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MicroHub: Utilising biogenic feedstock for hydrogen and CO₂ production

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 “MicroHub - Utilising biogenic feedstock for hydrogen and CO₂ production” 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.

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Views expressed in this report are those of the researcher and not necessarily those of the UK Government.



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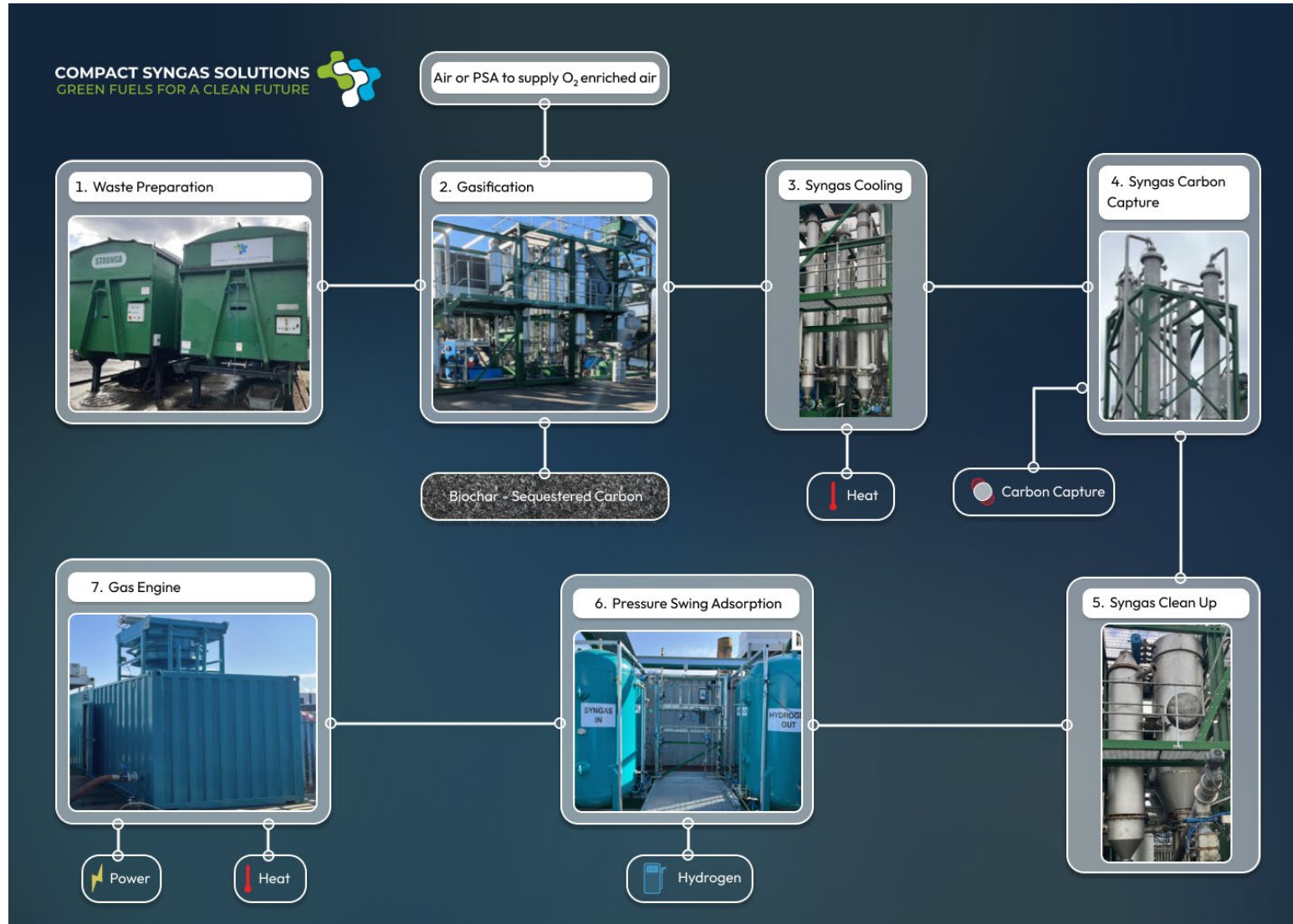
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1.3 Graphical Abstract



2 Glossary

Atkins	Atkins Ltd
BPC	Bath Process Consultants Ltd
CAPEX	Expenditure on capital items of equipment
CCUS	Carbon Capture, Utilisation and Storage
CH4	Methane
Cobalt	Cobalt Energy Ltd
CO	Carbon Monoxide
CO2	Carbon Dioxide
CSS	Compact Syngas Solutions Ltd
CV	Calorific Value
FOAK	First-Of-A-Kind
Gasifier-500:	This term is used to describe a gasifier capable of producing a nominal 500 Nm ³ /h of dry Syngas (this design of gasifier is used for all of the trials)
Gasifier-1000:	This term will be used to describe a gasifier capable of producing a nominal 1,300 Nm ³ /h of dry Syngas (features in commercial vision)
Competition Guidance Note	Requirements for the Hydrogen BECCS Phase 2 Final Report, issued by DESNZ
HAZID	Hazard Identification Study
HAZOP	Hazard and Operability Analysis
HGF	Hot Gas Filters
H2	Hydrogen
H2BECCS	The Hydrogen Bioenergy with Carbon Capture and Storage Innovation Programme

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H2O	Water
H2-PSA	A pressure swing adsorption system, used to separate H2 from the gas fed into that unit.
HHV	Higher Heating Value
Insert	A proprietary wire wound device, which fits inside a tube to promote heat transfer and to facilitate the drainage of condensate – known as hiTRAN inserts, supplied by Cal Gavin Ltd.
IPR	Intellectual Property Rights
KPM	Key Performance Metric
LCA	Life-cycle Assessment (used in following carbon emissions)
LCOH	Levelised Cost of Hydrogen
LCHS	Low Carbon Hydrogen Standard
LHS	Left hand side (used to identify an item in a photo)
MicroHub	These are sites which use CSS gasification technology to convert different sources of waste into H2 as an energy vector
N2	Nitrogen
OPEX	Operating costs
O2-PSA	A pressure swing adsorption system, which is used to separate O2 from air.
PEC	Pure Energy Centre Ltd
PEAK	Peak Technology Solutions (part of March Engineering Ltd)
PFD	Process Flow Diagram
Phase 1	This refers to the first phase of the H2BECCS competition
Phase 2	This refers to the second phase of the H2BECCS competition
P&ID	Process & Instrumentation Diagram
PSA	Pressure Swing Adsorption
R&D	Research and Development

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Refgas	Refgas Ltd
RHS	Right Hand Side
RTFO	Renewable Transport Fuel Obligation
SAM	Serviceable Attainable Market
SOM	Serviceable Obtainable Market
SRF	Solid Recovered Fuel (also known as RDF: Refuse Derived Fuel)
Syngas	This term is used by CSS to represent the gas produced in their Gasifier consisting of CO, CO ₂ , H ₂ O, H ₂ , CH ₄ and N ₂ (regardless of its specific composition) Note: In the literature, the term 'syngas' is generally used to represent a gas which consists of CO, CO ₂ , H ₂ O and H ₂ . When N ₂ is present at a high level, with CO, CO ₂ , H ₂ O and H ₂ , then the gas is called Producer Gas.
TAM	Total Attainable Market
Train	A network of unit operations consisting of HGFs, heat exchangers and a demister. Reference is made also to a Train A and a Train B, which are two parallel trains in the process.
TRL	Technology Readiness Level
WP	Work Package

3 Executive Summary

This project, awarded to Compact Syngas Solutions Ltd (CSS), was a response to a government call to accelerate the commercialisation of innovative clean energy technologies and processes. Hydrogen (H₂) is recognised as a key clean energy fuel and the ability to produce H₂ from biogenic feedstocks via gasification combined with carbon capture and storage is a central objective of the project. The main focus of this project was to demonstrate the use of water, at plant demonstration scale, to scrub carbon dioxide (CO₂) from syngas. As a result, the engineering aspects related to this part of the system are described in greater detail.

The use of water, rather than chemical solvents such as amines, offers advantages in terms of safety and environmental impact. While this approach requires larger equipment to effectively scrub the syngas, the increase in size is considered an acceptable trade-off for this application. The CO₂ scrubbing system forms part of a novel MicroHub concept, which utilises biogenic feedstocks to produce hydrogen and electricity, while capturing carbon both as solid char and as CO₂.

In order to demonstrate the CO₂ scrubbing scheme, it was necessary to: (a) provide a continuous, clean and dry syngas stream from an operational gasifier; (b) supply the scheme's parasitic electrical load via the gas engine; and (c) design appropriate safety relief systems, including surge tanks and flame traps to the flare. The interface and interactions between the CO₂ scrubbing plant and the upstream and downstream processes added to the engineering challenges encountered. The CO₂ water scrubbing system was designed and constructed in accordance with engineering standards for pressure vessels and utilised column internals that can be readily sourced. The system was successfully demonstrated on a slipstream, processing syngas at a flow rate of approximately 100 Nm³/h, achieving over 90% CO₂ removal using water alone (without chemical solvents). This result exceeded the project target of 75%. The performance data generated was sufficient to support scale-up to a commercial-scale plant for example, one capable of processing approximately 1,300 Nm³/h of syngas per gasifier.

Trials were also conducted using a pilot-scale, in-house designed Pressure Swing Adsorption (PSA) system, which was constructed as part of the project. The trials demonstrated that H₂ could be successfully separated from the CO₂-depleted syngas. For the intended commercial end-use of H₂, a purity level of greater than 90–92 vol% is sufficient for many combustion applications and this level of purity was achieved during the trials.

In a project of this complexity, numerous challenges arose, but effective solutions were implemented, allowing the project to progress successfully. As waste wood was fed into the gasifier, the resulting syngas was cooled and cleaned, CO₂ was removed via water scrubbing and hydrogen (H₂) was produced from the CO₂-depleted syngas stream. The full process was successfully demonstrated. Operational issues were encountered and resolved during the trials. The opportunity to conduct extended trials revealed several mechanical and design

issues within the gasifier. Addressing these challenges led to a series of engineering improvements, including: (a) repair work involving the welding of new sections onto the gasifier's outer shell; (b) replacement of the char breaker-bar at the base of the gasifier and installation of a more powerful breaker-bar motor; (c) replacement of the biomass feed valves; (d) replacement of the char release valves; (e) adjustments to the air feed points; (f) re-design of the biomass mixer; and (g) design of a ceramic liner to protect the internal metal surfaces of the gasifier. Through the resolution of these issues, a deeper understanding was gained of the factors influencing control of the hot zones within the gasifier, which is critical to optimising process performance.

Budget constraints, combined with equipment delivery challenges, were addressed through the sourcing and adaptation of several used equipment items. In particular: (a) a syngas compressor; (b) a gas engine and electric generator; and (c) a vacuum pump for the CO₂ degassing column.

A carbon Life Cycle Analysis (LCA) was performed based on a vision of a commercial process. In simple terms, if 1 tonne per hour (t/h) of Refuse Derived Fuel (RDF) were incinerated, it would generate approximately 1.6 t/h of CO₂ emissions. In contrast, if that same quantity of RDF were processed in a CSS gasifier, the following carbon capture outcomes could be achieved: (a) approximately 0.7 t/h of CO₂ equivalent would be trapped in the form of char, suitable for sequestration; and (b) around 0.3 t/h of CO₂ could be captured via the water scrubber and subsequently sequestered.

An estimate was also performed of the project's performance against the UK Government's Low Carbon Hydrogen Standard (LCHS), which is used as a key metric. Using incineration (or landfill) as the counterfactual scenario, the project's calculated LCHS value was found to be significantly below the maximum threshold of 20.0 g CO₂e/MJ LHV of hydrogen product in fact, negative values were obtained. This analysis concluded that gasification of RDF offers a substantially superior environmental pathway compared to incineration or landfill.

Based on insights gained during this project, Levelised Cost of Hydrogen (LCOH) calculations were revised. The main adjustments included a lower parasitic electrical load, a higher cost assigned to the CO₂ scrubbing and degassing system and the need to assign a larger number of shift operators. The revised LCOH estimate now stands at £338.10 / MWh, inclusive of the estimated cost of hydrogen compression. If carbon credits could be claimed for the captured carbon, these credits could offset part of the cost and further reduce the LCOH.

4 Company & Project Background

4.1 Plant Location & Size

Compact Syngas Solutions Ltd (CSS), is an SME based in Sandycroft (Deeside, North Wales), originally started in 2007 as Refgas Ltd and was restructured to become Compact Syngas Solutions Ltd in March 2020.

CSS develops and operates its proprietary advanced gasification technology at its Deeside site, which also houses a fabrication facility providing mechanical and electrical maintenance and support. CSS utilises its in-house team wherever possible, while partnering with local contractors for specialised manufacturing such as the production of pressure vessels.

The CSS team comprises 12 full-time staff, 2 part-time staff and 3 retained consultants engaged as subcontractors. The team includes Paul Willacy (CEO), a mechanical engineer with 25 years of process engineering and specialist design experience; Karen Taylor (Chief Commercial Officer); and Jim Lavin (Finance Director). The wider team brings expertise in mechanical engineering and production, chemical engineering, electrical engineering, fabrication, maintenance and includes four dedicated plant operators. Additional technical support is provided by external partners including Atkins, Cobalt Energy, Bath Process Consultants, JM Dixons, Quicksilver Engineering and EJ Peak.

CSS served as lead partner for the H2BECCS Phase 2 project and was supported by key subcontractors: PEC, Atkins, Cobalt, and Bath Process Consultants.

4.2 Main Market Sector & Brief History

CEO, Paul Willacy and lead engineers at CSS, have over the last 17 years gained considerable experience developing gasification technology. Starting in 2007 Refgas designed and constructed a pilot 400 Nm³/h syngas gasifier. This led to construction and scale-up to much larger units (1,300 Nm³/h syngas), a rapid scale-up at the insistence of external sponsors.

In March 2020, CSS was formed with key Refgas staff transferring to CSS to develop the concept of 'Advanced Gasification Technology'. The objective was to produce two distinct product streams: H₂ and electrical power and strengthen the IPR base in-house. The scale of the gasifier was retained at 500 Nm³/h of syngas, to make the innovative steps easier (financial/operational) to implement and trial.

The initiative is led by Paul Willacy and supported by external Chemical Engineering Consultant, Prof Stan Kolaczowski, who remains involved. The reduced scale to a 500 Nm³/h syngas helped to de-risk improvements to the gasifier and down-stream unit designs and to produce a cleaner syngas with a higher calorific value. This was achieved by:

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- The construction of a MK II design of Gasifier-500 (IPR, transferred from Refgas to CSS in 2024).
- Development of a hot gas filtration (HGF) system (in-house IPR).
- The design of a cleaner method of syngas cooling/conditioning (in-house IPR).
- The use of O₂ air enrichment in gasification (in-house IPR) and the supply of that via PSA technology (in-house IPR and external IPR).
- The use of PSA technology to separate H₂ from syngas (in-house IPR).

CSS's extensive experience in gasification and waste management has shaped its business model around decentralised, small-scale modular MicroHubs, designed to mitigate feedstock supply risks. In contrast, other gasification developers operating at larger scales often face challenges in securing sufficient quantity and quality of waste.

4.3 Project Background

This project was a response to a call by Government to accelerate the commercialisation of innovative clean energy technologies and processes. H₂ is seen as a clean energy fuel and the ability to generate H₂ from biogenic feedstocks via gasification, combined with carbon capture and storage is a key objective. In order for CSS to further develop its technology, the Hydrogen BECCS Innovation Programme, which itself forms part of the DESNZ (formerly BEIS) Net Zero Innovation Portfolio, funded the development.

Low carbon H₂ will be critical for meeting the UK's legally binding commitment to achieve net zero by 2050 and H₂ generated via bioenergy has the potential to deliver negative emissions required to offset emissions from hard to decarbonise sectors. Biogenic waste feedstocks, such as waste-wood are typically disposed of through incineration or sent to landfill, both of which contribute significantly to climate change through carbon dioxide and methane emissions respectively. CSS's technology, however, converts this waste into syngas, which can then be used to produce hydrogen a sustainable and low-carbon fuel.

Accepting the Government's aims, the main commercial objective for CSS is to utilise a waste stream as a fuel and convert it into: (a) H₂ product stream and (b) to produce electricity.

As a by-product, carbon is captured in two forms: (a) in the char which is a by-product from the gasifier and (b) it can be separated from the gaseous syngas stream in the form of CO₂. These two forms of carbon can then either be sequestered or sold to an end-user.

This report addresses Phase 2 of the programme, which funded a number of demonstration projects, building on the outcomes of Phase 1, where 22 feasibility studies were supported. During Phase 1, the concept of using water instead of more carbon-intensive chemical solvents such as amines to remove CO₂ from syngas was explored through experimental trials. In parallel, chemical engineering simulation studies were conducted to inform the design of a scaled-up process. These Phase 1 findings directly led to the development of this Phase 2 demonstration project.

5 Project Overview

5.1 Aims & Objectives

5.1.1 Aims

The aim of Phase 2 is to develop CSS' technology further to recover the carbon dioxide from the syngas whilst producing hydrogen. At the start of the Phase 2 project, it was declared that CSS had developed an advanced gasification process.

A summary process flow diagram of the advanced gasification process is shown in Figure 1 and short description follows.

The process consists of a down-draft gasifier, which is fed by waste (waste wood / RDF) in batches from the top of the gasifier. The feedstock is then subjected to elevated temperatures, partial oxidation and negative pressure. Air is drawn in by the syngas blower.

The hot syngas released from the base of the gasifier is filtered by the hot gas filters (HGF) to remove fine particles. Over time, the HGFs build up with trapped char fines which results in a filter cake. To alleviate this, cyclic nitrogen pulses remove the char-fines which are collected in a hopper at the bottom of the HGFs.

Following the HGFs, the syngas passes through six heat exchangers to reduce the temperature prior to the syngas passing through the blower. As a result of cooling the syngas, bio-oils and water is condensed and drained at regular intervals.

Next, the syngas passes through the annular carbon bed which acts as a contaminant surge projection before feeding into the storage tank which is used to provide a constant flow of syngas into the gas engine. After the storage tank, the syngas is filtered once more by a carbon bed before being used as fuel in the gas engine which produces electrical power which is used in the process and any remaining is exported. The syngas produced by the process, contains about 12 to 14 vol% CO₂, which if fed into the gas engine, would be emitted with the exhaust gases into the atmosphere. Therefore, in this Phase 2 project, the plan was to install and demonstrate the use of water as a fluid which would absorb (scrub) CO₂ from the syngas produced, in a process to be installed down-stream of the blower.

This led to the below specific project objectives, deliverables and benefits:

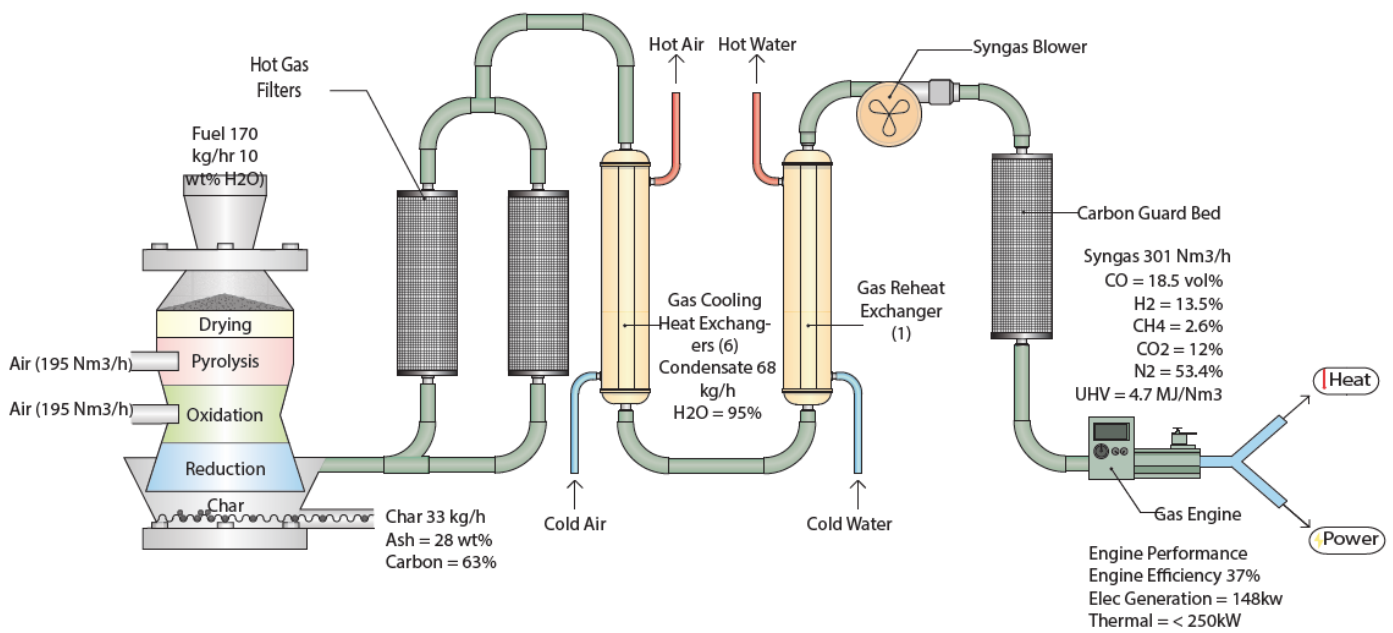


Figure 1 - Simplified schematic of the process at the start of phase 2

5.1.2 Objectives

Objective 1: To demonstrate the use of water (rather than chemicals) as a method of removing CO₂ from the gas mixture in syngas, such that the CO₂ can be captured and then either (a) stored/sequestered, or (b) purified and sold for use in an application where CO₂ is used (e.g. food packaging; drinks). By reducing the CO₂ content in the syngas, then: (i) the quality of the syngas is improved, (ii) it is easier to produce H₂ and (iii) the calorific value of the H₂ depleted syngas stream is raised making the operation of the gas engine more efficient.

Objective 2: To perform extended trial runs, aiming to achieve 1000-hour of continuous operation, thereby raising the Technology Readiness Level (TRL) of: (a) the specific CO₂ capture innovation closer to commercialisation and (b) that of the whole gasification process, including the part in which H₂ is produced.

Objective 3: To gather information from this demonstration project to attract potential financial investors to support scale-up of CSS' modular technology which is localised, processing local waste and producing a cleaner form of H₂ and electricity.

Modification to Objective 2: During the course of the project, as safety reviews were performed on the design, the scheme became more and more complex and concerns arose about the ability to assign a high level of supervision to a shift system capable of sustaining '1000-hour of continuous' operation. Hence with permission from DESNZ, this was replaced with a target of '10 sets of 100-hour of continuous operation'.

6 Technical & Commercial Aspects

6.1 Engineering Design

A key technical objective in this Phase 2 project was to advance the application of the use of water as a CO₂ scrubbing fluid and to demonstrate in a slip-stream trial that 75% of the CO₂ can be removed from that syngas stream which contains approximately 12 vol% CO₂. A removal of 75% was selected as a reasonable target level, based on the knowledge that for very high removal targets, the cost of the system would start to increase exponentially. The 12 vol% CO₂ was selected as an inlet concentration, as it reflected a typically measured level from plant trials at CSS.

To perform the planned trials, it was necessary to ensure that the current process equipment was operating in a satisfactory condition.

- The following equipment from the current design had to be reviewed to ensure they were in a satisfactory condition some of which is highlighted below:
- The feed system had to operate without mechanical issues
- Optimum gasification conditions to maintain optimum syngas quality
- The HGFs needed to operate without creating a high-pressure drop
- The heat exchangers needed to avoid high fouling which could create high backpressure.
- The syngas blower had to provide sufficient suction and discharge pressure and the desired flow.
- The carbon beds had to filter out the heavier hydrogen carbon species and other contaminants.

In response to the above challenges, many items of existing equipment had to be modified, or new equipment specially designed and constructed, or purchased to create what was required. A parallel Train B was built and installed (see Figure 2), to enable the HGFs and heat exchangers to be by-passed for cleaning or maintenance (while the gasifier could still be maintained operational and producing syngas). Train-B, consisted of;

- 6x heat exchangers (which cool the syngas from the HGFs).
- 1x demister (which removes liquid droplets from the cooled syngas).
- 1x heat exchanger (which raises the temperature of the syngas before the Syngas Blower).

Before the CO₂ scrubbing system (see Figure 2), it was necessary to compress the syngas to a pressure of about 7-8 barg and hence, a high-pressure compressor was installed to provide the required flow at that condition. The high-pressure operation is used to allow the CO₂ to be absorbed in the water before being pumped into separate system which reduces the pressure

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to allow for the captured carbon to be released from the water. For the process to run smoothly, equipment down-stream of the CO2 water scrubber had to be designed and constructed/ordered. For example, to use the syngas as a fuel, the gas engine had to operate with the calorific value and flow supplied and it had to produce electricity, which was required to operate the process. Also, for safety reasons, many vented gas streams from different parts of the process were sent through a central surge tank in which the pressure would fluctuate and the discharge of the gases sent to the flare had to be carefully controlled.

Peripheral process equipment also had to be procured, installed and commissioned as part of Phase 2. For example, the nitrogen generator (used for safety reasons) and the oxygen generator (used to enrich the air within the gasifier). However, the oxygen generator was only used in a few trials to highlight the benefit of reducing nitrogen in the syngas and thereby making it easier to remove carbon dioxide, hydrogen and increase the syngas CV.

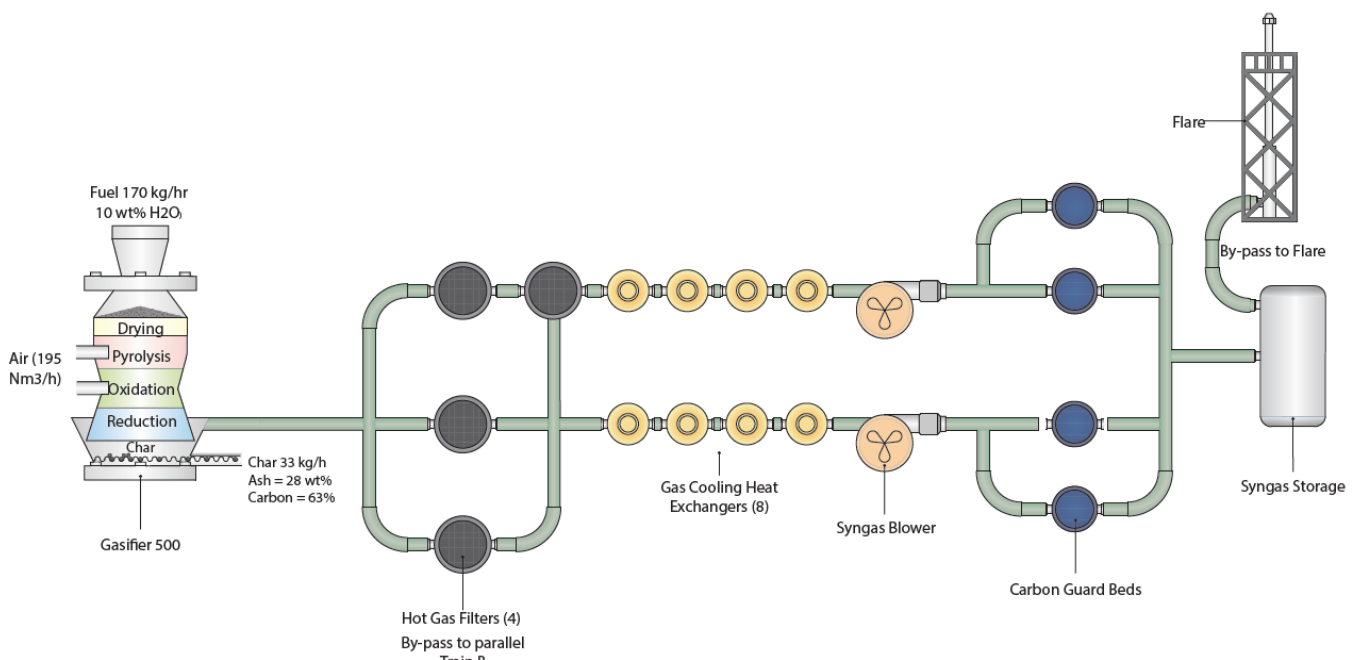


Figure 2 - Simplified schematic to illustrate the installation of a parallel Train B

6.1.1 CO2 Scrubber Design and Development

CSS were confident the novel development of the water scrubbing carbon dioxide system would work for the following reasons: experimental and theoretical work carried out by Prof Kolaczowski, the carbon dioxide scrubbing theory is well known and Phase 1 simulation studies followed up by trial results which were very promising.

Consequently, during Phase 2, further trials were performed at the start of the project using water on a once through basis through a single column constructed in Phase 1. This extra data enabled rigorous simulation studies performed by Atkins, which validated the concept design provided by Prof Kolaczowski (IP owned by CSS).

The outcome of above work led to the design which is described in simplified form in Figure 3.

In the simplified schematic in Figure 3 the flow of syngas (yellow) containing the carbon dioxide is in the opposite direction to the water (black) which scrubs out the carbon dioxide. The scrubbed syngas is then released out of Column 4 before passing through the remainder of the process while the water enriched carbon dioxide is sent to Column 6 to separate the carbon dioxide and water before the water is used again.

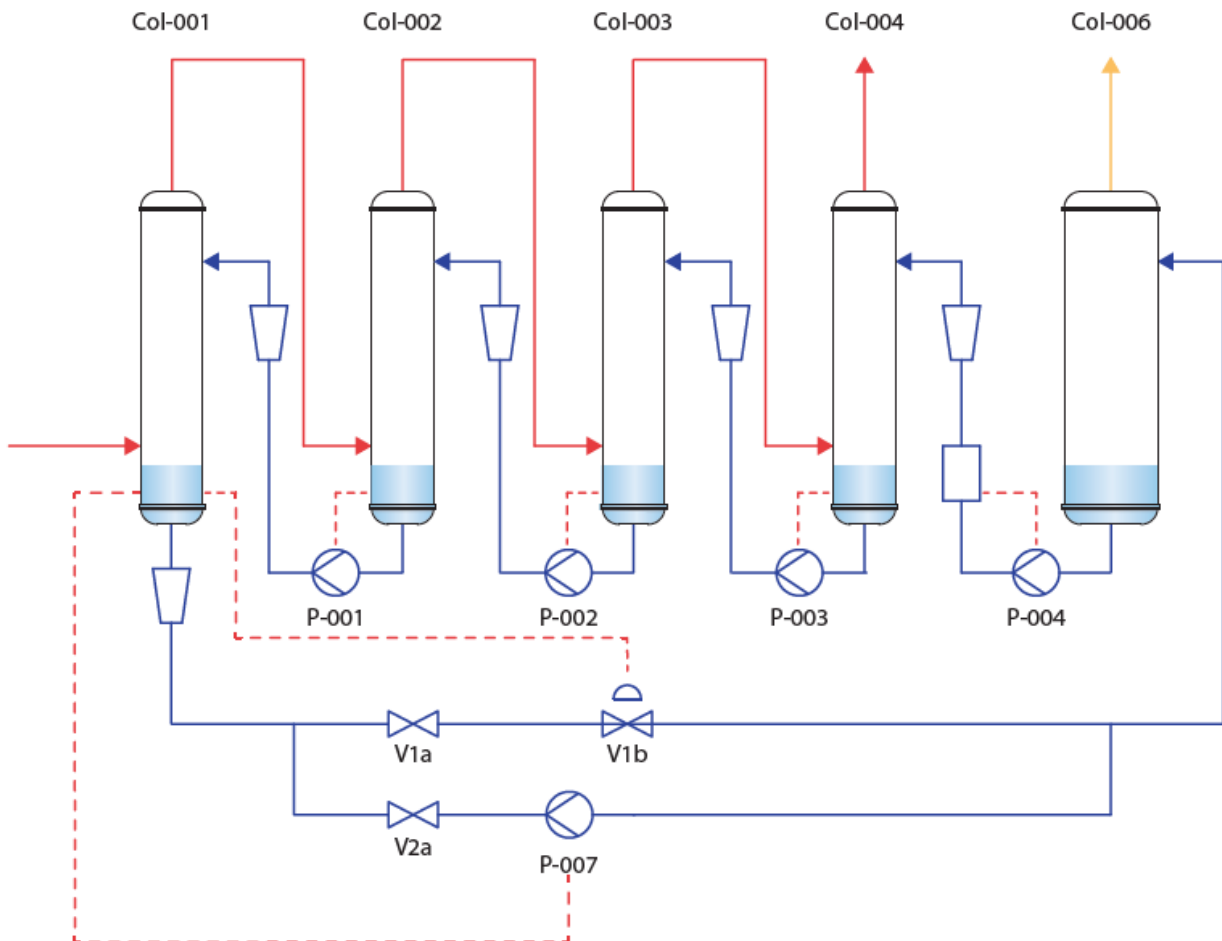


Figure 3 - Simplified Schematic of CO₂ Scrubbing Columns

P-001 to P-004 and P-007, are all positive displacement pumps, which circulate the water around this system. The Syngas enters COL-001, passes through COL-002 and COL-003 before finally passing through COL-004. A back-pressure (e.g. 7 barg) is maintained on the system by a flow control valve on the Syngas exit line from COL-004.

The water which is used as a scrubbing fluid is pumped with a positive displacement pump (P-004) from the sump of COL-006 into the top of COL-004. Then with pump P-003 from the sump of COL-004 in the top of COL-003 and onwards as shown in the Figure 4. From COL-001 at low pressures (0 to 3 barg) the water is pumped with P-007 into COL-006 and at high pressures (3 to 7 barg) the flow control valve V1-B is used to regulate the flow. The liquid level

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in COL-001 to COL-004 is controlled at a set-point range, while the liquid level in the sump of COL-006 is allowed to fluctuate. The water circuit can be considered to be closed so water is not expected to enter or accumulate in the system.

That water CO2 scrubbing scheme sits in the overall process as illustrated in a simplified manner in Figure 4.

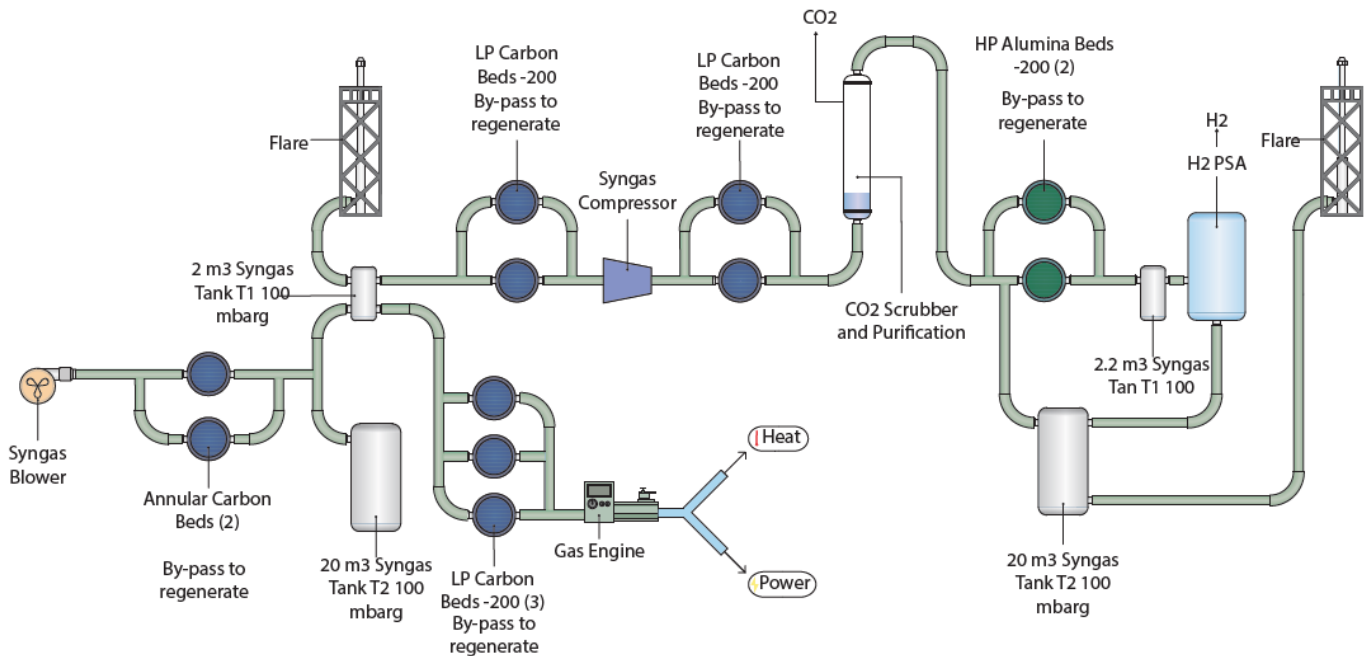


Figure 4 - The position of the CO₂ scrubbing & regeneration scheme in the process

After the CO₂ scrubber the gas flows through an alumina bed and then into the H₂-PSA where H₂ is separated from the CO₂ depleted syngas stream. The control of pressures and flows and the venting of gases in a safe manner (via surge tanks), which in turn is under transient conditions of operation (expected with H₂-PSA) is a complex task and full of challenges.

The design had to be interfaced with the rest of the process and to provide an impression of the scale and complexity of what was involved, different views of some of the equipment on the site are shown in Figure 5, Figure 6 and Figure 7.

On the RHS, is the conveyor feeding biogenic feedstock into the top of the gasifier. In the middle is the syngas storage tank. On the LHS, at the front, is the Flare and behind it different items of gas clean-up equipment.



Figure 5 - A view of the front-end of the gasification process



Figure 6 - Views showing hot gas filters (above blue drum in right-hand photo) and heat exchangers (middle of left-hand photo)

6.1.2 CO₂ Scrubber Challenges

The design, build and installation of the CO₂ scrubber proved very challenging. A number of these challenges and how they were overcome, are described below.

6.1.2.1 Column Water Carry Over

At the start of Phase 2, preliminary trials were performed using water on a once-through basis through the single column constructed in Phase 1. However, these trials were constrained by the limitations of existing equipment, achievable water circulation rates and syngas flows and pressures. To extend the benefit of such work, studies were also performed with pressurised air, which helped to provide data on the pressure drop and confirm that column flooding would not occur at the planned operating conditions with syngas.

As a result of the air/water trials, it was noticed that under certain conditions there was 'water carry-over' with the air from the top of the column, which confirmed the need to change the design of the liquid distributor (from spray nozzle to a liquid drip tray) and the need to provide a packing retaining mesh at the top of the bed. Internal inspection of the single column also confirmed that the packing level had dropped because of compression of packing in the bed.

6.1.2.2 Detailed Design

The detailed engineering design for the CO₂ water scrubbing system was developed by Atkins which became very complex and too expensive to implement within the project budget. Consequently, it had to be simplified and made more cost effective. Additionally, there was also a lack of integration between the water scrubbing process and the rest of the process, which was also outside of their remit/allocated budget. As a result, it had to be modified in-house (alongside BPC and Cobalt).

6.1.2.3 Safety Studies

The HAZID and HAZOP studies on the CO₂ water scrubbing system consumed a significant amount of time and in hindsight they were conducted too soon, making the engineering team reluctant to make changes which were important to make the scrubber design more practical within the time and cost constraints. This challenge was overcome by relaxing some constraints, mitigated by operating with a high level of supervision, which was made possible by on-site R&D experience and the advice of Prof Kolaczowski. Subsequently, the 1000-hour duration had to be changed altered to 10 x 100-hour to ensure availability of the required supervision.

6.1.2.4 Syngas Compressor

Finding a suitable syngas compressor that could meet CSS's technical specifications within the project's budget and time constraints proved challenging. Fortunately, CSS were able to acquire a compressor that had been ordered by another party but never used. The unit required modifications to operate at CSS's lower target pressure but this solution enabled CSS to meet both its technical requirements, budget and schedule constraints.

6.1.2.5 Water Circulation Pumps

The pumps used in the CO₂ scrubber system (Figure 3) had to be of a high technical specification to prevent cavitation which would have occurred if an “off the shelf” centrifugal pump was used (although it would have saved considerable time and cost). Furthermore, it was challenging to determine the pump specification due the operational pressure changing, thus maintaining a Net Positive Suction Head on the pump, resulting in broad operational conditions. As a result, positive displacement pumps were selected. The pump supplier raised concerns about P-007 (see Figure 3) which supplied water saturated with CO₂ into the degassing column. P-007 was due to experience a very high pressure on the suction side (e.g. 7 barg) than to the discharge side (e.g. 0.1 bara) and consequently, this led to a design alteration which diverted the flow to a parallel line using a flow control valve.

6.1.2.6 Level Control in the Column Sumps

Due to the system having 4 scrubbing columns plus the degassing column all with independent pumps there was a challenge to ensure that water was retained in each column sump to ensure the water flow was not interrupted. The flow of water was up to 18m³/hour and the sumps were around 1m³ therefore any misbalance would quickly lead to draining or overfilling, each scenario causing operational issues. In the water scrubbing columns, COL-001 to COL-004, the liquid level in the column sumps were controlled by a process control algorithm which combined feedback and feedforward control. The liquid level in the degassing column (COL-006) was allowed to move up and down while the liquid levels in the 4 scrubbing columns were maintained within a prescribed offset.

6.1.2.7 Vacuum Pump

A vacuum pump on the CO₂ degassing column (COL-006) lowers the pressure and extracts the gas stream rich in CO₂. However, due to challenges with sourcing a suitable pump a used vacuum pump was sourced and, to mitigate the risk of one not working, in the end three were purchased at reasonable cost. In the end, it was fortunate that CSS purchased three because they all had to be stripped down (in-house) and rebuilt in-house to get them operational.

6.1.2.8 Process Control

From a process control perspective, there were many safety features included in the P&ID for the scheme, which all had to be connected to a control scheme. This had to be specially designed and it also had to be interfaced with the rest of the process.

6.1.3 Other Process Challenges

6.1.3.1 Feedstock

CSS explored different waste wood feedstock sources and struggled to find a supply which would fulfil the objective set at the start of the project, which was to be of uniform size and low moisture content (about 10wt%). Shape, size and moisture content were all important factors in selecting a suitable feed system and how the gasifier operates. However, much knowledge was gained because of these trials and finally a feedstock of clean woodchip generated from a local company, ManCoed was selected. This material was trialled for several weeks, but the

consistency and moisture content varied too much, which affected the performance of the gasifier (e.g. lower gas CV). As a result, CSS decided to switch to Grade A waste wood which was supplied by Jenkinson and delivered to CSS in 8 tonne loads contained within 40 yards skips before being transferred into the walking floor feed systems. The shape of the feedstock is not uniform resulting in bridging inside the gasifier and preventing waste wood from moving down into the throat. This issue was resolved by using a mechanical agitator which encouraged the waste to move in a downward direction to the throat of the gasifier. Ideally, large pellets or briquettes of a regular shape would be preferred which is easier to predict their movement and behaviour in the gasifier. However, trying to form large pellets or briquets from the raw feedstock would add an extra up-front processing cost which would just add to the LCOH of the H₂ produced.

6.1.3.2 Gasifier

Prior to the project, several issues were identified which were addressed in order for the project to proceed:

- The gasifier had poor sealing of wood feed valves and char discharge valves was in part resolved by replacing them with a different design of valve.
- Hot zones have formed in the upper section of the gasifier and consequently, the startup procedure and ignitors had to be adjusted.
- High spot temperatures caused thermal stresses within the gasifier, which had to be repaired.
- The air injection nozzles blocked because of faults with shut-down procedures which in turn were modified.
- The char breaker bar at the base of the gasifier had to be redesigned and a more powerful motor fitted.

6.1.3.3 HGFs

The two parallel HGFs experienced unacceptable pressure drops across the filters causing the gasifier to be shut down. To mitigate this, only one filter was used and a new type of filter was installed.

6.1.3.4 Syngas Char Fines

Char fines in the syngas are very small particles which travel through the syngas. Most of the char fines are removed by HGF one and HGF two. However, some pass through and are carried into the heat exchanger.

6.1.3.5 Automatic Condensate Drainage

As the syngas cools, condensate forms in the heat exchanger which consists of a mixture of water and bio-oils. It is critical to recover the bio-oils otherwise they can restrict the syngas flow and be carried over into the heat exchanger downstream. To recover the oils, a novel drainage system was developed which allowed CSS to extract oils whilst overcoming the negative pressure within the heat exchanger. At first, in Phase 1, a manual drain was developed which

was later modified into an automatic drain in Phase 2. This made a significant improvement in the syngas cooling efficiency due to the increase in heat transfer efficiency and reducing the pressure drop in the heat exchanger Train.

6.1.3.6 Syngas Blower

There is a delicate balance between the suction pressure required down-stream of the blower and the positive pressure required up-stream of the blower. At a fixed flow there is a fixed pressure difference across the blower. That means that there is a fine balance to be achieved. This is now much better understood at a practical, operational level as a result of the trials performed. The pressure on the suction side changes as the pressure drop across the HGFs and heat exchanger Train increases. This adds extra complexity in the sizing of the blower for a commercial process, which will be very CAPEX and OPEX sensitive.

6.1.3.7 Gas Engine

At the start of the project, CSS were aware that the purchase of a new gas engine was not possible within the budget and had to find a used gas engine at the right price and which could handle the correct CV and flow of syngas. The creation of electrical power and its distribution on site, required additional analysis and effort. A view of the gas engine container is shown in Figure 7 below.



Figure 7 - View of the container in which the Gas Engine is positioned

6.1.4 Other Organisational & Financial Challenges

- Planning authority: Identifying the correct decision maker within the planning authorities proved to be a lengthy process.
- Complex cautious design: The detailed scheme developed by Atkins for the CO2 scrubber & degasser was too complex for a pilot and would have been too expensive to implement. This had to be simplified and made more manageable for the budget.
- CO2 Scrubber Integration: The Atkins CO2 scrubbing & degassing scheme needed to be integrated with other parts of the process, which was outside their remit and allocated budget. Hence, the issues had to be solved in-house (with help from BPC and Cobalt).

6.1.5 Verification Activities

Trials were conducted to verify various concepts and to better understand certain variables which are highlighted in the Table 1 below.

Verification	Issue considered	Outcome
Operation of the Gasifier	Syngas composition and CV need to be determined.	The syngas analyser needs to be calibrated at regular intervals.
Operation of the Gasifier	The performance of the HGFs, heat exchangers and syngas blower.	This front part of the process was tested and the gas produced sent to the flare.
Operation of the Gasifier	Performance with different feedstocks of wood and sources of biomass.	A suitable feedstock was selected for the main trials.
Operation of the Gasifier	Moving the hot zone to lower down the bed produces a higher CV syngas.	Trials were performed in which the supply of air was varied between the 4 points of air injection into the gasifier and an optimal combination was selected.

Verification	Issue considered	Outcome
Operation of the Gasifier	Can the CV of the syngas be improved with the addition of O2 with the air into the gasifier?	Trials were performed in which the air supply was enriched with a 95/99% O2 stream from an O2-PSA generator and also from oxygen bottles. It was shown that gas CV can be increased, leading to an increased vol% of H2.
HGFs (two in series)	Will the use of just one HGF help to reduce the pressure drop across the filtration step?	When the 2nd HGF was bypassed, it did reduce pressure drop, but there was more particulate carry-over to the exchangers.
Performance of syngas compressor	This had to be commissioned and operating experience gained.	Trials were first performed with air and then with a feed of syngas.
Performance of the syngas compressor and carbon guard beds	Can the required 100 Nm3/h flow and adequate pressure (7 to 8 barg) be achieved such that the CO2 scrubbing system can be tested with water scrubbing?	The system was shown to satisfy this requirement.
Heat Exchanger Train	To quantify the restriction of gas flow through the exchangers because of fouling and if that restriction has been cleared after cleaning.	Using the syngas blower air was sucked through the gasifier and train of heat exchangers. The pressure drop across the various heat exchangers as a function of gas flow was measured and provided the information required.
Heat Exchanger Train	Can heat transfer and condensate drainage be improved in the heat exchanger with the aid of a device inserted into the heat exchanger tubes?	Trials were performed in two of the exchangers using HiTRAN tube-inserts from Cal Gavin Ltd and these were shown to be beneficial. However, there was extra pressure drop incurred.

Verification	Issue considered	Outcome
CO2 Water Scrubbing Plant	This had to be commissioned and operating experience gained.	Trials were initially made with the flow of air (representing syngas) while the water circulation and liquid level and flow process control algorithms were tested and adjusted.
CO2 Water Scrubbing Plant	Trials with syngas	These were performed starting with operations at low pressures and then gradually increasing the operating pressure in this circuit.
Gas Engine	Can the engine operate with the CV of the syngas produced and generate electricity?	The engine management system had to be adjusted to ensure it operated smoothly, which it did.
Planned 100-hour continuous operation trials.	The need to try-out the shift system and train operators.	The syngas was sent to flare and not through the CO2 scrubber. Such a run was performed (12-13 Nov 2024), with 46-hours of continuous operation providing training for the shift operators.

Table 1 - Example of verification activities

6.1.6 TRL at the Start and at the End of Phase 2

Although the process is being demonstrated on a slipstream, consisting of 100 Nm³/h of syngas, performance data gained is sufficient to permit scale-up to a larger commercial size of plant, for example, one producing 1,300 Nm³/h of syngas per gasification train. A critical factor is the ratio of the column to packing diameter, which at 16:1, means that wall effects will not be a big concern. On scale-up the same size/type of packing should be retained.

Technical Data

All technical data is important, but some examples are provided in Table 2.

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Theme	Parameter	Possible operating conditions	Comment
Gasifier-500	Feedstock:	Waste-wood	Achieved
	Feed:	160 - 320 kg/h	Explored
	Moisture:	10 to 15 wt%	±Observed
-	Air flow:	170 - 340 Nm ³ /h	Explored
	Temperature:	ambient to 150°C	Achieved
--	Throat temperature:	500 - 800°C	Range observed
Syngas	Flow:	250 – 500 Nm ³ /h(dry gas)	Explored - often operated at 300 to 350 Nm ³ /h
--	Dry gas (vol%) composition:	CO: 16 – 21%; H ₂ : 10 – 15%;	Ranges observed
		CH ₄ : 1 – 4%; CO ₂ : 10 – 14%	Ranges observed
		O ₂ : 0 – 1%; N ₂ : 49 – 55%	Ranges observed
Slip-stream feed to CO ₂ scrubbing	Flow:	50 - 100 Nm ³ /h (dry gas)	Explored
	Temperature:	10 to 40°C	Observed
	Pressure:	1 to 8 barg	Explored
Theme	Parameter	Possible operating conditions	Comment
CO ₂ scrubbing columns	Packing type:	Pall Rings (25 mm)	Total packed bed length = 16 m
	No of columns:	4 of (each 400 mm diameter and 4m packed bed)	
-	Water flow:	10 to 20 m ³ /h	Explored
-	Pressure:	0 – 8 barg	Explored
-	CO ₂ removal target:	> 75%	Achieved

Theme	Parameter	Possible operating conditions	Comment
CO2 degassing column	Packing type:	Pall Rings (38 mm)	-
	Vacuum:	0.2 – 0.1 bara	
	No of columns:	1 of (800 mm diameter; 1580 mm packed bed)	
H2-PSA	No of beds:	2 of (each 888 mm diameter and 1.5 m packed bed)	labelled as PSA1 & PSA2
-	Pressure:	PSA1: 0 to 7 barg PSA2: 0 to 3.5 barg	0 - 6 barg reached Achieved
-	H2 production:	4 Nm3/h (at 85 to 92vol%)	Achieved
-	purity target:	> 90% H2	Achieved
Hydrogen compression & storage	Pressure target:	200 barg	50 barg achieved into H2 storage
Gas engine	Syngas feed:	250 – 500 Nm3/h	-
- -	Elec. Output:	125 – 245 kW	-

Table 2 - Example of relevant technical data for the process demonstrated in Phase 2 with a Gasifier-500

6.1.7 Consents/Permitting Applications and Other Regulatory Approvals

To achieve the required planning and regulatory approvals, CSS had to employ suitable external consultants.

CSS applied for an exemption in the Environmental Permitting Regulations contained in Schedule 1, Paragraph 3(c) and/or (g) to operate a Research and Development Activity. This allowed CSS to run trials on multiple feedstocks with the additional processed introduced for H2BECCS for the duration of the project.

The exemption enabled the operation of the plant to facilitate the programme of R&D works that are being contracted by the UK Department for Energy Security & Net Zero (DESNZ) and allows the completion of the works scheduled for 2025.

A modification to the existing planning permission was granted for the construction and operation of a small-scale biomass gasification CHP plant for research, development, testing and controlled trials. The existing planning consent CSS had for the site only included the

gasification equipment and therefore introducing many new features such as syngas compression, 8m tall scrubbing columns, PSA and H₂ compression required an amendment.

6.1.8 Key Concepts of the Demonstrator Design

The inspiration behind the design was derived from literature research and earlier work by Prof Kolaczowski (conducted at the University of Bath) on a small diameter column (50mm).

Prof Kolaczowski, who proposed the use of water scrubbing to achieve a reduction in CO₂ was the technical lead in the writing of the grant application for this project and remained involved throughout.

It was well known that water can act as a scrubbing fluid to remove CO₂ from a gaseous stream and trials performed on a 400 mm diameter scrubbing column (Phase 1 project) confirmed that it was possible to apply to a syngas.

The concept was then further developed to demonstrate the ability to degas the water (i.e. remove the absorbed CO₂) and to reuse that water in a closed circuit. The concept of utilising a high pressure (e.g. 7 to 8 barg) to absorb the CO₂ and then lower the pressure of the water (e.g. down to 0.1 bara) to release the CO₂ had to be demonstrated. Consequently, further calculations and more rigorous process simulations indicated that the degassing operations would need to be done in the presence of a vacuum which was applied to the concept design. However, to demonstrate that a high removal of CO₂ from the syngas could be achieved, the concept required a much longer length of packed bed in the scrubbing section.

Simulation studies concluded a bed length of 16 m and the syngas outlet molar composition was predicted to be: 20.5% carbon monoxide (CO), 16.3% H₂, 3.2% methane (CH₄), 2.8% CO₂, 56.8% N₂, 0.4% water (H₂O) As a result, 78% reduction in the CO₂ was predicted

To achieve the length of packing required (16 m), it was decided to have 4 columns each of 4 m high. Hence, achieving the required 16 m. However, to allow for space above the packing and space in the sump of each column, the columns exceeded 4m in height. The overall height was set by what was considered reasonable to install on the site from a visual perspective (environmental impact) and to allow for safe access to the top of the column for maintenance.

Rather than fabricate internally, the column internals including the required packing, packing support plates, liquid distribution system, packing retaining mesh and liquid demister were obtained from a recognized supplier. This will aid eventual commercialisation.

The possibility of configuring the pipework, to by-pass any column, was considered but not progressed because of complexity and extra cost.

The need to achieve a design that was safe to operate was imperative and HAZID and HAZOP studies contributed to many small improvements to the design.

6.1.9 Test Results

The results discussed below are focused on the use of water to remove CO₂ from syngas. Further results will be provided to show the performance of the rest of the plant, which is essential to the central CO₂ scrubbing theme.

6.1.9.1 Single Column data trials using water to scrub CO₂ from syngas

At the start of Phase 2, there was a commitment to perform additional trials on the CO₂ scrubbing single column, which was used in Phase 1. In the trials, fresh water was to be used in the scrubbing column (instead of recirculated water), thereby increasing the driving force for mass transfer in a single column and making it easier to quantify the capture of CO₂. Also, using a source of fresh water eliminated uncertainty associated with the performance of the simplified CO₂ degassing system which had been used in Phase 1 of the project.

The purpose of the trials was to gather additional data which would assist in the design of a scrubbing system to be demonstrated in this project.

6.1.9.2 Outcome from Preliminary CO₂ Scrubbing Trials (single column)

The data from the preliminary trials were analysed by Atkins, who incorporated it into their process simulation to confirm the calculations by Prof. Kolaczowski. In addition, Atkins considered the concerns expressed by Prof Kolaczowski about the high energy demand from the two exchangers in the scheme presented at the end of Phase 1. They confirmed that as suggested by Prof Kolaczowski, they were not necessary. For a commercial process this provides savings in CAPEX and OPEX.

A learning from removing the two exchangers was that the water temperature in the circuit increased from 10°C to 25°C. The 1st CO₂ Degassing Stage was also removed for performance and downstream safety reasons which led to there being only a single vacuum degassing stage in the scheme.

6.1.9.3 Single Column Trials to Check on Flooding Point

At the flooding point of the column, water no longer drains down the column over the packing but starts to be held up in the column and the flow of gas through the column becomes more difficult and pressure drop increases; this is an operating condition which must be avoided. In the Phase 1 trials, this was not a problem.

6.1.9.4 Outcome from the air/water Flooding Trials (single column)

Over the range of test conditions using air, flooding was not detected and hence such conditions are not expected. In full operating conditions with syngas no flooding was encountered.

However, it was suspected following Phase 1 trials with syngas that some carry over may have occurred in the column and the air/water trials provided the opportunity to test this. The trials confirmed flooding when air flow was increased due to the presence of water in the air stream

at the top of the column. Also, some of the pall rings had been lifted from the top of the packed bed and were found in the pipework (gas exhaust line from scrubber).

To manage these issues, it was recommended that the spray nozzle was replaced with a drip-tray design of liquid distribution system and that the packing should be restrained at the top of the bed and a demister be installed on the gas outlet line from the last column- all of which was implemented.

A positive displacement water pump was purchased (with a higher flow capacity) and the 100 Nm³/h syngas compressor was installed; the flooding trials were repeated at higher liquid flows (20 m³/h) and higher syngas flows (100 Nm³/h).

6.1.9.5 Multi-Column Trials Using Water to Scrub CO₂ from Syngas

Photos of the columns, illustrated earlier in the schematic (Figure 3), are shown in Figure 8 a & b.



Figure 8 a & b - Carbon capture in the CO₂ Scrubbing Skid

- In the centre of the photo is a view of the skid with the 4 syngas scrubbing columns (COL-001 to -004). On the left is the CO₂ degassing column (COL-006).
- A magnified side-view of the skid, showing more clearly the water pumps at the base of the columns.

6.1.9.6 Air & Water Commissioning

As a starting point and as planned, various commissioning trials were performed, with air representing syngas and water as a scrubbing fluid. These were to check: (a) there were no leaks, (b) the pumps worked as expected, (c) the method of level control worked and associated process control algorithms worked (although some required tuning), (d) the process instrumentation worked, (e) the back-pressure control worked and (f) the two different methods of flow control from COL-001 to COL-004 and COL-006 all worked.

As in any commissioning exercise, small problems were encountered, which were mostly resolved. However, at this early stage of commissioning, the vacuum pump was not ready to be included in these early trials.

6.1.9.7 Commissioning Trial with Syngas and Water

An extended trial run commenced on the 10 Dec 2024. After the gasifier had been brought up to its operating temperature the syngas was diverted to the CO₂ scrubbing process.

The highlights from that trial were as follows:

- Initially the gasifier was running well and the CO₂ process control system was stable.
- The back-pressure controller had not yet been commissioned, so was still being manually controlled.
- A scrubbing column operating pressure was set at 4.5 barg which was successfully maintained. This is less than the planned operating pressure of 7 barg but was deemed expedient to perform exploratory trials at a lower pressure.
- The water flow was set at 10 m³/h which was maintained. This is less than the planned flow of 18 m³/h but was considered a useful starting point at which to test the system. It also matched a water flow used in the Phase 1 part of the project.

Challenges to be resolved:

The inlet syngas flow meter was consistently reading 99 Nm³/h for a while before it dropped off and eventually stopped reading. It was determined that the flow meter was malfunctioning. However, CSS were confident that constant syngas flow was maintained close to its design condition of 100 Nm³/h,

The CO₂ sensor on the inlet to the scrubbing column, seemed to freeze – so it was necessary to look at the CO₂ levels reported on the main syngas analyser.

The vacuum pump used to degas CO₂ in COL-006 from the water being recirculated overheated. The vacuum pump was cooled with a separate water supply and the water pump on that circuit had to be replaced with another pump. This helped, but then the vacuum pump kept stopping on what appeared to be an intermitted pressure sensor fault.

When the vacuum pump was turned off, the CO₂ outlet concentration from COL-004 did slowly creep up, but not to the extent observed in Phase 1 trials. It was interesting to observe that when the vacuum pump started to work, then within 5 mins, it quickly pulled the vacuum in COL-006 and the CO₂ outlet from the scrubbing side of COL-004 started to decrease.

The results of the demonstration trials will be presented in summary Table 6.

6.2 Updated Cost Estimates Leading to LCOH Estimates

The Levelised Cost of Hydrogen (LCOH) is an internationally recognised industry standard metric used to estimate and compare the cost of producing hydrogen via different technologies. This, in simple terms, is the ratio of the total cost of a plant to the total amount of hydrogen expected to be produced over the plant's lifetime. Both are expressed in net present value terms. The LCOH does not include revenue streams available to producers (e.g. from sale of H₂).

The calculation is performed using the higher heating value of hydrogen (25.4 kg \equiv 0.85 MWh of H₂) and in values which are sometimes reported in the literature. This excludes the capital and operating costs of compressing and storing the hydrogen.

Making use of information obtained during the course of this project, the LCOH was calculated to be £338 / MWh of H₂.

More information on the calculations and assumptions is presented in Appendices 15a and 15b.

From the calculations performed there are some important conclusions which can be drawn which help to set the scene for the commercialisation path to be followed. These are reflected in the subsections that follow.

6.2.1 A hypothetical Production Scenario at end of Phase 2

Moving forward at the end of this Phase 2 project, if funding was available, then a demonstration plant could be constructed consisting of one gasifier (Gasifier-500).

That process, would operate with: (a) an O₂-PSA enabling operation with enriched air at 40% O₂; (b) a Gas Engine with an electricity generator; (c) carbon capture in the form of char (80 kg/h); (d) H₂-PSA, which would produce 7.6 kg/h of H₂; (e) H₂ Compression & Storage; and (f) carbon capture (42 kg/h) in the form of CO₂.

The H₂ depleted syngas stream would be fed into a gas engine and 337 kWe of electricity generated. This would cover all of the parasitic electrical load (about 270 kWe) with a small surplus for any peripheral equipment used.

Such a process would not be commercially viable – however, it could feature in a product development phase.

6.2.2 A hypothetical Production Scenario in 5 Years

This 'Hypothetical Production Scenario' was used to estimate the LCOH value for a commercial process. That would consist of eight parallel trains, each with a Gasifier-1000, operating on enriched air (40% O₂), see Table 3.

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The 8 Trains use a feed of RDF (total = 8 x 1410 = 11,280 kg/h) and produce H₂ (8 x 19.8 = 158.4 kg/h \equiv 6.28 MW). In addition, any surplus electricity could be exported to the grid or private wire.

The rate of H₂ production reflects what could be produced and sold in a commercially viable scenario and the overall viability will depend on: (a) the value of the H₂ and (b) the value to be gained from some form of carbon capture credits.

Parameter	Performance per gasifier
RDF feed at 10% moisture	1,400 kg/h
Enriched air with O ₂ at	40% O ₂
Syngas flow	1,300 Nm ³ /h
Hydrogen separated/stored	19.8 kg/h
Carbon (captured as char)	263 kg/h of carbon
Carbon (captured in CO ₂)	150 x 0.75 = 112 kg/h of carbon
Electrical power from Genset	877 kW

Parasitic load	kW	Parasitic load	kW
O ₂ -PSA Compressor	122.2	Dry air compressor	2.86
Syngas Compressor	182	N ₂ -PSA	4.16
Water & Vacuum pumps	156	Wood feed store/drier	2.08
H ₂ -Compressor	143	Gasifier	7.8
Blast cooler	10.4	Chiller	39
Syngas blower	31.2	Dry air compressor	2.86

Table 3 - Expected performance from each Gasifier-1000 - Sub-total of parasitic = 700.7 kW - Surplus = Generated – Parasitic = 877 – 700.7 = (+ve) 176.3 kW

It is assumed that 75% of the H₂ and 75% of the CO₂ is removed from the syngas and that the syngas is then used in a gas engine to produce electricity which provides for the site parasitic load (see Table 3).

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All of the gasifiers operate with an O2-PSA enabling operation with: (a) enriched air at 40% O2; (b) a gas engine; (c) carbon capture in the form of char; (d) H2-PSA; (e) H2 compression & storage; (f) carbon capture from the syngas in the form of CO2.

The revised calculated LCOH is £338 / MWh of H2 (including the cost of H2 compression). In this scenario, it has been assumed that wastewater from the site would need to be disposed at a cost of £350 per m³. This is seen as a very high cost (about £6.1M per year). Further R&D is planned to reduce this cost penalty which would clearly have a big impact on the LCOH calculated.

The disposal cost of char has been assumed to be cost neutral, but it is hoped that this could be turned into an income stream (either carbon credits for sequestration, or a market found). Without that incentive, carbon capture from this process will be difficult to justify.

The total CAPEX = £55.1 M and the OPEX = £7.9 M per year. Using the above and LCOH spreadsheet supported by other calculations steps, the summary is as follows in Table 4:

Variable	Cost per MWh
Capex	£146 / MWh
Fixed Opex	£187 / MWh
Variable Opex	N/A in Workbook
CO2 T&S Cost	£10.1/MWh (see Note 1)
Carbon Cost Emitted	£37.6/MWh (see Note 1)
Total excluding carbon cost	£380.7 / MWh
Carbon Cost Sequestered	£- 42.6 / MWh (see Note 1)
Total including carbon cost	£338.1 / MWh

Table 4 – LCOH summary

Note: In the absence of information for CSS's scale and type of process, the same base-line values have been assigned as for the waste gasifier with CCUS – 48MW because of the challenge and benefits in these categories will be similar.

Main uncertainties in terms of cost estimates arise in the following areas:

- The allocation of costs for CO2 purification and storage/transport to an end-user.
- Uncertainty about the on-stream life of the adsorbents used in the various sub-systems on the plant (i.e. O2-PSA Beds; Carbon Beds; Alumina Beds; H2-PSA Beds).

- Uncertainty over the consequences of continuous trials on the core equipment (e.g., Gasifier Feed System and Reactor, Char Removal, Hot Gas Filters, Heat Exchangers and condensate removal).

6.2.3 LCOH for H2 Compression

The LCOH for H2 compression has been included in the calculation of the LCOH presented for this process. However, in this section an extra calculation was performed, to look at the LCOH value just for the cost of H2 compression at a small scale (as used in this demo-scale project) and in a situation in which electricity has to be purchased. The results were interesting, and the outcome is summarised below in Table 5 below:

Variable	Cost per MWh
H2 compression:	15 kg/h up to a pressure of 200 barg
Compressor:	200 kW (from 7 barg to 200 barg)
Compressor CAPEX	£520 k (from 7 barg to 200 barg)
Electricity cost:	£0.25 per kW.h
Operation for:	7,500 h per year
LCOHOPEX	93.7 £/MW.h
LCOHOPEX	15.3 £/MW.h
LCOHOPEX	109.0 £/MW.h (just for H2 compression)

Table 5 – LCOH for H2 compression

It needs to be emphasized that in this calculation several extra costs have been excluded. For example, the cost of pre-compression of H2 to 7 barg (before the main compression stage). The cost of compressed H2 storage, manpower on site, cost of the site and safety aspects need to be considered. Plus, the process equipment cost to safely dispense the H2 into a vehicle. Hence, this is not a low-cost activity, and the prevailing price of electricity will also be an important factor.

6.3 Demonstration and Testing Results

As aforementioned, it was critical to make sure key process equipment, such as HGFs, syngas blower etc were working in a satisfactory manner. As to be expected, issues were highlighted which had to be rectified prior to addressing the Key Performance Metric (KPM), which was the removal of 75% of CO2 from a 100Nm3/h stream of syngas. After this, CSS shifted its focus to

the CO₂ scrubbing system and then to the PSA unit which separates hydrogen from the syngas at purities of up to 92%. This hydrogen recovery was an added benefit beyond the main KPM for Phase 2 of the project.

6.3.1 Performance of Gasifier and its Train

Throughout Phase 2, CSS performed multiple trials on the PSA system. For example, over a 1-year period (from 4.12.2023 to 14.11.2024), the gasifier was operated on 27 occasions with an average trial run 8.4 hours. The shortest run was for 2 hours and the longest 45 hours. Exposing the gasifier and its train to 27 start-ups and 27 shut-down operations placed a strain on the system and weaknesses were soon identified. However, once identified, the issues had to be addressed making it challenging to meet the initial schedule.

During the trial data was captured on flows, temperatures and pressures throughout the process, with charts/graphs produced to analyse how they varied with time. An example of parameters closely followed were:

- The change in syngas composition over time.
- The change in temperature at various positions in the gasifier train, as a function of time.
- The variation in pressures at different positions in the gasifier train at a snap-shot in time.

No	Date & Details	Gasifier run time (hrs)	CO ₂ system run time (hrs)	PSA (hrs)	H ₂ compression (hrs)	Maintenance before next run (hrs)	Hrs	Notes
#	22-Oct-24 - 24-hour gasifier run	26.5	0	0	0	0	26.5	No issues
1	12-14 Nov-24 - 72-hour gasifier run	46	0	0	0	86	132	No issues
#	03-Dec-24-DESNZ Demo	6	5	0	0	0	6	No issues
2	10-11 Dec -24-100 attempt with CO ₂ system	21	15	0	0	16	37	High temps due to gasifier crack

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No	Date & Details	Gasifier run time (hrs)	CO2 system run time (hrs)	PSA (hrs)	H2 compression (hrs)	Maintenance before next run (hrs)	Hrs	Notes
3	14-16 Jan – 25 - 100 attempt with CO2 system	58	53	0	0	9	67	Hot spots in gasifier
4	28-30 Jan – 25 -100 attempt with CO2 system	57.5	49.5	0	0	40	97.5	High DP across system
5	11-13 Feb – 25 -100 attempt with CO2 system	62	52	0	0	80	142	Foaming in CO2 system
6	11-13 Mar – 25 - 100 attempt with CO2 system and PSA plus H2 compressor commissioning	78	75	30	10	6	84	No issues
7	19-21 Mar – 25 - 100 attempt with CO2 system and PSA	47	42	24	0	9	56	Operators on leave leaving team short staffed
8	26-Mar-25 - 100 attempt with CO2 system and PSA	18.5	13.5	10	0	26	44.5	Char Breaker Blocked
9	1-4 Apr – 25 - 100 attempt with CO2 system and PSA	71	65	32	0	14	85	No issues, operators had completed

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No	Date & Details	Gasifier run time (hrs)	CO2 system run time (hrs)	PSA (hrs)	H2 compression (hrs)	Maintenance before next run (hrs)	Hrs	Notes
								their shift pattern
10	8-10 Apr – 25-100 attempt with CO2 system and PSA	68	66	30	0	12	80	Stopped to unblock conveyor – then shut down when shift pattern complete
11	15-18 Apr – 25-100 attempt with CO2 system and PSA	72	69	12	0	8	80	No issues, operators had completed their shift pattern
12	22-25 Apr – 25 - 100 attempt with CO2 system and PSA and H2 Compression	75	72	48	20	14	89	Small crack in gasifier found in shutdown.
13	29 Apr - 2 May- 25 - 100 attempt with CO2 system and PSA and H2 Compression	74	72	60	60	0	74	No issues
Totals		780.5	649	246	90	320	1100.5	

Table 6 - Gasification train performance

6.3.2 Performance of CO2 Scrubbing Scheme

The scrubbing trials started towards the end of November 2024 and continued through the remainder of the project. In the period (from 12.11.2024 to 02.05.2025), the CO2 scrubbing system was operated on 12 occasions with the shortest run being 15 hours and the longest 72 hours.

The total duration of trials on the CO2 scrubbing system was 649 hours, which can be compared to a total of 1,000 hours (10 x 100h) of continuous operation which was set as a target at the start of the project. Although it is usual to set targets at the start of the project, in hindsight, it is clear that 1000 hours of continuous operation was ambitious for a FOAK project with many challenges and learnings and time/budget constraints.

Parameter	Design condition	Trial 14/1/25 to 16/1/25	Trial 28/1/25 to 30/1/25	Range from trial on 13/3/25 over 8h of the extended trial
Duration of extended trial	-	56 hours	49 hours	-
-	Simulated Performance	14/1/25 Spot measurement at 12:00 hrs	30/1/25 Spot measurement at 01:30 hrs	Range of values from 11:30 to 19:30 hrs (8 h period)
Set parameters	-	-	-	-
Syngas flow in	100 Nm3/h	99	76	73.1 - 100
Operating pressure	7.4 barg	4.8	5.9	3.6 - 7.8
CO2 inlet	11 vol%	15.75	14.7	9.44 - 15.59
Water flow in	18.6 m3/h	15.4	13.8	11.5 – 14.4
Packing total depth	16 m	16	16	16
Temperature	25 °C	-	-	-
Level of vacuum in COL-006	- 0.9 barg 0.1 bara	- 0.9 0.1	- 0.9 0.1	- 0.88 to – 0.98 0.12 to 0.02
Performance	-	-	-	-
CO2 outlet	2.8 vol%	5.04	2.3	1.08 - 6.42

Parameter	Design condition	Trial 14/1/25 to 16/1/25	Trial 28/1/25 to 30/1/25	Range from trial on 13/3/25 over 8h of the extended trial
Syngas flow out	89 Nm ³ /h	66	54	2.19 – 57.7
CO ₂ removal	77 %	78	88	>75% if rogue readings excluded
Project target for CO ₂ removal	>75%	>75	>75	>75

Table 7 - Examples of results from extended trials

Spot measurements and an indication of the range in the readings in one 8-hour trial are presented in Table 7.

Some highlights are listed below:

- The target design syngas flow of 100 Nm³/h through the slipstream was achieved and this was successfully and safely fed through the CO₂ scrubbing system.
- Operation was demonstrated with a backpressure of 4 to 6 barg and adequate performance (high CO₂ removal > 75%) was achieved at 6 barg, without having to raise the pressure further (a pressure of 7 barg had been considered).
- Operation was demonstrated with a water flow from about 10 to 15 m³/h, although the design was intended for higher water flows (i.e. 18.5 m³/h), these were not necessary to achieve the target >75% CO₂ removal from the syngas.
- At the conditions tested, it was shown that the pumps and liquid level control and design of columns all performed as expected.
- Problems were identified with some of the instrumentation; they were understood and gradually resolved.
- The scheme was demonstrated on a slipstream with a feed of syngas at a flow of 60 to 100 Nm³/h and under pseudo steady-state conditions, more than 80% of the CO₂ was shown to be scrubbed from the syngas just with water (and no chemicals), which exceeded the project target of 75%. This is a fantastic achievement, especially as it was achieved at (6 barg) without the need to reach the designed higher operating pressure (7 barg).
- The CO₂ degassing column (COL-006) appeared to be working much better than expected achieving a good level of CO₂ degassing, which was reflected in a high level of CO₂ removal being sustained with the water returned to the scrubbing system. However, this success was very dependent on being able to sustain performance from the second-hand vacuum pump and with 2nd hand-equipment there was always uncertainty about durability.

6.3.3 Production of H₂ in the H₂-PSA

During the last two months of Phase 2, with the process producing CO₂ depleted syngas, the H₂-PSA was operated on 8 occasions when extended 100-hour runs were attempted as part of the main project on CO₂ scrubbing. Initially, it was planned to only operate the H₂-PSA for 5h-periods during a day shift, however, as confidence grew, continuous runs from 10 to 60 hours in duration were performed and extra knowledge gained. In total, as illustrated in Table 6 the H₂-PSA operated for 264 hours without any safety related incidents on the H₂-PSA.

Although a H₂-PSA system could have been purchased from a commercial manufacturer (outside of the UK), that option was not progressed, mainly because of: (a) the cost grossly exceeded the available budget, (b) CSS were concerned that restrictions on IPR from such trials could have been imposed by the supplier and (c) CSS wanted to develop some know-how in that field and gain expertise with a product which could then be manufactured under a license held by a UK company.

The vision for a commercial design (Figure 9) was explored in trials during the course of this project. The expected H₂ purity was relaxed from >95 to >90 vol% because it was discovered that due to the presence of argon in the air (which is fed into the gasifier) it would concentrate and appear in the H₂ stream. Hence, 96% is probably the max theoretical purity which could be reached. As an aside, a similar problem exists with the use of PSA to separate O₂ from air because of the presence of argon in air, a theoretical max purity of 95.7% can only be achieved.

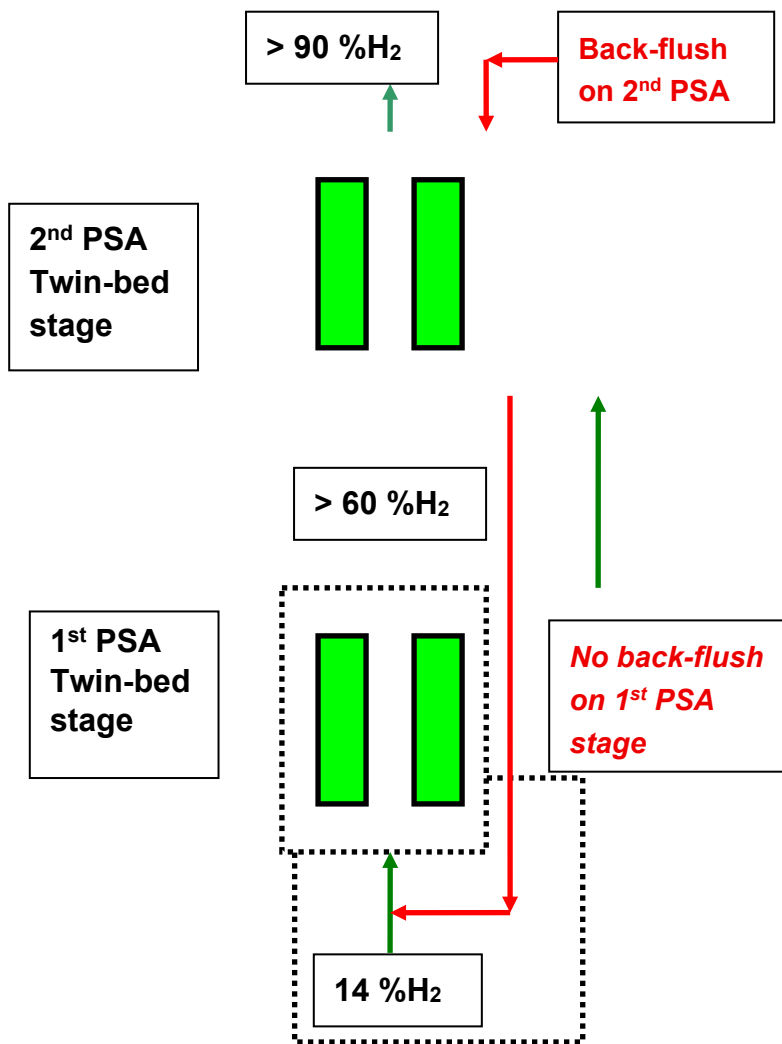


Figure 9 - Simplified vision of a possible commercial design

For Phase 2, a single PSA vessel (instead of twin-bed) was used for the 1st stage and 2nd stage. The key parameters for the H₂-PSA beds were as follows in Table 8 below:

PSA Items	Detail
Number of PSA vessels/beds containing adsorbent	2
Internal diameter of each bed	888 mm
Height of adsorbent packing in each bed	1500 mm
Mass of adsorbent in each bed	603 kg
Operating pressure: PSA1 (1st stage)	0 to 7 barg (design 10 barg)
PSA2 (2nd stage)	0 to 3.5 barg (design 10 barg)

Table 8 – PSA Key design information

As the trials progressed, operating conditions were adjusted to gain a deeper understanding of the H₂-PSA process and its interactions with the plant up-stream and downstream. Some of the highlights from that work are summarised below:

6.3.3.1 H₂ Purity

The PSA process is very complex and over a series of set time-intervals (seconds/minutes), different operational conditions occur.

For example:

- Pressures increase.
- H₂ is produced, sent from PSA1 to PSA2 and then to a H₂ receiver.
- Pressures decrease.
- The bed is backflushed with a purge of H₂ product gas.
- Pressures can be equalized between PSA2 & PSA1.

By adjusting the time interval at which these activities take place, it was shown that using the syngas from the CO₂ scrubber as a feed, that a H₂ purity >90% can be achieved. This was a great achievement and depending on the set time-intervals, values in the range of 90 to 94 vol% were easily obtained. It is emphasized that the back-flush purge step (with H₂ product) in the cycle was an important factor. Also, if the temperature of the syngas was too high (e.g. >25°C) then performance decreased due to the beds' capacity to adsorb decreases with an increase in temperature. If temperature was too low (e.g. < 8°C), there was a risk of damage to the adsorbent as temperatures could drop below 0°C in parts of the bed resulting in moisture creating ice crystals and damaging the adsorbent.

6.3.3.2 H₂ Product Flow

Besides H₂ purity, product flow is another important parameter. Trials were performed in which a product flow of 4 Nm³/h was continuously taken (during the PSA cycle) from the H₂ product receiver. Trials were also performed in which the H₂ product was successfully compressed and placed into intermediate low-pressure storage. Then, it was taken and compressed again and then placed into a high-pressure storage system demonstrating the next steps in a potential commercial process.

6.3.3.3 H₂ Recovery from Feed Flow

Hydrogen recovery is an important parameter and would need to be studied in further work. In the Phase 2 trials, a single bed was used for each stage but in a commercial application a twin-bed system would be used at each stage. By using a twin-bed system during a pressure equalisation stage, an enriched H₂ volume of gas is exchanged between the beds, which reduces the need for a fresh feed. Hence, H₂ product recovery is increased. As an aside, although it is desirable to maximise production of H₂, any H₂ which is vented with the CO₂/H₂ depleted syngas would be fed into the gas engine and used as a fuel to generate heat/power.

6.3.3.4 Supply Pressure of the Syngas

In the H₂-PSA process, so as to maximise the use of the PSA, the 1st Stage is rapidly fed with syngas and the consequence of that activity is that the pressure drops rapidly in the syngas supply tank. The rate of pressurizing the 1st stage, equates to an estimated peak flow > 400 Nm³/h, which is much greater than the supply of syngas from the slipstream (depleted of CO₂) from the CO₂ scrubber (e.g. 80 Nm³/h). So, the need for the pressure to recover in the syngas storage tank, had to be included as dead-time in the H₂-PSA cycle. This also then had a back-pressure effect on the operating pressure of the CO₂ scrubber, which dropped. In terms of translating this to a commercial situation, once the optimum operating conditions have been identified for the H₂-PSA, the size of the H₂-PSA beds will need to be carefully matched with the ability of the process to provide the required flow of feed gas. The present design is capable of handling a much higher syngas flow and producing much more H₂. The size of the syngas feed tank will also need to be carefully calculated and back-pressure control valves installed in key places to retain the operating pressure in the CO₂ scrubber.

Having demonstrated the viability of this technique being applied to syngas produced from the gasification of waste, further work is now necessary to assess if there is a commercial market for such a product. If the answer is 'yes', then further work/equipment will be required to: (a) to optimise the H₂-PSA configuration; (b) to increase level of instrumentation; (c) to review all aspects connected with safety; (d) to review syngas pre-treatment and guard-bed regeneration. Such work should be done with more technical input from experts in this specialist field of PSA and H₂-PSA.

6.4 An Updated Carbon Life Cycle Assessment of the Technology

Considering the urgent need to decarbonise multiple sectors in the economy globally, CSS' technologies can offer a solution which can reduce carbon across the waste, transportation and power industries.

From a broad perspective, CSS' technology diverts waste from incineration whilst generating low carbon products which can save/prevent further emissions such as hydrogen for transportation, heat and power as well as char which can be used in construction/agriculture. Furthermore, CSS' novel carbon capture process uses water (rather than carbon intense amine) to further reduce the carbon impact of its process.

Two studies were conducted to assess the carbon impact of CSS' technology: a Life Cycle Assessment (LCA) and a carbon tracker study. The LCA, was a cradle to gate study and followed ISO14040 and RTFO methodologies. It factored in more detailed factors such as construction and end of life emissions, as well as the transportation of feedstock. However, the carbon tracker study was more solely focused on emissions from the technology and excluded emissions which could vary on a case-by-case basis such as transportation and construction. It

also allowed CSS to understand the impact of just gasification and the combination of gasification with carbon capture and hydrogen production. Furthermore, the carbon tracker allowed for the inclusion of avoided emissions to assess the broader impacts of the process.

Making use of data gained from the Phase 2 Demonstrator, the information was used to scale-up the demonstration plant to a possible commercial scenario, in which a MicroHub-500e was constructed. Such a plant at 100% load could produce 1,000 Nm³/h of syngas. This then led to two studies - one in which RDF/SRF was used as feedstock, and another which used waste-wood. Both studies, where possible, aligned to the LCHS methodology and evaluation were carried out for both RDF/SRF and waste-wood feedstocks. The LCA and carbon tracker study demonstrated that with the gasification, carbon capture and H₂-PSA technology, waste wood had the lowest carbon intensity at -25.2 gCO₂/MJ of hydrogen and -21.4 gCO₂/MJ of hydrogen respectively.

6.4.1 Carbon Life Assessment Conclusion

From a very simplistic perspective, if 1 t/h of RDF was to be incinerated, then it would create about 1.6 t/h of CO₂.

Whereas, if that amount was fed into a CSS gasifier, then:

- The equivalent of 0.7 t/h of CO₂ would be trapped in the form of char, which could be sequestered and
- 0.3 t/h could be captured using the CO₂ water scrubber (developed in this Phase 2 project) and then sequestered.

In either case sequestration will only be possible if the infrastructure and fiscal incentive are in place.

If that 1 t/h of RDF was to be sent to landfill, then over time it would degrade and because of the anaerobic nature of biological degradation reactions which take place it would result in both CO₂ and CH₄ emissions: the CH₄ emissions are more damaging to the environment than CO₂ emissions. In addition, there would be a leachate which unless captured and treated, would over time permeate into the water table.

In conclusion, gasification of RDF provides a much better environmental pathway than incineration or landfill.

6.4.2 Estimate of the LCHS Value

The LCHS is a framework and regulatory standard used by Government agencies to compare the emissions performance of different technologies for the production of H₂. According to Government guidelines, the emissions intensity for hydrogen to qualify as low carbon hydrogen according to the standard should not exceed 20.0 g CO₂ e/MJLHV of H₂ product.

As identified in the LCA analysis, because a waste stream is being used as a feedstock, it is possible to offset any CO₂ emissions against a counterfactual (meaning - an alternative method of disposing off or using the waste).

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Using the hypothetical commercial vision of a site in 5 years' time, which has 8 Gasifer-1000 producing H₂, the outcome of such a calculation is presented in Table 9. The electrical power produced in the process provides the electrical power load (parasitic load) and there is no need to import any significant quantities of electricity or any other fuel which makes the calculations of the Low Carbon Hydrogen Standard (LCHS much easier to follow).

In this LCHS calculation, the following key assumptions were applied:

- The facility is installed on a site which receives and segregates waste and produces a RDF/SRF feedstock. No extra processing is required for the feedstock or need to transport it to the site.
- The counterfactual (alternative disposal route for RDF) has been kept simple, for example, (a) an incinerator with no carbon capture or energy recovery, or (b) a situation in which waste goes to a landfill site (without energy recovery from gas produced). However, if sent to landfill, some of the carbon would react to form CH₄, which is a more potent greenhouse gas than CO₂.
- When the process moves to a commercial situation, then the credit for the counterfactual will depend on what is being used at that point in time and would need to be recalculated.
- The produced H₂ is used on site, in trucks that have had their engines adapted to run on H₂ (instead of diesel).

Parameter	Value	Extra comments
Gasifier-1000	8 on the commercial site	Processing 1,410 kg/h of RDF per gasifier
Max amount of CO ₂ if the carbon was all oxidised	8 x 2,346 = 18,768 kg/h	Used as a counterfactual representing a basic incinerator/landfill site
equivalent to	14.07 x 10 ⁷ kg/year of CO ₂	7,500 h per year production
-	-	-
H ₂ production	1,188,000 kg/year	7,500 h per year production
equivalent to	55,025 MW.h per year	Using LHV for H ₂
equivalent to	55,025 x 3,600 = 19.8 x 10 ⁷ MJ per year	1 W ≡ 1 J/s 1h ≡ 3,600 s

Scenario 1 CO2 emissions	8.23 x 10 ⁷ – 14.07 x 10 ⁷ = (-ve) 5.84 x 10 ⁷ kg/year	The char is sent to a ‘solid carbon permissible end-use’ and counterfactual offset is applied
Parameter	Value	Extra comments
Scenario 2 CO2 emissions	7.6 x 10 ⁷ - 14.07 x 10 ⁷ = (-ve) 6.47 x 10 ⁷ kg/year	Scenario 1 and CO2 captured in Syngas water scrubbing unit is sent for sequestration
-	-	-
LCHS for Scenario 1	(-ve) 295 g CO ₂ e/MJLHV of H ₂ product	This is much lower than the max GHG emission Intensity
LCHS for Scenario 1	(-ve) 327 g CO ₂ e/MJLHV of H ₂ product	This is much lower than the max GHG emission Intensity

Table 9 - Estimates of LCHS for a hypothetical commercial process

To conclude, even if a 50% reduction was to be made to the offset claimed in the counterfactual, it is still very clear that from an LCHS metric, there is a very strong incentive to make progress with this technology. Further CO₂ reductions could be achieved if carbon capture was to be applied to the exhaust emissions from the gas engine, but that was outside the scope of this project.

In some potential commercial applications, agricultural waste could be used as a feedstock. If that waste is being allowed to degrade and emit CO₂ and CH₄ to the atmosphere, then the offset claimed could be very high.

6.5 An Updated Commercialisation Plan

CSS has developed a robust commercial plan that lays the foundation for becoming a global first mover in the emerging hydrogen energy economy. Building on our proprietary modular gasification platform, the plan outlines a phased strategy to capture near-term revenue opportunities, establish lighthouse projects and scale operations to meet growing demand across both industrialised and emerging markets. Our systems convert biomass and waste into clean, hydrogen-rich syngas enabling CSS to offer a practical and decentralised alternative to fossil fuels across hard-to-abate sectors.

A key catalyst for this commercialisation pathway is the company’s successful award of a UNIDO Accelerate to Demonstrate (A2D) project, funded by DESNZ. The project will see CSS deploy a first-of-its-kind modular gasification unit in Kenya’s tea industry, supplying clean power and heat while capturing carbon through biochar. This high-profile demonstration will validate technical performance, build investor and policy confidence and open channels for

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replication across East Africa and other agricultural value chains. It also strengthens CSS's credibility as a delivery partner in industrial decarbonisation and inclusive green growth.

In addition to this pilot, CSS is actively developing a pipeline of power and heat only 500 kW MicroHubs, tailored to off-grid and weak-grid industrial users in Kenya and the wider region. These systems are ideally suited for sectors such as tea processing, horticulture, agri-industrial parks and clean cooking fuel production offering a modular, affordable decarbonisation option where centralised infrastructure is lacking. Building on the A2D demonstration, the company is engaging with private off takers, energy cooperatives and development financiers to enable the scale-up of these units under BOOT (Build-Own-Operate-Transfer) and lease models from 2027 onward.

In parallel, CSS is advancing commercialisation of its 1 MW hydrogen MicroHub, a fully containerised system designed to generate green hydrogen at distributed scale. Construction of the first 1 MW unit will be completed by the end of 2026, with full commercial rollout beginning in 2027. This solution addresses a critical infrastructure gap in the UK and Europe's hydrogen value chain providing a flexible, decentralised alternative to centralised electrolysis or fossil-derived hydrogen.

Together, the A2D Kenyan pilot and 1 MW MicroHub represent pivotal proof points in CSS's business model. They support near-term revenue growth while reinforcing our long-term positioning as a leading provider of modular, scalable hydrogen and syngas systems.

6.5.1 Market Analysis

The global hydrogen market is set to witness significant growth due to increasing climate change initiatives and government support. The UK Government recently confirmed over £500m support for hydrogen infrastructure ([Source Gov.uk](#)), to create the UK's first regional hydrogen transport and storage network, connecting hydrogen producers with vital end users, including power stations and industry. Regulatory frameworks, financial incentives and infrastructure development provide a supportive environment. Additionally, European countries like Germany, France and Sweden, known for their bioenergy advancements, offer significant opportunities.

In CSS's assessment, the transportation sector, particularly hydrogen-powered vehicles and sustainable aviation fuel, represents major growth opportunities, alongside industrial clusters aiming for carbon neutrality.

The hydrogen sector's projected growth is bolstered by advancements in carbon capture and storage, with the global CCS market expected to reach \$10.3 billion by 2032 ([Source - Einoresswire](#)). Our technology aligns perfectly with this trend, providing sustainable solutions and positioning our company at the forefront of the hydrogen economy.

6.5.2 Target Market

Target Market: Our target market focuses on industries and regions with high hydrogen demand and commitment to decarbonization. Key sectors include:

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- Heavy Industries: Steel, cement and chemicals industries requiring hydrogen for high-temperature processes.
- Waste Management: Companies looking to convert waste into clean energy.
- Transportation: Road haulage and logistics, public transport systems and aviation seeking low-emission fuel alternatives.
- Energy Providers: Waste to energy project and power plants integrating hydrogen for sustainable energy production.

A commercial and economic analysis conducted with a waste company has shown that the diversion of 10,000 tonnes of SRF can produce enough hydrogen with power equivalent to 1,100,000 litres of diesel. This is the equivalent of a direct saving of approx. £1.7m (based on £1.55 a litre 2025) per annum on purchasing diesel making for a strong value proposition to this sector.

6.5.3 Product Strategy

Our product portfolio focuses on modular gasification systems that offer scalability, cost-efficiency and versatility. These systems produce hydrogen, power and heat, serving sectors such as waste management, manufacturing, agriculture and transportation. Continuous investment in R&D will ensure our systems remain cutting-edge, with enhancements in production efficiency, cost reduction and carbon capture integration. Our products not only meet current industry needs but also anticipate future demands ensuring long-term competitiveness.

6.5.4 Marketing Strategy & Route to Market

We will employ a multi-faceted marketing approach, leveraging digital platforms, industry conferences and strategic partnerships. Our targeted marketing campaigns will emphasise the economic and environmental benefits of our solutions, tailored for heavy industries, waste management firms and transportation companies. Collaborations with academic institutions and government entities will enhance our credibility and drive further innovation.

Our marketing efforts will also include thought leadership through white papers, case studies and participation in key industry events, highlighting our technological prowess and commitment to sustainability.

CSS currently have operational gasification technology, proving our MicroHub Hydrogen process at scale which significantly extends our market position, having already brought to market gasification plants for power & heat, utilising waste-wood (end of life certification) and SRF/RDF at Refgas. Market exploitation is well primed and our route-to-market is clear, target customers are waste management companies and industrial/manufacturing companies with high volumes of biogenic waste and energy requirement.

6.5.5 Operational Plan

Operational excellence will be achieved through strategic partnerships for feedstock supply, logistics optimisation and the deployment of advanced monitoring systems. Our Deeside facility serves as a model for future installations, with plans for similar facilities in key industrial regions across the UK and Europe. Collaborations with local authorities, investors, industry stakeholders and supply chain partners will ensure seamless operations and continuous improvement.

We will also invest in workforce development, ensuring our team remains at the forefront of technological and operational advancements, thereby enhancing productivity and innovation.

6.5.6 Longer Term Business Model

Within the time frame of our 5-year financial model, we envisage manufacturing the MicroHubs at our site in Deeside, assisted by our established supply chain. CSS's ultimate aim is to become a technology provider through licensing the MicroHub and H2 technology. We see this as the fastest route to scaling the business particularly to expand rapidly into overseas markets.

6.5.7 Risk Management

We have identified key risks such as feedstock price volatility, regulatory changes and technological challenges. These will be mitigated through strategic partnerships, continuous innovation and active engagement with policymakers. Contingency plans will address operational disruptions, while financial buffers will safeguard against market fluctuations.

6.5.8 Sustainability and ESG Commitments

Our operations are guided by ESG principles, focusing on reducing carbon emissions, promoting circular economy practices and supporting community initiatives. Our technology facilitates carbon capture, waste reduction and energy efficiency, aligning with global sustainability goals. Carbon credits trading, renewable energy integration and community engagement form the pillars of our sustainability strategy.

6.5.9 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.

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Commercial MicroHubs are expected to roll out after construction and operation of a demonstration plant (expected February 2026). 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 licence to significantly increase the capacity of rollout.

6.5.10 Route-to-Scale

As at 2025 CSS already has a demonstration 500kW MicroHub Deeside which has proven gasification for power, heat, H2 production, carbon capture and SAF. Plant development follows the route-to-scale plan.

- 2025/26 – Build and commission 500kWh plant for deployment at a tea factory in Kenya.
- 2026/27 Build a MicroHub 1 MW demo plant at Deeside, scaling the technology, providing a demonstrator for full scale H2 production.
- 2027 – Launch the MicroHub Hydrogen into the UK market.

6.5.11 Future market with incentives for CO2 capture and H2 production

6.5.11.1 Renewable Transport Fuel Obligation (RTFO)

The UK's RTFO scheme presents a valuable revenue opportunity for Compact Syngas Solutions (CSS), particularly through the issuance of Renewable Transport Fuel Certificates (RTFCs). CSS's modular gasification technology designed to convert waste biomass into clean hydrogen qualifies under the RTFO as a producer of renewable transport fuel from a waste-derived, sustainable source.

This eligibility allows CSS to generate RTFCs for every kilogram of hydrogen produced and sold into qualifying applications, such as transport or mobility hubs. These certificates carry real market value and can be traded or used by obligated parties to meet their blending targets. Depending on certificate prices, this can add a significant income stream per unit of hydrogen, thereby improving the Levelised Cost of Hydrogen (LCOH) and overall project bankability.

Additionally, CSS's hydrogen may qualify under the RTFO's "development fuel" sub-target, which applies to advanced fuels with high GHG savings. This could enable CSS to earn double RTFCs, further improving the return on investment and accelerating payback for its MicroHub deployments.

Incorporating RTFC revenues into CSS's economic modelling strengthens the business case for near-term commercial projects in the UK and provides a clearer pathway for investor confidence. As CSS progresses towards deployment, active engagement with RTFO compliance processes and off taker alignment will be key to unlocking this value.

6.5.11.2 Carbon Credits

Carbon credits represent a key revenue and impact driver for CSS. The MicroHub gasification system converts biomass into hydrogen, power, heat and biochar, a stable form of carbon that qualifies for carbon removal credits when produced from biogenic feedstocks. While SRF derived biochar cannot currently be registered under most voluntary carbon standards, credits can still be requested and potentially recognised in the future, especially under emerging waste-derived carbon methodologies.

In addition to biochar, CSS's technology captures biogenic CO₂ in gaseous form, offering an additional carbon credit pathway through recognised Carbon Dioxide Removal (CDR) methods. This dual crediting approach via biochar sequestration and direct CO₂ capture significantly improves project-level economics and strengthens CSS's financial model, particularly in off-grid and decentralised markets. CSS is now advancing its Monitoring, Reporting and Verification (MRV) processes to align with global carbon standards, enabling participation in high-integrity carbon markets and enhancing the value proposition for customers and investors focused on climate-aligned solutions.

6.5.12 Alignment to Net Zero & Benefits to Hydrogen H₂BECCS Process

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

- Produce up to 30 kg / h (1.18MWh) of hydrogen 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 hydrogen generator which can be easily installed across the country to provide a decentralised refuelling network.
- This in turn will drive the uptake of hydrogen technologies.
- CSS' commercial partners intend to adopt hybrid engines which will further provide case studies to drive up technology uptake – such as Ulemco who offer dual fuel H₂ conversions for diesel vehicles.

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

- Supporting the development of hydrogen economy with revenue, taxes and jobs.
- Supporting the drive to reduce the cost of production of hydrogen (LCOH).
- Supporting businesses to reduce costs and improve their carbon footprint.
- Helping to reduce carbon emissions and improve the environment.
- Providing a supply of CO₂ for industrial use in the UK.
- Reducing waste sent to landfill and associated emissions and costs.

6.6 Key Successes

There are several key successes to highlight, the most significant being that the CSS H2BECCS demonstrator achieved the UK's first at-scale demonstration of continuous, water-based CO2 scrubbing, and is among the very first such demonstrations globally:

6.6.1 CO2 Water Scrubber & Degassing Scheme

Two major successes were achieved with the CO2 water scrubber system. The process control and liquid level control system in the columns was designed, demonstrated and refined. The control system scheme was demonstrated to perform at the targeted syngas flow and pressure. Additionally, a CO2 removal of >75% was achieved and exceeded

6.6.2 Parallel Train-B

The implementation of the parallel Train-B was a success because, if Train-A starts to foul and create a pressure drop or a heat transfer problem, then the dirty syngas could be diverted to a parallel Train B and the problem in the fouled train resolved. This reduced the risk of uncertainty over the frequency at which a unit operation in the Train may need to be cleaned, repaired or maintained.

The concept of a parallel Train mirrors what would be provided in the early commercial installations, which will enable a Train to be taken off-stream for cleaning, or maintenance. As more experience is gathered with continuous operations, the need may be simplified and a facility to take a smaller number of units operations off-stream required.

6.6.3 Automatic Condensate Drainage

A key success for the was the development of the automatic condensate drain. In Phase 1, this was manual but the migration to an automatic drain which uses a novel methodology by overcoming a negative pressure within a heat exchanger from which the liquid is drained,

That auto-drainage scheme continues to be refined – but has already made a huge difference to the efficiency of the syngas cooling process.

6.6.4 Overcoming many of the 'Project Constraints'

CSS had to successfully overcome many projects constraints up and downstream of the CO2 scrubbing and degassing scheme. While many of these challenges were addressed, allowing progress to continue, some proved more difficult to resolve within the available time and budget and have therefore been added to a future action list. For example:

- A solution was developed to improve supply and feed of waste-wood into the process – a suitable size and shape was obtained for the trials.
- Solutions were found to some of the early problems with the operation of the gasifier. For example, welding new sections to the outer shell of the gasifier, replacing char breaker bar trough at the base and installing a more powerful breaker-bar motor (to list

but a few). However, many remain such as installing a ceramic liner inside the gasifier, better control of biomass through the gasifier and control of the position of the hot zones inside.

- Adjustments were made to the start-up procedure for the HGFs to reduce the rate at which pressure drop increased across them. The metal candle-filters were replaced with a different size of mesh and the 2nd filter was by-passed. However, onstream time was limited and in the light of data from the extended trials it is clear that the way in which they are used and their function/design needs to be carefully considered.
- To overcome budget and delivery constraints on items that had a long lead-time, several used items of equipment were sourced which had to be modified for use in the project. In particular: (a) the Syngas Compressor; (b) the Gas Engine and the Electric Generator; (c) the Vacuum Pump on the CO₂ degassing column.

6.7 Lessons Learned

There were many lessons learned throughout the project and these feature as explanations throughout this report. In this sections emphasis is placed on a few technical and operational matters.

6.7.1 Project Aims, Objectives and Expectations

These were too ambitious for the resources which were available and what could be done in a 2-year project with the funding provided and prevailing economic climate.

6.7.2 Biomass Feed

With each source of feedstock, it has to be accepted that extended trials will need to be performed to assess how it needs to be prepared prior to feeding into the gasifier and how to keep it moving through the gasifier.

6.7.3 Gasifier

The present design of Gasifier-500 would benefit from the use of refractory lining to allow for higher operating temperatures without compromising the integrity of the vessel over long periods of operation. Higher operating temperatures will reduce the formation of tars and therefore minimise the cost of replacing activated carbon and condensate treatment. The system the ability to raise temperatures in the gasification zone by changing the distribution of inlet air.

6.7.4 HGFs

From the trials, it was clear that a preheat system should be devised to warm-up the HGFs and the heat exchangers. It is essential to mitigate the tendency for bio-oils to condense on very cold surfaces and then harden, blocking filters or fouling the down-stream heat exchangers.

6.7.5 Automatic Condensate Drainage Scheme

If condensate carry-over occurs from one unit to its down-steam neighbour, these units start to foul and pressure drop across them increase.

6.7.6 Syngas Blower

This needs to have more pressure capacity when operating at higher flows and to retain the flow when some of the units on the suction side in the train start to foul.

6.8 Next Steps

Besides what has already been mentioned in earlier parts of this report, emphasis is placed on some technical challenges as next steps:

6.8.1 Refuse Derived Feed (RDF) and SRF

Feed preparation remains an important prerequisite and also the inclusion of lime to trap acid gases in the form of chlorides and sulphates in the char. More detailed trials need to be performed and assessment made of where the contaminants in the RDF will reside in the process or process streams. To meet environmental emissions additional syngas clean-up unit operations will be required.

6.8.2 Char Removal & Collection

The operation of the solid's isolation valve in the char discharge line needs to be made more leak tight. Also, the scheme used for the collection of char in metal drums needs to be turned into a less labour-intensive process.

6.8.3 Char Sequestration

Trials should be performed on the storage of char underground in disused mines. Also, it may be advantageous to consider the use of char to remove residual contaminants from the condensate prior to discharge. The char could then pass through a pyrolysis reactor before sequestration underground.

6.8.4 Condensate Disposal

When the syngas is cooled a condensate is formed, it needs to be either treated or disposed off-site. The solution will depend on the geographical location of the plant and existing water treatment facilities or what is permitted. In some locations, the bio-oils separated from the condensate could be an important by-product and even have value.

6.8.5 Carbon Beds

Further work needs to be performed to confirm their effectiveness as a contaminant trap and the ability to regenerate and where that bed purge-stream with contaminants should be sent.

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6.8.6 Alumina Beds

Further work needs to be performed to confirm their effectiveness as a moisture and residual contaminant trap and their ability to be regenerated.

6.8.7 HGFs

Their expected performance and how that is to be achieved is to be reviewed.

6.8.8 Automatic Condensate Drainage Scheme

The condensate drainage system needs to be extended and tuned so that condensate is not carried over from one unit to its down-steam neighbour.

6.8.9 Network of Exchangers in the Train

The heat exchangers need to be tested at design operating conditions. The HiTRAN inserts needed to be re-installed in some of the exchangers to achieve lower syngas temperatures at a specific point and better condensate drainage aided by the inserts.

6.8.10 Mist Eliminator in the Train

This needs to be connected to the auto-condensate drainage scheme and its performance properly evaluated with an assessment of whether its design is really suitable for this application.

6.8.11 Syngas Blower

The duty for this unit needs to be reviewed, such that it can provide the required flow across a higher range of pressure differentials across it. To be able to compensate for pressure drop increase as the Train fouls before it needs to be cleaned. This may require a two-stage system.

6.8.12 CO₂ Scrubbing and Degassing Scheme

More long-term continuous trials will be performed to increase confidence level and data in such an approach and to quantify more accurately, CAPEX and OPEX for such a scheme.

6.8.13 H₂-PSA & CO₂-VSA

The use of PSA for the separation of hydrogen from the syngas will need to be explored further and this should involve collaboration with a supplier of PSA equipment. At present, because that system has been designed to operate at about 8 barg, the motivation to use water scrubbing before it to capture the CO₂ is high. However, from trials performed, CSS know that H₂-PSA can be operated at much lower pressures and CSS are now considering if it would be better to use a combination of vacuum swing adsorption with PSA, in order to trap the CO₂ and the hydrogen.

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