COMPACT SYNGAS SOLUTIONS
GREEN FUELS FOR A CLEAN FUTURE

Hydrogen & Sustainable Fuels

Unlocking the Energy Potential of Biomass & Waste Feedstocks

HII Demonstration Report

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2 Executive Summary

2.1 Overview of the Demonstration

The demonstration plant in Deeside, North Wales, integrates Compact Syngas Solutions' (CSS) advanced gasification technology to enable efficient hydrogen production, storage, and carbon capture. The facility processes a wide range of feedstocks including waste-derived materials to produce low-carbon hydrogen. This project aimed to validate the technical performance, scalability, and environmental benefits of CSS's innovative approach in a real-world setting.

2.2 Key Findings and Outcomes

- **Efficient hydrogen production:** The plant successfully produced high-purity hydrogen (over 95%) from various carbon containing waste feedstocks, providing a flexible and sustainable alternative to the production of H_2 from fossil derived fuels.
- **Effective carbon capture:** Integrated carbon capture technology significantly reduced CO_2 emissions, classifying the hydrogen output as low carbon positioned between blue and green hydrogen.
- **Waste valorisation:** The system converts waste into valuable energy, supporting circular economy principles and reducing landfill reliance.
- **Scalability and modularity:** The MicroHub's modular design enables flexible, decentralised deployment, making it suitable for off-grid and industrial applications.
- **Commercial and environmental viability:** Initial assessments suggest CSS's approach can be cost-competitive, particularly in regions with strong waste-to-energy incentives or under the UK ETS scheme.

2.3 Relevance to the Hydrogen Sector

This project offers significant implications for the future of hydrogen:

- **A practical alternative to waste incineration or landfill:** CSS's solution can produce hydrogen from a carbon containing waste feedstock. H_2 from Steam Methane Reforming (SMR) requires fossil based fuels as a feedstock (e.g. natural gas), and H_2 from electrolysis requires the use of electricity which in turn may be produced from fossil-based fuels or wind turbines.
- **Decentralised production:** The technology enables on-site hydrogen generation, reducing the need for transport infrastructure and associated emissions.
- **Waste-to-Hydrogen integration:** By turning non-recyclable waste into fuel, the system supports decarbonisation efforts across waste management, energy and industrial sectors.
- **Alignment with Net Zero goals:** The integration of carbon capture positions CSS as a key enabler in meeting national and industrial decarbonisation targets.

3 Introduction

3.1 Purpose of the Report

This report aims to document and present the outcomes of the hydrogen demonstration project conducted by Compact Syngas Solutions (CSS) as part of the Hydrogen Innovation Initiative (HII) Demonstration Programme 2024/25. The primary objectives of this report are:

- **Showcasing innovation:** To highlight the role of CSS in advancing hydrogen production through our gasification technology and its benefit to the hydrogen economy.
- **Project documentation:** To provide an overview of the demonstration, including technical performance, challenges, and key learnings.
- **Industry contribution:** To assess the relevance of the demonstrated technology to the broader hydrogen industry and its potential for commercialisation and scalability.
- **Regulatory and policy insights:** To identify any regulatory considerations, policy implications, and best practices derived from the demonstration.
- **Knowledge sharing:** To disseminate findings and recommendations that can inform future hydrogen projects and contribute to industry advancements.
- **Environmental and economic impact:** To evaluate the sustainability, cost-effectiveness, and emissions reduction potential of the syngas-to-hydrogen process.

This report serves as both a technical record of the demonstration and a strategic document for industry stakeholders, policymakers, and potential adopters of syngas-based hydrogen solutions.

3.2 Background on Compact Syngas Solutions

CSS is a UK company based in Deeside, North Wales specialising in renewable energy technologies, particularly focusing on the production of synthesis gas (syngas) through gasification processes. Founded by CEO Paul Willacy in March 2020, CSS leverages over two decades of experience in gasification to develop innovative solutions for sustainable energy production.

3.2.1 Mission and Core Values

CSS is committed to creating value through innovation, sustainability and impact. Its operations are grounded in core values of honesty, integrity, responsibility, commitment, and respect for people all of which underpin its technology development and stakeholder engagement.

3.2.2 Technological Innovations

The company has developed patented modular "MicroHubs" that convert non-recyclable waste products and biomass into sustainable energy and fuels. These MicroHubs utilise downdraft gasification technology to produce high-quality, low-carbon syngas which can be used to generate power, heat, cooling or be converted into clean hydrogen fuel.

Additionally, CSS's process supports decarbonisation by capturing carbon in the form of biochar, a charcoal-like substance that can be used as a fertiliser and for sequestration. Carbon is also captured in our novel water-based process that can remove up to 90% of carbon and is more eco-friendly and safer than current chemical-based systems. This carbon is captured in gaseous form, meaning it can be used for industrial processes or sequestered. The development of this technology was funded by Department of Energy Security and Net Zero (DESNZ) between 2023 and 2025 with the support of £4million grant funding through the hydrogen BECCS (bioenergy with carbon capture and storage) Net Zero Innovation Program (NZIP).

3.2.3 Leadership Team

CSS's leadership combines technical expertise and industry experience across engineering, sustainability, finance, and marketing:

- **Paul Willacy**, Chief Executive Officer, has a background in manufacturing engineering and extensive experience in designing and building gasification systems.
- **Neil Thompson**, Chief Operating Officer, brings over 20 years of experience in leading low-carbon and renewable energy businesses.
- **Karen Taylor**, Chief Marketing Officer, has a strong background in marketing, business development, fund raising and project management in the waste and sustainability sectors.
- **Professor Stan Kolaczkowski**, Senior Technical Advisor, is a chemical engineer with a rich history in environmental fields and academia.
- **Jim Lavin**, Finance Director, is a seasoned finance and operations director with significant experience in the waste and sustainability sectors.

Together the team is driving the company's mission to enable cleaner, more resilient energy systems by unlocking the potential of biomass and waste-derived hydrogen.

3.3 Background on the Technology

CSS specialises in gasification and syngas-to-hydrogen technologies, offering modular, small-scale solutions that convert biomass and waste-derived feedstocks into low-carbon hydrogen. This innovative approach supports decentralised hydrogen production, reducing reliance on large-scale centralised facilities and supporting energy resilience.

3.3.1 Gasification Technology

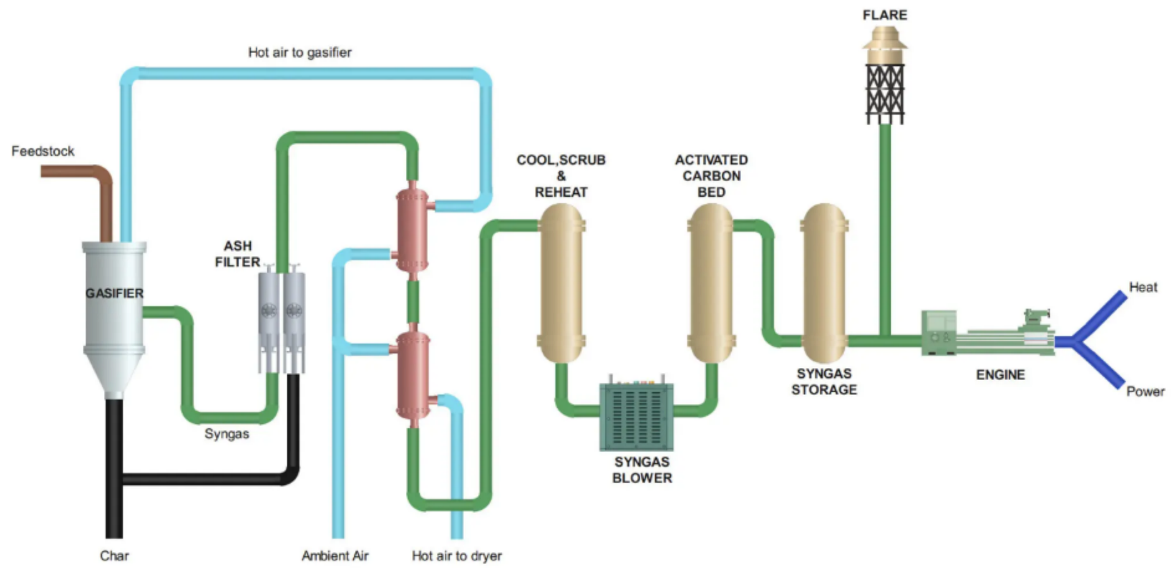


Figure 1 - CSS Gasification PFD

Figure 1 represents the biomass gasification process for producing syngas (synthesis gas), which can be used for power and heat generation and cooling. Below is a step-by-step explanation of the process:

3.3.2 Feedstock Input

- The process begins with the introduction of feedstock (biomass or other carbon-based material) into the gasifier.
- In the gasifier the feedstock undergoes thermochemical conversion under controlled conditions with limited oxygen, producing syngas (a mixture of CO, H_2, and CH_4 along with inert gases N_2 and CO_2 making up the balance) and char (solid carbon residue).

3.3.3 Syngas Filtration and Cleaning

- The produced syngas passes through an ash filter, which removes solid impurities such as ash and particulate matter. There are seven stages of syngas cleaning and cooling as part of our patented process which creates syngas of the highest quality.
- The syngas is directed towards a cooling and scrubbing system, which lowers its temperature and removes unwanted contaminants like tar and moisture with syngas being at a final temperature of 25°C.

3.3.4 Gas Conditioning

- After cooling and scrubbing the syngas is passed through an activated carbon bed, which further purifies it by adsorbing impurities, which helps to reduce emissions. CSS are working on methods of regenerating the activated carbon so that it can be reused.

3.3.5 Syngas Storage and Distribution

- The cleaned syngas is stored in syngas storage tanks at low pressure circa 200mbar(g) before being utilised.
- A syngas blower helps regulate the flow of syngas to different end-use applications.

3.3.6 End-Use Applications

- The stored syngas is directed to an engine which converts it into useful energy in the form of heat and power or cooling via absorption chilling.
- The system has a recirculation line meaning that any excess or unutilised syngas does not need to be flared, however, on start-up and shut down syngas is sent to the flare where it is safely burned to prevent environmental hazards.

3.3.7 Heat Recovery

- The system also incorporates heat recovery mechanisms. For instance, hot air is redirected to both the gasifier and drying units, improving the overall efficiency of the process.

This gasification system converts biomass and non-recyclable waste into clean, renewable energy, reducing reliance on fossil fuels and contributing to sustainable energy production. The process ensures efficient syngas production while effectively managing waste and emissions.

3.3.8 Hydrogen Technology

- Below is an illustration figure 2 of the syngas-to-hydrogen and energy conversion process, utilising our gasification system to produce syngas as highlighted above.
- This process shows our novel water-based carbon capture process and the separation of hydrogen through Pressure Swing Adsorption (PSA) technology, which then separates into either syngas for heat and power or hydrogen compression for multiple end-uses, including industrial applications and hydrogen refuelling.

3.3.9 Carbon Dioxide Capture Using Water

- The syngas first passes through a carbon bed, which reduces the level of impurities and thereby protects the syngas compressor.
- A syngas compressor increases the pressure so as to increase the solubility of CO_2 in water which is used as a

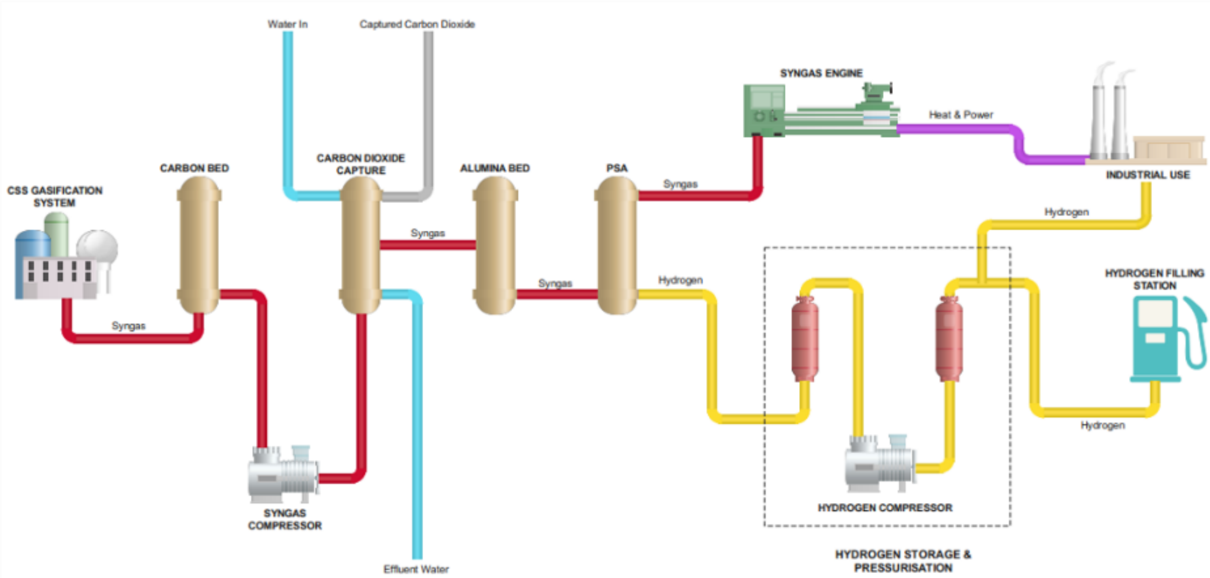


Figure 2 - CSS PFD for Carbon Capture & Hydrogen Recovery

scrubbing fluid. In a separate column, with the aid of a pressure decrease, the effluent water containing dissolved CO_2 is degassed using a vacuum. The water can then be recirculated and reused in the CO_2 scrubbing columns.

3.3.10 Pressure Swing Adsorption (PSA) for Hydrogen Separation

- The PSA unit separates hydrogen from the syngas stream.
- The remaining syngas is sent to a syngas engine, where it is used to generate heat and power for industrial applications.

3.3.11 Hydrogen Storage & Distribution

- Hydrogen storage and pressurisation: The hydrogen is compressed using a hydrogen compressor to increase storage efficiency. This can then be used for industrial applications and at a hydrogen filling station.

3.3.12 Key Features of the CSS Hydrogen MicroHub

The CSS hydrogen MicroHub is an innovative, sustainable energy solution that efficiently transforms biomass and waste into valuable syngas-based energy, hydrogen fuel and industrial heat & power while significantly reducing carbon emissions. **Key features:**

- **Carbon capture technology** – Captures and reduces carbon dioxide emissions supporting global decarbonisation efforts.
- **Multiple energy outputs** – Produces syngas-based power, hydrogen fuel, and industrial heat & power ensuring a versatile and flexible energy supply.
- **Decentralised hydrogen production** – Enables local hydrogen generation reducing reliance on large-scale hydrogen transport and lowering infrastructure costs.
- **Feedstock flexibility** – Capable of processing various biomass and waste materials contributing to waste reduction and a circular economy.
- **Significant carbon emission reduction** – Compared to fossil-based hydrogen production, gasification with carbon capture significantly lowers CO_2 emissions.
- **Modular & scalable design** – Compact and flexible, the MicroHub can be deployed in remote or off-grid locations making hydrogen accessible for diverse application.

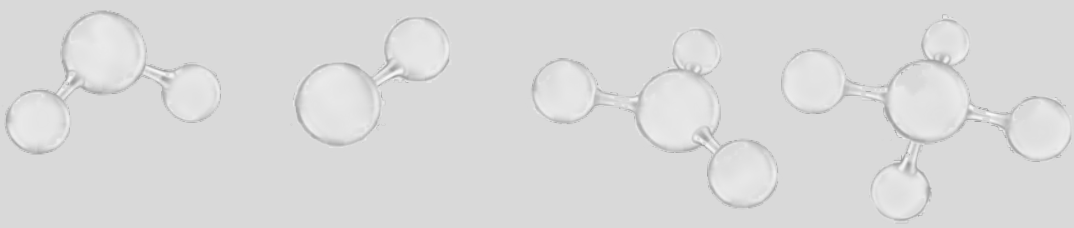
3.4 Objectives of the Demonstration

The key objectives of this demonstration include:

1. **Proving the viability of decentralised hydrogen production -** Demonstrate the MicroHub's ability to generate hydrogen locally and validate the economic and operational feasibility.
2. **Showcasing carbon reduction and environmental benefits -** Highlight the effectiveness of the integrated carbon capture technology, reducing CO_2 emissions compared to traditional hydrogen production methods.
3. **Optimising hydrogen production and storage -** Evaluate the MicroHub's capability to produce and store hydrogen efficiently.
4. **Demonstrating feedstock flexibility -** Test different biomass and waste materials to assess feedstock adaptability and establish optimal conditions for maximising hydrogen yield.
5. **Enhancing energy security and resilience -** Demonstrate how local hydrogen production can enhance energy independence and grid resilience in remote or off-grid areas.
6. **Supporting industrial decarbonisation and the hydrogen economy -** Validate the MicroHub's role in supplying hydrogen for industrial applications, transport and power generation.
7. **Building investor and stakeholder confidence -** Provide real-world data to support commercial adoption and investment and engage with policymakers, businesses, and industries to accelerate hydrogen market adoption.

Department for Energy Security & Net Zero

DESNZ BECCS funding focused on the development of carbon capture technology utilising biomass as a feedstock and funded plant upgrades and long-term reliability trials. HII funding supported trials utilising waste feedstock. Both projects have been a critical step in proving and showcasing the scalability, efficiency, and sustainability of the CSS MicroHub, positioning it as a key player in decentralised hydrogen production and carbon-neutral energy solutions.



4 Project Description

4.1 Description of the Hydrogen Technology being Demonstrated and the Preceding Development

Preceding development of CSS MicroHubs

The development of the MicroHub has evolved over time, driven by advancements in the design and operation of the gasifier and down-stream gas clean-up technologies. Key milestones include:

1. Advancements in the use of specially designed heat exchangers to cool the hot humid syngas and allow the bio-oils and water to condense. Adjusting temperatures carefully in the heat exchanger network to reduce the risk of severe fouling and volatile hydrocarbons condensing in feed lines to the gas engine.
2. Development of flexible gasifiers: Innovations in small-scale gasification technology allow for syngas production from diverse feedstocks and the ability to use oxygen enriched air to increase the calorific value of the syngas produced.
3. Integration of carbon capture technologies: The capture of carbon in the char was already an integral part of the design acting as the '1st carbon capture step' in the CSS process. To that, a '2nd stage of carbon capture' was added, in the form of CO_2 removal from the syngas by scrubbing with water.
4. Hydrogen purification & storage improvements: Pressure swing adsorption (PSA) has been applied to demonstrate the viability of applying this process to produce a hydrogen product stream ~~or~~ of adequate purity (90 to 95%) for many industrial (e.g. furnaces) and transport (e.g. diesel-powered engines converted to run on H_2) applications.

The technologies that have been utilised for the HII trials are highlighted below.

4.1.1 CSS Gasifier 500

The MicroHub 500 produces 600 kW of heat and 500 kW of electrical power enough to service between 100 to 500 households. Running constantly (7,500 hour per annum), it can handle 3,750 tonne per annum of biomass and/or solid recovered fuel (SRF), while about 36% of the carbon is captured in the biochar.

The MicroHub 1000 doubles the amount of heat and power being generated, delivering. 1 MW of electrical power and 1.2 MW of heat. It can handle 7,500 tonne of biomass and solid recovered fuel (SRF) per annum.

Figure 3 - CSS' Gasification Skid – Gasifier 500 scale

From the syngas produced, with the aid of a PSA process a hydrogen product stream (up to 95% pure) can be created and about 15 kg per hour of H_2 could be produced from a MicroHub 500, and 30 kg per hour from a MicroHub 1000. The hydrogen is suitable for internal combustion engines converted to hydrogen systems in industrial or transport applications.

Figure 4 - Syngas Carbon Capture Technology

4.1.2 Carbon Capture Technology

The CO_2 scrubber system is at the heart of the DESNZ H2BECCS project and was successfully commissioned in December 2024. The process was first fully tested with compressed air representing the compressed syngas and running the water recirculation pumps at full speed. The scrubbing columns were operated at full pressure using air to test for leaks and to tune the automatic pump sequences. The system compromise of multiple process features: -

- 4 x scrubbing columns rated to 10 barg.and tested to over 15 barg.
- 4 x scrubbing pumps, 2 x 5.5 kW and 2 x 15 kW rated.
- Degassing column: This column operates at 0.1 bara vacuum and is designed to remove the CO_2 from the water that is circulated around the columns.
- Vacuum pump.

4.1.3 Pressure Swing Adsorption (PSA)

The PSA receives CO_2 depleted syngas from a vessel from the CO_2 scrubber system at a pressure of up to 7 barg. The pressure is controlled via a control loop via PCV-005 valve. The system is ATEX compliant in-line with the RPS DSEAR study.

Figure 5 - Pressure Swing Adsorption Columns

The PSA system features the following main items:

- An alumina vessel – to ensure that the syngas is dry before entering the PSA.
- Duty standby alumina vessel – to ensure that the syngas is dry before entering the PSA.
- Moisture meter – to measure the moisture content of the CO_2 depleted syngas.
- Syngas receiver – to hold syngas at up to 7 barg before it enters the PSA-1 vessel.
- PSA-1 vessel – running at up to 7 barg specifically designed vessel containing an adsorbent. This vessel is expected to carry out the main syngas separation with H_2 exiting at approx. 60% purity.
- PSA-2 vessel – running at up to 3.5 barg, takes product from PSA-1 which contains an adsorbent. In this vessel the H_2 purity is increased from 60% up to 98% In a future commercial reconfiguration of this scheme, extra vessels would need to be added to sustain H_2 product flow and to retain high levels of H_2 purity.
- Hydrogen receiver.
- Instrumentation and controls.
- Control panel.

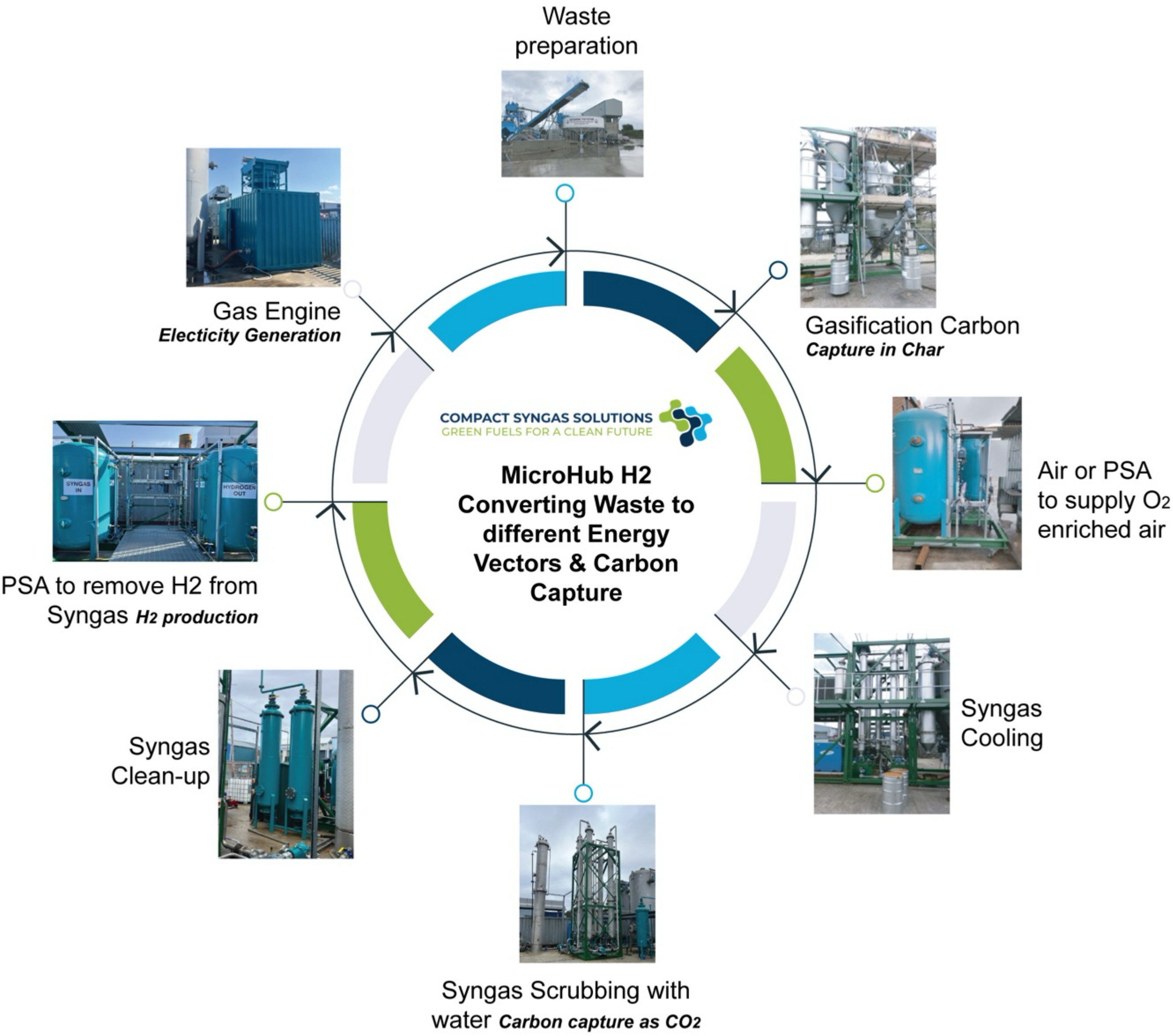
4.1.4 Hydrogen Storage and Compression

The hydrogen compressor boosts hydrogen pressure up to 350 barg in 2 stages so that it is suitable to be dispensed to a compatible vehicle.

The system is broken down into 3 main components:

1. Hydrogen compressor.
2. Hydrogen storage (50 kg at 200 barg).
3. The hydrogen dispensing unit.

Figure 6 - Hydrogen Storage and Compression Processing Unit



4.2 Location and Partners Involved

CSS have successfully integrated multiple advanced technologies into a fully operational demonstration plant in Deeside, North Wales. The plant now features a state-of-the-art gasification system alongside several complementary technologies, working in unison to enable hydrogen production, storage, and carbon capture. The hydrogen produced falls between blue and green on the spectrum, influenced primarily by the feedstock and specific processes employed, details of which will be explored further in Section 6.4.1.

This facility has been developed with support from private investment, commercial partnerships, DESNZ BECCS grant funding.

CSS did not have any partners on this project but would like to mention the following suppliers for their support and contribution to building the plant and trials.

Circom	fitzgerald CivilEngineeringContractors	Tilston Ventures
Bath Process Consultants	FARRALLS GROUP	pure ENERGY CENTRE

4.3 Timeline of the Demonstration

The demonstrations were conducted in Q1 2025 and also incorporating comparative data from previous trials between 2022 - 2024. CSS will continue trials in Q2 2025, focusing on showcasing system reliability, testing a wider range of feedstocks and initiating electricity export to the grid.

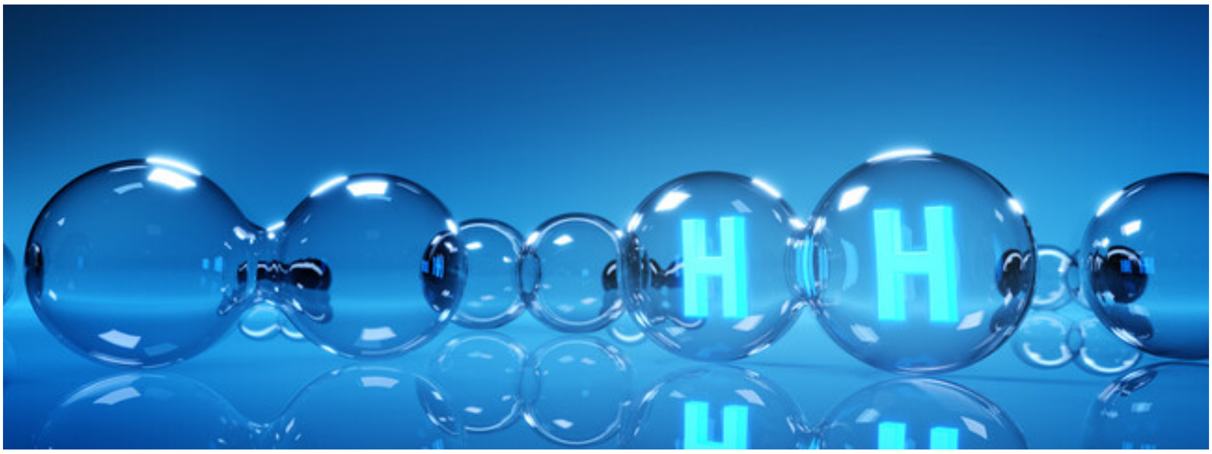
5 Demonstration Activity

5.1 Methodology and Procedures

CSS has a robust operating and sampling procedure for any trials carried out on different feedstocks. Prior to processing, a sample of the feedstock is sent away for analysis and the composition is assessed. Using this data CSS then generate a theoretical mass balance based upon CV, moisture and ash content. While processing the feedstock, CSS sets the syngas production rate and start the process on a known feedstock such as waste wood to get the system up to temperature before introducing the new feedstock.

The feedstock is continuously weighed, and the syngas composition is logged throughout the duration of the trial. CSS then compare the energy content of the feedstock against the CV and production rate of syngas to calculate the conversion efficiency.

The char produced is also measured and sent away for analysis. However, when measuring the char, it requires a longer trial and more feedstock to ensure the start-up feedstock is fully purged through the system so ensuring the char samples are fully representative. Other analysis that is carried out include syngas contamination conducted by an independent laboratory. This allows CSS to understand whether any additional syngas cleaning or dosing is required. The final analysis completed is for the condensate to look for contamination in the water produced, this enables the production of an elemental balance.



5.2 Safety, Risk Management, and Regulatory Considerations

Throughout the evolution of CSS' technology, CSS have used external experts to ensure the gasification, carbon capture and hydrogen systems are constructed and operated safely. This involved meeting international design standards and conducting design studies such as DSEAR and HAZOPS with external experts to ensure a safe operation.

5.3 Data Collection and Monitoring Methods

To ensure accurate collection of data for the trial, CSS deployed a variety of techniques depending on the frequency and ease of the data collection. Where possible, continuous monitoring of Key Performance Indicators (KPIs) via sensors was used however, in some cases scheduled sampling and monitoring was required due to continuous monitoring not being practical.

The feedstock, ash and condensed water produced were all measured by weighing the material on a calibrated weighbridge or scale. Live monitoring of the ash and condensed water was not required because the mass produced is relatively low and can be calculated at scheduled periods. Moisture within the feedstock was measured by taking samples of the biomass to build a representative picture of the true moisture; this is because it was not practical to sample all of the feedstock's moisture due to the sheer volume and time required.

However, the remaining key KPIs such as heat and power generated, syngas and hydrogen produced were generated by using live sensors within the process.

6 Results and Analysis

6.1 Performance of the Technology

6.1.1 Waste Wood & SRF Mass and Energy Balance- Raw Data

Due to the inherent design flexibility of CSS' system, it can run on both waste wood and SRF. Not only does this provide the operator with greater commercial flexibility with regards to gate fees, but it also allows the operator to assess the technical impacts of running either feedstock.

Figure 8 below shows the comparison between SRF and waste wood on the trial data that CSS obtained.

to SRF. The lower CV means that more waste wood can be run through the gasifier without hitting the design limit on CV. The high CV and therefore higher energy generation is experienced when running on the SRF due to the high plastic content within the SRF fuel.

Although SRF generates more char than waste wood, a high proportion of the char is ash which is within the feedstock and 'passes through' the gasifier without reacting. However, the SRF char which is not ash is still commercially attractive because it 'locks' in the carbon giving the possibility of the operator to claim carbon credits.

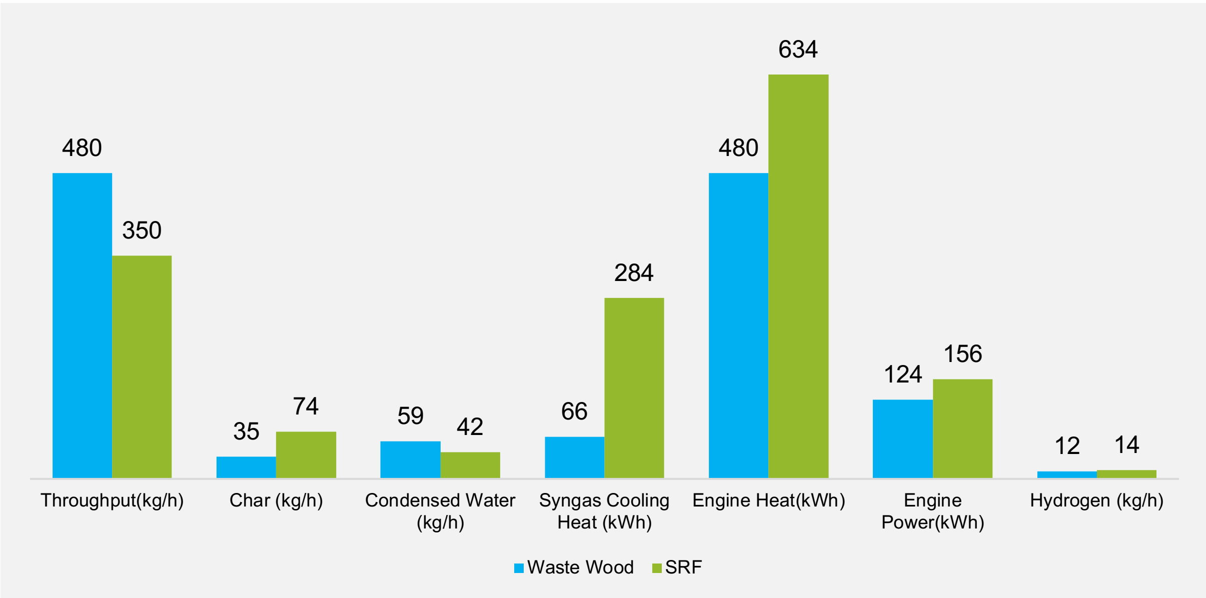


Figure 8 - Waste Wood and SRF Trial Mass Balances

Despite waste wood having a higher throughput, it yields less char and lower energy due to the higher moisture content and lower calorific value (CV) when compared

The syngas cooling heat from the SRF feedstock is much higher than for waste wood because the energy density is significantly higher. SRF syngas has c. 2.5 times more energy in the syngas than waste wood. Not only does this provide a cost saving because the heat is used for drying the feedstock and heating the gasifier, but the cooling of the syngas is also a necessity to meet the input requirements of the syngas engine.

The engine produces both heat and electricity for both SRF and waste wood feedstocks. The waste wood, as expected, produces significantly less heat than SRF but only marginally less power. However, it is important to note that both SRF and waste wood's NET power is significantly lower when producing hydrogen and capturing carbon vs just producing power. This is because the parasitic load increases significantly due to the compression and storage of hydrogen. Plus, by removing the hydrogen, there is less combustible gas in the syngas before entering the engine.

Hydrogen production is also higher for SRF (14kg/h) than waste wood (12 kg/h) despite waste wood having a great hydrogen concentration of hydrogen. This is due to a greater volume of syngas being produced by SRF than waste wood.

6.1.2 Waste Wood & SRF Mass and Energy Balance-Relative

To more accurately compare the yields for the mass and energy balances, each KPI was divided by the throughput (kg/h) to help understand which feedstock could be more commercially attractive.

SRF yields a higher proportion of heat, power and hydrogen due to the plastic within the SRF producing both a higher CV and higher proportion of hydrogen. With regards to heat, SRF yields almost twice as much heat from the gas engine vs waste wood highlighting the significant gap in CV between SRF and waste wood.

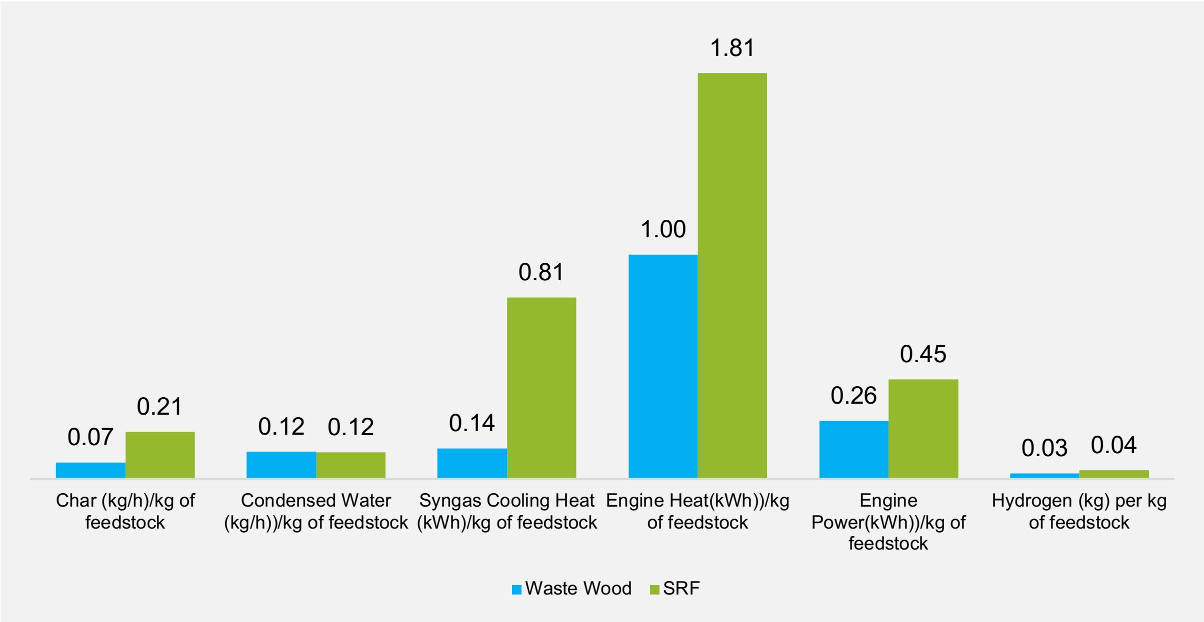


Figure 9 - Waste Wood and SRF Relative Mass Balance

6.2 Economic Analysis

Due to the inherent design of CSS' technology, it generates multiple revenue streams providing flexibility and increasing commercial attractiveness. Table 1 displays the different potential revenue streams from CSS' gasification technology for process either SRF or waste wood. Additionally, Table 1 highlights the potential impact of the carbon tax on EFWs (energy from waste facilities) which is due to come into force in 2028.

Note - the prices and revenue streams below are indicative and could vary as the markets mature.

	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Feedstock	SRF	SRF	Waste Wood	Waste Wood
Gate Fee	£70-100/t	£70-100/t + £50/t on fossil content	-£20-0	-£20-0
Char	-	-	£50-200/t	£50-200/t
Char Carbon Credits	NA	30% of captured carbon is biogenic	NA	100% of captured carbon is biogenic
Hydrogen	£4-6.5/kg	£4-6.5/kg	£4-6.5/kg	£4-6.5/kg
Engine Heat	Sell via local heat networks	Sell via local heat networks	Sell via local heat networks	Sell via local heat networks
Engine Power	Sell to grid	Sell to grid	Sell to grid	Sell to grid

Table 1 - Revenue Comparison Table

6.2.1 SRF

Scenario 2 shows stronger profitability prospects for processing SRF vs Scenario 1 due to the addition of the carbon tax. The carbon tax will allow operators of CSS' technology to increase gate fees accordingly and, despite also having to pay the carbon tax on emitted carbon, the captured carbon would not be taxed and thus benefiting from the higher gate fee. Additionally, it is anticipated that operators will be able to sell the biogenic carbon captured on the open market. Furthermore, CSS' process produces hydrogen which can be sold at c.£4-6.5/kg to displace diesel in heavy goods vehicles. Plus, the biogenic carbon captured in the char will generate carbon credits which can be sold on the open market. Finally, the excess heat and power generated from the process can be sold locally via heat networks and private wires respectively.

While Scenario 1 also offers many of these revenue streams, the saving on carbon tax by capturing the carbon makes it more financially attractive. The carbon tax saving could, however, be increased further with carbon capture at the end of the process post combustion.

6.2.2 Waste Wood

Scenario 3 and Scenario 4 benefit from the same product revenue streams however, Scenario 4 has a stronger profitability potential because it benefits not only from selling the biochar as a product for fertiliser or construction, but also the carbon credits on the open market.

6.2.3 SRF Vs Waste Wood

Based on the parameters in Table 1, Scenario 2 offers a better profitability potential. This is because SRF generates a gate fee whereas, waste wood at best would have zero cost. Although, the SRF would most likely have to be prepared which could cost £40-60/t reducing the overall gate fee. Additionally, when considering the carbon tax, SRF allows the operator to increase gate fees but save on the carbon tax via the application of carbon capture.

6.3 Environmental Impact

6.3.1 Life Cycle Assessment and Carbon Tracker Studies

In this section a comparison is made between two very different types of feedstocks, namely waste-wood and SRF (also known as RDF). The environmental impact from the use of these as feedstock can be interpreted in different ways and is open to debate. However, there are difference in their physical/chemical properties and hence in the syngas produced. For example:

- The ash content is 7 wt% (waste-wood), *versus* 21 wt% (SRF).
- The calorific value of the syngas produced is 4.7 MJ/Nm^3 (from waste-wood) *versus* 6.0 MJ/Nm^3 (SRF).
- The syngas composition is different with H_2 at x vol% (from waste-wood) *versus* y vol% (SRF).

These factors then mean that to produce 1 MW of electrical energy different quantities of syngas and feedstock need to be consumed. For example:

- 480 kg/h of waste-wood (at 15% moisture), *versus* 350 kg/h of SRF (at 6 wt% moisture).
- 396 Nm^3/h of syngas (from waste-wood) *versus* 855 Nm^3/h (from SRF).

Due to the inherent design of CSS' technology, it generates multiple revenue streams providing flexibility and increasing commercial attractiveness. Table 1 displays the different potential revenue streams from CSS' gasification technology for process either SRF or waste wood. Additionally, Table 1 highlights the potential impact of the carbon tax on EFWs (energy from waste facilities) which is due to come into force in 2028.

Life cycle assessments (LCA) and carbon tracker studies were conducted on the gasifier 500 which provides insights into the environmental impact of the technology. The carbon tracker allows the user to break the emissions down by each modular technology so the user can see the added benefit of the gasification unit on its own, and then the addition of both the carbon capture and hydrogen production technologies. Also, the user can see the impact of the avoided emissions on the overall carbon impact. Furthermore, the carbon tracker is not based on a specific case study so it does not consider specific details such as feedstock supply emissions (to list but a few) which would vary on a case-by-case basis.

On the other hand, the LCA includes details such on process and project development emissions and feedstock transportation emissions. Additionally, it generates emissions results which are based on the key inputs/outputs (waste wood, electricity and hydrogen) to both ISO 14040 and RTFO standards.

Note - both studies only consider the carbon impact, not the impact on biodiversity or water.

6.3.2 Carbon Tracker

Carbon Tracker Summary

Table 2 displays a summary of the scope 1-3 emissions for the different feedstocks and including/excluding avoided emissions. Waste wood (inc. avoided emissions) has the lowest carbon impact due to the waste wood avoiding landfill. However, SRF (excl. avoided emissions) has the lowest carbon impact because the process runs at a lower throughput when processing SRF vs waste wood.

	Scope1 (Tonnes per year)	Scope 2 (Tonnes per year)	Scope 3 (Tonnes per year)	NET Carbon (Tonnes per year)
Waste Wood (Exc. Avoided Emissions)	1,816	0	-506	1,311
Waste Wood (Inc. Avoided Emissions)	-690	0	-4,895	-5,584
SRF (Exc. Avoided Emissions)	1,535	0	-689	846
SRF (Inc. Avoided Emissions)	-1,625	0	-3,644	-5,269

Table 2 - Waste Wood & SRF Carbon Emission Summary

Carbon Tracker - Waste Wood

Figure 3 below shows a summary of the carbon emissions for waste wood. The NET Scope 1 emissions are 1,816 tonnes per year. This is offset by 1,083 tonnes per year due to CSS' carbon capture from the syngas. The Scope 2 emissions are negligible, based on the assumption that all power used by the office is electric and sourced 100% from renewable energy. Furthermore, the NET Scope 3 emissions represent a negative value of -506 tonnes per year due to the carbon sequestered in the waste wood char, which locks in carbon indefinitely. Finally, the NET carbon emissions associated with processing waste wood are 1,311 tonnes per year.

It is important to note that the emissions from waste wood are almost entirely biogenic. This is considered significantly more environmentally friendly than fossil fuels due to the shorter carbon lifecycle, as biogenic emissions are part of the natural carbon cycle, while fossil fuel emissions release carbon that has been stored underground for millions of years. When considering avoided emissions, the total carbon emissions are -5,269 tonnes, as diverting waste wood from landfill reduces methane emissions, a potent greenhouse gas. Additionally, displacing diesel with hydrogen and using energy from natural gas saves approximately c.900 tonnes and c.2,500 tonnes per year, respectively.

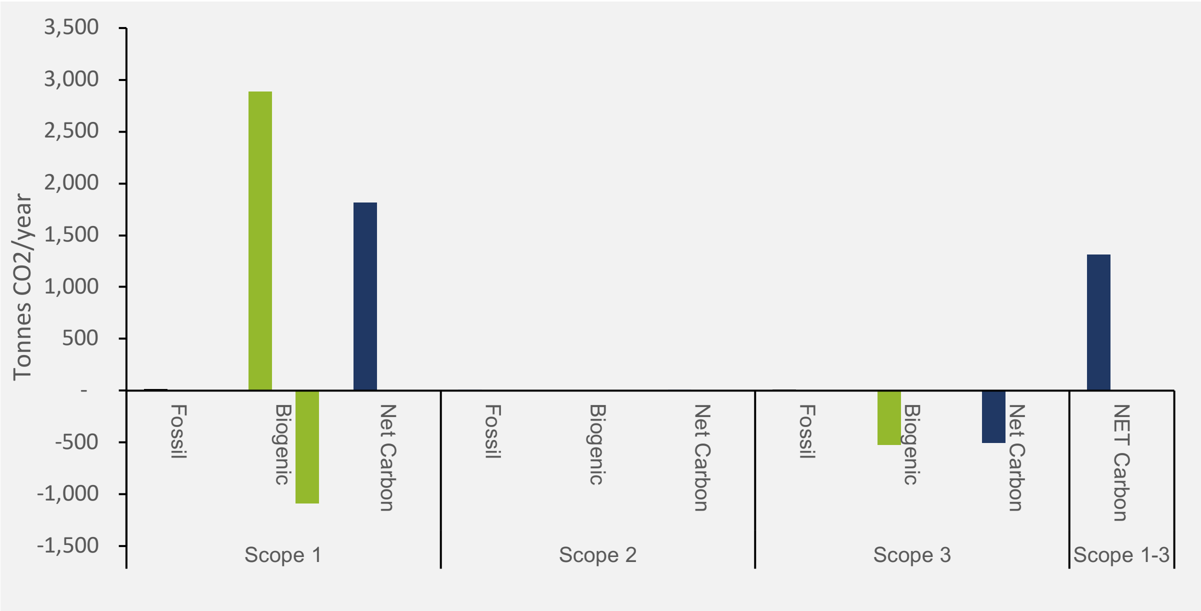


Figure 10 - Waste Wood Carbon Tracker Results

Carbon Tracker - SRF

Figure 11 below shows a summary of the carbon emissions for SRF. The NET Scope 1 emissions are 1,535 tonnes per year. These are offset by 913 tonnes per year due to CSS' carbon capture from the syngas. Additionally, Figure 11 highlights both biogenic and fossil carbon emissions from the stack, resulting from the compositional breakdown of SRF. As with waste wood, the Scope 2 emissions are negligible, based on the assumption that all power used by the office is electric and sourced 100% from renewable energy. Furthermore, the NET Scope 3 emissions are -689 tonnes per year, due to the SRF char locking in carbon indefinitely. Finally, the NET carbon emissions associated with processing SRF are 846 tonnes per year.

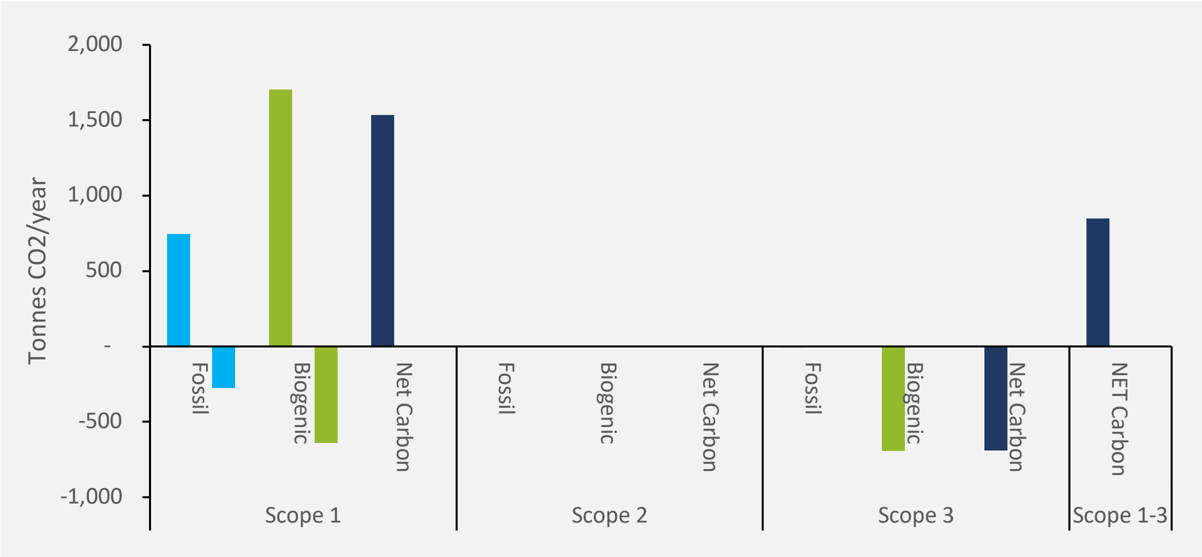


Figure 11 - SRF Carbon Tracker Results

When considering avoided emissions, the total is reduced to -4,672 tonnes because SRF is only partly made up of biogenic emissions and the landfill methane emissions are reduced proportionally. Additionally, displacing diesel with hydrogen and using energy from natural gas saves approximately c.1,050 tonnes per year and c.3,200 tonnes per year, respectively.

6.3.3 Life Cycle Assessment Analysis

The analysis of the carbon emissions for SRF and waste wood feedstocks reveals significant insights into their environmental impact throughout their life cycles. The total plant construction emissions for both SRF and biomass were minimal, contributing only 157 tonnes each due to the similarity in processes. However, the operational emissions showed a notable difference. With SRF the total life cycle emissions were 24,452 tonnes which is 3,903 tonnes lower than biomass due to the higher throughputs of biomass and lower yields of char.

Carbon capture technology played a crucial role in mitigating emissions for both feedstocks. For SRF, carbon capture prevented 19,724 tonnes vs 22,916 tonnes for biomass. Both SRF and biomass carbon emissions could be further reduced by deploying carbon capture on the stack (post combustion).

Table 3 below provides a breakdown of the emissions for the key inputs and outputs for the process.

	ISO 14041	
	SRF	**Waste Wood**
Electricity (kg CO_2/kWh)	0.423	0.497
Feedstock (tCO_2/t feedstock)	0.493	0.489
Hydrogen (tCO_2/tH_2)	16.65	19.58

Table 3 - SRF & Waste Wood LCA Feedstock/Product Emissions

SRF yielded the lowest carbon impact on hydrogen and feedstock processed (16.65 tCO_2/tH_2 and 0.0.493 tCO_2/t feedstock) when compared to waste wood. Furthermore, SRF also generated less carbon per kWh (0.423 $kgCO_2$/kWh) when compared to waste wood.

However, due to the composition of SRF, a proportion of the carbon emitted is fossil carbon whereas, biomass is 100% biogenic carbon which is viewed as less environmentally damaging than fossil carbon due to its shorter carbon cycle.

6.4 Comparison with Alternative Technologies

Hydrogen production technologies vary in efficiency, feedstock, environmental impact, and scalability. Below is a comparative analysis of CSS technology against other existing or alternative hydrogen production methods.

6.4.1 CSS Technology – Green & Blue Hydrogen

Overview
CSS employs an advanced gasification system integrated with complementary technologies for hydrogen production, storage, and carbon capture. It processes various feedstocks, including waste-derived materials, to produce hydrogen that falls between green and blue hydrogen in sustainability.

Advantages

- Versatile Feedstock: Can utilise biomass (e.g. waste wood) and SRF.
- Lower Carbon Footprint: Lower Carbon Footprint: Potentially carbon-neutral or even carbon-negative when combined with carbon capture and storage (CCS).
- Scalability & Modularity: Can be implemented in distributed settings, avoiding reliance on large-scale centralised plants.
- Distributed Production: Can be implemented in localised energy systems.
- Reduced Waste & Circular Economy: Converts waste materials into valuable hydrogen, reducing landfill use.

Challenges

- Feedstock Variability: Performance depends on the quality and consistency of input materials.
- Gas Cleanup Complexity: Biomass-derived syngas contains impurities that need additional treatment.
- Efficiency Variability: Performance depends on feedstock and gasification conditions.
- Technology Adoption: Competes with more established hydrogen production methods, requiring policy incentives.

6.4.2 Steam Methane Reforming (SMR) – Grey & Blue Hydrogen

Overview
SMR is the most widely used method for hydrogen production, converting methane (natural gas) and water into hydrogen and CO_2. When combined with CCS, it is referred to as "blue hydrogen."

Advantages
- Mature & Scalable: Well-established infrastructure with extensive global deployment.
- Cost-Effective (Without CCS): One of the cheapest hydrogen production methods at scale.
- Continuous Production: Provides steady hydrogen output, unlike intermittent renewables.

Challenges
- High CO_2 Emissions (Without CCS): Grey hydrogen contributes significantly to greenhouse gases.
- Natural Gas Dependency: Vulnerable to supply chain fluctuations and price volatility.
- Carbon Capture Costs: Blue hydrogen requires expensive CCS technology, and capture efficiency varies.

6.4.3 Electrolysis – Green Hydrogen

Overview
Electrolysis splits water into hydrogen and oxygen using electricity. When powered by renewable energy (solar, wind, hydro), the process is carbon-free, producing green hydrogen.

Advantages
- Zero Emissions (with renewables): Most environmentally friendly hydrogen production method.
- Energy Storage Potential: Can balance intermittent renewable power generation.
- Increasing Policy Support: Governments worldwide are incentivising green hydrogen production.

Challenges
- High Energy Demand: Electrolysis efficiency is limited (~60-70%), requiring significant electricity input.
- Infrastructure Gaps: Limited large-scale production and transport infrastructure.
- Cost: More expensive than SMR and gasification-based methods unless electricity prices drop significantly.

6.4.4 Thermochemical Water Splitting & Other Emerging Technologies

Newer hydrogen production methods, such as high-temperature thermochemical water splitting and photoelectrochemical (PEC) water splitting, are in the research phase. These technologies could provide future alternatives but are not yet commercially viable. Table 4 summarises the different hydrogen generation options being developed.

	Emissions	Feedstock	Efficiency	Maturity	Cost	Scalability	Challenges	Emissions
CSS Gasification	Lower (with CCS)	Waste, biomass	Medium-High	Emerging/ Developing	Medium	High (modular)	Feedstock supply & variability, gas clean up and policy support	Lower (with CCS)
SMR	High (grey) / Medium (blue)	Natural gas	High	Established	Low (grey) / Medium (blue)	High	CO_2 emissions, gas dependency	High (grey) / Medium (blue)
Electrolysis	Zero (with renewables)	Water & electricity	Medium (60-70%)	Developing rapidly	High	Medium (depends on energy source)	High energy demand, cost	Zero (with renewables)
Thermo-chemical Splitting	Zero (potentially)	Water & solar/heat	TBD	Experiment al	High	Low (early stage)	Technological maturity	Zero (potentially)

Table 4 - Summary of CSS' Gasification Technology vs Other Available Technologies

In summary, CSS' technology offers a unique balance between waste reduction, hydrogen production and carbon capture, making it a promising alternative for sustainable hydrogen. Biomass gasification can be a carbon-neutral alternative but faces feedstock and efficiency challenges. Alternatively, SMR, the current method of hydrogen generation, is heavily dependent on fossil fuels despite being the most cost-effective solution. Electrolysis, a more sustainable source of hydrogen, is very expensive and energy intensive.

We believe CSS's technology stands out for its ability to utilise waste as a feedstock, simultaneously reducing emissions and producing hydrogen efficiently. However, its widespread adoption will depend on continued technological advancements, regulatory support, and economic competitiveness with traditional methods.

The hydrogen market has space for multiple technologies and at CSS we are actively involved in co-location projects that integrate diverse energy solutions. For example, by combining solar power with our MicroHub technology we can ensure a continuous energy supply producing power and heat when needed and seamlessly switching to hydrogen production as required. This flexibility enhances system reliability and supports a more resilient, low-carbon energy ecosystem.

7 Challenges and Solutions

7.1 Technical Issues Encountered

During the development and operation of the demonstration plant, CSS encountered a range of technical and operational challenges. These were addressed through internal innovation, expert input, and adaptive engineering. This section outlines the most critical issues and the actions taken to overcome them.

7.1.1 CO_2 Scrubber Design & Integration

The original CO_2 scrubber design by Atkins was highly complex and too costly to implement and consequently, it was simplified to ensure feasibility. Additionally, the scheme lacked integration with other process components, requiring in-house modifications with support from Bath Process Consultants Ltd (Prof. Kolaczkowski) and Cobalt Energy to ensure connectivity within the system.

7.1.2 HAZID & HAZOP Studies

Significant effort was invested in HAZID and HAZOP studies. Conducting the HAZOP study prematurely introduced rigid design constraints, restricting later stage modifications. This challenge was addressed by leveraging on-site R&D experience and consulting Prof. Kolaczkowski, allowing for some relaxation of constraints under high supervision and a hot-work permit system.

7.1.3 Syngas Compressor Procurement

Finding a syngas compressor that met the required flow and pressure at a reasonable cost and timeline proved difficult. A suitable unit was located originally ordered but never used which required pressure modifications but was secured within budget and time constraints, preventing significant delays.

7.1.4 Water Circulation Pumps Selection

The CO_2 scrubbing scheme required five water circulation pumps. Although centrifugal pumps were the simpler option, concerns about dissolved CO_2 and fine gas bubbles (potential foaming) led to the selection of positive displacement pumps based on advice from Prof. Kolaczkowski. This required detailed specifications, supplier negotiations, and commissioning. Additionally, one pump's operating condition raised concerns, leading to a parallel flow design with a pressure-adjusting control valve to ensure stability.

7.1.5 Liquid Level Control in Column Sumps

A process control challenge arose in managing liquid levels across the four scrubbing columns and the degassing column. Variations in liquid flow impacted levels across units, requiring a custom process control algorithm that combined feedback and feedforward control. The solution allowed controlled fluctuations in the degassing column while maintaining stability in the scrubbing columns.

7.1.6 Vacuum Pump Procurement Issue

A procurement error resulted in a vacuum pump that lacked the necessary capacity due to misinterpretation of flow reference conditions. The pump was repurposed for a separate CO_2 capture R&D project, but a suitable replacement exceeded both budget and timeline constraints. The issue was resolved by acquiring three used vacuum pumps, stripping them down in-house, and rebuilding a working unit using salvaged parts.

7.1.7 Process Control Integration

The system's P&ID included multiple safety features requiring integration into a cohesive control scheme. This system was custom designed to interface seamlessly with the overall process, ensuring operational safety and efficiency.

7.2 Operational/Logistical Challenges

As with all systems that use solid fuels as an energy source, careful consideration is required for the supply chain and management of feedstock. One of the challenges of having a small site where the system has evolved adding many more processes is having enough space to store and manage fuel. The process is more manageable with biomass such as woodchip as this requires less preparation, however when moving to SRF then the decision must be made on a case by case basis on whether to bring in the material as a final fuel, i.e. a prepared pellet or whether this business model makes more financial sense to complete this operation on the process site as heat is available for drying. Typically doing waste preparation as part of the overall scheme onsite is only viable when dealing with over 30,000 tonnes per year, which is enough for 4 x 1000 MWe system as the equipment required for shredding and screening does not scale down too well below this and becomes less viable. When it comes to the CO_2 scrubbing system that CSS has developed to remove CO_2 gas from the syngas, it's important to consider who and where the off taker for this will be. The challenges listed below were highlighted when operating the plant and running trials.

7.2.1 Feedstock Sourcing and Feeding System

Extensive trials were conducted, initially selecting arboriculture woodchip, but this contributed to lower gasifier performance than expected. The decision was made to switch to Grade A waste wood, now supplied by a leading forestry products business.

However, irregular feedstock shapes sometimes caused bridging, requiring mechanical intervention. Although uniform pellets would improve reliability, additional processing costs would increase the Levelised Cost of Hydrogen (LCOH).

7.2.2 Gasifier Performance Issues

The gasifier faced several challenges, including:

- Poor sealing of wood feed and char discharge valves.
- Bridging of biomass and movement of hot zones into undesirable areas.
- Need for improved ignition positioning and redesigned char breaker bar with a more powerful motor.

7.2.3 Hot Gas Filter (HGF) Performance

With two HGFs in parallel, extended trials resulted in an unacceptable pressure drop, leading to shutdowns. To mitigate this, only one filter was used, new filters were installed, and a modified start-up procedure ensured syngas reached 250°C before entering the HGF. While this reduced the pressure drop issues, it led to char fines traveling downstream, affecting the heat exchangers.

7.2.4 Char Fines in Syngas and Heat Exchangers

Char fines carried in the syngas accumulated in heat exchanger HE1, forming a honeycomb-like coke structure with bio-oils. Fines continued to be detected in exchanger condensate and deposits, requiring further mitigation strategies.

7.2.5 Automatic Condensate Drainage

As syngas cooled, condensate (water and bio-oils) formed, restricting gas flow. A manual drainage scheme was converted into an automated system, overcoming negative pressure in the exchanger. This significantly improved syngas cooling efficiency and reduced pressure drop increases over extended trials.

7.2.6 In-line Demister Issues

Removing tube inserts from the final syngas exchanger improved pressure drop but caused water droplet carry over into the demister, increasing condensate load. The demister now needs integration into the automated condensate drainage system.

7.2.7 Syngas Blower Balancing

Balancing the suction and positive pressure of the syngas blower proved complex, as during a trial, pressure drop changed across the hot gas filters and heat exchangers. These trials provided key insights for future commercial-scale blower sizing, which is CAPEX and OPEX sensitive.

7.2.8 Gas Engine and Electricity Generation

Due to budget constraints, a new gas engine was not feasible. Sourcing a used engine was challenging, as it needed to accommodate syngas calorific value (CV) and flow. The final selection had gas inlet flow restrictions, requiring modifications. A genset was connected, enabling on-site electricity production to support the plant's parasitic load, but its integration required additional effort.

In summary, while the demonstration project encountered expected challenges in pioneering new technology, CSS successfully navigated them through agile problem-solving and engineering adaptation. Lessons learned from this phase will directly inform the commercial design and deployment of future MicroHub systems.

8 Key Learnings

8.1 Technical Lessons Learned

There have been many lessons learned in relation to the optimal operating conditions for the gasification system. Biomass and SRF require different air distribution and bed depths to ensure the highest conversion of fuel. The residence time inside the gasifier and removal rates for char/ash are also different, however the CSS system has flexibility to operate in different conditions and we are looking at developing AI within the control system that manages changes in input fuel to ensure that the process automatically optimises as we know that feedstock is unlikely to be completely uniform, particularly with waste applications.

8.2 Policy and Regulatory Insights

8.2.1 Hydrogen

A clearer pathway to hydrogen deployment is urgently needed, along with well-defined mechanisms to incentivise low-carbon solutions. While hydrogen is attracting significant interest across the market, uncertainty remains around how it will be produced and distributed particularly beyond large-scale blue hydrogen projects, which are still 5 to 10 years from full deployment. This lack of visibility creates hesitation among potential off takers who must invest in compatible equipment. The CSS solution offers a compelling alternative: it can be deployed within a relatively short timeframe and eliminates the need for hydrogen transport via road or pipeline by enabling flexible, onsite generation at the point of use.

8.2.2 UK ETS

The inclusion of EFWs in the UK ETS enables higher gate fees when processing SRF, as more revenue can be generated, assuming carbon capture is implemented. Increased carbon tax rates further enhance the commercial viability of producing hydrogen from waste while discouraging the use of the SMR process, which is highly fossil carbon intensive. Additionally, the value of sequestering biogenic carbon creates further revenue opportunities for CSS' technology, particularly through the commercialisation of chars and captured biogenic carbon.

8.2.3 Recommendations for Future Demonstration Projects

CSS has been highly successful in securing government funding for R&D and the construction of demonstration facilities. However, progressing to the next stage and commercialising the product to a level deemed bankable requires a new round of investment to support long-term trials and data collection. Attracting private investment for this phase has proven challenging, largely due to the perceived risks associated with the technology, despite a significant increase in its Technology Readiness Level (TRL). This stage is often referred to as "the valley of death," where many promising technologies fail to reach the market because innovators exhaust their funds before achieving commercial viability.

9 Implications for the Hydrogen Industry

9.1 Role in Decarbonisation and Energy Transition

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

9.1.1 Waste

By processing SRF and waste wood, CSS' technology prevents emissions from the breakdown of biogenic emissions within the SRF and waste wood at landfills. When broken down by microorganisms, methane emissions are generated from the biogenic fraction in each waste steam which is vastly more damaging than carbon dioxide. However, it is important to note that the avoided emissions for SRF are almost half that of waste wood due to the lower biogenic carbon content.

9.1.2 Transport

Hydrogen's diversity offers a broad range of potential for its application in the transportation sector which is proving very challenging to decarbonise. Applications requiring high energy density such as HGVs, buses and the shipping industry can utilise hydrogen to save emissions versus diesel.

9.1.3 Heat & Power

CSS' localised and modular technology enables industrial processes to decarbonise. Typically, these processes use natural gas boilers or engines to provide heat and power to the process. However, both heat and power can be provided locally by CSS' innovative modular technology.

9.2 Potential for Commercialisation and Scalability

9.2.1 Case Study: Circom's Innovation in Waste Management and Hydrogen Fuel Production

Circom

Overview - Circom is a national waste management company that specialises in complex waste streams for multi-site businesses. The company processes up to 2,000 mattresses a day at its Coventry site. Circom recovers as much recyclable material as possible, with the remaining non-recyclable parts turned into Solid Recovered Fuel which is used to power nearby cement kilns or sent to power stations as a renewable fuel. Circom is planning to partner with CSS's to turn unrecyclable waste into hydrogen fuel.

The challenge: Managing complex waste streams - Circom handles around 6,000 tons of mixed textiles annually, with a significant portion proving hard to recycle due to contamination and moisture content. Three shredding lines efficiently break down materials to allow the recovery of clean polyester and metals, while other waste components are converted into fuel sources. High disposal costs for waste materials highlight the need for innovative waste-to-energy solutions.

CSS technology creates a sustainable future for waste management - Circom is working with CSS to assess the benefits of installing a MicroHub to create a new revenue stream in the form of hydrogen fuel. The CSS modular technology offers a cost-effective investment compared with traditional large-scale solutions. The implementation aligns with Circom's commitment to sustainability and interest in hydrogen fuel for its logistics operations.

Key benefits of CSS technology for Circom

- **Efficient waste-to-energy conversion:** Transforms waste materials into a renewable hydrogen fuel source.
- **Carbon capture:** Reduces emissions by capturing and storing carbon during the production process.
- **Net Zero:** The technology will be key to helping the UK reach its Net Zero 2050 target. The production of low-carbon hydrogen from waste materials stops it reaching landfill and creates a fuel that has very low greenhouse gas by-products.
- **Modular scalability:** Extra MicroHubs can be easily added at the site, providing flexibility for incremental investment and expansion.

Strategic partnerships and implementation plans - Circom has committed to trialling hydrogen fuel for its logistics fleet, starting with a dual-fuel truck pilot. Circom's role will also be in supplying hydrogen for this initiative and reinforces its position as an innovator in the waste management industry. However, financial constraints, site availability, and grid connection remain key barriers to the planned summertime implementation timeline.

Conclusion - Circom's innovative approach to waste management and its investment in CSS technology shows the company is a leader in sustainability. By converting waste into renewable hydrogen fuel, Circom is not only addressing the challenges of high disposal costs but also contributing to the broader transition toward greener energy solutions.

9.2.2 Case Study: How Farrall's Group Plans to Decarbonise its Fleet with Hydrogen Fuel

Overview - Farrall's Group is a family transport business based in Deeside, North Wales, that is being pressured by clients to reduce their carbon emissions. After realising that electric vehicles lack the necessary range for long-haul transport, Farrall's has invested in hydrogen technology, including custom-built hydrogen vehicles and retrofitted diesel/hydrogen mixed-fuel options. Farrall's is exploring a partnership with CSS to use the MicroHub technology to convert waste wooden pallets into hydrogen fuel for their vehicles.

The challenge: Decarbonising long-haul transport - Farrall's Group has experimented with electric vehicles but found them unsuitable for long-distance logistics operations due to range limitations. Additionally, Farrall's currently incurs substantial costs disposing of waste wooden pallets, creating both an environmental and financial burden.

CSS technology creates a sustainable solution for transport decarbonisation - Farrall's is located near CSS and this proximity presents an opportunity for Farrall's to work with CSS on a potential joint project, to install an on-site hydrogen production facility that would transform their waste wooden pallets into a hydrogen fuel source. The CSS MicroHub technology offers a practical solution to both their waste management challenges and their fleet decarbonisation goals.

Key benefits of CSS technology for Farrall's Group

- **Waste-to-fuel conversion:** Transforms waste wooden pallets into a renewable hydrogen fuel source.
- **Cost reduction:** Eliminates current waste disposal costs while creating on-site hydrogen production.
- **Emissions reduction:** Supports the company's decarbonisation goals by providing low-carbon fuel alternatives.
- **Self-sufficiency:** Reduces dependence on external hydrogen infrastructure, which is currently severely lacking in the UK.

Strategic partnerships and implementation plans - Farrall's Group is currently looking to retrofit existing vehicles to run on a diesel/hydrogen mix. The planned implementation of CSS's MicroHub technology would complete their hydrogen ecosystem by providing the necessary fuel infrastructure on-site.

Conclusion - Farrall's Group's innovative approach to fleet decarbonisation demonstrates the challenges and potential solutions facing the UK transport sector. By investing in hydrogen vehicles and exploring on-site hydrogen production through CSS technology, Farrall's is addressing both client demands for reduced emissions and the practical realities of long-haul transport. Their story highlights both the difficulties and innovative pathways available in the transition to greener logistics solutions, setting an example for other transport companies facing similar challenges

10 Conclusion

10.1 Summary of Key Findings

The CSS demonstration project successfully validated the technical, economic, and environmental feasibility of decentralised hydrogen production from biomass and waste feedstocks. Key achievements include:

- **Efficient hydrogen production:** The MicroHub demonstrated the capability to produce hydrogen from diverse feedstocks, including waste wood and SRF, producing a hydrogen product stream (95% pure) suitable for use as a fuel in furnaces and as a fuel in engines (e.g. diesel engines) converted to run on hydrogen. This H_2 is not being produced for fuel cell applications, which demand a very high purity (>99.97%) of hydrogen which is very expensive to produce and not necessary in many commercial uses of hydrogen.
- **Integrated carbon capture:** CSS's innovative gasification process captures about 36% of the carbon in the form of char from the gasifier. In a 2nd stage of carbon capture, it was demonstrated that the use of a water-based CO_2 scrubbing process could be used to reduce more of the CO_2 emissions. Thereby approaching a clear 52% reduction in carbon emissions with the two steps demonstrated in the project. This places the scheme in a unique position as it converts waste into energy vectors (electricity, heat, H_2) and it also captures significant amounts of carbon. The carbon trapped in the char being in a form which could be much more easily sequestrated than gaseous CO_2 which requires more pretreatment, compression, and a complex infrastructure to be in place to transport and store to a distant sequestration site.
- **Feedstock flexibility and circular economy benefits:** The system effectively utilises otherwise unrecyclable waste materials, supporting waste reduction, landfill diversion, and contributing to Net Zero goals.
- **Economic viability:** The technology offers multiple revenue streams including hydrogen sales, carbon credits, gate fees, and power/heat generation, especially under future UK ETS conditions.
- **Modular and scalable design:** The MicroHub's compact footprint and decentralised model make it deployable in remote locations, enabling localised energy resilience.

Hence taking all of these various factors into account, it could be argued that this places the hydrogen output from this waste-to-energy gasification process between 'blue' and 'green' classifications.

10.2 Impact on Future Hydrogen Projects

This demonstration reinforces the potential of small-scale, modular waste-to-hydrogen systems to complement larger-scale hydrogen strategies. Key impacts include:

- **Accelerating decentralised deployment:** By removing the need for large-scale infrastructure or extensive hydrogen transport networks, CSS's approach provides a more agile and distributed model for hydrogen adoption.
- **Bridging the infrastructure gap:** With centralised blue hydrogen projects facing long timelines (5–10 years), the CSS MicroHub can fill a crucial short-term gap, offering immediate decarbonisation benefits.
- **Incentivising low-carbon innovation:** The project highlights the importance of policy clarity and investment incentives to de-risk emerging technologies and attract private sector participation.
- **Supporting hard-to-decarbonise sectors:** CSS's technology presents viable hydrogen solutions for transport, heat, power, and industrial applications that lack access to clean energy alternatives.

10.3 Next Steps and Future Development Areas

Building on the success of the demonstration, CSS aims to pursue the following strategic priorities:

- **Commercial deployment:** Transition from demonstration to commercial-scale projects through partnerships with off-takers and investors, with a focus on high-potential applications such as industrial clusters and off-grid energy.
- **Extended feedstock trials:** Expand testing across a broader range of feedstocks to further validate system robustness, improve operational efficiency, and unlock new waste streams.
- **Technology optimisation:** Continue development of AI-assisted control systems for automated optimisation based on real-time feedstock variability.
- **Carbon capture enhancements:** Investigate post-combustion CO_2 capture from the syngas engine to further improve overall carbon performance.
- **Policy engagement:** Collaborate with government and industry bodies to shape supportive policy frameworks, particularly around hydrogen offtake, carbon credits, and waste incentives.
- **Investor readiness:** Secure long-term trials and financial modelling to support technology bankability and unlock private investment, helping the solution bridge the "valley of death."

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