA) task of H2Boost aimed to determine the lifecycle greenhouse gas (GHG) emissions of the H_2 generated in H2Boost via the DF route. The LCA was undertaken in compliance with approaches and guidance detailed in the UK Low Carbon Hydrogen Standard (LCHS)[6], which underpins access to UK government support schemes. The LCHS requires low carbon H_2 to have a final GHG emissions intensity of no more than 20 gCO_2eq/MJ_{LHV}.

A custom GHG calculator was developed as an interactive Excel tool. Data input was based on 12 months of operation and emissions results were expressed per MJ of H_2 output. The model was capable of being run in three modes to examine the impacts of widening the scope of the GHG analysis:

- DF only
- DF combined with AD
- DF, AD and CC

Owing to operational challenges in the H2Boost demonstration plant, and with the DF and AD units not running in a fully integrated phase, the calculations were largely based on model data for a fully commercial plant and using data from supporting lab trials (explained in detail in the full standalone report for the GHG LCA). These operational parameters and assumptions were agreed and shared with the parallel TEA analysis. Feedstock was assumed at 22 $\%_{dm}$ and 87 $\%_{vs}$ content (typical food waste values). The model also integrated the ability to examine uncertainty in the data (and sensitivity) through the ability to select individual levels of either ‘low’ ‘medium’ or ‘high’ levels of impacts or performance for variables including feedstock transport distance (25 to 200 km), electrical demand, fugitive emissions and H_2 yield from feedstock and fugitive CH_4 emissions from AD. For electricity demand, utilisation was assumed to be either 25 % lower or higher than modelled demand for the commercial scale plant (and ranged from 1.15 to 1.91 GWh per year). H_2 yields of 50,100 and 150 mLl H_2/g dry matter in feedstock were based on expectations derived from lab work and reported literature values. In the absence of measured values, a standard value was adopted for fugitive H_2 loss from DF and H_2 upgrading (5 %), H_2 and CH_4 loss via flaring (0.01 %) and CH_4 loss from AD (1 %).

DF only exploits a fraction of the energy available in feedstock (around 10 %) which would otherwise be wasted if not integrated with another exploitation process (AD in this case). This also helps with GHG emissions burden sharing between exploitation pathways.

H_2 generated from DF in isolation is unlikely to be compliant under the LCHS, with emissions around 70.12 gCO_2eq/MJ H_{2LHV} (46.3–118 gCO_2eq/MJ_{LHV}) depending on assumptions used (Table 9). Feedstock transport accounts for the majority of these emissions (given it’s a bulky material with a high moisture content).

Table 9. GHG emissions for H_2 derived from DF in isolation under a range of performance assumptions

	Optimistic	**Medium**	**Pessimistic**
Feedstock transport (km)	25	100	200
gCO_2eq/MJ_{LHV} H_2	**46.33**	**70.12**	**101.85**
Electricity demand (kWh/year)	1,149,000	1,532,000	1,915,000
gCO_2eq/MJ H_{2LHV} H_2	**61.85**	**70.12**	**78.39**
Fugitive CH_4	0.0 %	0.1 %	1.0 %
gCO_2eq/MJ_{LHV} H_2	**64.80**	**70.12**	**117.96**
H_2 yield (mL H_2 per g DM)	50	100	150
gCO_2eq/MJ_{LHV} H_2	**59.54**	**70.12**	**101.85**

One molecule of acetic acid or similar volatile organic compound is generated as a residual for every one or two molecules of H_2 generated (by enteric-type or Clostridial bacteria, respectively). AD is a well-suited technology to exploit these residual volatile organic materials and the energy they contain.

When DF is combined with AD, the emissions burden of the feedstock transport and process energy can be shared between the co-products: H_2 and exported electricity and/or heat (i.e. used outside of the process itself). In this case, emissions for H_2 generation fall to around 14.98 gCO_2eq/MJ_{LHV} and under most scenario assumptions would be compliant with the LCHS (Table 10). However, this is dependent on effectively controlling fugitive emissions of CH_4 generated during DF (when the DF process destabilises and moves towards methanogenesis).

Table 10. GHG emissions for H_2 derived from DF linked to an AD process under a range of performance assumptions

	Optimistic	**Medium**	**Pessimistic**
Feedstock transport (km)	25	100	200
gCO_2eq/MJ_{LHV} H_2	**10.69**	**14.98**	**20.70**
Electricity demand (kWh/year)	1,149,000	1,532,000	1,915,000
gCO_2eq/MJ H_{2LHV} H_2	**13.56**	**14.98**	**16.41**
Fugitive CH_4	0.0 %	0.1 %	1.0 %
gCO_2eq/MJ_{LHV} H_2	**9.67**	**14.98**	**62.82**
H_2 yield (ml H_2 per g DM)	50	100	150
gCO_2eq/MJ_{LHV} H_2	**14.73**	**14.98**	**15.18**
Fugitive CH_4 (% CH_4 in biogas)	1 %	2 %	4 %
gCO_2eq/MJ_{LHV} H_2	**13.01**	**14.98**	**18.92**

The LCHS GHG methodology only permits emissions allocation to co-products based on energy content using wet LHV. Under such constraints, wet digestate would have a LHV of zero. Therefore, the ability to adopt emissions allocation in this case (to deliver the above results) relies on an additional digestate dewatering step between the DF tank and the AD tank; without this, emissions from H_2 (in a DF and AD scenario) are around 63.03 gCO_2eq/MJ_{LHV}. This anomaly reflects that LCHS GHG methodology was developed assuming combustion of energy containing co-products (where ‘useful’ energy in feedstock needs to account for energy required to drive off water in the feedstock). However, biological conversion processes rely on the presence of moisture. This anomaly should be reviewed in future updates of the LCHS for use with biological conversion processes.

A stream of CO_2 is generated from the separation of DF biogas to extract H_2. Capturing this CO_2 and effectively sequestering it would provide an additional carbon credit to the H_2 generated. After taking account of the estimated emissions associated with capturing, storing and transporting this, and the efficiency of CO_2 capture systems (around 80 %), it is estimated that additional carbon savings of around 218 gCO_2eq/MJ_{LHV} of H_2 can be achieved which can provide net negative low-carbon H_2 of −202 gCO_2eq/MJ_{LHV}. This is dependent on a future scenario of available carbon capture and geological storage (CCS) facilities and infrastructure.

A novel algal photobioreactor processes was trialled in the H2Boost project for capturing CO_2 and utilising nutrients in the digestate. However, high energy demands for supply of heat and artificial light meant that in UK conditions GHG emissions outweighed the CO_2 savings. Such processes may be more suited to projects in warmer climates.

6 Process configuration & scale

H2Boost is an integrated set of processes; the technical and LCA performances of each stage are considered in stages, starting with DF, adding AD and then the PBRs.

For H2Boost, there are process stage interfaces to improve in order to achieve maximum scale, including increasing H_2 yield performance to around 330 L/kg_{vs}, controlling DF digestate properties to better meet the needs of AD, achievement of suitable CO_2 quality to ensure PBR performance is not affected, or for geological storage. Achieving suitable quality and pressurised H_2 (target 99.999 % pure at 350 bar for heavy goods vehicle transport use) is of critical importance, although assumptions about H_2 distribution will vary depending on whether a facility relies on a pipeline link for product supply or specialized logistics to deliver the products in an acceptable form for the end user, for all uses. The supply chain influences are significant including feedstock contracting and logistics, and the knock-on impact on scale economics of H_2 supply. This will not fully resolve until the system performance is improved.

A market scan determined that H_2 compression equipment has a limited supply base for throughputs lower than 10 kg/hr H_2 (c.80 t/yr), representing a lower practical production volume constraint. Also, experience from the demonstration plant highlighted limitations in terms of separation and quality performance and flexibility of the VPSA. Control and stability of the H_2 and CO_2 ratio in the H_2 biogas produced by DF leads to improved VPSA performance.

Ultimately, each commercial project will involve one or more compromises in scale. Key constraint factors for the whole system have been identified, Table , supporting a view on which size system could be deployed. The DF and H_2 constraints noted above, were assessed as the most critical determinants of scale, including supply of suitable quality DF feedstock, and assuming a site suitable for electrical grid connection and water supply.

Table 11. Operational scale - key constraints (single project basis)

Project Parameter	Scale Factors	Volume Range (Current view)	Constraint
Feedstock	• Available Volume • Composition and quality • Supply Contractibility	• Up to 90 kt/yr (247 t/day) is contractable at target quality	Upper contracting limit
H_2	• Yield performance raised to 330 LH_2/kg_{vs} • Low volumes of H_2 may not match some uses • Customer or logistics proximity key to volume acceptance	• Upper scale of 90 kt/yr feedstock could produce c.482 t/yr (19 GWh) H_2 • Lower limit of 80 t/yr H_2 set by equipment availability	Lower = equipment Upper = feedstock
Equipment	• 350 bar H_2 compression equipment readily available above 10 kg/hr H_2 • VPSAs - additional equipment may be required to maximise H_2 separation and improve quality	• 10 kg/hr H_2 upwards	Lower limit

If a plant configuration without PBR technology is selected, CO_2 separation for despatch to a CO_2 store at appropriate quality and state will be required. The demonstration scale facility only separated CO_2 from the DF unit but in an operational system, CO_2 also arises from AD and onsite CHP systems, which may improve the investment case for this route.

A first of a kind concept plant has been designed to receive feedstock at 22 $\%_{dm}$, which is diluted to 12 $\%_{dm}$ for reactor infeed and modelled to produce H_2 at 100 L/kg_{dm} (115 L/kg_{vs}). The compression equipment constraint of at least 10 kg/hr H_2 volume, a plant size of around 43 kt/yr feedstock reception is required. This quantity of feedstock for DF is available and contractable in principle in the south-east, north-west and east of England. Such a system would produce around 80 t/yr H_2, rising to 24 0t/yr H_2 with yield improvements (up to 330 L/kg_{vs}). This scale has been used throughout this review and assumes the yield improvement can be achieved.

7 Policy & regulation influences

In the UK, the H2Boost system is affected by a range of policies, regulations and industry compliance requirements, covering feedstocks, products and operations, shown in Table 12. Policy and regulation will also play a crucial role in the financial success of H_2 production technologies by shaping market incentives, funding opportunities, and cost structures through subsidies, carbon pricing, and infrastructure support.

Table 12. Policies and regulations influencing H2Boost

Area	Policy	Summary of impact
Net Zero & CO_2	Net Zero Strategy [7] 6th Carbon Budget [8] Great British Energy Bill [9] Crown Estate Bill [10] Industrial Strategy [11] National Wealth Fund [12]	A wide range of approaches in UK to accelerate and achieve Net Zero by 2050. Low carbon H_2 is a core focus.
H_2	UK's Modern Industrial Strategy[13] Hydrogen Sector Development Action Plan [14] Hydrogen Production Business Models [15] Low Carbon Hydrogen Agreement [16] Renewable Transport Fuels Obligation Order [17]	Financial support available. Biological H_2 production methods supported. Alternative support mechanisms available for H_2 as 'development fuel'.
CH_4	Green Gas Support Scheme [18] Renewable Transport Fuels Obligation Order [17]	AD is a well-established process with existing support policies. CH_4 gas grid injection is supported until March 2028. Ongoing support as a transport fuel.
Environment & Waste	Environment Act 2021[19] Environmental Plan (2023)[20]	H2Boost will be subject to waste policy and regulation, including environmental permitting and end of waste. Regulation in place to increase source separated collection of food waste.

7.1 Hydrogen policy

The UK's Modern Industrial Strategy[13] supports Hydrogen, incentivising investment, supporting industries like steel, chemicals and materials to decarbonise. The Hydrogen Production Business Models (HPBM)[15], provides financial assistance through a Low Carbon Hydrogen Agreement (LCHA)[16]. Securing support also requires Low Carbon Hydrogen Standard (LCHS)[6] compliance. However, the LCHA does not support gas grid injection, which leaves defined off-takers of product as the only way forwards under this mechanism. Each Hydrogen Allocation Round (HAR) settles a “strike price”, providing a fixed price for the H_2, with the government providing a Contracts for Difference (CFD) style payment for the price gap between the H_2 price (Strike Price) and a reference price (typically natural gas). HAR1 strike price is £241/MWh (£9.49/kg) (2023 prices)[21], below in Table 13, providing a guide price for H2Boost. HAR1 was for electrolyser-based production with future rounds expected to include production using natural gas via Steam Methane Reforming (SMR) with CCS, and to allow access for biobased production.

Support for H_2 is available in the form of Renewable Transport Fuel Certificates (RTFCs) under the Renewable Transport Fuels Obligation Order[22]. H2Boost H_2 would be classed as a development fuel allowing RTFCs at a higher certificate buyout-price than other fuels (£0.80 vs £0.50) and doubling certificate issues rate[22],Table 13. Certificates for Sustainable Aviation Fuel (SAF) are higher, although H_2 as a raw material component for SAF would not attract the value directly, leaving securing of additional value to be commercially negotiated

Table 13. HAR1 and RTFC H_2 value comparison

Support Scheme	Value
LCHA Strike Price (HAR1):	£241/MWh equiv’ £9.49/kg
RTFC (£0.80/cert buyout and 9.16 certs/kg)	£7.33/kg
Note: RTFC prices to fuel producers are typically lower than the buyout price	

7.2 Biomethane (CH_4) policy

AD is a well-established process and there are support policies covering electricity generation, production of heat, gas grid injection and use of CH_4 as a transport fuel.

The Green Gas Support Scheme (GGSS)[18] is closing to new entrant projects (at commissioning) 31 March 2028 and, although a future CH_4 framework for support is being considered within government, it is not yet public. For the purposes of H2Boost, March 2028 is too soon to rely on commercial scale deployment for gas grid injection. CH_4 used in transport will attract RTFCs but the buyout price per certificate will be lower than H_2 as a development fuel (£0.50 vs £0.80), equivalent to £0.95/kg. Whether the CH_4 produced via H2Boost could be classed as a development fuel has not been clarified, but it is assumed not for the TEA modelling.

7.3 Environment, waste and regulation

The Environment Act 2021[19] and associated Environmental Plan (2023)[20] focus attention on improving the natural environment, waste reduction and included source separation of food waste and paper & card wastes. The policy is oriented towards the use of food waste in AD, providing H2Boost (dark fermentation) an opportunity to potentially benefit from higher arising rates of feedstock.

Operating a facility in the field of wastes carries additional regulatory and compliance requirements. These include: a need to meet the Waste Duty of Care: Code of Practice[23] compliance requirements which also captures licensing as a Waste Handler and Waste Processing Facility. There will also be a requirement to digitally track wastes from 2026, which will impact operational design and management, and need specialist associated software. Each H2Boost facility will also be required to secure and comply with an environmental permit[24].

H2Boost systems will be subject to the requirements of End of Waste (EoW)[25] for products, where EoW refers to a point at which a waste material is considered a secondary resource and is no longer subject to waste legislation. In the case of AD there is a Quality Protocol (QP)[26], compliance to which allows self-certification for EoW for CH_4 and digestate arising. The QP has been reviewed by the Environment Agency and will be re-issued as a Resource Framework (RF). The RF is understood to support the potential for H_2 production and CCS.

The extent of regulation is limited around low carbon H_2, although there are compliance requirements for environmental impacts under permitting and health and safety. The LCHS includes sustainability criteria, which are also extensive under RTFO compliance requirements.

8 Markets (supply chain)

8.1 Feedstock market

The H2Boost system targets food, paper, and card waste as feedstock, but not all materials convert to H_2 equally well. Custom feedstock blends with selected enzymes were developed for trials, expanding the catalogue of suitable and unsuitable materials. The DF process faces challenges with mixed food wastes due to variable composition and unknown contaminants. More research is needed to identify harmful contaminants, acceptable concentration limits, and effective pretreatments.

In the UK, waste is classified using the European Waste Catalogue system, assigning codes based on type and origin. A list was created to indicate which waste coded[27] materials are suitable for DF, which need further investigation, and which may require pretreatment.

This approach helps identify single stream food wastes, for example, from manufacturers and processors, allowing control over blends for suitable DF infeed. As H2Boost progresses, an increasing breadth of waste will become useable and accessible.

For England, 2022 data show 7.7 million tonnes per year (Mt/yr) of suitable feedstock, 20.95 Mt/yr potentially suitable (subject to further analysis findings), and 8.21 Mt/yr needing further assessment, Table 14. Laboratory testing determined specific materials which convert well to H_2, and a generalised composition, including for example, convertible sugars, or cellulose which can be modified through treatment. A range of unsuitable materials were found and accounted for, and some materials which may require pretreatment such as separation or size reduction in addition to biological treatments. Use of Waste Codes in some cases counts multiple material forms, including materials which have so far not been assessed, which provides an indication of proportions of the waste streams yet uncharacterised.

Table 14. Quantity of waste received per annum in England, 2022, their potential for use in dark fermentation and requirement for pretreatment (Mt)[27]

Waste fraction as categorised within selected waste codes	Feedstock requires pre-treatment?			Total (Mt)
	Yes (Mt)	No (Mt)	Further assessment required (Mt)	
Suitable for DF	1.29	3.54	2.87	**7.70**
A fraction is suitable for DF	0	1.25	19.70	**20.95**
Requires further investigation for DF suitability	1.89	4.44	1.88	**8.21**
Total (Mt)	**3.18**	**9.22**	**24.46**	**36.86**

The geographic distribution of wastes received, on the same breakdown, shows significant variation throughout England, Figure 7. Wastes received suitable for DF broken down by origin Region in England[27], with suitable material showing greatest availability in the south-east, north-west and east of England regions.

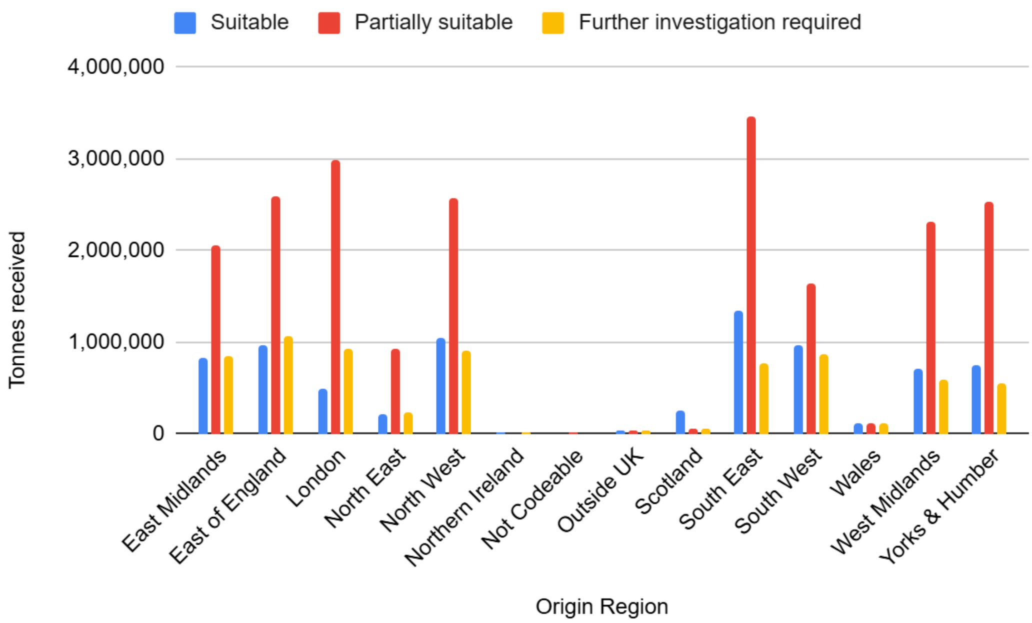

Figure 7. Wastes received suitable for DF broken down by origin Region in England[27]

Waste suitable for DF is currently managed within the UK's waste infrastructure and at this stage of the technology development, direct contracting for specific materials is a lower risk approach than procuring a bespoke mix which carries supply quality risk. Suppliers expressed commercial confidence to supports contracts at 10-20k/yr, with potential for multiple contracts for 45kt/yr to 90kt/yr. Bespoke pre-mixed supplies would incur additional costs and carry higher prices, although mixed waste pricing is expected to remain with a gate fee price of at least -£30/t for the foreseeable future, favouring controlled purchase of

separate waste streams[28]. Adding H2Boost to existing AD plants could leverage current feedstock contracts and minimise competitive volume and price pressures if the feedstock quality requirements of DF and AD can be aligned.
For a standalone system, the Northwest, with high quantities of suitable waste received, shows good potential for feedstock contracting due to the low local density of AD plants.

8.2 Hydrogen market

Hydrogen application studies by The Royal Society and The Royal Academy of Engineering (RS&RAE)[29], US based US based Renewable Thermal Collaborative (RTC)[30] and the IEA[31] arrived at similar conclusions that H_2 is useful for high heat (up to 2,100 °C) and chemical use applications, with the IEA and RA&RAE adding synthetic fuels, Figure 8.

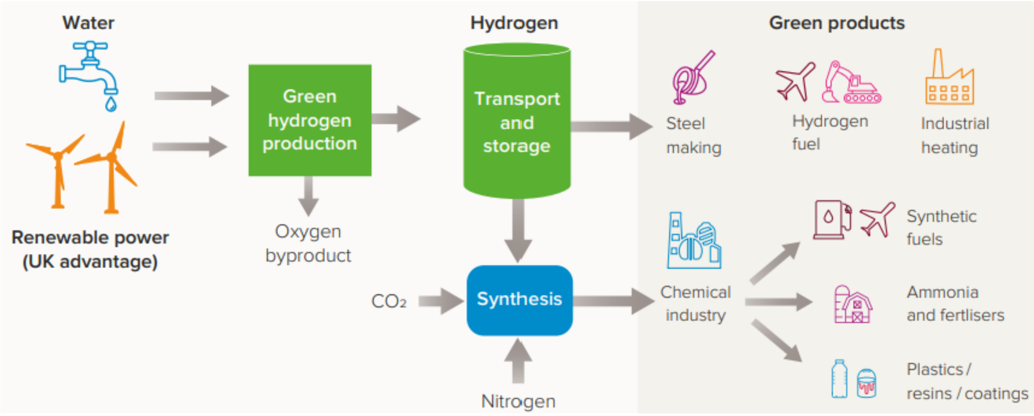

Figure 8. Hydrogen value chain[29]

Global H_2 demand, taking account of existing and new applications, is projected to rise from c 97 Mt/yr in 2023 to around 150 Mt/yr by 2030, assuming international efforts remain focussed on net zero by 2050[31].

In the context of government expectations, HAR1 has committed to support 11 projects with 125 MW capacity in total (at 50 kWh/kg H_2 for electrolysers this equates to c. 8.1 t/hr or c. 64 kt/yr at 90 % availability)[32]. HAR2 is aiming for 875 MW (c. 448 kt/yr) capacity. In this context, a commercial H2Boost system would be a smaller producer of H_2 (241-482 t/yr 1.2-2.4 MW_{HHV} capacity).

H2Boost has targeted H_2 supply as transport fuel, representing among the hardest uses to displace fossil fuels. H_2 use in fuels cells for transport use requires H_2 with a purity >99.999 % and supply at pressures of 350 bar or 700 bar for heavy goods and passenger (incl. light goods) vehicles, respectively.

The Advanced Propulsion Centre's (APC)[33] technology roadmap for UK supply chain development of hydrogen[34], projects UK sourced supply of critical automotive supply chain equipment to be in place between 2030-2035, with full progress by 2035-2045.

As an alternative market, H_2 for high heat (1,000 – 2,000 °C) use has no fixed quality standard, although around 98 % purity is a reasonable indication of requirement, and pressure needs are lower, especially for co-located demand.

The gas network is being upgraded to allow up to 20 % H_2 alongside natural gas and CH_4 which represents an almost unlimited demand, but it is not supported by the LCHA and not considered further here.

Other high heat applications include manufacture of cement, glass, ceramics, Table 15, and possibly steel.

The UK cement industry has the highest energy demand including from eleven (11) operational manufacturing sites with a combined capacity of around 10 million tonnes per year. A 50:50 blend of biomass and H_2 in the rotary kiln (40 % of demand) stage[35] could replace fossil fuels[35]. The glass industry has the second-highest H_2 demand due to high operating temperatures exceeding 1400 °C, representing 60-80 % of the operational energy demand. There are seven (7) industrial scale glass sites, with heaviest concentrations in the north-west and Yorkshire. The ceramics industry could achieve high H_2 demand, with 70-90 % of site energy used for processes above 1000 °C (typically 1,400 °C) and 8 major sites across the UK.

In all heat demand cases, site demand has a lowest demand of around 1,000 t/yr H_2 and up to 6,000 t/yr H_2. Table 15 shows the potential H_2 demand for thermal use in glass, cement and ceramic manufacture.

Table 15. High heat applications - potential demand

Industry	Total Sites	Total Energy Demand (GJ/day)	H_2 Demand (kg/day)	Annual H_2 Demand (tonnes/year)
Glass	7	15,520	77,600 - 103,460	28,310 - 37,760
Cement	11	82,500	137,500	50,160
Ceramics	8	10,000	58,330 - 75,000	21,270 - 28,360
Total	**26**	**108,020**	**273,430 - 315,960**	**99,740 - 116,280**

High temperature heat demand in steel mills is currently satisfied with natural gas, although H_2 is an alternative fuel [36]. However, the temperatures for rolling mills at a maximum of 1,200 °C is lower than the other industrial applications considered, and less attractive as a result.

In all cases, whether transport or heat, electrical options are available, and this represents a competitive consideration. With heat demand concentration in the north-west, the evolving HyNet scheme and the most available food wastes, this region is promising for deployment of a commercial H2Boost system. However, with potential H_2 volumes for each heat end user greater than the largest projected H2Boost system, a mixed solution may be required. Automotive required continued attention as the smaller scale of demand centres (down to vehicle scale) may be a better solution from a volume perspective. Use in chemicals is a diverse applications base and has not been considered in further detail to date.

8.3 Biomethane (CH_4) & digestate markets

Government policy continues to support AD as a process, specifically prioritising food waste to be used as feedstock in line with the 2025/6 segregated food waste collection being implemented. Also, the Environment Agency (EA) have been reviewing the End of Waste position in respect of AD and related digestate, and a re-issue of the self-certification scheme for CH_4 and digestate (Resource Frameworks) is imminent and AD is expected to continue to be supported under the amended scheme.

CH_4 demand is principally dependent on projects being gas network connected, which is a site-specific requirement and not a technology or an out of the ordinary supply chain factor. Otherwise, the current outlook is for commodity market demand as the government's financial support via the Green Gas Support Scheme (GGSS) is ending for new entrant projects.

Digestate application requires consideration of local farm/spread to land capacity in line with environmental policies and regulations, which is in line with current practices and considered an operational factor.

Both products have demand and neither product is considered as volume constrained.

8.4 Photobioreactor (PBR) products market

Several applications are being considered for PBR products. One is direct application in agriculture, where nutrients in algae/cyanobacteria act as a fertiliser, replacing fossil alternatives and minimising processing steps.

Another application is converting algae/cyanobacteria into solid carbon for long-term CO_2 storage. Such conversion involves elevated temperature processes including pyrolysis (300-800 °C), hydrothermal carbonisation (170-280 °C), and hydrothermal gasification (>370 °C). These processes produce liquid and gaseous co-products useful for further conversion or energy recovery. Although capital and operational costs are high, they offer a potential route for CO_2 storage, depending on LCA.

All applications require improved LCA performance and further PBR process improvements to proceed.

8.5 Supply chain summary

All markets for renewable H_2 are nascent with significant timing uncertainty. For example, fuel cells and engineering systems for transport holds a particularly complex set of requirements, including adoption of H_2 as a fuel of choice by transport system owners and end users of vehicles. Demand location concentrations are variable, and selection of early adopter locations for H2Boost, aligned with specific transport hub and bespoke projects will be required for deployment.

Use in industrial heat applications may align with site capabilities handling a range of other fuel materials, such as biomass use at cement kilns. There may be additional potential benefits including use of CH_4 as a co-fuel to manage combustion temperature. In all heat cases, electricity is emerging as a competitive source of energy, although in-combination benefits of H2Boost may remain of interest.

With H2Boost looking likely to represent relatively small volumes in industrial terms, at commercial H2Boost scale, close partnerships will be required to achieve bankable secure offtake volumes, which may be better suited to smaller potential demands.

Algae/cyanobacteria are less geographically constrained from a raw material and product supply chain perspective, although access to appropriate quantities of low-priced renewable electricity is crucial and may not be suited to the UK where ambient temperatures and light levels are low compared with other warmer countries.

9 Feasibility (Incl. Levelised Cost of Hydrogen)

9.1 Financial modelling

Financial modelling for H2Boost considers the business case for proceeding with development of the technology using scenarios, including alternative plant configurations, as detailed in Table 16. Plant configurations along with fixed financial assumptions in Table 17. In addition, a calculation of the Levelised Cost of Hydrogen (LCOH) is included in section 9.2 using the methodology provided within the government's document[37]. The system boundary for the LCOH calculation used here will be the same as that for determining H_2 compliance with the LCHS[6], which is pre-high pressure compression of H_2. If the H_2 cannot comply in a given scenario, it is considered non-viable at the current projected performance potential.

Table 16. Plant configurations

Scenario	Configuration
A	Dark Fermentation
B	Dark Fermentation + Anaerobic Digestion
C	Dark Fermentation + Anaerobic Digestion + Photo-Bioreactor CCS

Table 17. Financial assumptions

Inflation	2 %
Qualifying Capital Allowances	18.0 %
Depreciation	15 Years
Corporation Tax	25.0 %
Discount Rate	8.0 %
Equity Investment	100 %

Although a discount rate of 8 % is low for a first of a kind technology, it is assumed the technology will mature and be derisked. The modelling approach built up from plant configuration A to B and then C, testing for ideal conditions to achieve acceptable performance within the constraints of the financial assumptions. Baseline performance indicators are parameters developed from demonstration trial findings representing achievable yield increases with further process development. In addition, where required to support the financial aims, a more challenging "reach" target has been set to determine what will be required for the technology to achieve a minimum investment case. The modelling is dynamic such that, if a greater improvement is achieved in one factor, it may reduce the requirement on another.

The financial model considers the case for commercial operation, which includes the costs of project development, reception and management of feedstock before pre-treatments, preparing products for final form despatch and integration of all relevant plant outside the core LCOH battery limits. For the purposes of financial assessment, Table 18, assumes the Commercialisation Performance Goals set out in Table 8, below, details the design basis throughputs and actual values achieved.

Table 8 have been achieved and the PBR has been sized to utilise all CO_2 arising from the DF for conversion to algae/cyanobacteria, which is discussed further below.

Table 18. Financial Performance Projections

Performance Factor	Performance Projection
Dark Fermentation	
Feedstock	43.7 kt/yr
Feedstock (22 $\%_{dm}$ 19.1 $\%_{vs}$)	-£30 /t
Price H_2	£9.49/kg*
H_2 yield	330 L/t_{vs}[38]
H_2 produced	240.5 t (9.48GWh)
Electricity demand	65 kWh/t vs
Electricity Supply	Co-located AD (wholesale supply)
Capital Cost	£15.14m
Financial Return Indication	**10.4 %**
Dark Fermentation + Anaerobic Digestion**	
Feedstock (DF digestate)	-£30/t
CH_4 (85 % converted to electricity for internal system supply plus export)	£83/MWh_e
CH_4 produced	1,284 t (19.8GWh)
Electricity Generation	10,200 MWh
Electricity demand (balance exported)	3,294 MWh
Capital Cost	£21.5m
Financial Return Indication	**8.4 %**
Dark Fermentation + Anaerobic Digestion+ Photo Bio Reactor CCS**	
CH_4 (85 % converted to electricity for internal system supply plus import)	£83/MWh_e internal use £230/MWh_e import
Algae/cyanobacteria production (odt)	2,340 t
CO_2 Conversion (incl. harvesting)***	3,596 t
Product Price (mid-range, indicative market)****	£19.33/kg
Financial Return Indication	**7.0 %**

*HAR1 strike price (assumes achievement of technology support at this price) **AD modelled with no financial incentives ***The CO_2 conversion value is not a net CO_2 position, which is accounted for in the LCA as net emissive ****High price uncertainty + & -

This approach is designed to assess where technology performance lies and what additional performance will be required to achieve a viable system configuration. This also provided core data to assess the long-term potential for reducing LCOH.

H_2 yield is a critical feature and as noted in Table 6, paper and card waste can yield higher quantities than the ambition of 300 mL/g_{vs} for food wastes. Notwithstanding this, the return projections for DF and DF + AD are positive, with room for further improvement. Potentially DF units could be added to an existing AD facility which could reduce capital requirements and labour costs through shared resourcing whilst minimising other operational expenses. Wastewater treatment works with AD on-site may be worthy of consideration to locate in as an energy positive location with access to inoculum material.

A larger system consuming up to 90kt/yr feedstock will provide further cost reduction potential and opportunity to reduce reliance on a LCHA with a fixed strike price, assuming this contracting approach becomes available.

The commercial potential for algae/cyanobacteria is promising however the energy demands are significant and out of balance with the DF and AD stages. This needs further consideration in addition to the energy strategy for this element of an H2Boost system. A PBR could be sized to use all residual electricity generated by the AD plant rather than importing energy. This process change could provide a more favourable commercial case due to significantly more favourable terms (£83/MWh versus £230/MWh for import).

9.2 Levelised Cost of Hydrogen Modelling

The method used here for calculating LCOH follows the guidance outlined in H_2 production costs 2021 - GOV.UK[37]. The system requirement is to meet the LCHS standard as a minimum with any additional CO_2 captured attracting carbon certificate value. In this case, there is no current projection for algae capture and it has been assumed the DF unit is a stand-alone system with residues arising being used in a co-located AD. The electricity supply is generated by the AD unit while CO_2 from the DF is 80 % separated and transported for geological storage using the nominated default values.

The demonstration plant ran as set out in Table 8, below, details the design basis throughputs and actual values achieved.

Table 8. The best performance period was extrapolated to determine the annualised operating parameters considered in the LCOH calculation and are set out in

Table 19 alongside the project LCOH values given in Table 20.

The discount rate applied to H_2 volume produced is 0 %, on the basis that volume produced will not vary year to year.

Table 19. Project specific data assumptions

	Cost Factor & Volume	Unit	Demo	Phase 2 + 5yrs*+	Commercial (Reach Ambition)
Plant	Biomass Input (22 %dm)	t/yr	183	183	43,884
	Capacity (H_2)	t/yr	0.404	2.43	241
	Capacity (H_2)	MW	0.002	0.012	1.2
	CO_2 Captured	t/yr	-12	60	7,399
	Capex	£	0.707m	1.01m	15.14m
Variable Opex	Biomass Cost**	£/yr	0	0	-1,282,530
	Energy	£/yr	1,000	6,900	131,555
	CO_2 Transport & Store	£/yr	0	1,668	237,748
	Other Variable Opex (excl CO_2 Trans/Store)	£/yr	300	2,555	150,288
Fixed Opex	Labour	£/yr	175,680	180,000	280,000
	Other Fixed Opex (Incl. Site, Admin, Maintenance)	£/yr	42,500	137,000	1,085,000
Finances	Discount Rate	%	10	10	10
	Inflation	%	2.0	2.0	2.0
	Construction Period**	years	3	3	3
	Annual Hours	hours	8,000	8,000	8,000
	Calculation Period (operational)	years	25	25	25

*Data remains subject to further revision **Gate fee cost is revenue but LCOH modelling requires to be shown as Opex ***3 years used as consistent metric + +5yrs represents the period to update the process and demonstrator plant design*

Table 20. Project LCOH values

Development Stage	£/kg Including (Excluding) CO_2 saved	£/MWh Including (Excluding) CO_2 saved
Phase 2	633 (636)	16,077 (16,161)
Phase 2 + 5 years	156 (157)	3,962 (3,979)
Commercial* + **	7.01 (7.67)	178 (195)

*requires value engineering of conservative concept design for DF and achievement of Phase 2 +5 aims
+c. 7,399 t/yr CO_2 at 80 % capture rate for deep store
**Remains subject to further revision

9.3 Competing technologies

A literature review of H_2 producing technologies determined (where data was available) technology maturity, current scale, emission performance and was used to identify levelized costs. The CO_2 performance is considered in relation to the LCHS threshold of 20 gCO_2 eq/MJ_{LHV} and where values are above the threshold (RED), can be compliant (Amber), compliant (Green). Some data was not found in the literature search and is noted as not determined. The compliant operational configuration for H2Boost is projected to achieve average emissions of 14.98 (13.01–18.92) gCO_2 eq/MJ_{LHV}, which is close to the literature findings for DF. Addition of CCS to the DF + AD system provides a strong carbon negative case, although the projected cost base needs further improvement to compete with the lowest cost alternatives.

10 Lessons learnt

Many important lessons have been learnt whilst undertaking the H2Boost project, which can be taken forward to further develop the technology and commercialise the system.

Having the right team to deliver a large complex project on time and on budget was critical to the success of H2Boost. Equally, allowing sufficient time to develop a new process, design, build and run a demonstration plant. The timetable for an innovative project needs to be realistic and allow development time. Time is also required to complete and obtain the regulatory elements; planning permission, environmental permitting and HAZOP/HAZID as external factors can cause major delays in the project development.

The identification of optimal feedstock (and non-optimal) has progressed the H2Boost project further, creating potential for higher H_2 yields. This is complemented by a better understanding of the production of DF inoculum through various processes with lower energy input. This will reduce the production time and cost of DF inoculum and enable supply for the production of H_2.

The design of H2Boost would require some key engineering plant design changes to optimise the system and save energy. Further research on DF and AD integration, whether through feedstock development, use of DF digestate in AD, injection of H_2 into AD or the removal of VFAs, would influence a future design of H2Boost, along with the lessons learnt during this project. Also, further research is required to gain a better understanding of requirements for using digestate as an algal and cyanobacteria cultivation medium.

The LCA and TEA, along with the LCHS have shaped the commercialisation strategy and the direction of development of H2Boost. The next phase will focus on DF associated with AD

10.1 Key successes

Within an 18-month period, H2Boost researched and developed the technologies described in this report, and designed, built and ran trials for over 1,200 hours at the demonstration scale plant producing H_2 and capturing CO_2, all within budget. The plant produced 57.6 Nm^3 H_2 and captured 18.98 kg of CO_2 in algae or cyanobacteria, both key successes of the project. The trial generated data, process understanding and knowledge, sufficient to advance the scale up and commercialisation of low emission H_2 production.

The consortium built strong relationships quickly during the project, collaborating well together and creating solutions for any issues, and delivered an on time and on budget project. The team had not previously worked together and many of the partners had not previously undertaken such a complex project.

Securing an environmental permit and subsequent officer monitoring provided an opportunity for EA staff to engage with the technology and explore matters of relevance. Operating within an existing food waste management facility and running a hydrogen-methane plant highlighted complexities relating to commercial operation compliance. A future system will need to build on this learning, ensuring any health, safety and environmental risks are fully identified. Daily monitoring on-site and remotely was effective, allowing rapid resolution of issues and deployment of mitigation steps this reduced the risk of operational failure and/or plant downtime.

Data generated during the operation of the demo plant gave valuable process insights, such as the accumulation of VFAs or low concentrations of trace elements leading to the decline in H_2 production. This has given vital information for future commercialisation and next generation plant build.

The production of H_2 was highly variable during operation of the demo plant and featured periods of peak production followed by a steep decline. To mitigate these declines fresh inoculum was produced and introduced to the DF along with removal of large quantities of the reactor contents. Future plant build would need to consider a stable introduction of inoculum to give consistent H_2 yields and avoid the mass rejection of contents that then need to be treated under waste regulations. Integration issues were seen in a number of process steps; when AD was fed solely of DF residue there were negative impacts to the stability of the AD system, shown in the biogas composition and FOS/TAC ratio. This knowledge would be used to build flexibility into the process flow allowing a ratio of DF residue to be fed to AD rather than the full daily outflow. This would allow time for the AD microbes to equilibrate and adapt.

10.1.1 Dark fermentation

The continuous nature of the demonstration plant allowed development of a greater understanding of biological reasons the DF reaction curtailed after a period of operation. These include feedstock variability, restricted nutrients and trace elements, suboptimal C:N ratio and VFA build-up in the reactor.

As reaction stability is a critical goal for commercialisation, the understandings above provide opportunity to improve the process. Removal of VFAs offers an opportunity to evolve H_2 consistently while creating other valuable products in the individual VFAs[39]. VFA control and improved nutrient availability could lead to a 6-fold increase in H_2 yield to around 330 L/kg_{VS}[38].

Improvement of the DF process is expected to result in a DF digestate more suitable for direct use in AD. This is due to the VFA level being lower and not inhibitory for AD microbes alongside higher nutrient availability.

Use of enzymes to treat feedstock in the DF reactor broadened the range of materials suitable for H_2 production and for the scope of material blending available. Extensive laboratory testing of feedstock materials forms a growing catalogue of potential feedstocks for DF. This knowledge enables feedstock blend design, such as that used for the trials, avoidance of unsuitable materials and the possibility to contract required feedstock supply volumes.

10.1.2 Anaerobic digestion

Time needs to be allocated for developing fully mature biological systems prior to testing, particularly in the AD tank. DF residues indicated properties not typically suitable for AD. Although the AD reactor had not reached full maturity for the trials, an initial increase in CH_4 was seen when DF residue was first added, ahead of a decline in the health of the AD tank. The initial increase in CH_4 yield suggests that a mature system with flexible feeding to allow ramping up of DF residues fed in would be able to tolerate and eventually thrive on DF additions.

10.1.3 CCS (algae)

Algae growth in a medium containing between 15.7-32.3 % of treated digestate demonstrated the feasibility of using nutrient-rich waste products as a sustainable and cost-effective growth medium, eliminating the reliance on defined media. A further key advancement was the preliminary step of saturating digestate with CO_2 prior to algae cultivation which significantly enhanced algae growth by creating a medium both nutrient-rich and carbon-optimised. This proved to be a more efficient method of delivering CO_2 compared to direct injection or bubbling into cultivation tanks, resulting in improved carbon utilisation. Almost 100 % of the solubilised CO_2 in digestate was converted into algae biomass at demonstration scale.

Algal growth was carried out utilising CO_2 emissions from the demonstration plant and with potential extrapolation for CO_2 emissions from AD biogas combustion. The dual-stage approach of CO_2 solubilisation and microalgae cultivation amplified carbon sequestration potential while reducing the overall carbon footprint.

Utilising digestate for algae cultivation reduced the risk of nutrient leaching and waterway pollution in agricultural applications. The resulting algae biomass retained residual nutrients, making it suitable for use in agricultural applications, thereby closing nutrient loops and supporting sustainable soil health. H2Boost was able to fully quantify the CO_2 conversion from input gas to output biomass to present a volumetric capture rate of 0.32 g/L/CO_2/day and aerial capture rate of 48.44 g/CO_2/m^2/day for commercialisation analysis.

10.1.4 CCS (cyanobacteria)

Over the performance testing period, over 15 kg (C4-C7) of CO_2 was captured. Furthermore, the CO_2 conversion was fully quantified from input gas to output biomass to present an average volumetric capture rate of 0.32 gCO_2/L/day and average aerial capture rate of 48.44 gCO_2/m^2/day for commercialisation analysis.

10.2 Persistent barriers

As would be expected, delivery of such a project to a tight timescale and budget encountered some persistent issues and barriers.

10.2.1 Project management

During the project, research, demonstration scale design and build were undertaken in parallel. As the laboratory research influenced the demonstration scale design and processes, this caused challenges during the project, as changes were required post build. H2Boost started with a mixture of TRLs for the different parts of the process, which resulted in steep learning curves in some areas, to reach a demonstration scale plant.

The novelty of the technology meant the process of going through planning permission and gaining EA approval caused challenges with the project and timescales.

10.2.2 Feedstock issues

The DF microbes were sensitive to minor feedstock changes. This was seen in the laboratory trials where feedstock variability had a huge impact on H_2 production. Following variable laboratory results with food waste soup, more consistent feedstocks were targeted, however waste materials will always have an inherent amount of variability.

10.2.3 Demonstration plant

The demonstration plant was designed before any laboratory work had been completed. This led to some of the plant design being suboptimal. The shared pipework between DF and AD had to be altered to remove the risk of methanogen contamination of the DF tank. Temperature of the DF tanks struggled reaching the set points during lower ambient temperatures. Ideally the AD tank should have been proportionately larger in comparison to the DF tank to cope with the nature and volumes of DF residues produced.

The DF inoculum treatment vessel had two major issues. The cooling system was not appropriate for the site, due to the cooling time taking 12 h. Also, the heating of the demonstration plant relied on the biogas produced via AD. As an experimental system digesting DF residues, this meant that the methane yield was not always optimal which was then detrimental to the heating of the whole plant.

Taking measurements at the demonstration scale was also inhibited, resulting in a difficulty to see real time results and the average flow rates.

Scaling the PBR system while maintaining consistent results was challenging due to multiple factors. Light penetration in the PBRs emerged as a critical barrier. Dense algal cultures often led to self-shading, limiting the availability of light. This reduced photosynthetic efficiency and required advanced reactor designs or operational strategies, such as better mixing or using thin-layer PBRs, to optimize light distribution. Additionally, biofouling of PBR surfaces by algae and other microorganisms further decreased light penetration and reactor efficiency, increasing maintenance demands and downtime.

10.2.4 Testing

The fixed functional testing period did not allow for a robust and mature biological systems to be ready for experimentation. The AD microbiome was still equilibrating to the new feedstock and had not yet reached the target organic loading rate when DF residues began to be fed into AD1. Had the system been mature, DF residues may have been tolerated better allowing for DF1 and AD1 to work in-line as planned.

The DF went through distinct periods of exponential H_2 production followed by plateau. The process behaved more like a batch system.

While the digestate provided a nutrient-rich medium for algae cultivation, its composition often contained imbalanced nutrient ratios (e.g. high nitrogen but insufficient phosphorus). This limited the optimal algae growth and required additional supplementation, which introduced potential environmental trade-offs such as higher resource use and costs. Although saturating digestate with CO_2 improved algae growth, achieving consistent and uniform saturation proved challenging. Incomplete CO_2 solubilisation could lead to localized CO_2 off-gassing, contributing to air quality concerns and reducing overall carbon capture efficiency.

The PBR process required significant volumes of water, both for algae cultivation and for diluting digestate to suitable concentrations. This raised concerns about water resource competition, particularly in regions facing water scarcity. Additionally, effective recirculation of spent media after biomass harvesting is still challenging due to the buildup of salts, organic matter, and flocculant. These accumulations require periodic removal or treatment, adding operational complexity and increasing the risk of system inefficiencies or environmental impacts if not properly managed.

In addition, the energy required for mixing, and maintaining optimal algae cultivation conditions posed a barrier to achieving net-negative emission outcomes. Algae harvesting and digestate pretreatment posed unique challenges. Flocculation, used as the primary harvesting method at the Maltings, required chemicals that raised concerns about potential contamination and environmental impacts. While alternative methods such as centrifugation or filtration are available to avoid chemical inputs, they can significantly reduce energy efficiency.

There were also periods of downtime. These were short and occurred for various reasons such as a site-wide power outage caused by a storm, system leak, or a power overload. These reasons were beyond operator control but were quickly rectified and resulted in improvements to our operations and system design.

11 Commercialisation and conclusions

11.1 Commercialisation

In order to progress H2Boost, a further demonstration scale operation at a similar scale to the Phase 2 demonstrator, is required, including consideration of alternative process and plant configurations, to improve carbon performance, to demonstrate improved process stability and confirm potential to reach higher yields. Specific attention to H_2 cleanup and compression is also needed. All is required to attract deployment equity funding.

PBRs as a form of CCUS can be considered independently of the DF and AD elements of H2Boost, to achieve high digestate inclusion, improved carbon performance and defined preferred deployment geographies. As a result of low technology readiness of PBRs, H2Boost will need to include a more conventional non-biological approach to CCS.

A large-scale reference operation will then be required to prove technical performance and commercial viability in support of system technology sales to end users, other supply chain interests or developers, looking to build their own capacity. H2Boost deployment and potential will arise from development of end user partnerships which will refine market knowledge and support investment for individual projects. This will also support investment in a technology sales opportunity.

11.1.1 Extended demonstration (2025-2028)

This would require H2Boost to:

- secure funding
- advance process engineering for upgraded demonstration plant design
- remove yield constraints including VFA removal
- increase feedstock conversion databank of acceptable material forms
- extend scope of enzyme use
- achieve DF digestate compositional control to improve AD performance
- deliver transport grade H_2 at dispenser pressure
- achieve CO_2 separation to target quality
- extend laboratory work for PBR use of digestate as a nutrient source
- formalise and secure IP rights
- re-assess commercial viability
- use H_2 production to build application partnerships, especially for reference site location

11.1.2 Reference site (2028-2032)

Including development activity, H2Boost will need to:

- select and agree a preferred reference site partnership and location
- secure the required investment
- develop engineering design for a reference site
- secure necessary permits and consents
- develop feedstock supply contracts for the reference site
- secure detailed engineering design and contractor bids for supply of equipment
- secure a LCHA, if available or RTFC compliance for transport use
- deliver performance improvements, including commercial effectiveness
- confirm target user markets and commence promotion

Study findings suggest north-west England is a preferred region to advance from a feedstock availability, and H_2 use commitment by government, including the HyNet initiative, and would be an ideal area to site the reference plant.

11.1.3 Technology sales (commercial package (2030 onwards)

This requires development of the technology package to be offered commercially, and establishment of the roll-out business, including:

- secured investment funds
- defined and secured business resource requirements
- fixing licensing and ongoing process revenue charges
- confirmation of wider service offerings including; engineering supply for core equipment, process monitoring, commissioning, operations support
- extent of operational data analysis service
- advisory services available, such as for feedstock sourcing, product uses, local system integration

11.2 Funding

Delivery of commercialisation via the pathway set out requires funding and investment with indicative requirements and outcomes set out in Table 21. Funding requirements for the technology sales business will be developed during the extended demonstration phase. Sources of funds are still to be identified.

Table 21. Projected funding requirements (£M) and outcomes

Commercialisation Stage	**Capex £M**	**Opex, R&D and Commercial Development £M**	**Total £M**	**Outcome**
Extended Demonstration	1.8	5.5	7.3	• process and performance proved • economics confirmed • preferred market applications selected • funding secured for reference site
Reference Site	10	10	20	• technical and commercial performance suitable for investor scrutiny • data sufficient to fix technology sale packages • business model finalised and funding secured to deploy

11.3 Deployment & deployment risks

H_2 use in transport represents one of the hardest to abate sectors and has high technical thresholds for use in PEM fuel cells and related logistics. H2Boost system use for heat applications has the benefit of also having low emission CH_4 available as a co-fuel, making this potentially more attractive. In terms of chemical use applications, a greater understanding is needed to assess use potential. In all cases, to build market interest, H2Boost needs to demonstrate ability to produce H_2, control its quality and confirm financial viability in each application format.

Of note is H2Boost securing support from the Carbon Trust led and DESNZ funded Acceleration Support Programme. The Carbon Trust, along with Sustainable Ventures, offered support to the H2Boost team in the development of a Business Model Canvass supporting refinement of the potential markets for H2Boost.

Policy changes since July 2024 have increased emphasis on speed of deployment for clean energy projects and government commitment to HyNet in the north-west and the Teesside H_2 cluster has increased confidence in H_2. There is always risk that these projects become subject to delay and that demand centres outside direct gas grid injection take longer to come into reality than ideally the case.

H_2 generated from DF in isolation is unlikely to be compliant under the LCHS, with emissions around 70.12 $gCO_2eq/MJ\ H_{2LHV}$ (46.3–118 gCO_2eq/MJ_{LHV}) depending on assumptions used. When DF is combined with AD, the emissions burden of the feedstock transport and process energy can be shared between the co-products: H_2 and exported electricity and/or heat (i.e. used outside of the process itself). In this case, emissions for H_2 generation fall to around 14.98 gCO_2eq/MJ_{LHV} and under most scenario assumptions would be compliant with the LCHS

Access to development fuel RTFC's is attractive and perhaps more flexible that the LCHA. Once open market values of the products are considered, the value of RTFCs and LCHA result in a total revenue of the same order and the technical threshold for LCHA applications may be substantially lower than for fuel cell applications.

EoW is a risk for deployment whilst there are still no Resource Frameworks issued and further steps to secure such for DF H_2. In addition, as H_2 is at an early stage in development, the logistics and infrastructure systems are limited at this stage, which naturally increases the risk of the project.

Change of Law policy and regulatory risks are significant factors for projects with multi-year development periods, and mitigation requires consistent and long-term engagement with policy makers, government departments and agencies, also working with industry groups to take knowledge to these bodies. H2Boost will need to engage more fully with these as an element of commercialisation.

11.4 Conclusions

H2Boost was successful in delivering and achieving the objectives of the Phase 2 DESNZ funded project, producing H_2 and capturing CO_2 in a demonstration scale facility over more than 1000 hours. However, to advance H_2 production and CO_2 capture there needs to be an improvement in performance before an economically competitive process can be commercialised successfully against other technologies.

The further development of the system will include:

- further feedstock optimisation to extend the acceptable waste streams
- development of the DF process to optimise H_2 production
- continue the development of low energy DF inoculum production
- optimise the design of the H2Boost plant, to address the issues from the trial
- building of end user partnerships using H_2 produced to fix preferred applications
- explore further the downstream processing of cyanobacteria to create a valuable product with less energy use
- further develop the algal CCS system to reduce energy demand and develop algal biomass valorisation markets
- advance H_2 and CO_2 product qualities for off-site logistics
- improved emissions performance, achieving carbon negative with CCUS inclusion

Although rapid technology deployment is a core aim, H2Boost needs an additional phase of process development to address identified process improvements and increased feedstock acceptance. This additional stage would enable optimisation of the system and engineering design which will provide opportunities for performance limits to be met and cost reductions, along with energy savings.

Following the further development and adaptations of H2Boost, a new business case and TEA will be developed with all data, and consideration of additional plant and costs beyond the LCOH scope, and potential for investment.

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