Funded by
Department for Energy Security & Net Zero

H2Boost
Phase 2

H2Boost Industrial Webinar:

Innovative Processes and technologies for producing biohydrogen for the UK.

Biorenewables Development Centre
UNIVERSITY OF LEEDS

aardvark environment matters
ab agri
CM90
CYANOCAPTURE Scalable carbon capture technology
Maltings organic treatment
The Bioeconomy Consultants NNFCC
QUBE renewables
RAMBOLL

Agenda

- Welcome
- Introduction H2Boost Project – Debs Rathbone
- Biorenewables Development Centre, Alex Jukes
- QUBE Renewables Ltd, James Rundell
- University of Leeds, Miller Alonso Camargo-Valero
- Cyanocapture, David Evans
- CM90 Ltd, Chris Corner
- NNFCC, David Turley
- Q&A

H2Boost: a Hydrogen BECCS Innovation Programme Project

Department for Energy Security & Net Zero

Introduction to the H2Boost project

Dr Deborah Rathbone
Bioscience Innovation Team Leader
Biorenewables Development Centre

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H2Boost phase 1:

Department for Business, Energy & Industrial Strategy

UNIVERSITY OF LEEDS

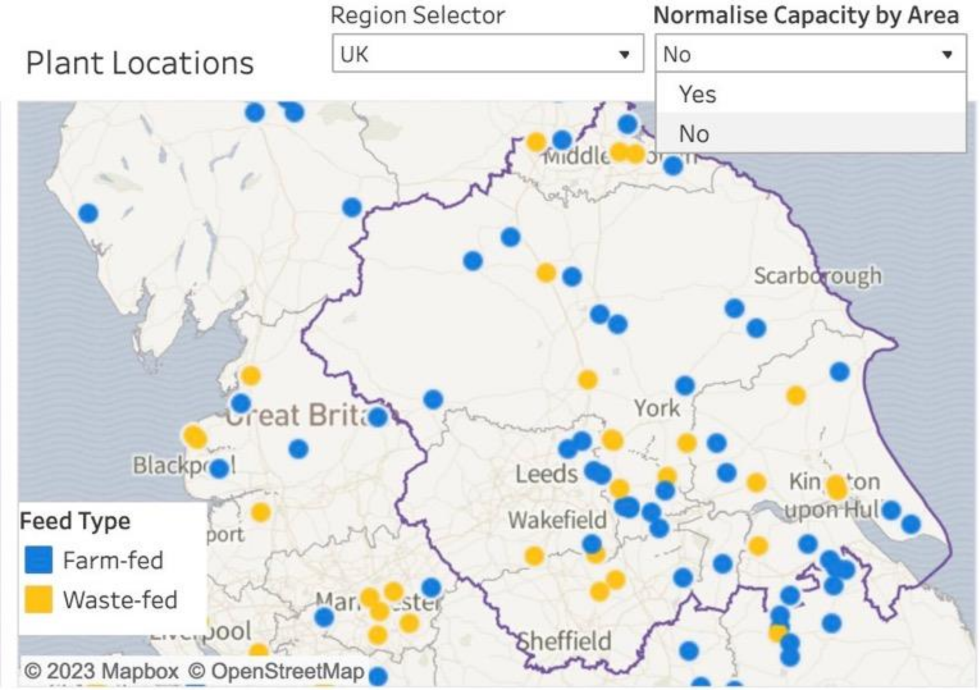
- **Identify and map available wastes / feedstocks in England**

❖ Household food waste
❖ Paper and card
❖ Arable crop residues
❖ Cattle manures and slurries
❖ Poultry wastes: feathers and litter
❖ Fisheries residues
❖ Food manufacturing residues
❖ Conservation sites/grass verges
❖ Forestry waste

Mapping wastes and AD plants

Data from:

- Local authorities (WasteDataFlow database)
- WRAP reports
- Defra surveys
- Natural England
- Forestry Commission



https://www.virtualthymeregion.com/maps

Yorkshire & Humber, East Midlands, Eastern England and the South East (excluding London)

H2Boost phase 1:

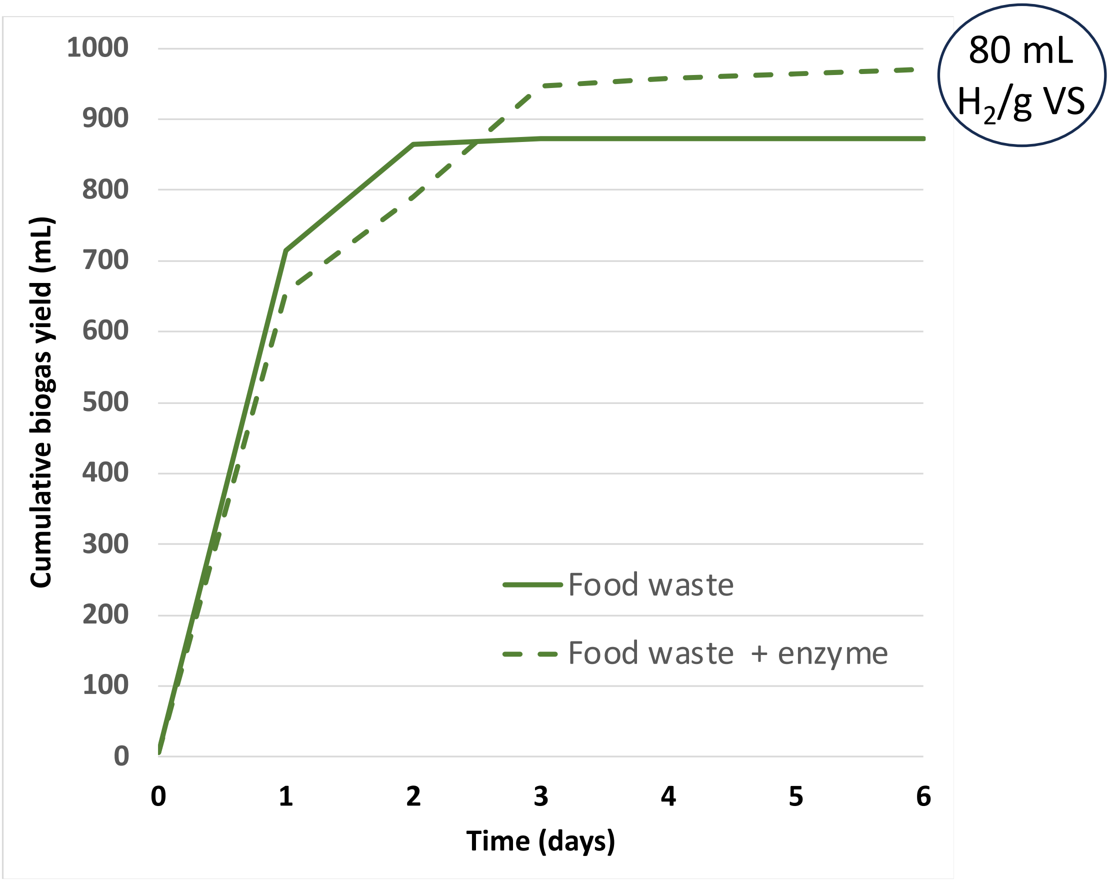
- Identify and map available wastes / feedstocks in England
- **Assess bio-hydrogen production from pre-treated feedstocks (dark fermentation; DF)**

❖ Inoculum preparation
❖ Pre-treatment of feedstocks / enzyme addition
❖ Production of H_2
❖ Microbial profiling

Dark fermentation: H_2 production

Individual feedstocks and combinations:

- Gas yield & composition
- Volatile fatty acid composition
- Microbial profile



Example of H_2 production using food waste

H2Boost phase 1:

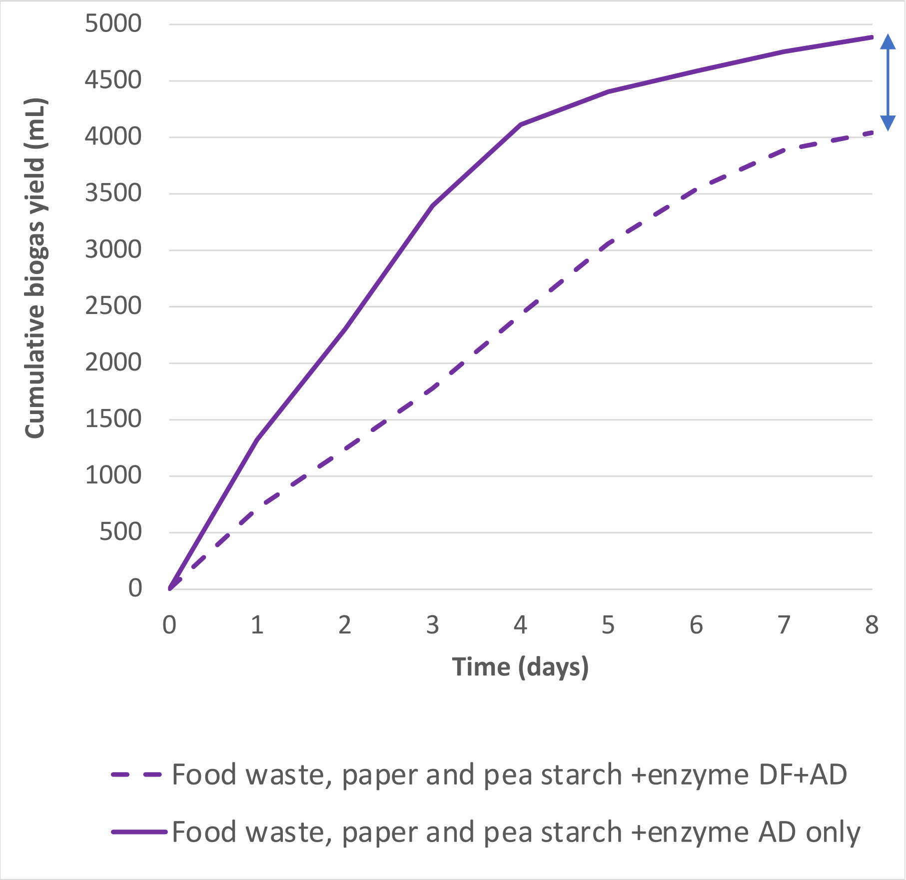
- Identify and map available wastes / feedstocks in England
- Assess bio-hydrogen production from pre-treated feedstocks (dark fermentation; DF)
- **Assess biomethane potential of DF residues**

❖ Production of CH_4
❖ Digestate characterisation

Anaerobic digestion: CH_4 production

Residue from DF used as feedstock for AD:

- Gas yield & composition
- Volatile fatty acid composition



Use of dark fermentation residue in AD

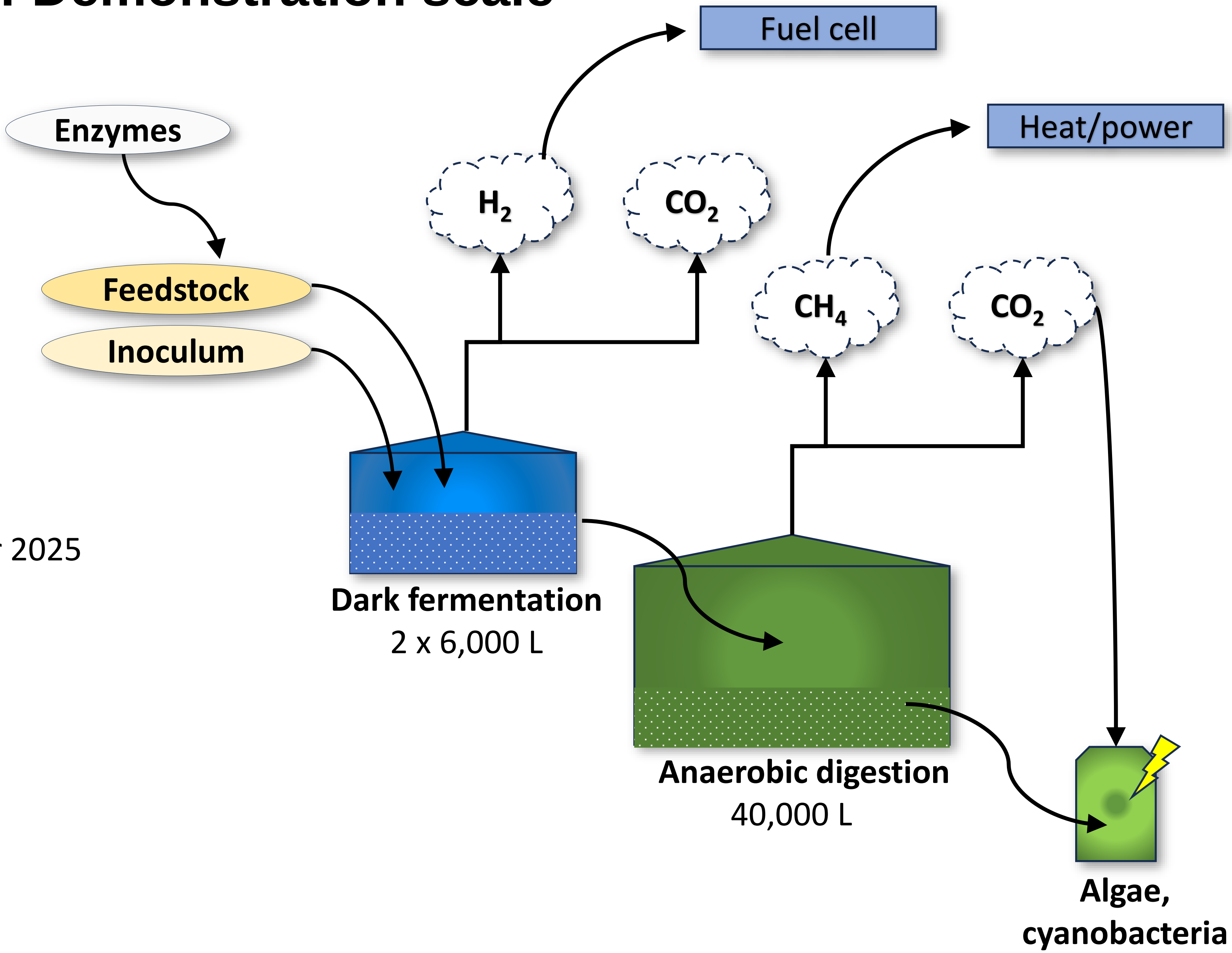
H2Boost phase 1:

- Identify and map available wastes / feedstocks in England
- Assess bio-hydrogen production from pre-treated feedstocks (dark fermentation; DF)
- Assess biomethane potential of DF residues
- **Carbon capture**
- **Design of potential plant and commercial feasibility**
- **Biohydrogen utilization routes and methodologies**

- Growth of microalgae
- Plant design
- CAPEX
- OPEX
- Technoeconomic analysis (TEA)
- Carbon calculator / Life cycle analysis (LCA)

H2Boost phase 2: Demonstration scale

Department for Energy Security & Net Zero



Project value: £5m

Timelines: Jul 2023 – Mar 2025

H2Boost phase 2: Project activities

Lab scale R&D
- Inoculum development
- Feedstock pre-treatment / enzymes
- Dark fermentation
- Anaerobic digestion
- Algae & cyanobacteria strain evaluation & growth systems

Demonstration scale build and testing
- Planning & permitting
- Design, build & installation
- Performance testing
- Hydrogen clean up
- CO_2 separation

Supply chain analysis and market engagement
- Supply chain attractiveness
- Preferred scale to match supply chains

Sustainability analysis and development
- LCA
- TEA
- Regulatory & policy considerations

Industry dissemination workshops
- April & September 2024
- January 2025

Project management / engineering project management

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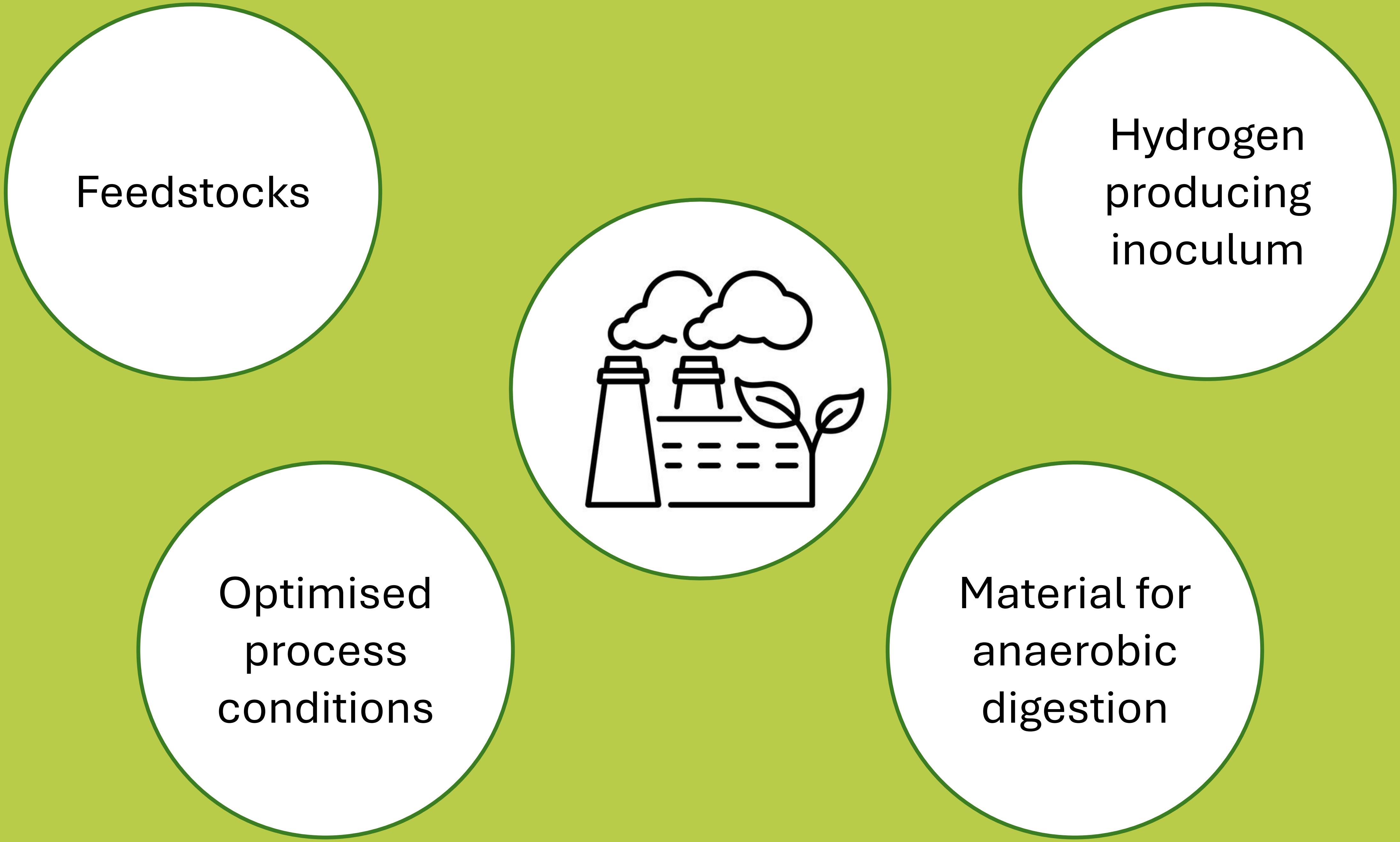
H2Boost at the BDC

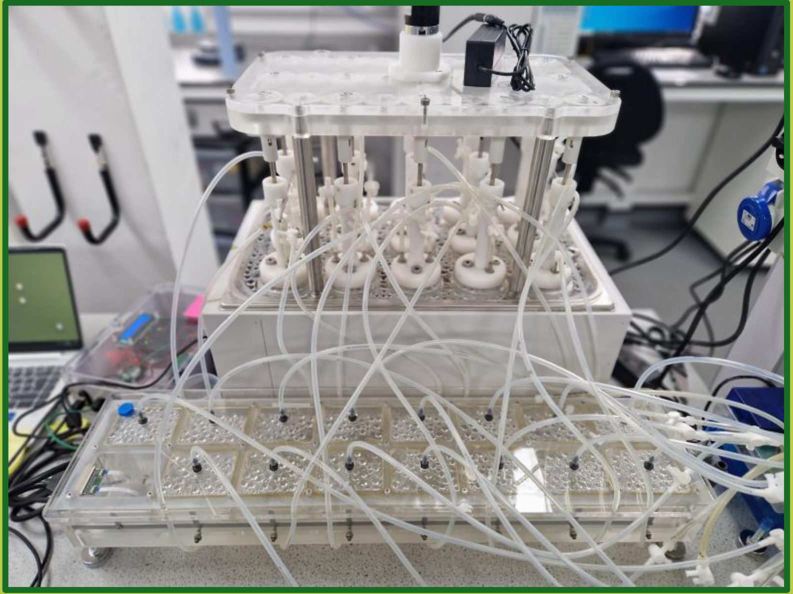
Presented by Alex Jukes


Feedstocks
Hydrogen producing inoculum
Optimised process conditions
Material for anaerobic digestion

Method

Trial inoculum

Trial feedstock



Optimise process conditions

Optimise process conditions

Inoculum

Aims

Increase hydrogen content of biogas

Mixed culture

Reduce/ remove methanogens

Feedstock flexibility

Rate of conversion

Stability

Repeatability

Sources

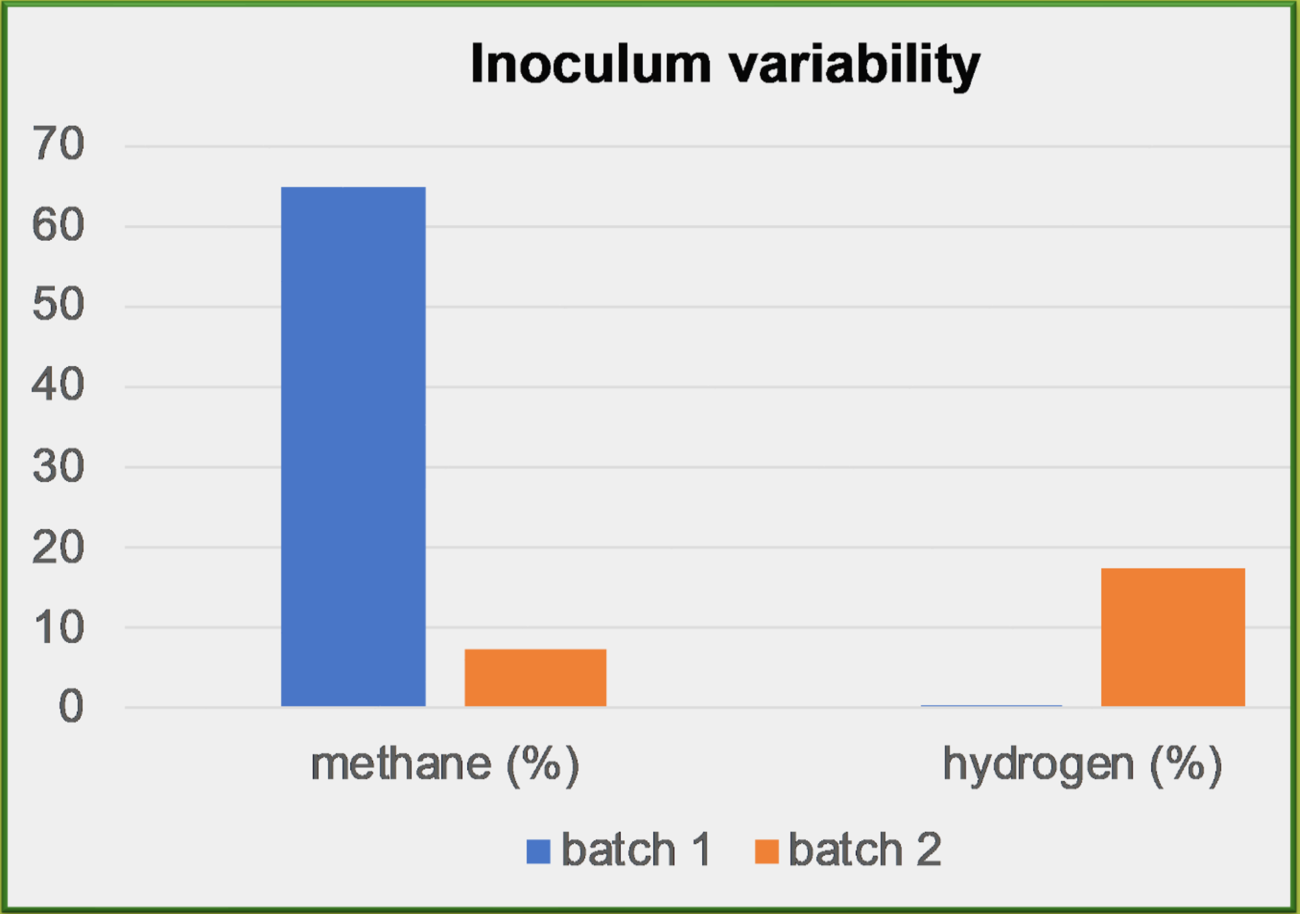
Farm digestate
Food waste digestate
Plant based digestate
Sewage digestate

Methods

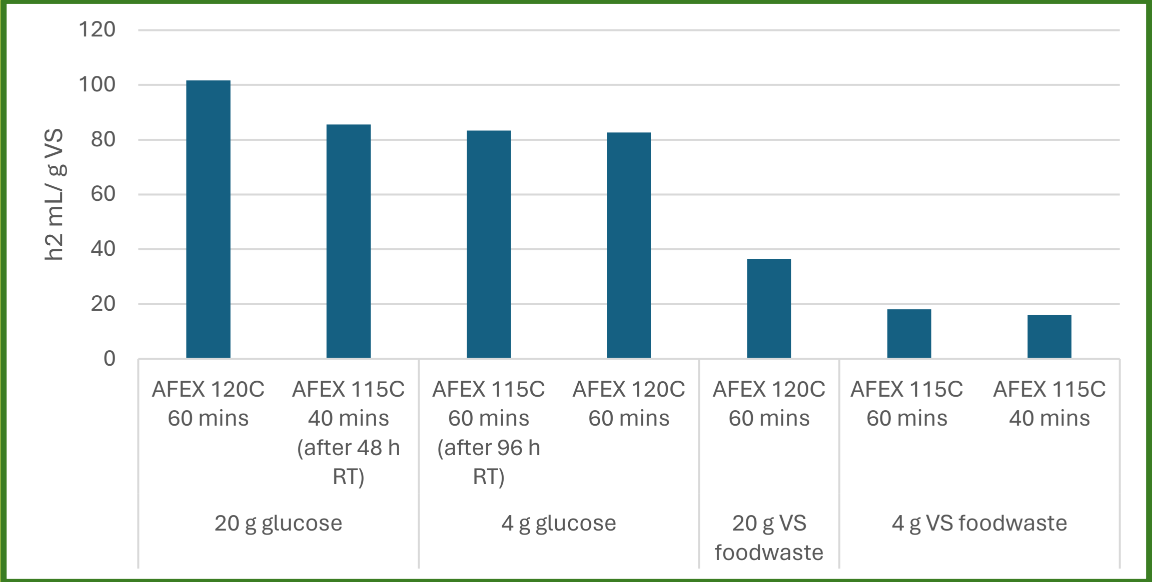
Chemical addition
Heat
pH control
Cavitation and ozone
Microwave

Heat treatment

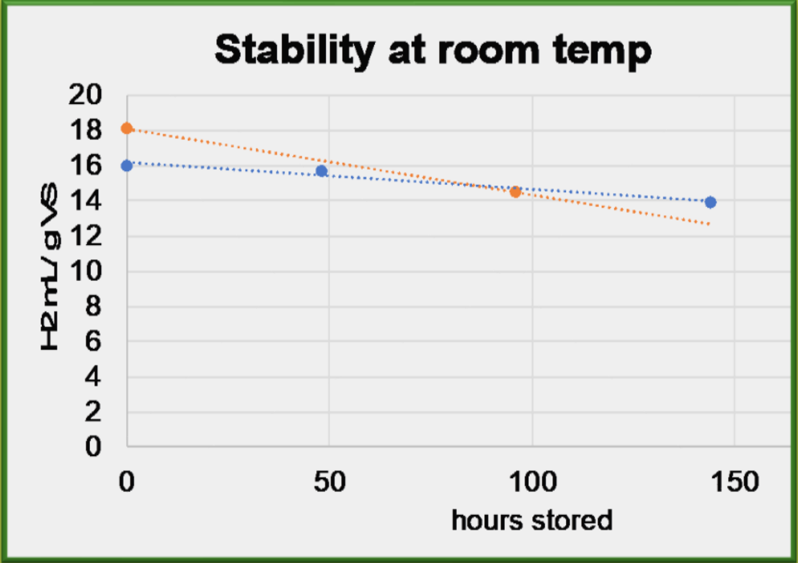
- Started with autoclave treatments
- Success with this method in phase 1 (small volume)
- Tested with food waste digestate, removed methane potential but very little hydrogen produced
- Farm digestate gave promising results but high variability, from 0% h2 to 35% (biogas content)



Heat treatment

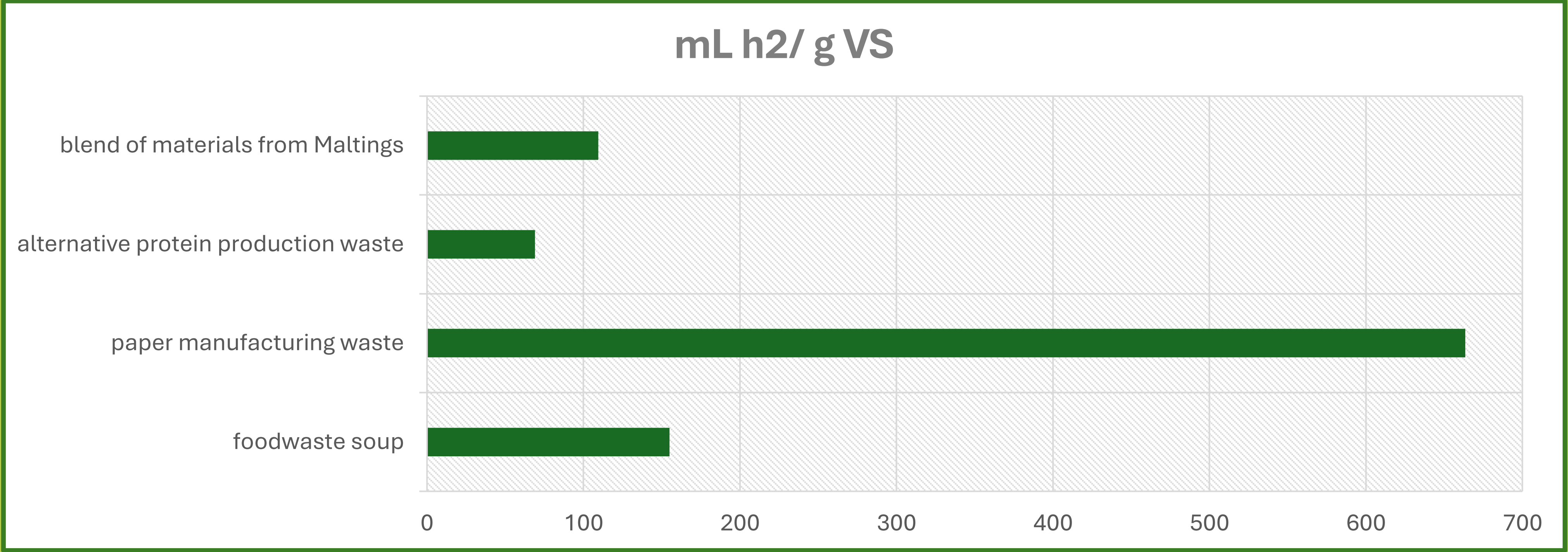


- Moved on to treatments using a 100L high temperature, stirred vessel with a temp probe situated in the material.
- Tested a range of temperatures and durations – 90-120°C, 30-60 mins.
- Dark fermentation in the batch system was carried out with either glucose (control) or food waste soup.



- Increase from 0 – 1.7 % methane at 96 hours storage

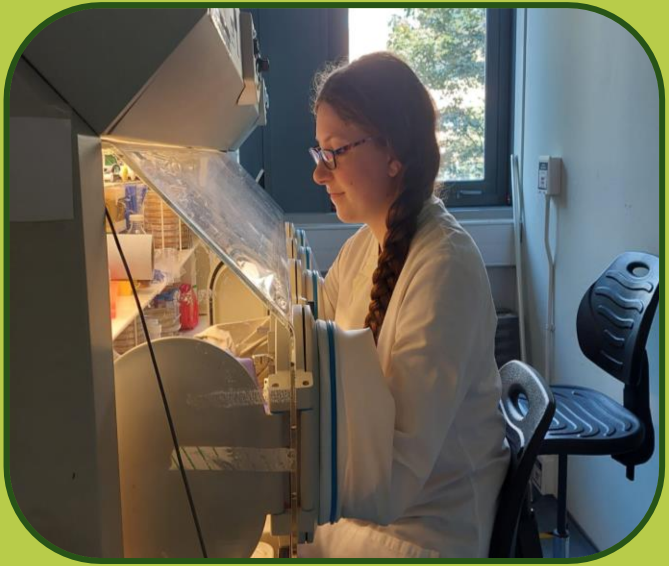
Feedstock



Changing the inoculum to sewage sludge, with the same treatment conditions has allowed us to increase the h2 produced in the Maltings blend to 184 mL h2/ g VS.

Paper manufacturing waste was subject to enzyme treatment.

Next steps



- Move from batch experiments to continuous for the demo plant feedstock
- Continue testing other feedstocks at batch scale
- Comparison of microwave treatments against the current heat treatment for inoculum preparation

SMALL SCALE AD TECHNOLOGY

CONVERTING YOUR WASTES INTO RENEWABLE ENERGY

H2Boost Industry Workshop 1

April 25.04.2024

OUR HISTORY

- 2011 MOD requested an AD solution for Forward Operating Bases in Afghanistan as fuel costs were over $200 per litre.
- Aardvark EM undertook a desk top study and were unable to find anything on the market.
- Aardvark EM and Loglogic Limited built the first digester - that digester is still producing biogas today and is run here as our demo and trials unit, and Loglogic still host our factory.
- In 2013 QUBE Renewables Ltd was established and has since developed other biogas technologies and deployed projects around the world.

QUBE Renewables Ltd design and build small scale local embedded biogas energy generating systems

QUBE VIEWS BIODEGRADABLE WASTES NOT AS A PROBLEM BUT AS A VALUABLE RESOURCE

bio**QUBE**

quick**QUBE**

power**QUBE**

fugi**QUBE**

dry**QUBE**

lagoon**QUBE**

batch**QUBE**

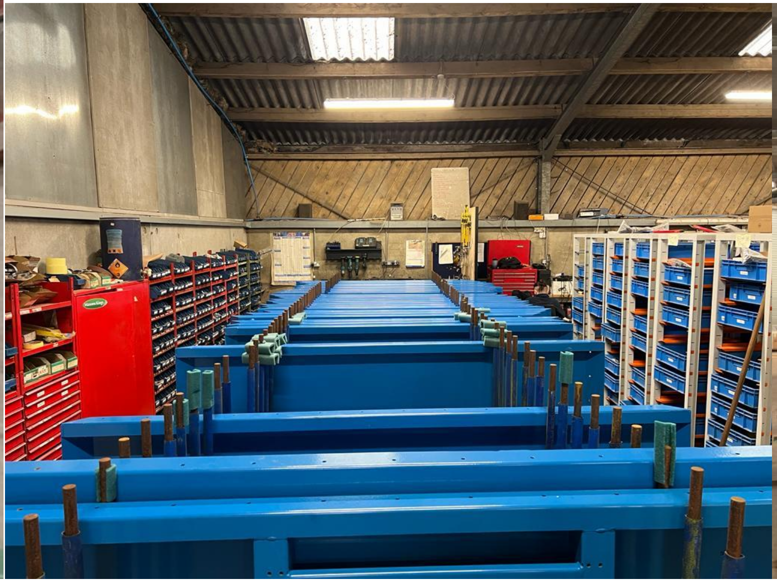
BESPOKE SYSTEMS FOR RESEARCH AND DEVELOPMENT

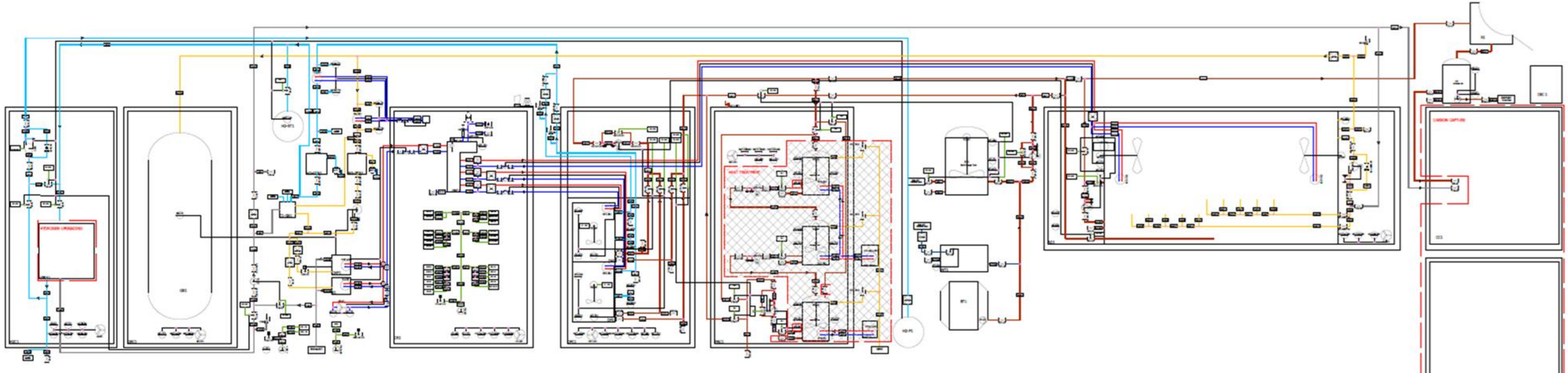
Design and manufacture of bespoke systems for clients who wish to test different feedstocks

- Digestion parameters and methodologies
- Additives or pre-treatments
- Containerised design with individual digestion tanks to enable replicates
- Test rig systems with full analytic capability
- Laboratory facilities with real time remote access and analytic ability
- Full feed system for variety of waste inputs
- Comprehensive data collection platform

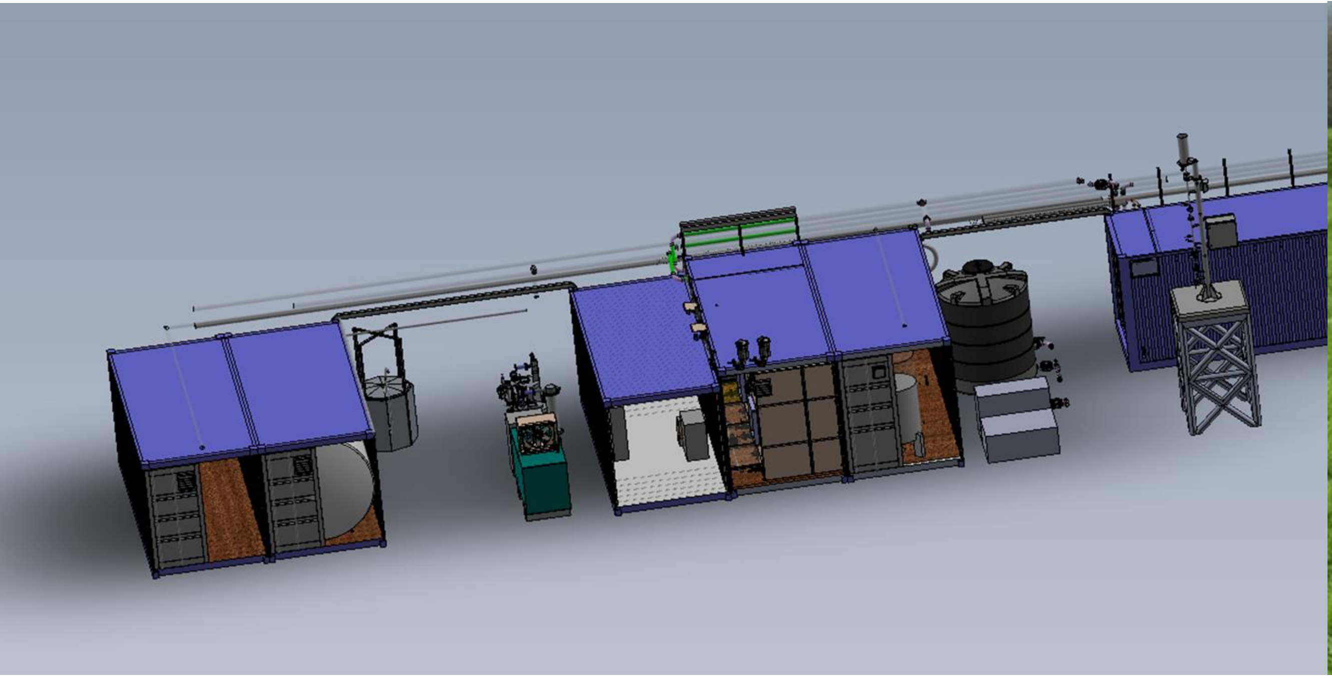
H2Boost Design Brief

- Container based Biohydrogen generation system
- Following the modular approach QUBE adopts for large multinational builds
  - Factory built and commissioned, agile design
  - Plug and play controls
  - Minimal on-site installation
- Integration with third parties for specialist technologies around hydrogen upgrading and carbon sequestration

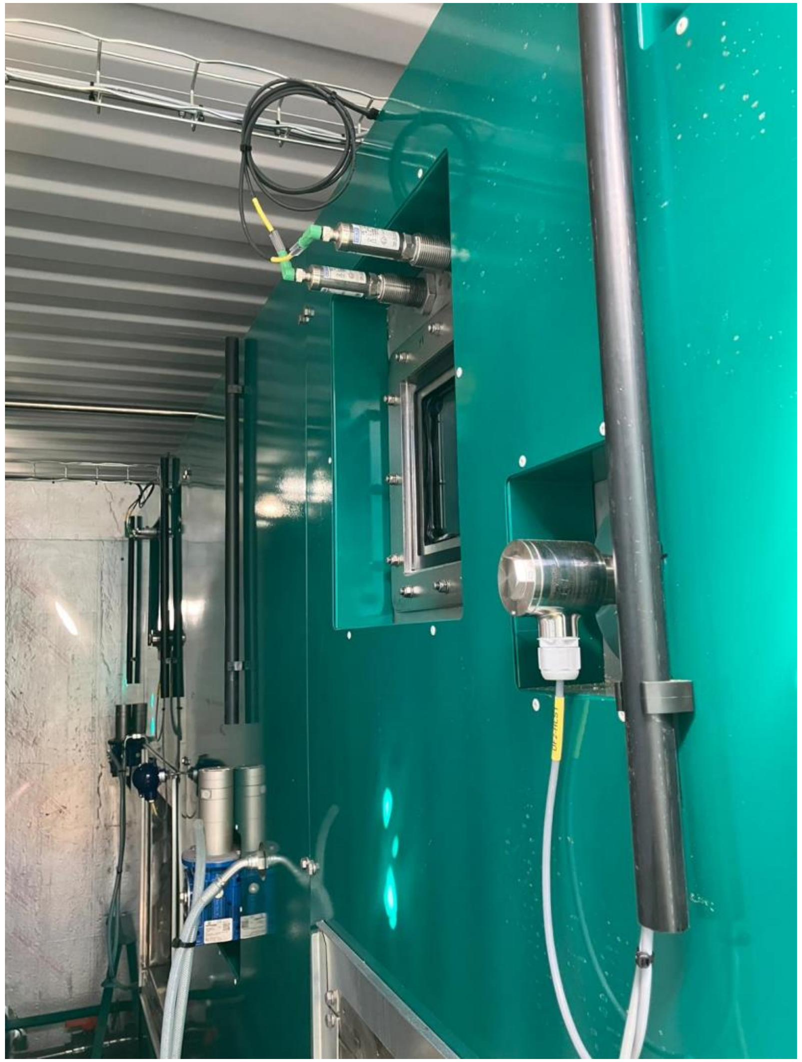



Full P&ID to design drawings to fabrication at the factory



Anaerobic digester unit for biogas production



Dark Fermenter unit for bio-hydrogen production

Control room

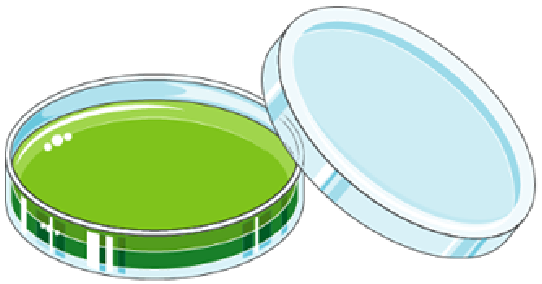
Biogas treatment pod

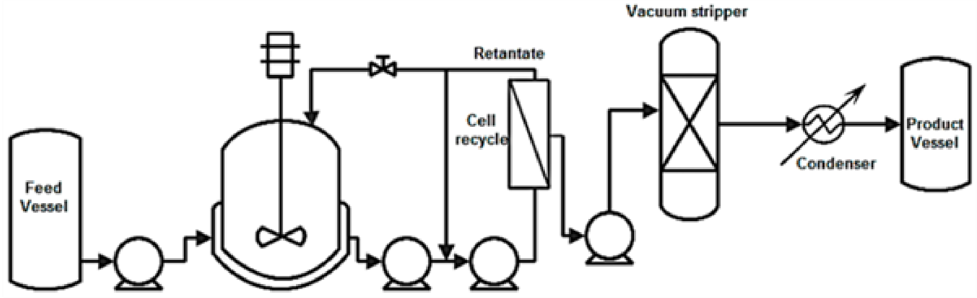
Piping and valves

Resource recovery and reuse from waste streams

BioResource Systems Research Group: What are we looking for?

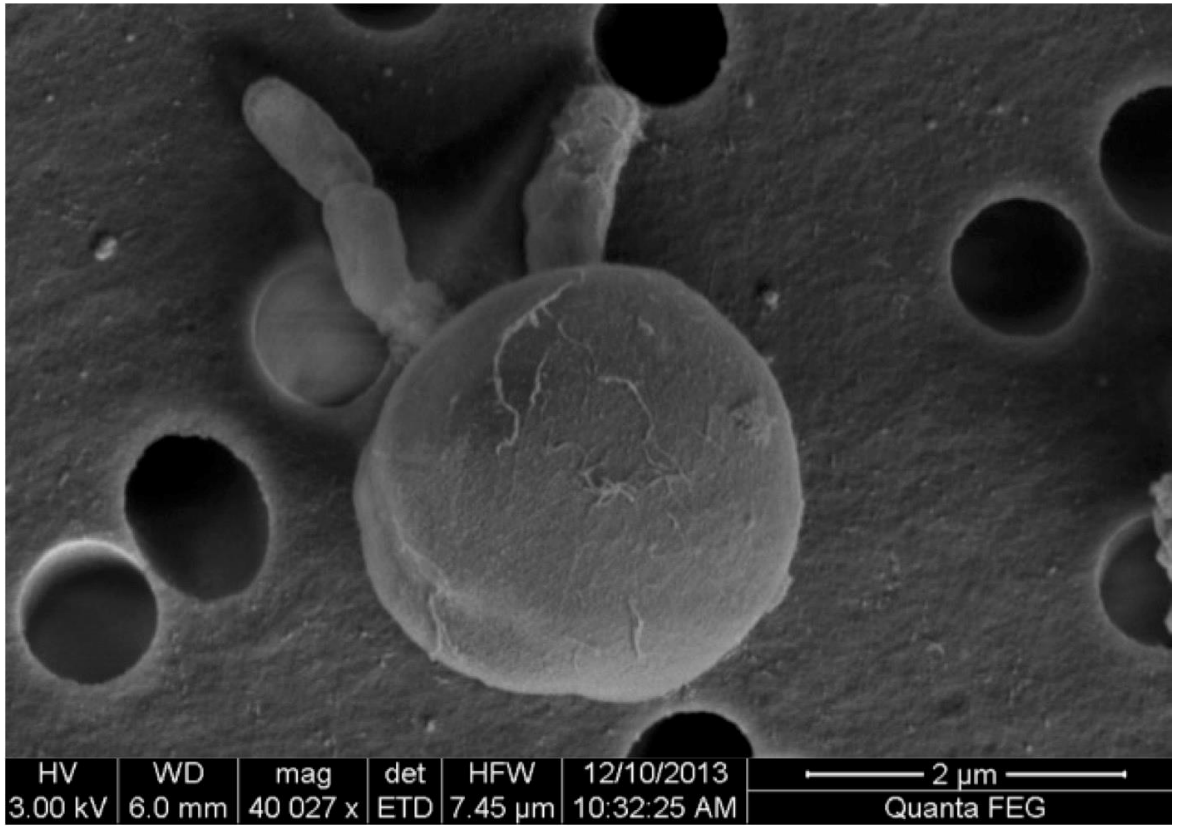
Meaningful answers to unsolved problems in fundamental science that will lead to greater understanding of biochemical processes and potential engineering solutions to global challenges.



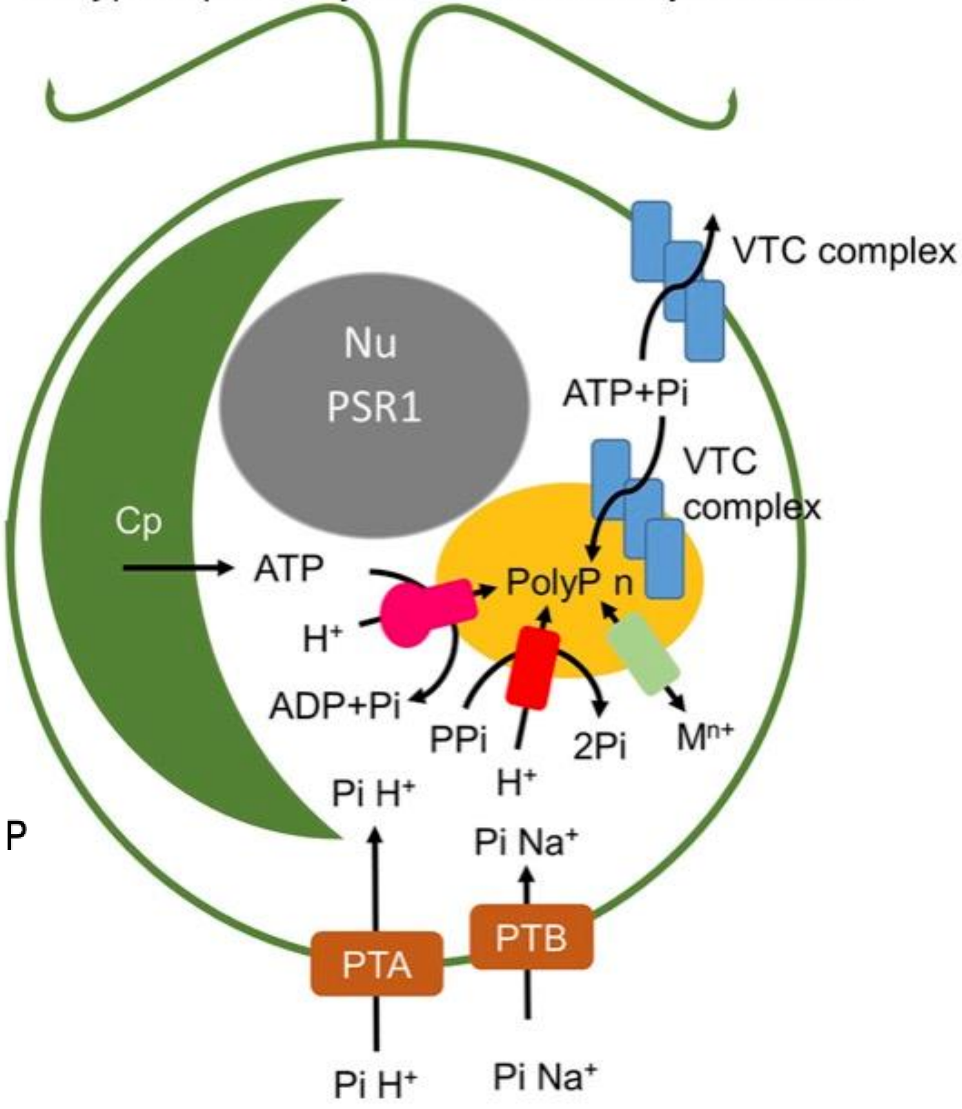


from lab to market products

Simultaneous carbon, nitrogen and phosphorus uptake by microalgae



Polyphosphate synthesis in Chlamydomonas



Regulation of polyphosphate metabolism in Chlamydomonas and potential for exploitation as a P sink in nutrient recovery systems. BBSRC (BB/N016033/1), £500k (2016-2020)

[1]Baker A, [2]Camargo-Valero M A, [1]Chu L, [3]Wood N, [1]Slocombe S, [2]Zuniga-Burgos T.
[1]School of Molecular and Cellular Biology, University of Leeds
[2]School of Civil Engineering, University of Leeds
[3]School of Chemical and Process Engineering, University of Leeds

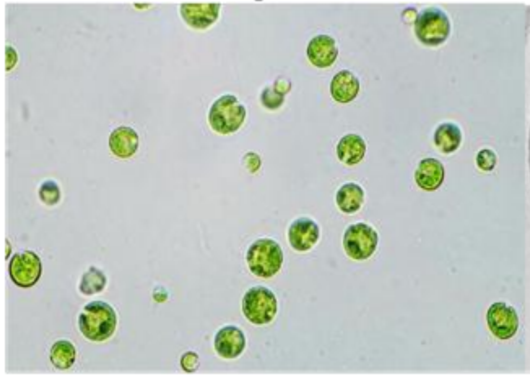
Phosphorus transformations induced by microalgae

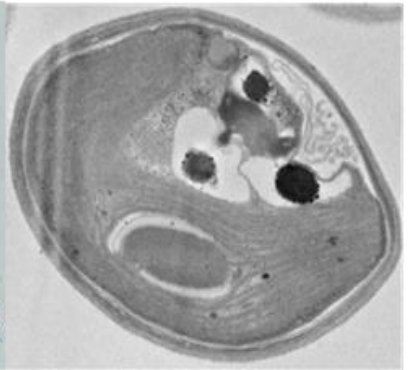
Close the broken P cycle and mitigate its effects on our environment by:

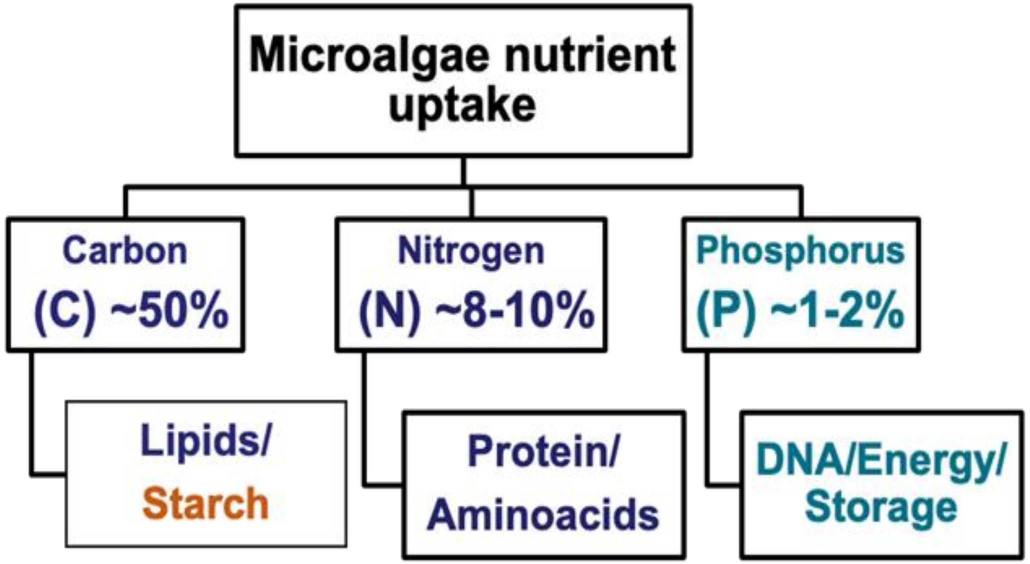
Recovering P from wastewater via:

1. **Cost-effective** means
2. In a bioavailable way that allows P **recycling into agriculture**

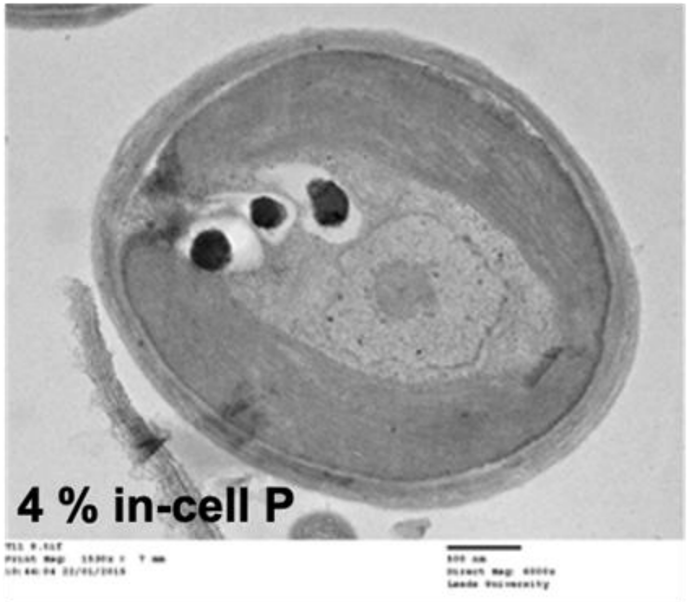
We believe microalgae may be a possible solution

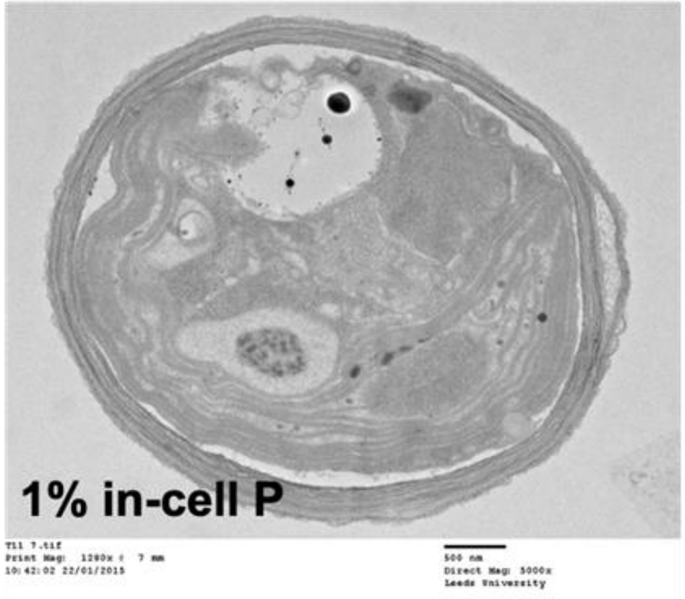

Light microscopy of C. reinhardtii cells (400x)

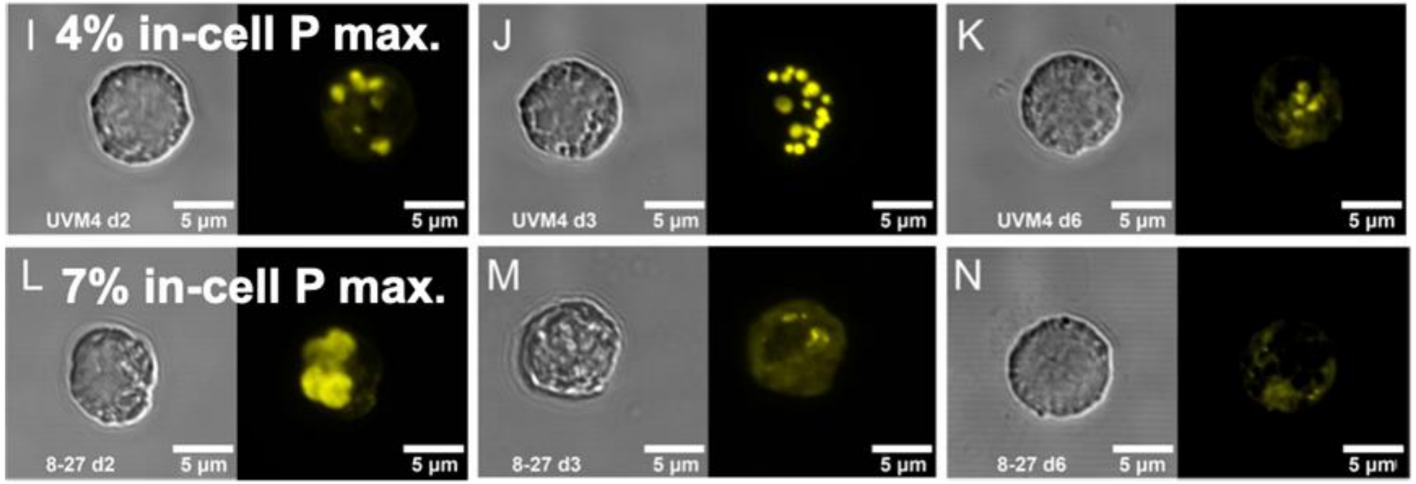

TEM microscopy of a C reinhardtii cell (Yulyestorini,2016)



Phosphorus recovery from wastewater using microalgae







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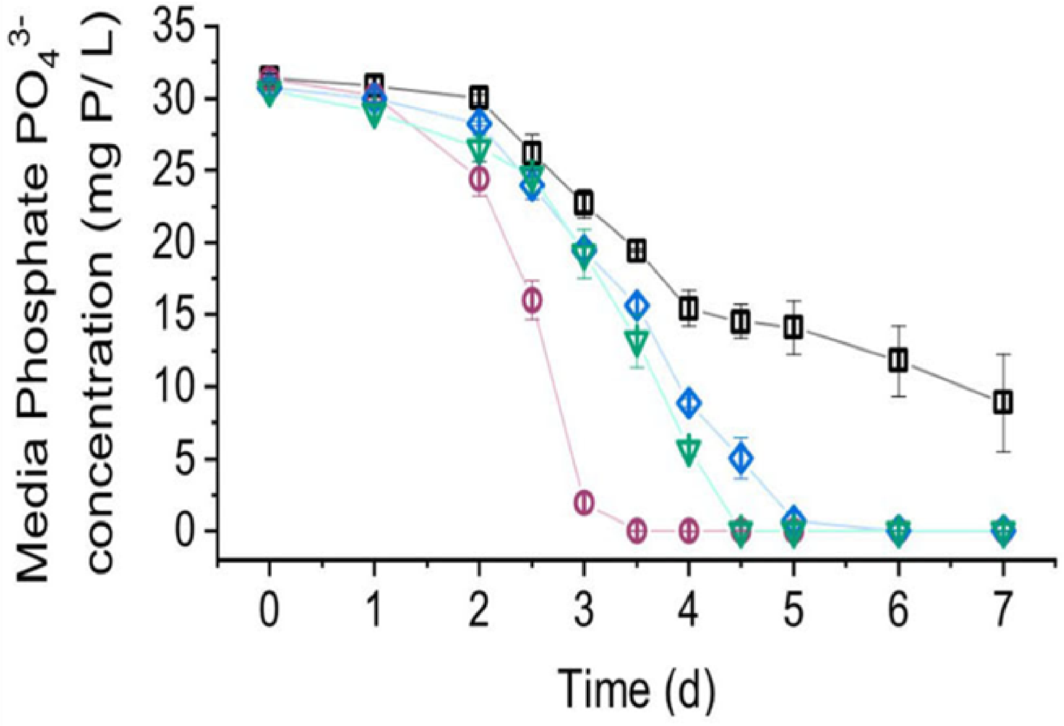
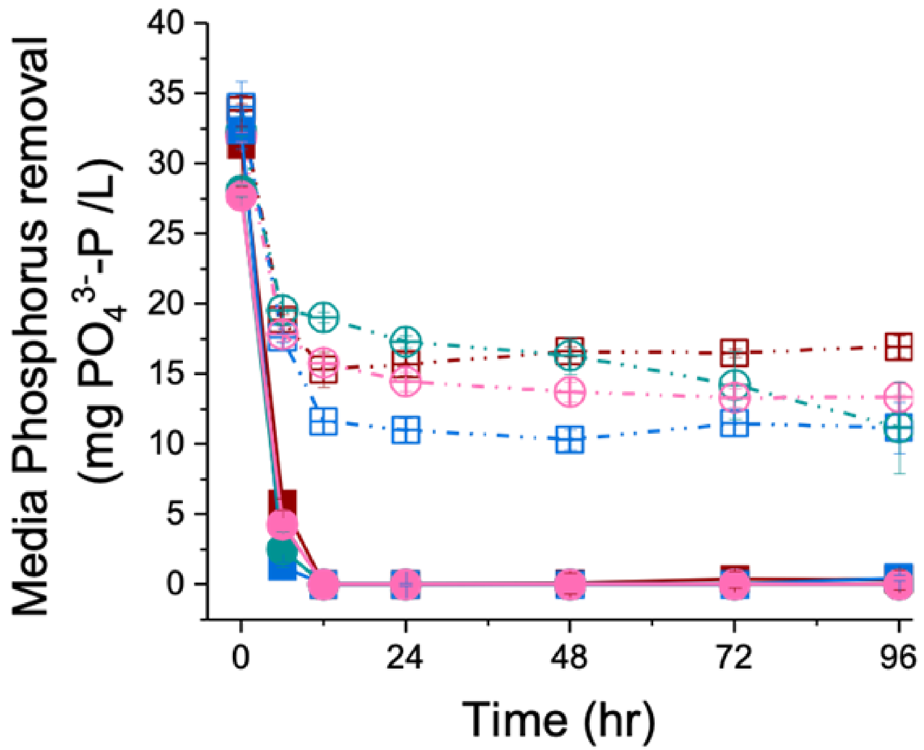
[3]School of Chemical and Process Engineering, University of Leeds

Zuniga Burgos L T (2019 – 2023). *Manipulation of Chlamydomonas reinhardtii Phosphate overplus response for biological phosphorus recovery from wastewater*. School of Civil Engineering, University of Leeds.

Phosphorus recovery from wastewater using microalgae



Optimised P uptake with PSR1 over expression



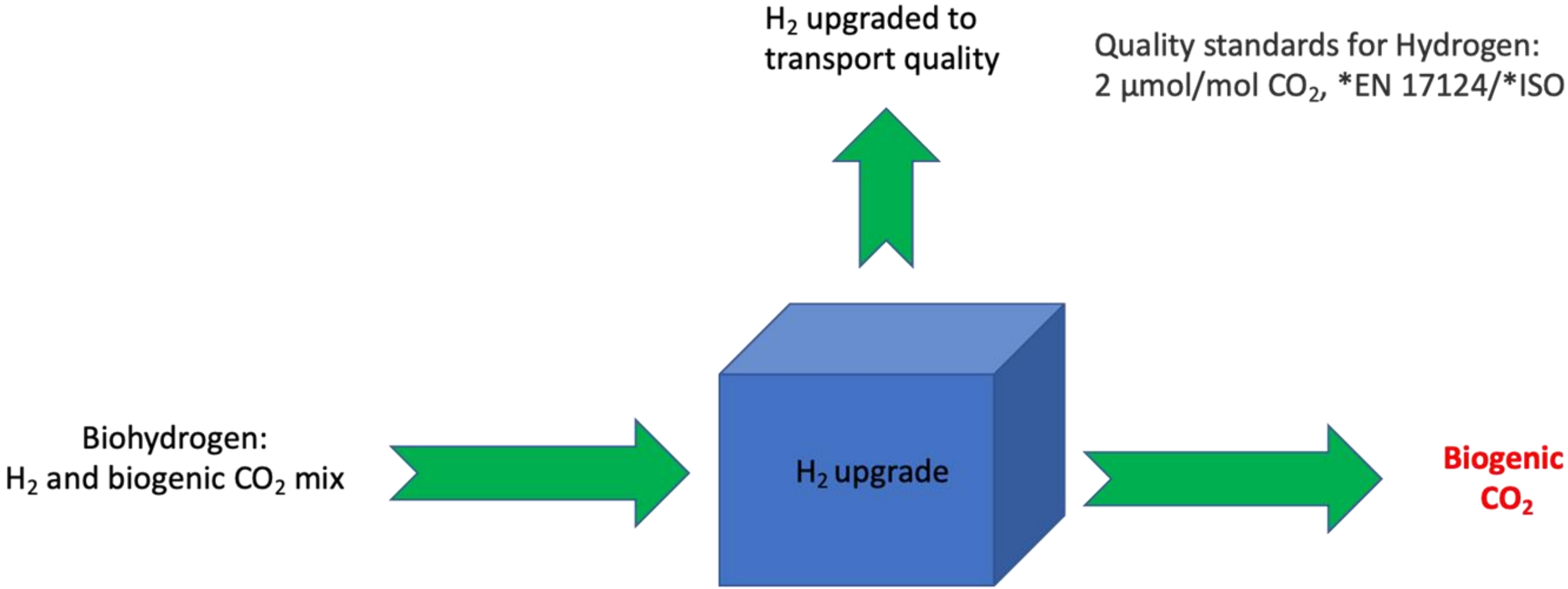
Optimised P uptake Non-GM

Slocombe S P, Zuniga-Burgos T, Chu L, Mehrshahi P, Davey M P, Smith A G, **Camargo-Valero M A** and Baker A (2023). Overexpression of PSR1 in *Chlamydomonas reinhardtii* induces luxury phosphorus uptake. *Frontiers in Plant Science*, 14:1208168. https://doi:10.3389/fpls.2023.1208168

Zuniga-Burgos T, Saiardi A, **Camargo-Valero M A** and Baker A (2023). A story of P overplus physiology in C. reinhardtii: the highlight of RNA and nutrients other than P (*Algal Research, under review*)

Carbon capture and utilisation using microalgae: CO2 sources

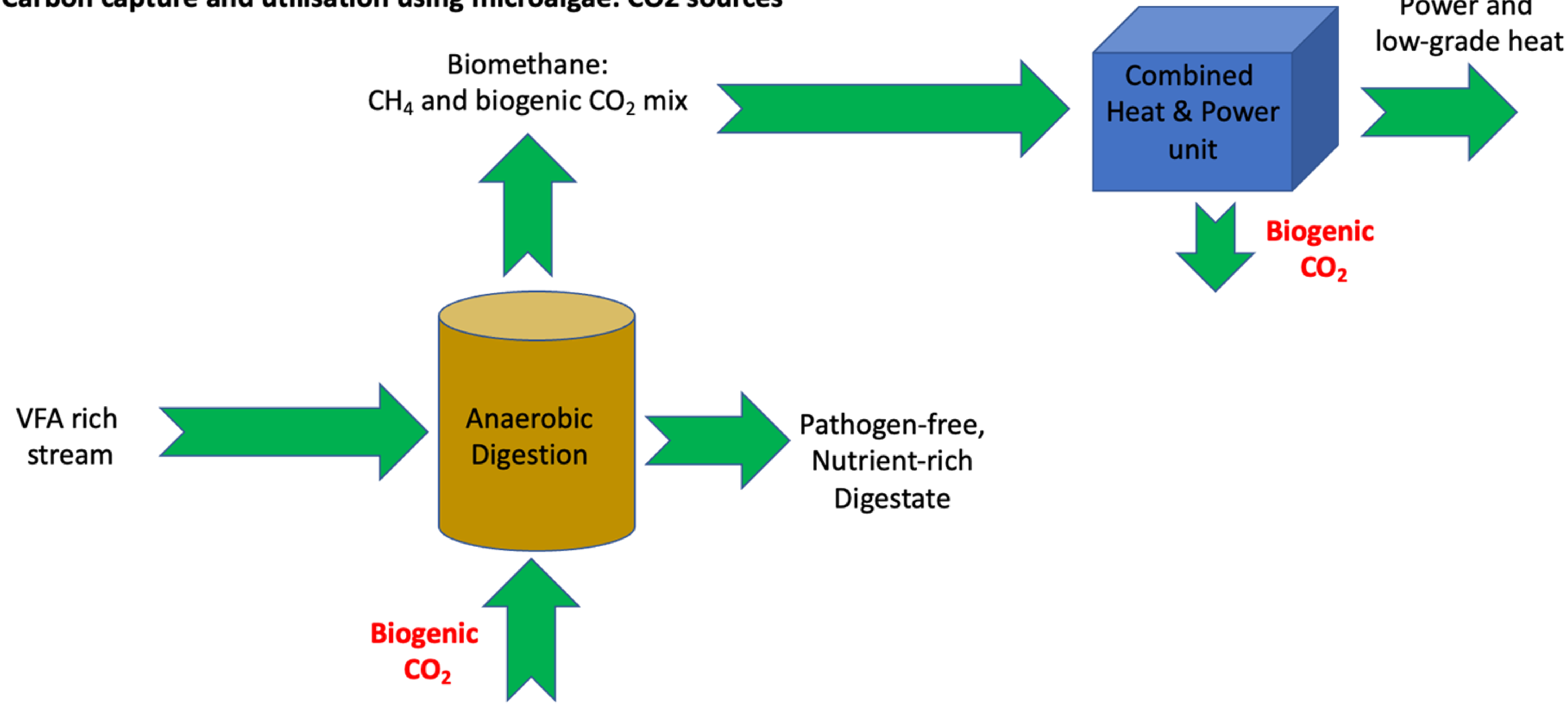
Quality standards for Hydrogen:
2 µmol/mol CO_2, *EN 17124/*ISO 14687



*EN 17124:2018 Hydrogen fuel. Product specification and quality assurance. Proton exchange membrane (PEM) fuel cell applications for road vehicles, european committee on standardisation, Bruxelles (2018)

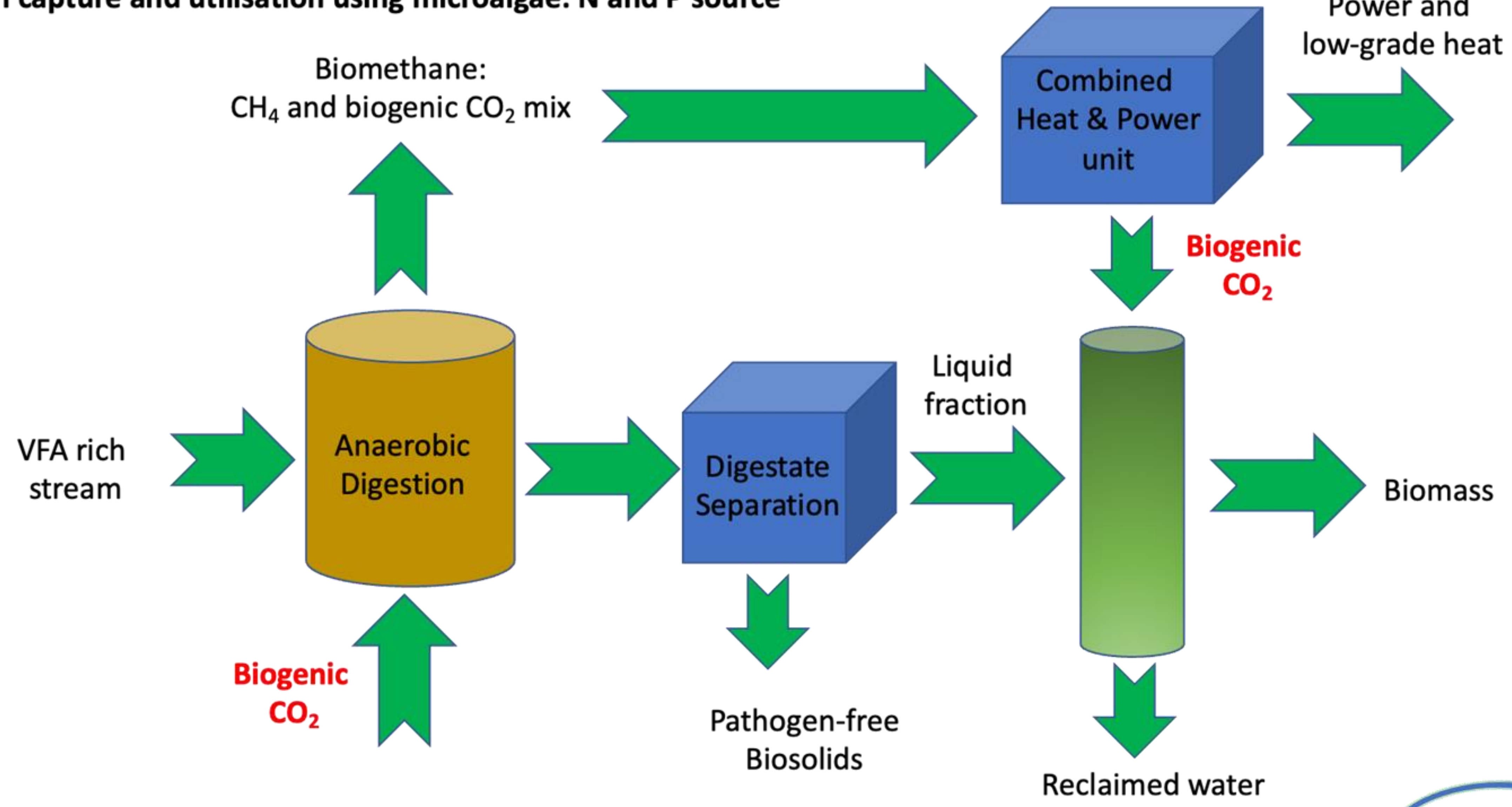
*SO 14687:2019 Hydrogen fuel quality—product specification International organization for standardization (2019) Geneva, Switzerland

Carbon capture and utilisation using microalgae: CO2 sources

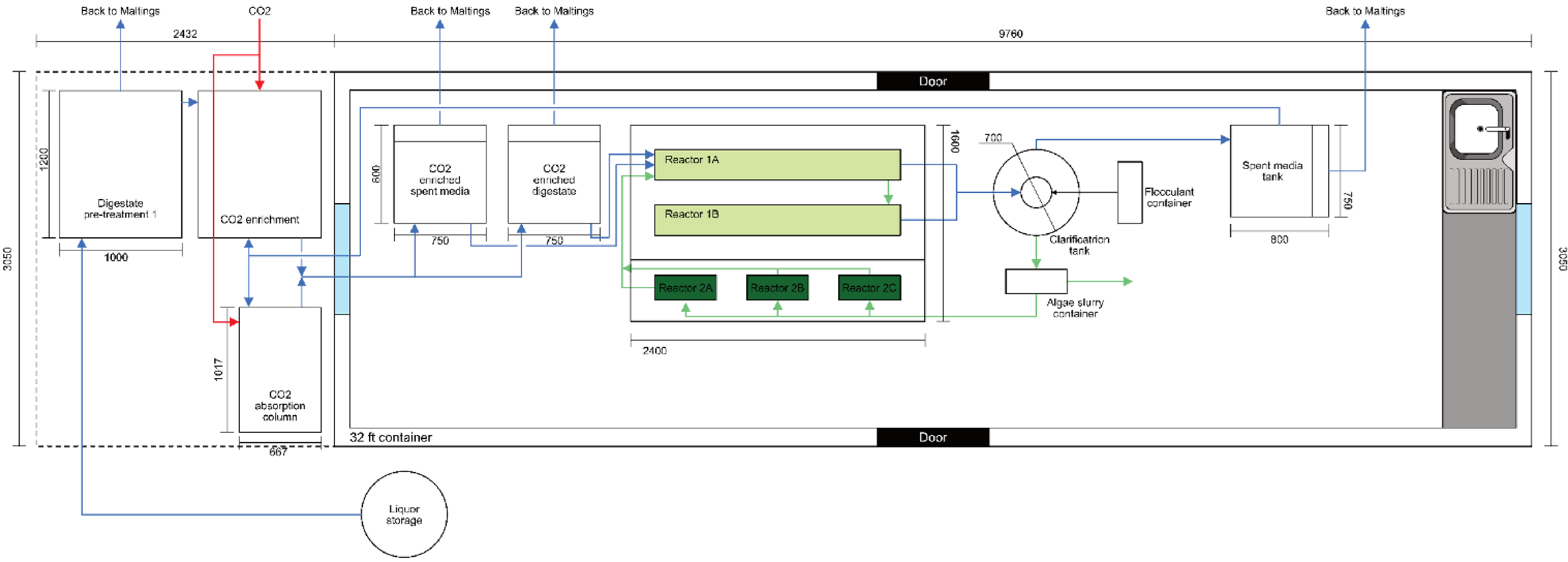


- C. Salomoni, A. Caputo, M. Bonoli, O. Francioso, M.T. Rodriguez-Estrada, D. Palenzona.Enhanced methane production in a two-phase anaerobic digestion plant, after CO2 capture and addition to organic wastes, Bioresource Technology, Volume 102, Issue 11.
- Yadira Bajón Fernández, Ana Soares, Peter Vale, Konrad Koch, Anne Laure Masse & Elise Cartmell (2019) Enhancing the anaerobic digestion process through carbon dioxide enrichment: initial insights into mechanisms of utilization, Environmental Technology, 40:13, 1744-1755

Carbon capture and utilisation using microalgae: N and P source



Carbon capture and utilisation using microalgae: pilot plant



BIO

Resource Systems

RESEARCH GROUP

CYANOCAPTURE

Scalable carbon capture technology

H2Boost Industrial Webinar

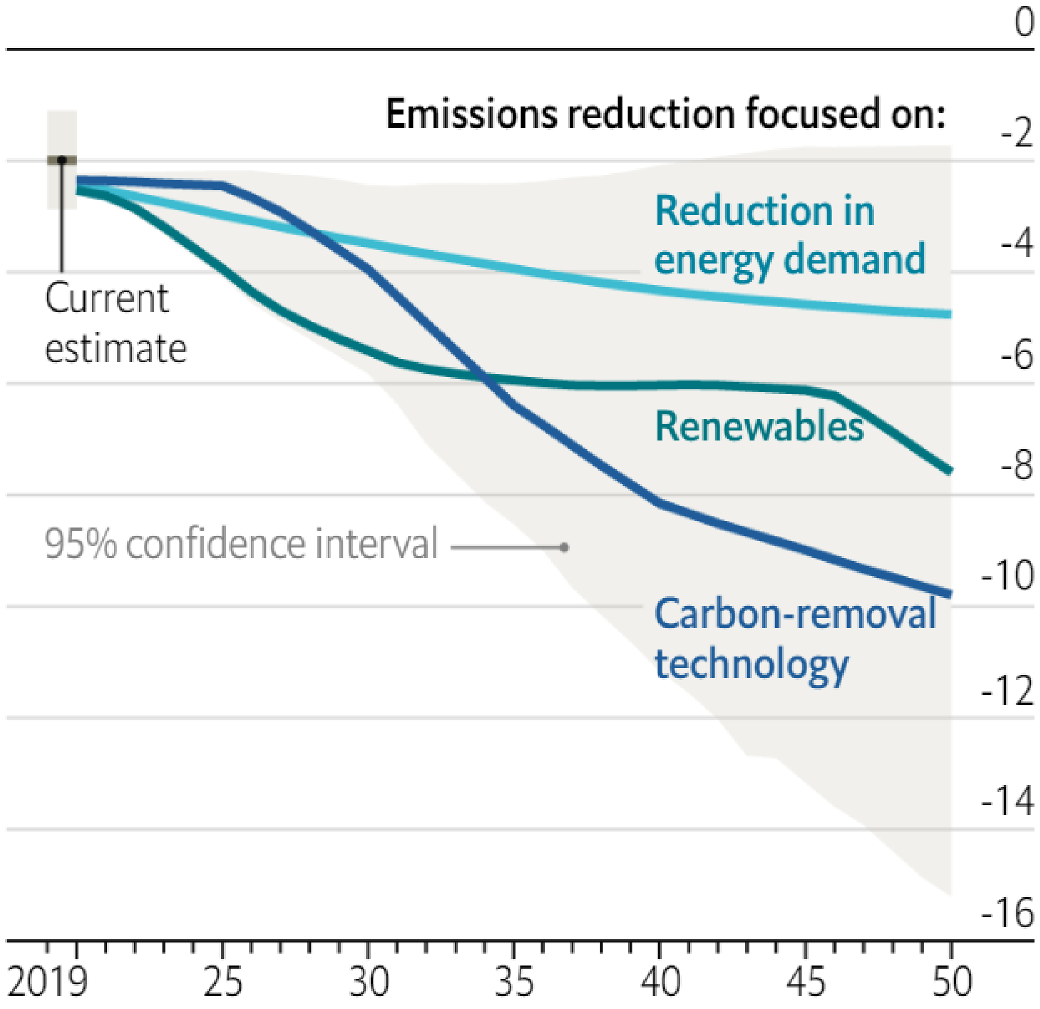
25th April 2024

www.cyanocapture.com

CONFIDENTIAL ©2024 CYANOCAPTURE LTD.

We use energy from sunlight to convert CO2 into high value compounds that only biology can make.

CYANOCAPTURE
Scalable carbon capture technology



Necessary CO2 removal below 2°C of warming,
bn tonnes of CO2 per year
Source: "The state of CO2 removal, Smith et al., 2023

Short of a miracle, no amount of new solar panels or wind turbines will be enough to avoid catastrophic levels of global warming.

Climate models are unanimous: as well as slashing the amount of greenhouse gases they produce, humans will also have to suck vast quantities out of the atmosphere.

The Economist

Carbon Capture is bottlenecked

Atmospheric carbon removal is too energetically costly

- Most Carbon Capture & Storage (CCS) technologies still use upwards of 1250kWh/TCO2 captured
- To meet IPCC targets of 10 gigatonne/year, this would equate to using 43% of global electrical supply every year
- Even at the thermodynamic minimum, this would use more than 4% of global energy supplies

10 GT/y	$4 trillion/y	43%
CCS target	Cost	Global electricity use

CDR is too expensive and slow

- $2.34 billion spent on carbon removal for 5.8 million T CO2, averaging $404/T CO2
- To meet IPCC targets, this would cost $4 trillion every year
- Only 5.1% of all carbon credits sold on the market have delivered as completed projects

Most leading CCS technologies present a permanent cost

- Even with the best case projected learning rates for energy and cost, leading technologies extrapolated to the 10 gigatonne/year scale, pose a significant drain on resources that could be allocated to more effective solutions

BECCS & Biochar have feedstock shortages

- Purpose grown biomass competes with agriculture for arable land and has a major footprint at scale

Carbon Capture is expensive

CYANOCAPTURE
Scalable carbon capture technology

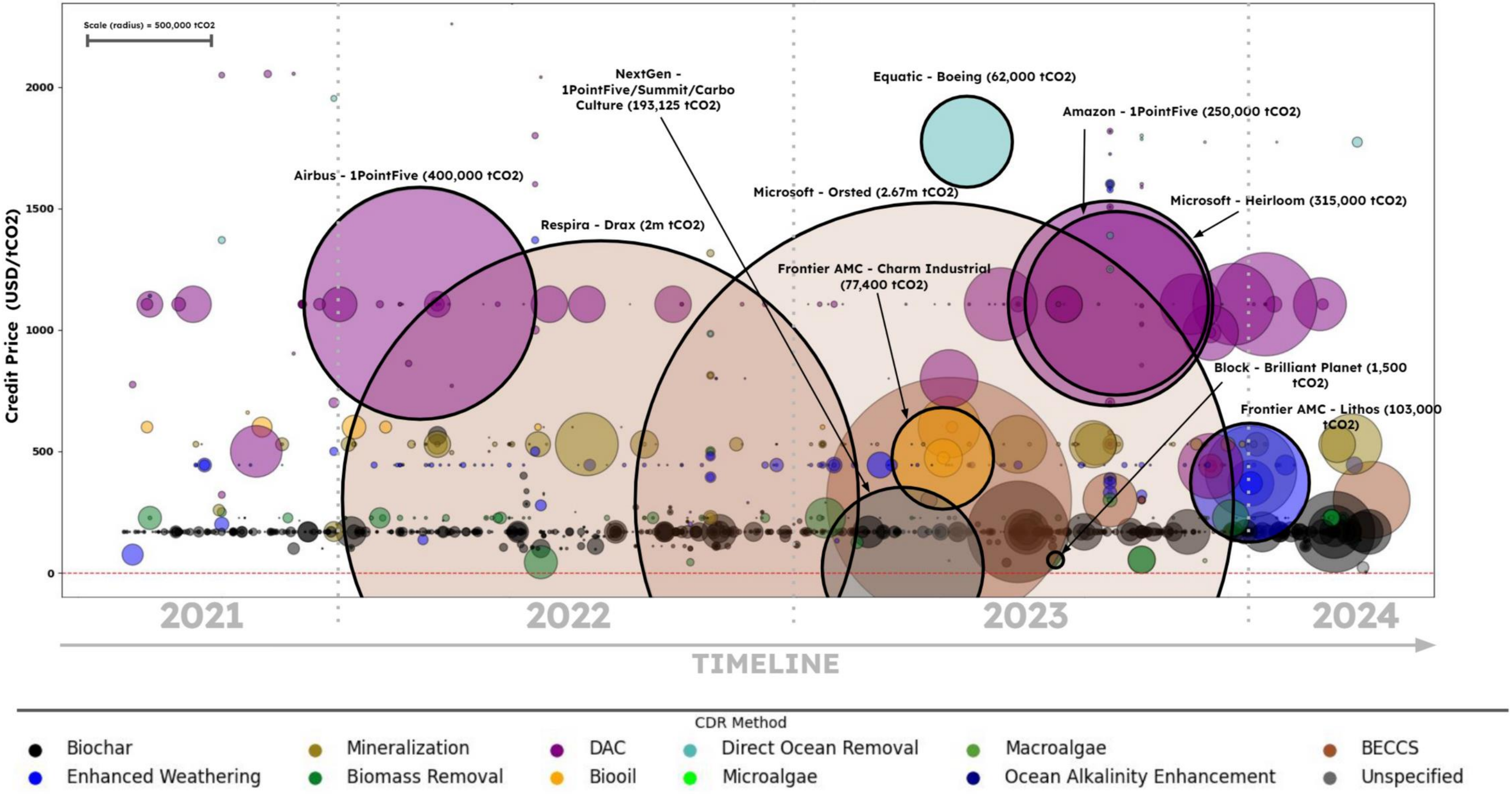


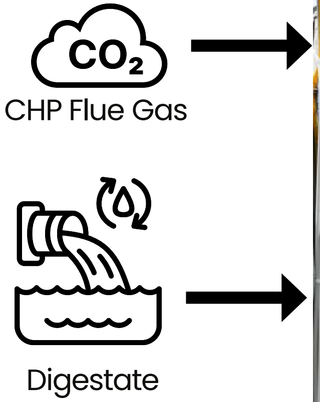
Figure produced by K. Gathani - CyanoCapture 2024

We took the most photosynthetic bacteria discovered…

… then gave it a boost.

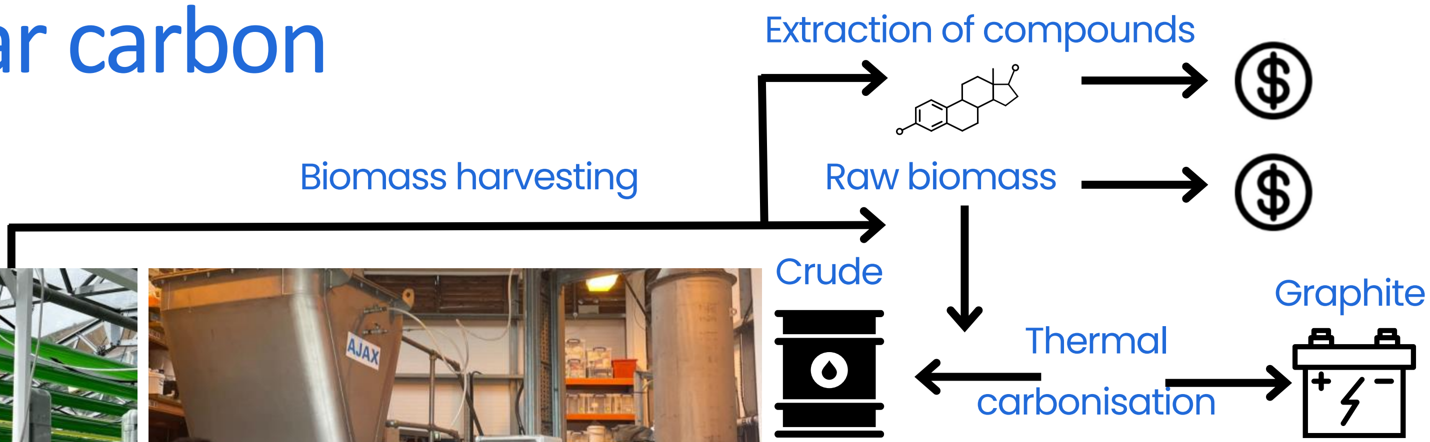
CYANOCAPTURE
Scalable carbon capture technology

H2Boost process: modular carbon capture system



CyanoCapture strains ~1000L PBR

Pyrolysis



Algal biocrude (left) & biochar (right)

CyanoCapture PBRs

Photobioreactors are intelligently designed for low-cost and are tailored for indoor vs outdoor use. Employing our in-house developed chemostatic cultivation SOPs enable higher net yields.

Drying, extraction & pyrolysis

Cyanobacterial biomass is continuously harvessted from the liquid using cheap techniques taken from the water treatment industry. Compounds of interest are extracted and purified.

Thermal carbonisation

Remaining biomass is processed to produce spherical graphite (undisclosed process), char (torrefaction), biochar (pyrolysis) or biocrude (HTL).

THE RESULT

We are fixing carbon capture

LOW-CAPEX

£10.6m

CAPEX for 10,000 TCO2/y gross*

- Payback period <3 years
- Modularised - can scale up or down accordingly

PROFITABLE

-£39.46

Negative LCOC minus revenues

- Profitable even without carbon credits
- Diversified, de-risked sales
- Other revenues possible from EV graphite materials or biomanufacturing

ENERGY EFFICIENT

247kWh

Energy use per T CO2 captured

- Net CO2 removal adjusted
- High quality MRV
- Possibility of reducing this further to 53kWh/T CO2 in the graphitisation scenario.

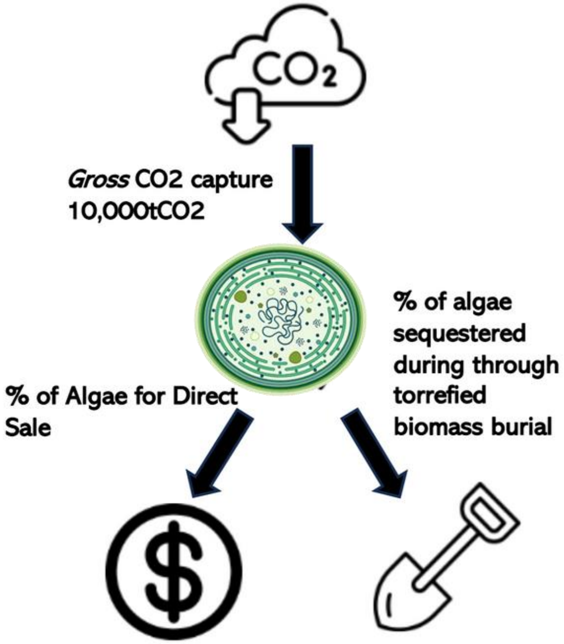
*or 4396 TCO2/y net, assuming 35% algal sales

CYANOCAPTURE

Scalable carbon capture technology

GO-TO-MARKET

CO2-to-permanent removal



For a 10,000 T CO2 capture unit, 5348 T of dried algal biomass are produced annually. The overall process amounts to only 247 kWh/T CO2 captured.

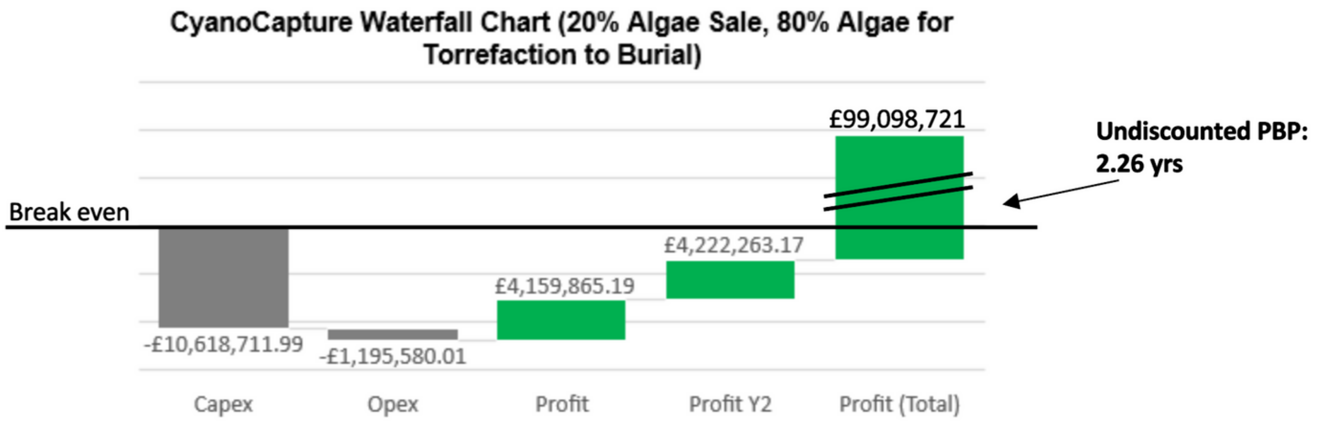
Approximately 20% of the algal biomass is then sold at £1/kg raw algal biomass (Range: £1-£25/kg) to the agricultural industry and the remaining 80% undergoes torrefaction and burial to provide carbon removal at £300/T CO2.

£96.38/TCO2*

LCOC minus non-credit revenues at 20% algal sales + 80% torrefaction

-£39.46/TCO2**

LCOC minus non-credit revenues at 35% algal sales + 65% torrefaction

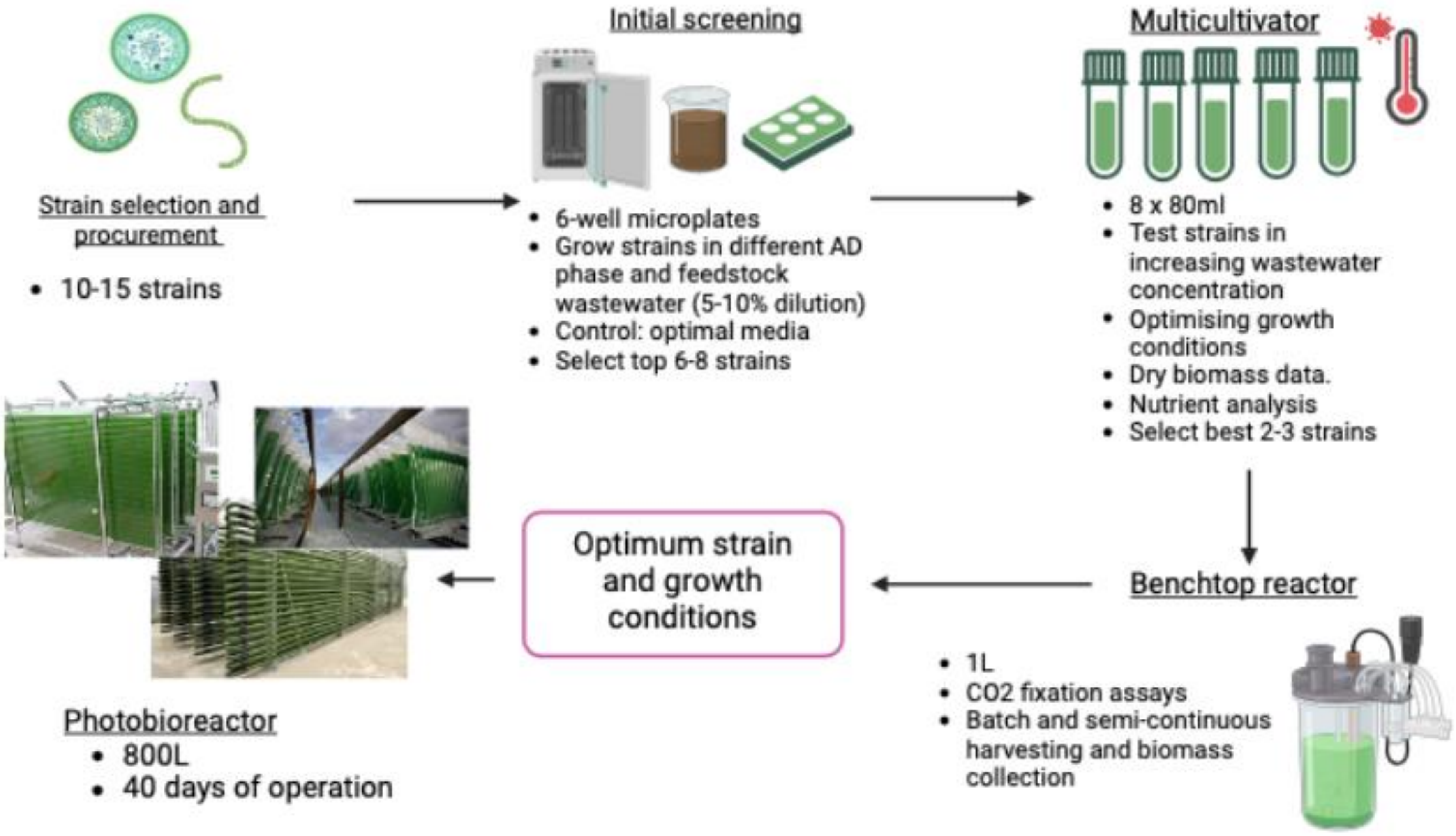


*6315 TCO2 net removal.

**4396 TCO2 net removal, profitable without carbon credits.

H2Boost Biology Roadmap

CYANOCAPTURE
Scalable carbon capture technology



H2Boost Biology Findings

- Digestate is turbid from high solid particle count. To overcome this digestate was flocculated by BDC
- Flocculant initially impacted growth then decreased after a few days
- Digestate source variability requires testing for toxic substances and required nutrient supplementation. For sample 1 &2 (Figure 1) main variation is in Formic and Acetic acid
- Toxic compounds were found in digestate: volatile fatty acids and ammonia
- A suitable digestate dilution of 2.5% in the media with supplementation of nutrients overcome growth inhibiting factors (Figure 2 Box)

	Sample - 1	Sample - 2
pH	8.3	9.68
COD (mg/L)	93508	5948
Nutrients (mg/L)		
Carbonates	766	2607
Phosphate	856	43.7
Ammonia	1686	1210
Nitrate	3160	32.9
Volatile Fatty Acids (g/L)		
Formic acid	46.4	0.06
Acetic acid	16.8	0.35
Propionic acid	0.67	0.38
Isobutyric acid	0.02	0.08
Butyric acid	0.14	-
Isovaleric acid	0.03	0.09

Figure 1

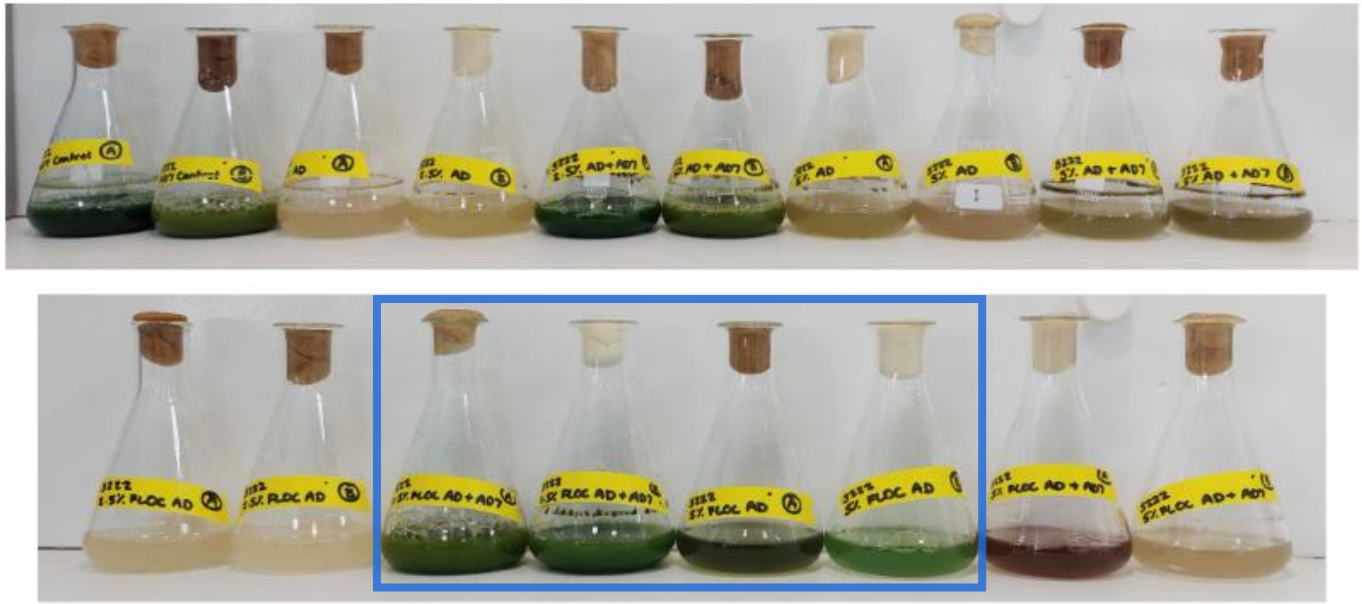


Figure 2

H2Boost System

- Closed 825L tubular photobioreactor (PBR) (Figure 1)
- Ancillary tanks: circulation; harvest; dilution and flocculation
- Inputs: CO_2 supply (CHP); digestate; electricity & water (Figure 4)
- Final hard size of the PBR revised to fit inside 32ft container
- Optimised Light Plan (Figure 3) for artificial light
- Onsite inoculum preparation PBR (15L) built and tested for continuous cultivation. 4 of these systems built in-house (Figure 2)
- SOP is prepared and awaiting HAZOP clearance.

Figure 1

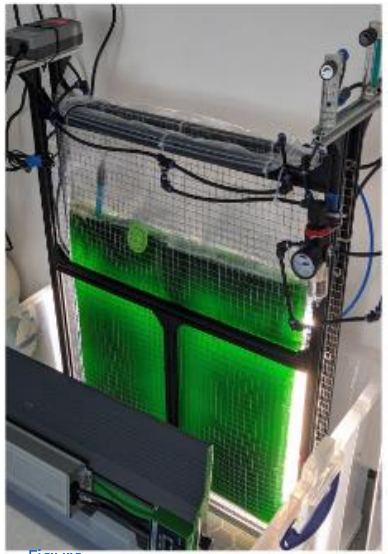


Figure 2

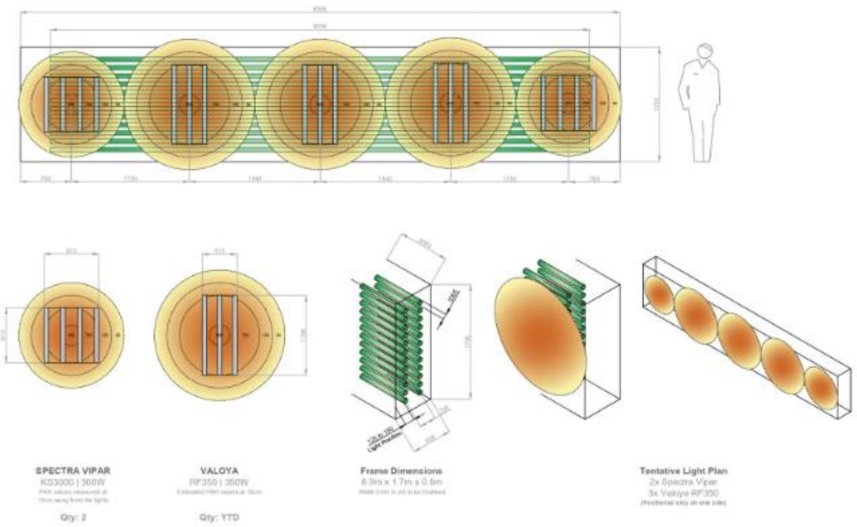


Figure 3

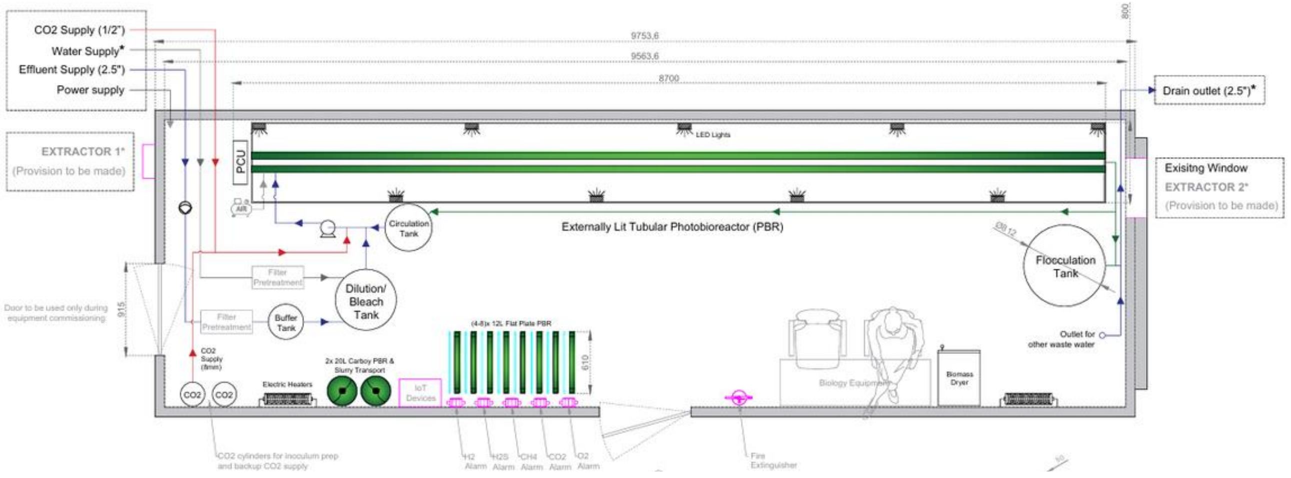
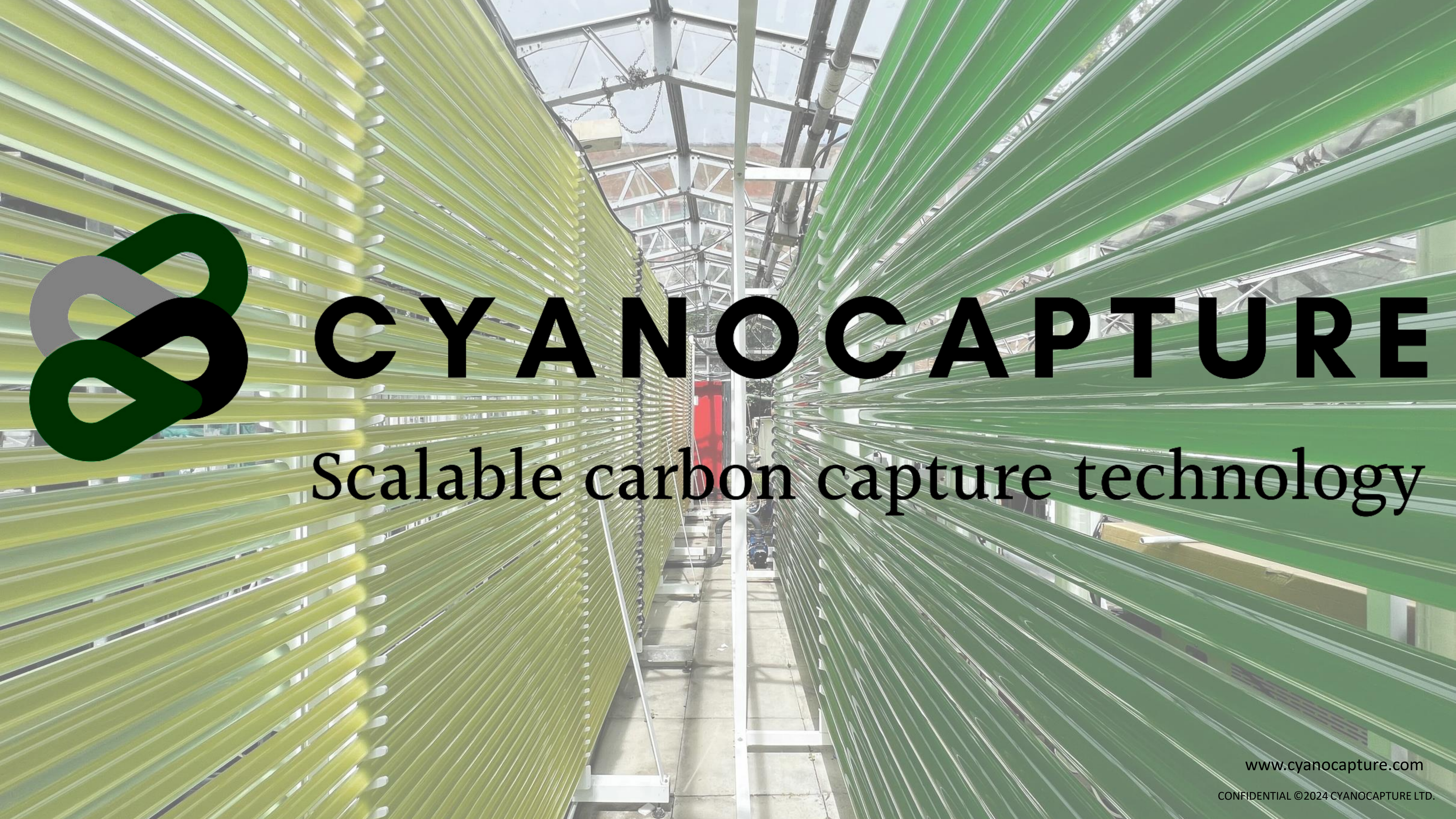


Figure 4



CYANOCAPTURE

Scalable carbon capture technology

www.cyanocapture.com

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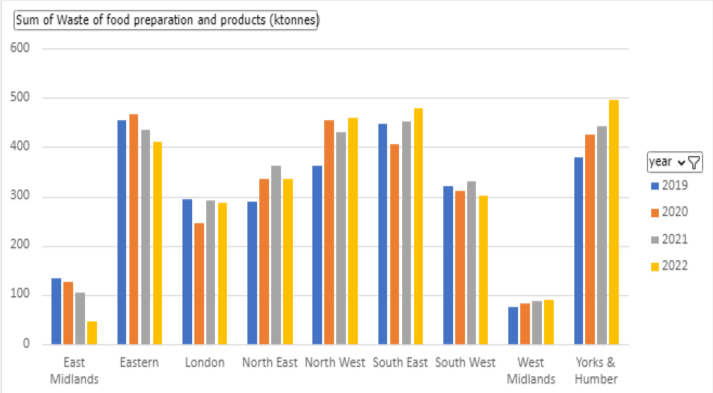
Techno Economic Assessment

(structure of approach)

- Project **Data** Arising
- Consideration of **potential performance**
- **Contractable** qualities, volumes and prices, including market outlook - **Feedstock & Products**
- **Equipment constraints** (technology, supply chain and scale factors)
- H2Boost **commercial scale** deployment design, constraints and **LCA performance**
- **Policy** Influences & Regulatory Requirements
- **Hydrogen supply chain** status, opportunities and constraints
- **Financial modelling** assumptions and projections
- **Investment** attitudes
- **Market interest** in deployment of H2Boost

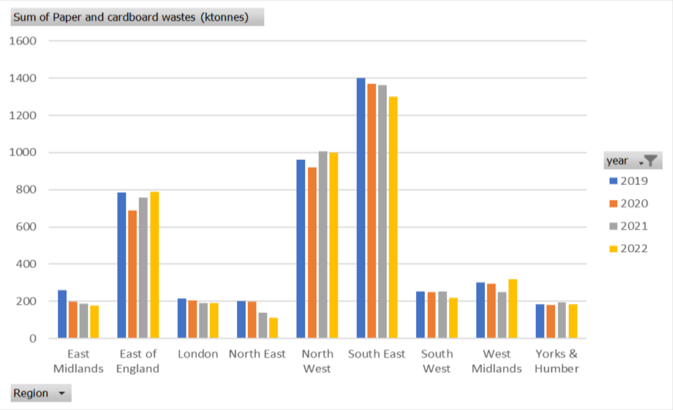
Supply Chain – Feedstock
(assumed plant scale 47ktpa feedstock)

Food Waste
£29 - -1/tonne 2024 (AD grade)
letsrecycle.com
4.8mtpa into AD 2022
2025/6 segregated waste will yield more



Quantities of food waste received by facilities holding relevant environmental permits from 2019 - 2022 (Waste data interrogator)

Paper & Card Waste
£5-50/tonne 2024 (Merchant)
letsrecyle.com
4.3mtpa 2022
2025/6 segregated waste **may** increase volumes



Quantities of paper and card waste received by facilities holding relevant environmental permits from 2019 - 2022 (Waster data interrogator)

Market Engagement

- Industry and associations approached
- 47ktpa supplies are available but will require a range of material qualities and related materials management
- Likely multiple contracts
- Input mix will need to consider inclusion of commercial food and paper mill wastes to meet input quality controls
- Plant design for feedstock management will be influenced
- Alignment with existing AD facilities remains under consideration

Supply Chain – Products

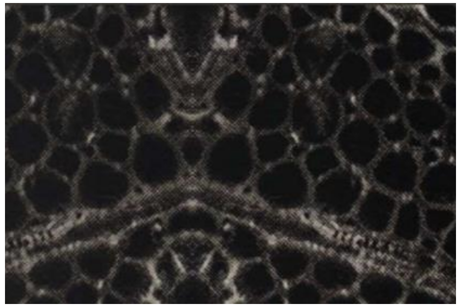
(assumed plant scale 70-140 tpa hydrogen)

Hydrogen

Government target 10GW of low carbon H_2 by 2030

Gas grid injection not approved in UK

Transport use nascent



Algae/Cyanobacteria > Biochar

Biochar supported in policy principles for carbon reduction

BUT largest potential for use on land limited to date

Await bio-product from H2Boost to assess further

Market Engagement

H2

- Industry and associations approached
- Limited H_2 offtakers currently available in the transport sector (it is coming is the message)
- 5x9's quality (99.999% pure) H2 is required for fuel cell use with some industrial applications accommodating lower purity. There is demand at the right price = competitive with fossil origin
- Suggestions of approaching use in SAF production
- Quality, pressure, **logistics and storage remain uncertain** and will **influence H2Boost commercial site locations**

Biochar

- Technology providers and system operators approached
- Significant morer advanced systems currently rely on government support
- Use a soil improver the subject of field trials
- Environment Agency engaged but no regrets approach takes time

Biomethane

- No market engagement to date
- Assumption that gas grid injection will prevail as exist AD units

Policy & Regulation
(a wide range of influences)

Policy and Regulation Area	Policies and Regulations	Project Impacts
Net Zero & CO2	Net Zero Strategy, Carbon Budget and Carbon Markets	**Low Carbon H2 specifically supported including biohydrogen with CCUS**. **No CO2 certificates** directly available to low Carbon H2.
Hydrogen	A range of strategies, sector development plans, support schemes, and compliance requirements including Renewable Transport Fuel Obligation	**Supportive and inclusive of the H2Boost system in principle** Storage and logistics support is still evolving. **Support schemes available** for production of low carbon H2 and as a renewable transport fuel. **Gas grid injection not currently supported**.
Bio-methane	Green Gas Support Scheme (GGSS) extension to 2028, Renewable Transport Fuel Obligation	GGSS extension to 2028 is to allow AD to access additional food wastes but the scheme does not extend further. **Consultation under way for the future but presents an uncertainty to H2Boost.**
Biochar	Net Zero Strategy acknowledges potential for biochar. No meaningful regulation for application to land (the largest potential)	**Uncertainty in ability to deploy the finished product other than development of inclusion in concrete**
Environment & Waste	Waste segregation at source. End of Waste	Additional biomaterials will be available from net waste streams, feedstock. **End of Waste presents a potential risk to technology deployment**
Consenting	Planning Permissions	The lack of regulatory framework around hydrogen may hold up planners approving projects

H2Boost – GHG impacts of Dark Fermentation for Hydrogen Production

David Turley

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GHG impacts of dark fermentation

- Phase 1 study
  - Examined GHG impacts based on
    - Informed estimates and expert input on biological and engineering aspects
    - Limited laboratory testing
  - New work
    - Enables full process evaluation from feedstock collection to delivery of pressurised hydrogen
    - Working to a common GHG accounting methodology across all projects

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Low carbon hydrogen standard

The UK **Low Carbon Hydrogen Standard** defines what constitutes 'low carbon hydrogen' up to the point of production.

The intent of the Standard is to ensure UK hydrogen production contributes to UK GHG emission reduction targets under the Climate Change Act

The LCHS establishes a common approach to GHG impact assessment to enable comparison of the GHG impacts of different hydrogen production processes

To meet the LCHS, hydrogen must have a final GHG emission intensity that is less than or equal to the LCHS threshold of 20 gCO_2e/MJ_{LHV} hydrogen product (@ at least 3MPa and 99.9% H2)

Scope

Includes

Scope 1
Scope 2
Scope 3 (partial) (excl construction, end of life etc)

Excludes

- Distribution of H_2
- Use of H_2
- Emissions up to point of waste aggregation
- Use of carbon offsets

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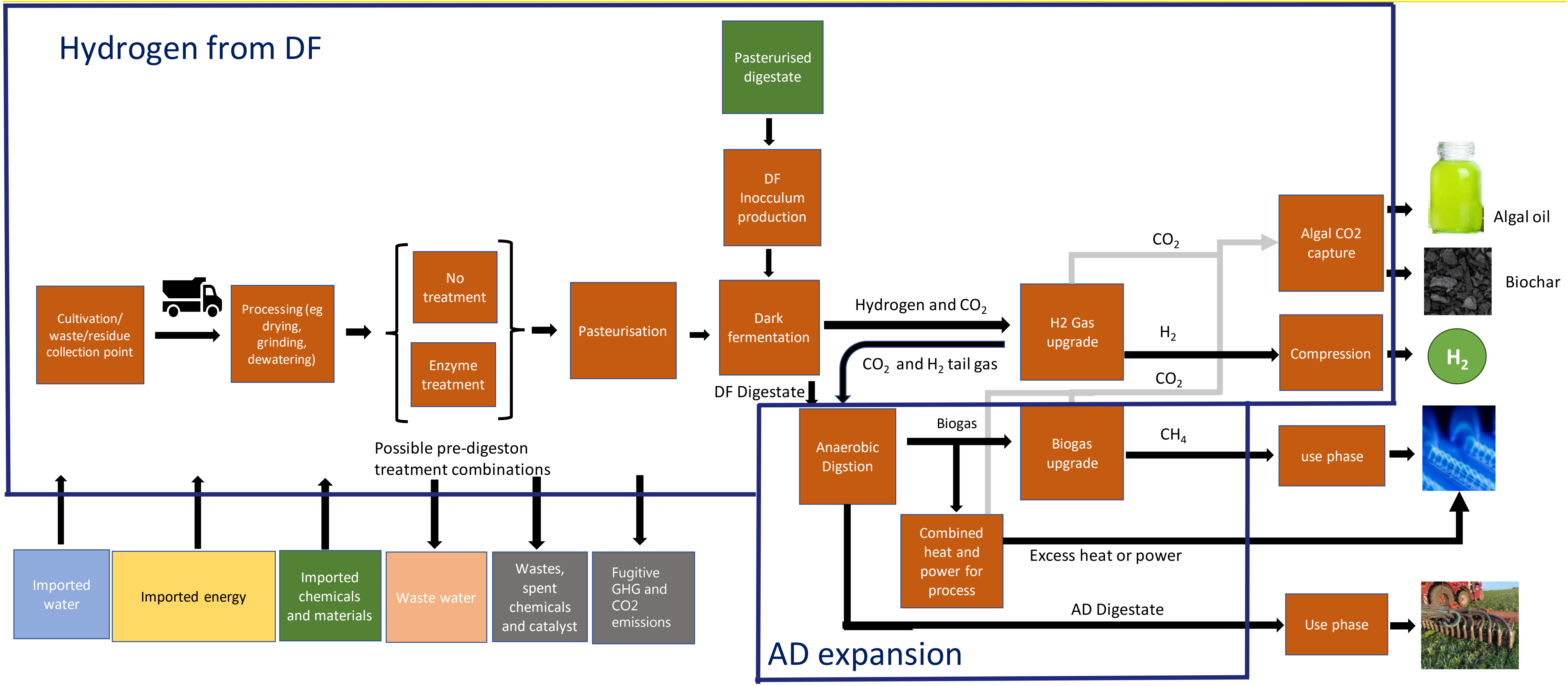

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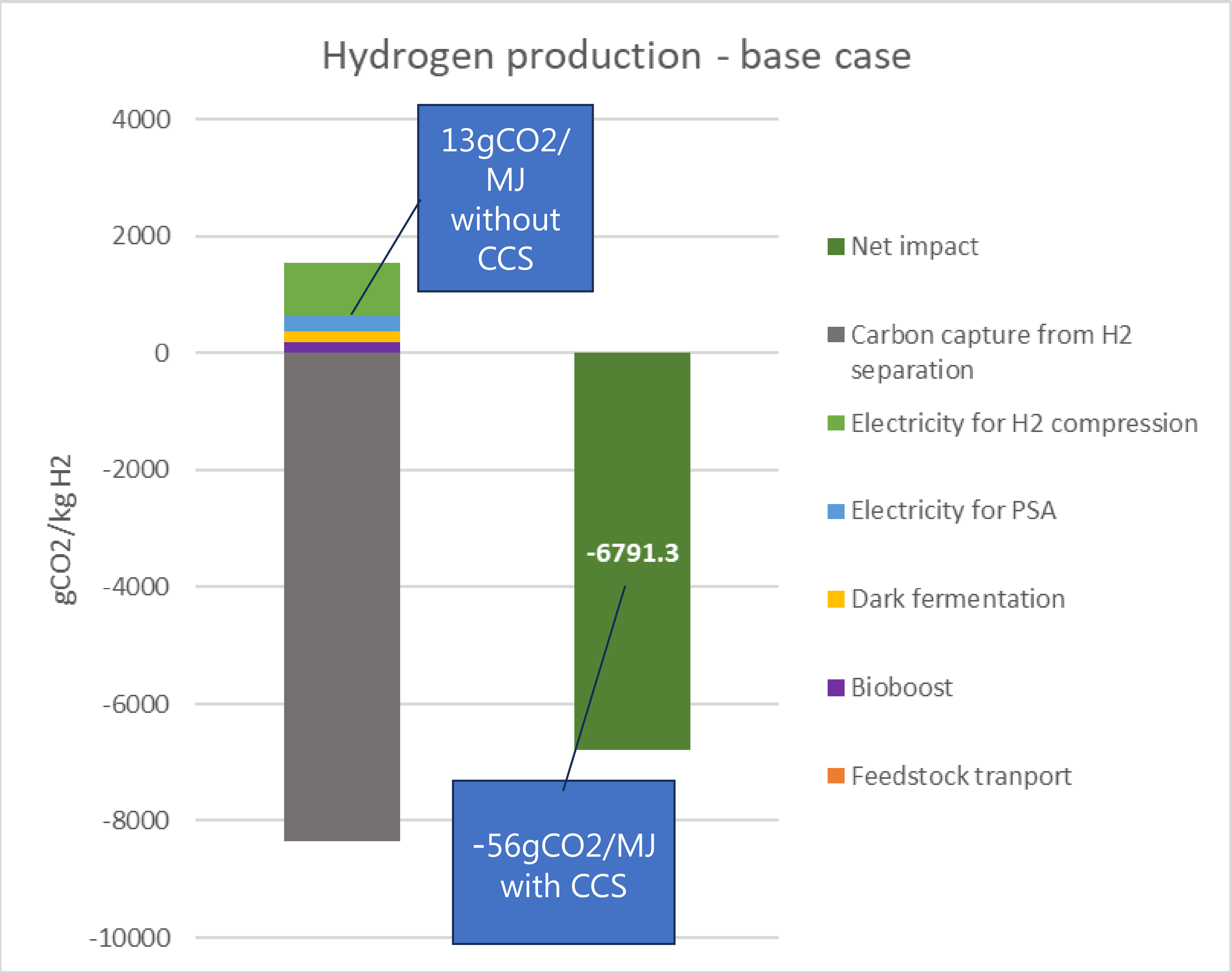
Phase 1 results (no allocation to digestate)



Focus

- Assess GHG impacts of H2 production for an end to end (cradle to gate) dark fermentation demonstration process (to LCHS)

  - Assess wider impacts of integration with biomethane production (from DF digestate).

  - Develop an energy and mass balance model to support techno-economic evaluation.

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Q & A Session

Thank you

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