COMPACT SYNGAS SOLUTIONS
GREENER FUELS FOR A CLEAN FUTURE

MicroH2-Hub

Utilising biogenic feedstock for H_2 and CO_2 production

Contents

2 Glossary

Glossary

H2BECCS	The Hydrogen Bioenergy with Carbon Capture and Storage Innovation Program
BEIS	Department for Business, Energy & Industrial Strategy
CCGT	Combined Cycle Gas Turbine
CCUS	Carbon Capture, Utilisation, and Storage
CH_4	Methane
CO	Carbon Monoxide
CO_2	Carbon Dioxide
CSS	Compact syngas Solutions
CV	Calorific Value
DEFRA	Department for Environment, Food & Rural Affairs
EOR	Enhanced Oil Recovery
H_2	Hydrogen
H_2O	Water
HEN	Heat Exchanger Network
HETP	Height Equivalent to Theoretical Plate
HHV	Higher Heating Value
LCA	Lifecycle Assessment
LCOH	Levelised Cost of Hydrogen
M&EB	Mass and Energy Balance
N_2	Nitrogen
NDT	Non-Destructive Testing
PFD	Process Flow Diagram
PM	Project Manager
PSA	Pressure Swing Adsorption
R&D	Research and Development
RTFO	Renewable Transport Fuel Obligation
SAM	Serviceable Attainable Market
SMR	Steam Methane Reformation
SOM	Serviceable Obtainable Market
SRF	Solid Recovered Fuel
Syngas	Synthesis Gas
TAM	Total Attainable Market
TRL	Technology Readiness Level
UK	United Kingdom
USP	Unique Selling Point

3 Executive Summary

Executive Summary

For this feasibility study Compact Syngas Solutions (CSS) has successfully designed and constructed a water-based carbon capture plant which is capable of processing 100 Nm3/h of syngas to extract >75% of Carbon Dioxide (CO_2) from the gas stream. This report outlines the viability of using water as a CO_2 capture solvent, as opposed to other prominent solvents such as amines.

This capture plant has been tested in conjunction with the CSS gasification system and proven it is feasible to integrate both systems. The works in this report have allowed CSS to increase the system design and it is now believed the system is rated to Technology Readiness Level (TRL) 6, uprated from TRL4.

CSS has successfully completed multiple trials which have allowed the optimisation of Hydrogen (H_2) and stable CO_2 production which was used for the design and construction of the scrubbing column.

Although physically CSS were unable to test the system to its full capacity simulations based on real life data confirmed the design validity. This has allowed optimisation and scale-up of the system in Phase 2 for a feasible working system.

CSS has completed a Lifecycle Assessment (LCA) which has indicated the system will provide a significant emissions reduction when compared to competitive technologies, at a Levelised Cost of Hydrogen (LCOH) that is not unreasonable. The system is an inherently low carbon system due to the sequestration of carbon in the biochar generated in the gasifier, and the additional capture of CO_2 in the scrubbing column.

CSS has identified a significant market available for the technology and have developed a business plan to commercialise the technology. CSS predicts that from 2025 to 2030 approximately 46 MicroH2-Hubs will be sold generating, 30kg/hour of H_2 per module. This will directly feed 400,000MW into the UK's Hydrogen economy. CSS aims to license the plant design from 2027 onwards to allow large-scale rollout.

In this report CSS has outlined the improvements to the engineering design that will be made in Phase 2 and how CSS targets to prove the long-term performance of the plant in future availability testing. CSS considered to process 500 Nm3/h of syngas through the CO_2 Scrubbing Scheme. However, due to the additional thermal heating and cooling capacity, and parasitic load associated with implementing the 2nd Water Regeneration Step in combination with CO_2 purification, this option is unviable within the resources available for Phase 2.

Following the planned work in Phase 2, the CO_2 scrubbing and purification scheme to be demonstrated at 100 Nm3/h of syngas, could be scaled-up with confidence to a commercial Gasifer-1300 design.

Phase 1 of the H2BECCS competition has been a great success for CSS and has proven the viability of using water as a scrubbing agent for CO_2. This will be a great benefit to the development of a low carbon H_2 economy.

4 CSS Project Overview

CSS Project Overview

4.1 Introduction

The UK government has set out its ambition to generate 10GW of low carbon H_2 by the year 2030 as part of its H_2 strategy [1]. H_2 is intended to be used to decarbonise heat, power, and transport in the UK, as part of the UK government's net zero strategy [2]. Currently the majority of H_2 produced in the UK is a product of carbon intensive Steam Methane Reforming (SMR). Less than 1% of H_2 supply comes from green sources (e.g. electrolysis).

To support decarbonisation and development of the UK H_2 economy the Department for Business, Energy, and Industrial Strategy (BEIS) has launched the Hydrogen Bioenergy with Carbon Capture and Storage Innovation program (referred to within this report as the H2BECCS competition).

The H2BECCS competition aims to fund innovative technologies. The programme is split into two phases; Phase 1 being the completion of a feasibility study to outline the design of the technology and its viability, and Phase 2 being the production of a demonstration prototype to prove the design.

CSS has developed a small-scale modular gasifier (the Gasifier-500) which is capable of producing a synthesis gas (syngas) from Solid Recovered Fuel (SRF) or biomass. Using a self-developed pressure swing adsorption (PSA) system, CSS is able to produce a high purity H_2 stream, whilst being self-sufficient by generating electricity from the residual syngas sent to a gas engine.

In this feasibility report CSS has completed the design and prototype construction of a carbon capture system which uses water (H_2O) as a scrubbing agent rather than amines. Amines are almost exclusively used by carbon capture system designers for scrubbing CO_2 from flue gases. However, amines are dangerous and degrade into harmful chemicals which pose an environmental issue. Use of water also offers a cost saving.

The use of H_2O as a scrubbing fluid is well known, however, it has not been used at small-scale. CSS is exploiting changes in pressure which are inherent in the system to capture and release CO_2 in the generated syngas.

As well as capture of CO_2 in the gas stream, the gasifier inherently captures carbon by creating an inert biochar from the fuel feed. This immediately captures approximately 40% of all carbon fed to the gasifier, which can then be stored in a safe manner underground (sequestration) or potentially used as a soil improvement tool. Other competing technologies such as SMR are limited to carbon capture of flue gases. This has a high energy cost due to the need to artificially introduce heat and pressure changes to flue gases before they are discharged.

The CSS solution is key to decarbonising the UK waste sector by providing a route to valorising waste biomass and SRF which has a low carbon intensity and produces high purity H_2. Its small modular design allows companies with high concentrations of waste to locally generate H_2 which can be used to decarbonise a vehicle fleet or sold on for commercial gain.

4.2 Objective of Phase 1

The objectives outlined by CSS for this Phase 1 feasibility study are as follows:

1. Develop a concept design of and build a test rig for a water-based CO_2 scrubbing column which is capable of processing 100 Nm3 / h of syngas.
2. Complete gasification trials to identify and select suitable gasifier operating conditions, at which H_2 production is maximised, to record CO_2 production.

3. Operate the CO_2 scrubbing column to assess the feasibility of capturing carbon reliably with H_2O and gather data to validate the design of the system for effective scale-up.
4. LCA of the Gasifier-500 when used in a commercial plant utilising the devised carbon capture system.
5. Complete an assessment of the available market for the CSS system(s) and develop plans for further development of the system.
6. Complete the engineering design for a Phase 2 demonstrator of the capture system with a robust testing plan to assess its long-term performance.

Along with the objectives above, CSS are verifying the TRL of the combined gasification, H_2, carbon capture system, which is currently considered TRL4. The objective of this feasibility study is to improve this to TRL6 and outline the design of a system which will raise the level to TRL8.

4.3 Terminology

Inclusive of the glossary, the following terms are used throughout this report:

Gasifier-500: This term will be used to describe a gasifier capable of producing a nominal 500 Nm3/h of dry syngas (with which all trials have been completed).

Gasifier-1300: This term will be used to describe a gasifier capable of producing a nominal 1,300 Nm3/h of dry syngas (the scaled-up commercial unit).

syngas: This term is used by CSS to represent the gas produced in their gasifier consisting of CO, CO_2, H_2O, H_2, Methane (CH4) and Nitrogen (N2).

Note: In the literature, the term syngas is generally used to represent a gas which consists of CO, CO_2 H_2O and H_2 When N2 is present at a high level, with CO, CO_2 H_2O and H_2, then the gas is called Producer Gas.

Phase 1 – This refers to the first phase of the H2BECCS competition i.e., this feasibility study.

Phase 2 – This refers to the second phase of the H2BECCS competition i.e., a demonstrator prototype.

5 Plant Design & Construction

Plant Design & Construction

5.1 Core Plant Outline

CSS own the exclusive right to use the gasification technology developed by Refgas Ltd and plan to adapt the technology for uses beyond power generation.

Figure 1 shows a simplified process flow diagram (PFD) of the gasification technology. This system takes a feed of biomass (or SRF) containing carbon and volatile hydrocarbons and generates a syngas at high temperature. The hot syngas passes through a set of filters (to remove char fines) and is then cooled in a series of bespoke heat exchanger network (HEN), from which the condensate (water and bio-oils) are drained. The syngas produced has the general composition: CO = 19 vol%; H_2 = 15 vol%; CH4 = 3 vol%; CO_2 = 13 vol%; and N2 = 50 vol%.

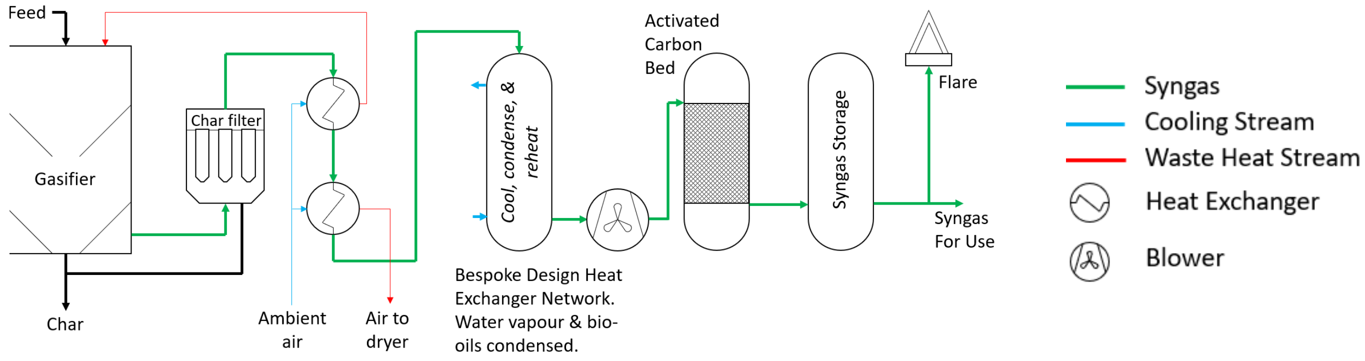

Figure 1 ***PFD of the core gasification technology developed by CSS.***

CSS has developed a PSA system to produce a concentrated H_2 gas stream. Residual syngas is passed to an engine to generate electricity for the plant, or to be sold. These systems are not within the specific scope of this report.

The core gasification technology at the Gasifier-500 scale (syngas flow of 500 Nm3/h) is established and considered TRL8 in accordance with BEIS guidance and is available for use to produce syngas as a fuel for a gas engine. However, that gasification process has been supplemented by additional unit operations to enable more H_2 to be produced as a main objective, and also to capture CO_2 as a by-product.

Therefore, the expected TRL8 of the overall combined process at the onset of the H2BECCS competition was considered to be TRL4.

Phase 1 of the H2BECCS competition aims to demonstrate at scale that it is technically and economically feasible to produce low carbon H_2 efficiently using the combination of technologies outlined above and complete the research and development necessary to bring the process to TRL6.

The works done in Phase 1 will provide the blueprint plant design for Phase 2 of the H2BECCS competition; allowing a commercial pilot to be constructed and further improve the system to a projected TRL8.

5.2 Carbon Capture Plant Design

CSS commissioned Flex Process to complete the design of the carbon capture system. The concept design was outlined by Prof Stan Kolaczkowski (Bath Process Consultants) bringing experience in the use of water as a scrubbing medium. The system was designed to take a 20% slip stream (≈100 Nm3/h) from the syngas produced. For trials in Phase 1, only a single stage degassing concept was trialled to gain practical experience with the scheme, and to quantify the Height Equivalent to a Theoretical Plate (HETP) for the packing in this application – thereby permitting scale-up in Phase 2.

Only a 20% reduction in CO_2 was necessary to show in Phase 1. The key elements in the design, consisted of a syngas compressor, scrubbing column, water regeneration vessel, and cooling & pumping circuit.

5.3 Pilot Plant Build

The engineering scheme in Figure 2, was then turned into a pilot-scale plant connected to the syngas storage tank (fed from the gasifier). Photos to illustrate some of the components assembled are presented in Figure 2 and Figure 3.

Figure 2 ***The CO_2 scrubbing column (left), water regeneration vessel (middle) and flare pot (right) fabricated and mounted in position.***

Figure 3 ***Arrangement of the final CSS Gasifier-500 and carbon capture pilot plant.***

5.4 Trials

5.4.1 Pilot Carbon Capture Plant

The assembled pilot-plant was trialled which provided lessons learned, demonstrated CO_2 removal from syngas, and provided an estimate value for HETP to aid work in Phase 2. The equipment is ready to be used at the start of Phase 2.

Successful completion of the trials resulted in the collection of data which provided a degree of confidence in the ability to (a) remove impurities from a real syngas in a Carbon Bed, (b) compress the syngas, and then (c) to apply the technique of water scrubbing, employing pressure release to release absorbed CO_2 (1st stage water regeneration) from the recirculated water (see Figure 4).

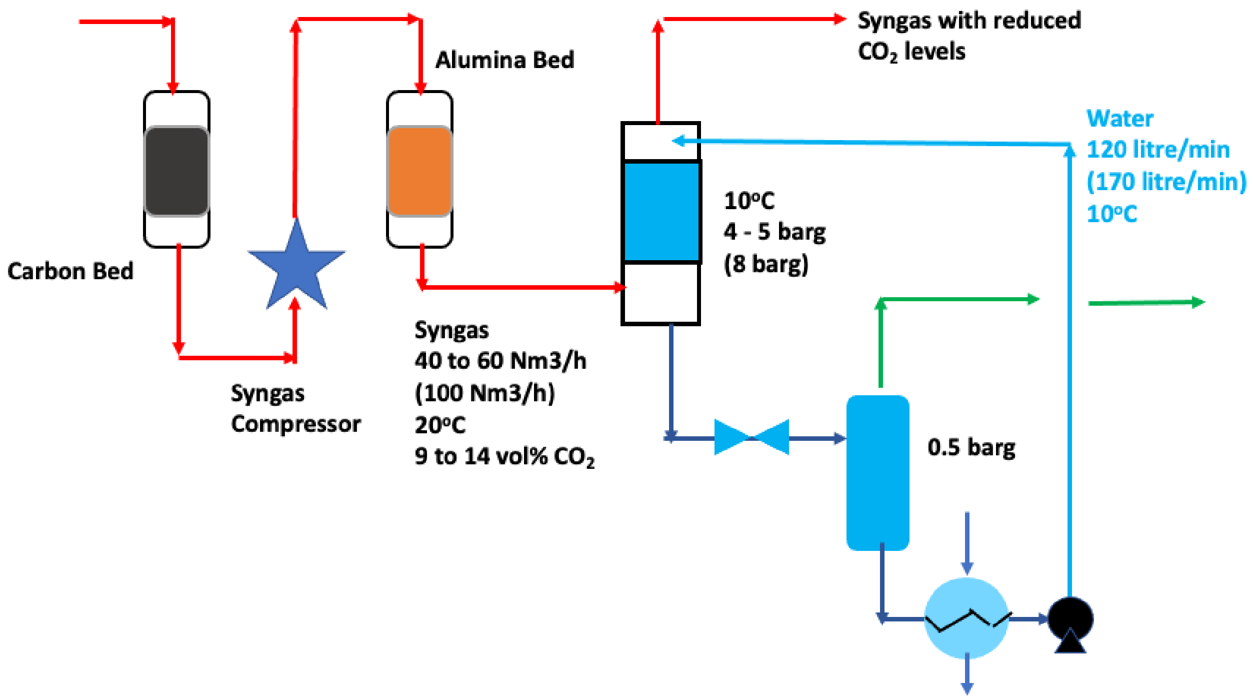

***Figure 4** Illustrating the CO_2 Capture scheme constructed and commissioned in Phase 1. Measured values are indicated and values in brackets indicate design conditions for this scheme still to be reached in early part of Phase 2.*

Trials were performed throughout October and November 2022. The data collected showed that pressure drop across the column is approximate 0.1 bar (100 mbar), which shows that there is no danger of flooding conditions at this operating point.

The unknown variable in the design of the carbon capture plant was the HETP for the packing, when used in an application of scrubbing CO_2 with water from a syngas. The average value of the results obtained were sent to Flex Process who, using Aveva Pro/ii software, developed a simulation to back calculate HETP.

Using the information from the simulation it is possible to complete preliminary sizing of the Phase 2 carbon capture plant with a 2nd stage of degassing. This is outlined in section 6.2.

5.4.2 Gasifier Process Condition Optimisation

Whilst completing trials using the carbon capture plant, CSS has been able to complete optimisation of the gasifier plant with the following key findings:

1. By increasing the temperature inside the gasifier (with the aid of gasification air pre-heating), the vol% of H_2 in the produced syngas can be increased.
2. By using a feed of O_2 enriched air into the gasifier the vol% of H_2 can be increased – probably because of two effects (higher temperatures inside the hot zones, and reduction in the dilution effect of N_2).
3. When O_2 enriched air is fed into the gasifier the CH_4 content in the syngas increases. This appears to help maintain the ability to run a syngas engine after H_2 has been stripped from the gas.
4. Using the H_2 optimisation methods outlined above, CO_2 production also increases to ca. 23.5 vol% of syngas.
5. From the short trials performed (limited to the normal working day), the long-term effects of increasing operating temperatures inside the gasifier, are unknown.

5.5 CO_2 Purification, Storage, Transport, and End Users

In this Phase 1 study CSS has completed an outline assessment of methods to purify the CO_2 extracted by the carbon capture system, then store and transport the purified CO_2 to identified end-user. For purification CSS has identified there are three existing technologies, namely PSA, seperation membranes, and cryogenic separation. PSA and cryogenic separation will be considered in Phase 2.

To transport the CO_2 product, CSS has identified that liquefaction or compression are necessary depending on whether road transport or pipeline transport is used respectively.

End users include abattoirs, Enhanced Oil Recovery (EOR), concrete curing, dry ice manufacture, metals moulding, and ecological sequestration. These end users require a CO_2 purity of 70 vol% to 99.9 vol%, and the purification system will be selected based on end user.

6 Phase 2 Design

Phase 2 Design

CSS has identified the following objectives for a Phase 2 demonstration plant:

1. Completion of a 1,000-hour continuous operation test.
2. Further optimisation of the 100 Nm^3/h CO_2 scrubbing column.
3. Construction of a vacuum plant to increase CO_2 extraction from H_2O.
4. Construction or procurement of a CO_2 purification system.
5. Integration of a H_2 PSA system and test performance with the CCS plant.

Additionally, CSS will continue to complete trials on the gasifier to further optimise H_2 and CO_2 generation. As a secondary objective, this will only be done where this does not have a detrimental effect on the objectives outlined above.

To achieve the objectives CSS will minimise operational disruption by operating on biomass (grade C waste wood will be the feedstock utilised, to reduce variability and preparation costs at this scale) and implementing several key improvements as outlined in the sections below. Other minor improvements will be made beyond what is discussed in this report. All improvements have been identified as possible failure points for a 1,000-hour test.

6.1 CO_2 Scrubbing and Purification

The CO_2 scrubbing system will include a scrubbing column and stage 1 degasser as used in Phase 1. The system will be improved with an additional stage 2 degasser in the form of a vacuum stripping column.

Additional equipment that will be constructed for Phase 2 includes the vacuum stripping column, vacuum pumps, heat exchangers, circulation pumps, and a demister. All pumps will be duty standby to avoid downtime to spurious failures.

All equipment has been scaled for a nominal syngas inlet flow of 100 Nm3/h. CSS considered to process 500 Nm3/h of syngas through the CO_2 scrubbing scheme. However, due to the additional thermal heating and cooling capacity, and parasitic load associated with implementing the 2nd water regeneration step in combination with CO_2 purification, this option is unviable within the resources available for Phase 2.

Following the planned work in Phase 2, the CO_2 scrubbing and purification scheme to be demonstrated at 100 Nm3/h of syngas, could be scaled-up with confidence to a commercial Gasifer-1300 design.

No design has been outlined for the purification of CO_2, however of the identified technologies CSS will pursue development of a PSA or freezing technique during development of the Phase 2 demonstrator.

6.2 H_2 Separation

A CSS H2-PSA system will be fitted to the syngas discharge of the CO_2 scrubber to extract H_2.

6.3 Flare / Energy Recovery

Syngas will be sent to flare or to a gas engine for electricity generation. The expected performance characteristics of the gas engine to generate approximately 231 kW_e from 480 Nm^3/h of syngas with a nominal CV of 4.68 MJ/Nm^3.

CSS will not use an electrolyser unit during Phase 2 due to insufficient spare capacity in the electricity generated by the engine.

7 Detailed Approach to Testing

Detailed Approach to Testing

The Phase 2 demonstrator will be subject to functional and availability testing as outlined below. Each test will be completed and internally documented to capture lessons learnt, failure causes, and optimisations,

Functional testing will be completed on all parts of the system from the gasifier through to H_2 storage and distribution.

The system will be subject to scaling availability tests where the plant will be run continuously. These tests are planned to be completed in the following steps:

1. 24-hour continuous hot testing.
2. 100-hour continuous hot testing.
3. 250-hour continuous hot testing.
4. 1,000-hour continuous hot testing.

Depending on early progress the 1000-hours trial may be brought forward early.

The availability test is used to assess the performance of the plant over an extended operational run, identify high failure rate equipment, and allow optimisation for steady-state operation. During the availability tests the plant will be expected to produce a syngas flowrate of 300 – 500 Nm3/hr, a CO_2 scrubbing efficiency of >70%, and a CO_2 purity of >95%.

During availability testing the system may be subject to variation of conditions to allow for capacity testing and quality testing. During these tests the performance figures will be relaxed.

Should there be a critical failure on the plant that cannot be rectified or by-passed, then the plant will be shut down and the availability test restarted after remediation works have taken place. All failures will be fully investigated using root cause analysis tools, with pareto analysis being used to assess failure rates of equipment.

On completion of the availability testing some sections of the plant (e.g. the water circuit on the CO_2 scrubbing column) will be subjected to examinations such as Non-Destructive Testing (NDT) to understand corrosion characteristics of the plant, short and long-term wear, and identify serious failure points (e.g. cracks). Surfaces will be examined, and corrosion coupons placed at key points will also be examined.

8 LCOH & LCA

LCOH & LCA

When the Phase 2 work is complete, and 1,000-hours of continuous operation have been shown CSS expects a single train Gasifier-1300 (full scale) project will follow. This will gain confidence in the performance in all units at a larger scale, after which a commercial installation with eight parallel Gasifier-1300 trains could be considered.

This commercial size unit is used as the basis for the completion of LCOH calculations, and the LCA. Without this commercial vision and the benefit of economies of scale, it is difficult to show competitive comparisons to large-scale technologies such as SMR. The commercial vision assumes:

1. That four of the trains exclusively generate electricity for parasitic load use, other site use, and sale to the grid.
2. The remaining gas trains are used to generate H_2 fuel and provide some electricity generation.

Table 1 outlines the CSS variables leading to a final LCOH cost compared to a counterfactual with SMR.

***Table 1* Comparison of the eight train commercial vision with the SMR**

Item	CSS	SMR
SRF Processed	11,280 kg/h in the form of SRF + O_2 enriched air	None processed.
Fossil Fuel Use	None used.	Natural Gas (+ water + air)
Hydrogen purity	>95% (at 158.4 kg/h) >99.9% (at 26.4 kg/h)	99.9% [3]
Hydrogen Product Flow	184.8 kg/h (158.4 + 26.4)	8,994 kg/h *(H_2 HHV = 25.4 kg / MWh)* [4]
Equivalent H_2 thermal output	7.27 MW	300 MW [3]
Capital Cost	£52.5 M *(Includes H_2 compression)*	£240 M to £270 M [4] (Excludes H_2 compression)
Carbon capture	41% sequestered in char CCS up to 90% captured	CCS up to 90% captured *(High energy requirement)*
LCOH *(No CCUS)*	£162 / MWh	£54.9 / MWh [5]
LCOH *(With CCUS)*	£170 / MWh [7]	£46.76 / MWh [5]
Operating Lifetime	20 years	20 years
IRR	10 %	10 %

CSS has assumed an operational lifetime of 20 years and IRR of 10% as per BEIS guidance for H_2 production.

The LCOH for the CSS plant is higher than SMR however this is to be expected as a large SMR is able to benefit from economies of scale. Despite this, the CSS plant still provides a competitive price point, which does not capture the additional benefits a small, modular, and decentralised system can bring.

Using the same commercial vision as used for the LCOH, CSS has developed a LCA. The LCA considers emissions due to transport of fuel and consumables, the emissions from the production of consumables, the carbon balance over the system (i.e., sequestration of carbon in char, carbon capture, and emissions generated in combustion), carbon offsetting of Combined Cycle Gas Turbine (CCGT) electricity generation, and carbon offsetting by H_2 fuel production.

The LCA excludes the emissions of fuel preparation by third parties, emissions from the production of construction materials, emissions from fabrication and construction of the gasifier, emissions from the transport and storage of CO_2, and emissions from decommissioning and subsequent plant disposal.

Table 2 ***Lifecycle assessment of greenhouse gas emissions from the CSS plant***

Type	Units	Value
Transport Emissions	t CO_2 / yr	128
Consumable Production Emissions	t CO_2 / yr	538,382
Electricity Generation Offset	t CO_2 / yr	-17,330,028
CO_2 Balance Emissions / sequestration	t CO_2 / yr	-121,560
Fuel Offset	t CO_2 / yr	9880
Total Balance	t CO_2 / yr	-16,903,198

There is a significant reduction in carbon emissions from the production in H_2 by a CSS plant largely due to the ability for the system to be self sufficient by the use of a gas engine. This offsets the use of CCGT which has significant emissions per MWh. Without the offset of this electricity the plant would be expected to result in a net emissions of 426,830 tonnes of CO_2.

Using the same methodology for landfill as DEFRA the emissions for landfill for an SRF based fuel is estimated to be approximately 0.896 tonnes of CO_2 per tonne of fuel. Therefore, the equivalent waste to landfill would result in the addition of 75815.57 tonnes of CO_2 per year.

9 Phase 2 Project Plan

Phase 2 Project Plan

9.1 Deliverables & Timeline

The Phase 2 demonstration project is expected to last 24 months and is split into seven work packages. The project plan outlines the estimated delivery dates for key milestones.

Deliverables for Phase 2 are achievable and have been aligned to payment milestones allowing consistent cashflow throughout the project.

9.2 Project Management

The project will be managed with:

1. Use of stage-gate process, with iteration paths to meet objectives.
2. Weekly debrief/planning meetings, risk register updates.
3. Single-management-reporting-line system where staff report directly to Project Manager (PM).
4. Cloud-based Project Management software.

CSS identified resourcing and skill must be improved for Phase 2, with Chemical Engineering support brought in for Phase 1 proving necessary. CSS intends to hire additional personnel in Phase 2.

9.3 Risks and Risk Management

CSS has developed a risk register to outline the risks for a Phase 2 project. Risk summaries for technical, commercial, managerial and regulatory risks are outlined below:

Technical – This is associated with operational failures leading to the gasifier being unable to produce the required quantity of syngas for testing periods, as well as failures in effective equipment scale-up. Learnings in Phase 1 help to mitigate these risks and others.

Commercial – This is associated with a failure to find commercial success in the industry. This is mitigated by CSS experienced team, business planning, investment and commercial relationships.

Managerial – This is associated with a failure to effectively manage the Phase 2 project and successfully construct and test a demonstrator. This will be mitigated by CSS'extensive project management experience and new hires.

Regulatory – This is associated with a failure to comply to requirements in the design and build of the demonstrator. CSS' experience and comprehensive knowledge of gasification, R&D, health & safety, waste management and H_2 compression and storage, minimises many regulatory risks.

In summary, critical inputs to the Phase 2 demonstrator will be CSS' "know-how", sector knowledge commercially and industrially, core team skills, industry contacts and relationships, and extensive knowledge gained from this Phase 1 study.

9.4 Quality Assurance

CSS considers quality on the basis of the provision of services, the provision of goods, and quality of manufacturing.

Provision of Services – Any contractor used for the supply of services (e.g.

engineering support) will be sourced from trusted companies. Each company will go through an onboarding process using the BEIS supplier form and a CSS check. All service providers must pass credit and insurance checks to mitigate risk to CSS.

Provision of Goods – Any supplier used for the supply of goods will go through an onboarding process using a CSS supplier check form. All goods providers must pass credit and insurance checks to mitigate risk to CSS.

Quality of Manufacturing – Each unit that is fabricated by CSS or a third party will be required to be provided with a quality pack. The contents of the pack will vary per job but is likely to require the inclusion of material certificates, welding certificates and procedures, CE certificates / declarations of conformity, and testing certificates. All quality packs will be stored digitally for the duration of the project.

9.5 Project Oversight and Governance

A communication and project dissemination plan will be created and distributed at the start of a Phase 2 project. This will include the preparation and submission of reports required by BEIS and management and monitoring of the overall budget.

CSS' Project Manager (PM) will be the single contact point for BEIS. The PM will liaise with the monitoring officer to ensure receipt of all required information on the due date.

CSS adopt "best practice" across Board governance disciplines and are committed to making sure sound and effective management rules, policies, and controls are in place. This will also include setting company strategic direction, providing the leadership to ensure effective execution, supervision of business management, and looking after the needs of shareholders and other associated stakeholders. CSS will underpin all activity within a robust ethics policy.

To ensure transparency with stakeholders CSS will plan an engagement program for Phase 2. This will include BEIS, government, supplier, end-user, and public stakeholders.

9.6 Reporting Plans

CSS will complete reporting in line with lessons learned in Phase 1, meaning a robust reporting structure will be in place accounting for timing, data logging, work structure and work package value, and effective report quality control. CSS will use additional KPIs internally for the management of work which will include delivery time, report quality scoring, project hours spent, and result to objective verification.

CSS has developed reporting templates which will be used to standardise documentation. This includes revision control to ensure work cross-checking and authorisation.

The below is an outline of our meeting frequency for Phase 2 project.

- Internal – Project start, weekly project management meeting (budget / schedule), quarterly financial review.
- BEIS – Project start, monthly reporting (internal and with monitoring officer), quarterly reporting, report submissions (as due).
- Stakeholders – Quarterly engagement and feedback sessions.
- Suppliers – Project start, ad-hoc during procurement.

9.7 Dissemination

Sharing of project knowledge both internally and externally is critical to project development and forms an important part of BEIS' expectation under the H2BECCS competition. CSS has completed dissemination over the course of Phase 1 of the competition. In August 2022 CSS launched a public statement on the successes of winning the funding and also featured in the BEIS H2BECCS general press release, in total the release had over 40 hits via online media and some print media.

Throughout the project CSS have completed dissemination works including weekly team meetings, quarterly reports, in person and online showcases of CSS technology, engagement with public and private stakeholders, and online dissemination activities such as webinars.

A public version of this feasibility report shall be distributed post-project, online via CSS website and LinkedIn. The report will also be sent to all stakeholders that CSS have engaged with during the H2BECCS Phase 1 project.

If successful in Phase 2, CSS will host several stakeholder meetings with Government bodies, local community, supply-chain, and end users. Project information will be presented, and feedback collated to help shape the commercial development and support local engagement.

10 Commercialisation Plan

Commercialisation Plan

10.1 Target Market

CSS' market focus is transport and industrial quality H_2 users with a H_2 purity requirement of 95 – 98%. The waste management sector is a primary target, marrying the need for decarbonising heavy goods vehicles with CSS' market experience and network. Target market customers have the following key characteristics:

1. 10,000 tonnes of suitable waste production per year (Bimoass/SRF).
2. Typically have large fleets of HGV vehicles.
3. Are actively looking at ways to reduce emissions.
4. Heavy energy users, impacted by recent increases in energy and vehicle fuel costs and removal of red diesel.
5. Comfortable with environmental and vehicle permitting.

Analysis has shown that the diversion of 10,000 tonnes of waste can produce enough H_2 with power equivalent to 1,100,000 litres of diesel. This is the equivalent of a direct saving of approx. £1.87m (based on £1.70 / L diesel) per annum.

Major cities are also introducing low emission zones to encourage the reduction of emissions from heavy duty vehicles. Vehicles must meet the emission standards or face penalty charges. This will have a major impact on the waste sector, and several companies are turning to full or hybrid H_2 vehicles to meet emissions standards.

CSS has conducted a study of the UK waste market, identifying a Total Attainable Market (TAM) in the waste sector of 3,000 waste management companies. With a CSS gasification and PSA technology only, sale price of £2.65m this equates to a potential £7.9bn market. Reviewing this market based on a requirement of at least 10,000 tonnes of waste gives a Serviceable Attainable Market (SAM) of 301 companies. This market is valued at £797m. Further review for a Serviceable Obtainable Market (SOM) for waste companies with at least 40,000 tonnes of waste gives 91 companies, this is valued at £241m.

10.2 Scale & Deployment

10.2.1 Manufacturing Rollout

CSS has extensive experience in the delivery of gasification units having delivered multiple gasification units under the Refgas company name. This includes two pilot plant projects delivered in short (<5 month) timescales, and several full-scale gasifiers for commercial customers with shorter than usual timescales (8-15 month delivery).

Each unit is installed onto a modular container skid as it is fabricated or delivered. Each work package can be produced by CSS in-house or subcontracted to a third-party. CSS has identified three sub-contractors for each work package. This capability allows reliable fabrication and construction of multiple gasification units in parallel. As demand grows, recruitment will be increased to meet capacity.

CSS has named its combined gasification and H_2 production system MicroH2-Hub and the commercial roll out is expected after construction and operation of a demonstration plant (expected February 2025). Further engagement with investors and end users will continue during this period for future commercial sales.

As a small team CSS recognises the limited capability of the company to grow and fulfil large-scale orders. Therefore, it is anticipated to engage a large-scale manufacturing partner in 2027 to construct the gasifier units under license to significantly increase the capacity of rollout.

10.2.2 Route-to-Scale

CSS has developed an accelerated timeline to market as outlined in Table 3.

***Table 3**– Phased timeline of CSS' planned route to scale.*

Scale	Year	Location	Project Intent	Funding Req.
Gasifier-500 *(Pilot)*	2022	CSS (Deeside)	Proof of H_2 generation from SRF / biomass gasification. Proof of carbon capture with water.	n/a
Gasifier-500 CCUS *(Pilot)*	2023 – 2025	CSS (Deeside)	Prove 1000 operational hours whilst generating 15 kg / h on biomass feed. Finalise CCUS concept.	H2BECCS £5M
Gasifier-1300 (scale-up)	2023 – 2025	ASH Waste (Wrexham)	Prove 1000 operational hours whilst generating 30 kg / h on SRF feed.	LCH2 £6M
Multiple Gasifier-1300 with CCUS	2025	UK/EU	Commercial generation of 30kg /h per hour with carbon capture using SRF or biomass feedstocks.	Private Funding
License	2027	Global	Commercial generation of 30kg /h per hour with carbon capture using SRF or biomass feedstocks.	Private Funding

For the timeline outlined above CSS is assuming that grant funding will be achieved in the BEIS LCH2 and H2BECCS competitions to secure the ability to scale and develop a commercial scale Gasifier-1300 and carbon capture technology. If this funding is not sourced publicly then private funding will be necessary which may delay the timeline.

From the above roll out activity CSS estimates that from 2025 to 2030, 46 MicroH2-Hubs will be sold (Gasifier-1300 model) providing 400,000MW of UK H_2.

10.2.3 Commercialisation

CSS estimates a cumulative revenue of £124m will be achieved over the next 5 years and profit after tax of £29m. The carbon capture technology is yet to be proven at scale and potential revenue is estimated to add to the above a further £34.5m in sales and £10.2m in profit.

Supply of additional equipment and services can be provided by CSS in collaboration with industry partners on a cost-plus basis. This gives CSS flexibility as clients will have the ability to purchase the technology only or turn-key solutions. With this market position CSS have developed a business strategy for future roll out.

The key steps to commercialisation for CSS are as follows:

Funding – To have 1000-hours continuous of operation on existing plant for power and then H_2 production.

Scale - Crucial to scale-up the MicroH2-Hub and carbon capture technology from Gasifer-500 to a Gasifer-1300.

Carbon Capture Technology – CSS aim to speed up the development of the carbon capture technology to align with the TRL of the gasification technology.

Operational Demonstrator – The ability for prospective clients to see an operational plant will remove obstacles to investment decisions.

Renewable Transport Fuel Obligations (RTFO's) – If H_2 is utilised for transport (using eligible feedstock) then RTFO's significantly supplement the financial model for the CSS gasifier.

People – CSS must maintain its robust supply-chain to secure roll out of the MicroH2-Hub. CSS has developed recruitment plan for the Phase 2 and future rollout of the technology.

10.2.4 Alignment to Net Zero & Benefits to Hydrogen H2BECCS process

In line with the UK government H_2 and net zero strategy the CSS technology will accelerate these as follows:

- Produce up to 30 kg / h (1.18MWh) of H_2 per gasifier sold, with a predicted 400,000 MWh added to the UK network by 2030.
- Each gasifier will offset diesel use by 1.1M litres per year, eliminating a large proportion of vehicle emissions per year.
- Each gasifier will divert 10,000 tonnes of waste from landfill per year, eliminating significant landfill greenhouse gases.
- Provide a low cost, low footprint H_2 generator which can be easily installed across the country to provide a decentralised refuelling network.
- This in turn will drive the uptake of H_2 technologies.
- CSS' commercial partners intend to adopt hybrid engines which will further provide case studies to drive up technology uptake.

CSS expects further benefits to the UK economy and drive towards Net Zero by:

- Supporting the development of H_2 economy with revenue, taxes and jobs.
- Supporting the drive to reduce the cost of production of H_2 (LCOH).
- Supporting businesses to reduce costs and improve their carbon footprint.
- Helping to reduce carbon emissions and improve the environment.
- Providing a supply of CO_2 for industrial use in the UK.
- Reducing waste sent to landfill and associated emissions and costs.

11 Conclusions

Conclusions

In this feasibility study, CSS has achieved each of the objectives set out at the beginning of the project. Referring to these objectives:

- CSS constructed a functioning carbon capture plant which was able to process 100 Nm^3/h of syngas.
- CSS successfully completed multiple trials which allowed optimisation of H_2 and stable CO_2 production which was used for the design and construction of the scrubbing column.
- Simulations based on real life data have confirmed the design validity of the carbon capture system. This has allowed optimisation and scale-up of the system in Phase 2 for a feasible working system.
- CSS has completed a LCA which has indicated the system will be a significant emissions reduction when compared to competitive technologies, at a levelised cost of H_2 that is not unreasonable.
- CSS has identified a significant market available for the technology and have developed a business plan to drive commercial sales post project.
- CSS has completed a full design for the construction of a Phase 2 demonstrator prototype.

Phase 1 of the H2BECCS competition has been a great success for CSS and has proven the viability of using water as a scrubbing agent for CO_2. This will be a great benefit to the development of a low carbon H_2 economy.

The work package and project deliverables have allowed CSS to increase the system design and it is now believed the system is rated to TRL6.

CSS would like to thank BEIS for its support in funding the feasibility study and for the opportunity to apply for Phase 2 funding.

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