COMPACT SYNGAS SOLUTIONS
GREENER FUELS FOR A CLEAN FUTURE

MicroH2-Hub

Modular Gasification Technology for the Production of Hydrogen from Waste

Contents

1. Glossary

AD	Anaerobic Digestion	ML	Machine Learning
AI	Artificial Intelligence	CH4	Methane
ASH	Ash Waste Services	N2	Nitrogen
BEIS	Department of Business Energy and Industrial Strategy	OPEX	Operational Expenditure
CV	Calorific Value	OSA	Operational Service Agreement
CAPEX	Capital Expenditure	O2	Oxygen
CO_2	Carbon Dioxide	QMS	Portable Mass Spectrometer
CO2e	Carbon Dioxide Emissions	PSA	Pressure Swing Adsorption
CO	Carbon Monoxide	PFD	Process Flow Diagram
Cl	Chlorine	PLC	Programmable Logic Controller
CSS	Compact Syngas Solutions	PEC	Pure Energy Centre
DSEAR	Dangerous Substances and Explosive Atmospheres	QTECH	Q-Technologies
E-nose	Electronic Nose	RDF	Refuse Derived Fuel
EIA	Environmental Impact Assessment	RTFO	Renewable Transport Fuel Obligations
GW / kW	Gigawatt / kilowatt	SAM	Serviceable Attainable Market
GHG	Greenhouse Gas	SOM	Serviceable Obtainable Market
HAZOP	Hazard and Operability Study	SME	Small Medium Enterprise
HGV	Heavy Goods Vehicle	SRF	Solid Recovered Fuel
HCl	Hydrochloric Acid	SMR	Steam Methane Reformation
H2	Hydrogen	S	Sulphur
I&C	Instrumentation & Control	Syngas	Synthesis Gas
LoPA	Layers of Protection Analysis	TRL	Technology Readiness Level
LCOH	Levelised Cost of Hydrogen	TC	Thermocouple
LCH2	Low Carbon Hydrogen Supply 2 competition	TAM	Total Attainable Market

2. Executive Summary

This feasibility study has successfully proven the Compact Syngas Solutions (CSS) gasifier and associated Pressure Swing Absorption (PSA) system is capable of producing a high purity stream of hydrogen gas from syngas generated by Solid Recovered Fuel (SRF). This study has been successful in its objective to uprate the Technology Readiness Level (TRL) from 4 to 6 by hitting the following technical milestones:

- SRF briquettes produced with 40% biogenic content to allow claiming of Renewable Transport Fuel Obligations (RTFO) subsidies.
- Briquette flow suitability assessed and no disadvantages shown.
- SRF feedstock shows little difference to syngas generation compared to biomass feedstocks.
- Optimisation of the gasifier pushed syngas hydrogen composition up to 16.25 wt%. Oxygen enrichment pushing this figure up to 26.21%.
- A large-scale PSA and pre-scrubbing system has been developed. This has produced a 98% pure hydrogen product stream at kg scale.
- E-nose and portable mass spectrometry systems can provide a low-cost solution to gas species identification for the purpose of process control.
- The hydrogen gas produced by the gasification process is suitable for storage and distribution with low risk of liquification.

This study has allowed the engineering design of the CSS system to progress, with Process Flow Diagrams (PFDs) outlined within this report which shall form the basis of the design of a full-scale demonstration unit. This shall take the existing design from TRL6 to TRL8. CSS has collaborated with ASH Waste Group to progress a planning application for a demonstration plant at the ASH Wrexham site. The application has passed pre-planning and the Environmental Impact Assessment (EIA).

Comparing the plant to the predominant technology Steam Methane Reformation (SMR):

- Carbon emissions are low to negative in the range of -200 – 100 g Carbon Dioxide Emissions (CO2e) / kWh, compared to SMR at 305 gCO2e / kWh.
- Capital cost is low at £5.7M compared to £144.1M.
- Plant area is low being up to 800m2 compared to up to 17,500m2.
- Hydrogen yield (61% compared to 66.6%) and purity (up to 98% compared to 99%) are similar for both plants.
- CSS LCOH is £120 £ / MWh, compared to SMR £39.60 £ / MWh. Whilst comparatively high, SMR benefits from significant economies of scale.

Comparison is made to SMR as the current main contributor to the UK hydrogen economy. CSS' target market is small-scale waste disposal operations with ambitions to decarbonise with hydrogen which may not be readily accessible – which CSS has proven to be of similar affordability. Market assessment has indicated there is a Total Attainable Market (TAM) of £7.9bn. CSS has screened this market to a Serviceable Attainable Market (SAM) of £797m, and Serviceable Obtainable Market (SOM) of £241m.

CSS estimates that over the next five years approximately 46 MicroH2-Hubs will be sold generating 30kg/hour of hydrogen per module. This will feed 400,000 MW annually in the UK hydrogen economy and provide an additional waste disposal capacity to the UK waste sector of 400,000 tpa – particularly for hard to dispose wastes such as biomass and Anaerobic Digestion (AD) residues. CSS aims to license the plant design from 2027 onwards to allow large-scale rollout.

With further funding in phase 2 CSS will develop a commercial demonstrator. The objective of this project is to upscale the plant; building on the engineering knowledge gained from this study. The plant will run for 1000 continuous hours to prove the performance of the plant.

3. CSS Project Overview

3.1 Introduction

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

To support decarbonisation and development of the UK hydrogen economy the Department for Business, Energy, and Industrial Strategy (BEIS) has launched the Low Carbon Hydrogen Supply 2 competition (LCH2) to provide funding to develop a wide range of innovative low carbon solutions.

Compact Syngas Solutions (CSS) uses gasification to produce a low carbon hydrogen. The gasification process generates a synthesis gas (syngas) from readily available waste streams such as Solid Recovered Fuel (SRF) and low-grade waste wood. The syngas contains hydrogen which is removed by a novel Pressure Swing Adsorption (PSA) technology to produce a high purity hydrogen product.

SRF is derived from waste streams and therefore the CSS process has a dual benefit of producing hydrogen using low carbon fuel (i.e., the waste has served a useful life) and waste is diverted from landfill. The fuel developed for the CSS gasifier can also utilise low grade waste wood (grade C) which would otherwise be disposed of to landfill. Furthermore, the CSS process is self-sustaining requiring no fossil fuel support or energy from the grid whilst operational.

The hydrogen produced is intended, and is suitable, for use in vehicles. This is in line with the UK Hydrogen Strategy indicating HGVs, rail, and shipping to be widely using hydrogen as a fuel by the late 2020s. However, currently there are only 14 hydrogen fuelling stations in the UK (which are predominantly located in Greater London [3]). CSS further aspires to produce hydrogen in accordance with the Renewable Transport Fuel Obligation (RTFO) to enhance the projects financial viability beyond government funding.

The CSS solution is small and modular producing 1 MW of hydrogen at sufficient quality for internal combustion engines which have been converted to hydrogen systems. Its simple design can be paired with hydrogen storage and distribution systems. The aim of CSS' is to provide a system which can be used for local generation where access to mains supply of hydrogen is limited. CSS' target market is waste management companies with an ambition of decarbonising.

This report outlines the works completed in phase 1 of LCH2 to assess the feasibility of the CSS design, assess its financial and environmental viability, and develop a plan for further development, demonstration, and roll out to provide an additional 400,000MW per annum of hydrogen supply over the next 10 years.

3.2 The CSS Solution

CSS own the exclusive right to use the gasification technology developed by Refgas Limited (sister company to CSS); an established and award-winning solution. CSS' objective was to adapt the technology for uses beyond power generation.

Figure 1 shows the process flow diagram (PFD) of the core gasification technology. This system generates syngas through heating fuel to a high temperature (>850°C) with limited oxygen supply, and then scrubs the gas for impurities such as tars. The syngas produced contains high amounts of hydrogen and other combustible gases such as methane and carbon monoxide.

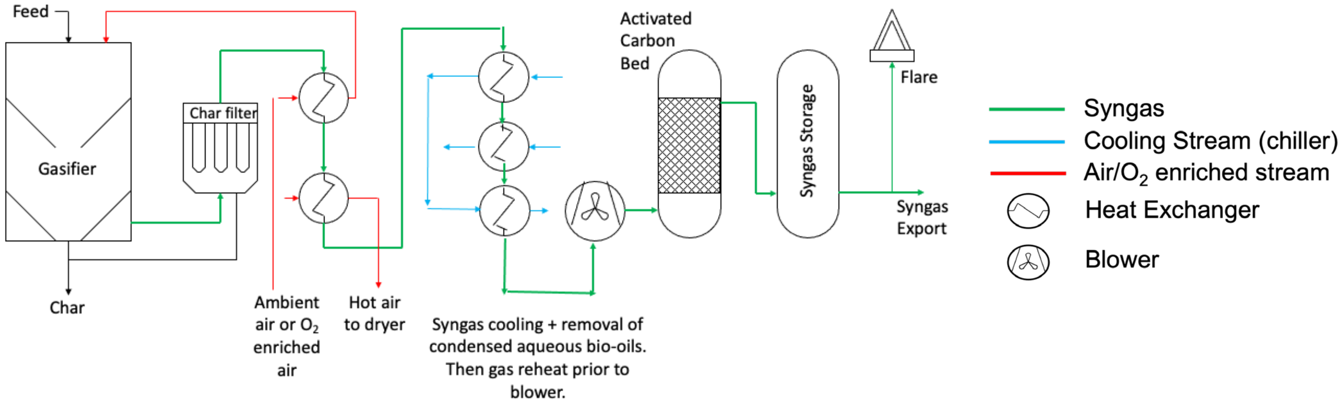

Figure 1 ***PFD of the core gasification technology developed by CSS.***

To purify the hydrogen CSS has developed a pressurisation set and PSA system to extract a pure hydrogen product. The residual syngas is passed to an engine to generate electricity for the plant, whilst hydrogen is passed on for storage and distribution to filling stations. This is shown in Figure 2 below. It was necessary to develop a bespoke PSA for the following reasons:

1. No suitable commercial PSA unit exists for the purpose and size required for the CSS system.
2. Suppliers offered to produce a bespoke system at a cost of €1M which is unacceptable for the available budget of a demonstrator unit.
3. Syngas is a difficult fluid to work with due to tarring and other contamination issues which would require any supplier to complete significant R&D which CSS has already completed.
4. CSS would own no IP in the PSA and be reliant on third parties to provide a turn-key solution.

Further optimisation can be achieved by the use of an electrolyser to supplement hydrogen generation and provide enrichment oxygen for the gasification system (replacement to ambient air in Figure 1 above).

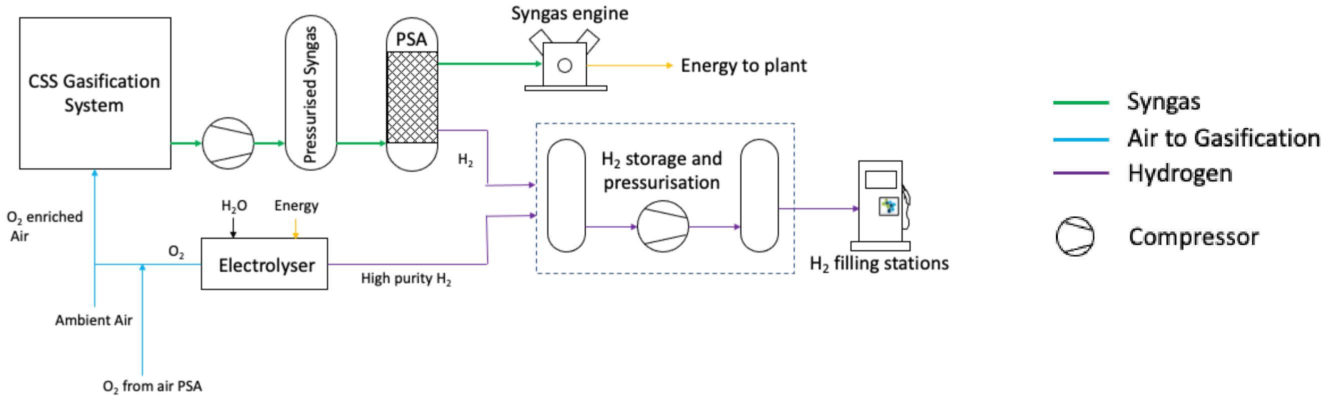

Figure 2 ***Process flow diagram of the CSS solution following feasibility study works for optimisation of hydrogen production.***

Further improvements have been made during this LCH2 Phase 1 feasibility study, this has been done in collaboration with a consortium of expert organisations:

- Ash Waste Services Ltd (ASH) – providing expertise in waste recycling and fuel preparation to aid feedstock optimisation and security of supply for a Phase 2 demonstrator project.

- Q-Technologies Ltd (QTECH) – providing expertise in sensor and artificial intelligence (AI) technologies to improve the gasification control systems.
- Pure Energy Centre Ltd (PEC) – providing expertise in electrolysis and hydrogen storage and distribution of the hydrogen.

The core gasification technology developed by CSS is established and is considered Technology Readiness Level 8 (TRL) in accordance with BEIS guidance.

However, the gasification process has been supplemented by additional processes as developed by CSS and the wider consortium, namely:

- Introduction of PSA technology.
- Addition of multiple sensors inclusive of mass spectrometry and an E-nose.
- Introduction of multiple waste streams.
- Addition of hydrogen storage and distribution using PEC proven technologies.
- Addition of an energy control management system and AI/ML.

Therefore, the expected TRL of the overall combined process at the onset of the LCH2 competition was TRL4.

Phase 1 of the LCH2 competition aims to demonstrate that it is technically and economically feasible to produce low carbon hydrogen efficiently using the combination of technologies outlined above and to complete the research and development necessary to bring the process to TRL6.

The works carried out in Phase 1 will then provide the blueprint plant design for Phase 2 of the LCH2 competition, allowing a commercial pilot to be constructed and further improving the system to a projected TRL8.

3.3 Objective of Phase 1

The primary objective of Phase 1 was to improve the TRL level of the combined process from TRL4 to TRL6 and prove the feasibility of the project. This was done through the following objectives:

- Assessment of feedstock preparation feasibility and its availability (i.e., securing reliable waste streams).
- Using a wide range of feedstock to understand the process limitations of the gasification system using SRF.
- Thorough testing of the air enriched with O2 to reduce nitrogen levels in the syngas to increase hydrogen production to 25 - 30% composition of syngas.
- Significant gasification trials to assess the stability of high hydrogen production on a continuous basis (previous works have been on a batch basis).
- Trialling of the PSA test rig to assess separation performance and fouling of the absorption media. This will be used for scale-up of the PSA system.
- Development and testing of the mass spectrometer and E-nose systems to validate performance with all syngas compositions.
- Development and testing of a novel AI to help digitalise the process for scale-up, improving the overall energy management system, and ultimately improving efficiency.
- A complete lifecycle assessment of a pilot scale project, providing robust operational and commercial data to secure funding for commercialisation.

4. Phase 1 Feasibility Study Results

4.1 SRF Feedstock Development

To maximise the performance of the gasifier and subsequently hydrogen generation CSS has engaged ASH with the objective to review the available waste market to produce an SRF feedstock which is suitable for the process. This included:

- Assessing the future availability of feedstocks and alternative fuels.
- Identifying the requirements for RTFO subsidies and assessing the feasibility of modifying the fuel to accommodate this.
- Outlining a process design for a fuel preparation system.

4.1.1 Feedstock Preparation

Over the course of this feasibility study ASH has supplied and produced the feedstock used in the gasification process. The feedstock was produced and optimised to:

- Maximise hydrogen composition in the generated syngas.
- Assess the feasibility of using briquette or pellet-based fuels.

ASH developed feedstocks in accordance with a specification provided by CSS, namely requiring a dry calorific value (CV) of 18-24 MJ/kg, an ash content of <25% (by weight), Cl of below 0.8g / kg, and a moisture content of <20% (by weight). The feedstock also needed to include high SRF contents to ensure diversion from landfill, and a high biogenic content to target RTFO subsidies.

The above requirements have been formulated into the following fuel matrix:

Material	ASH Annual Available Tonnage	Composition (%)	Preparation
RDF 350 mm	40,000	60	Raw
Biomass Process Residuals	7,000	40*	Finished to 10 – 40 mm
Anaerobic Digestion Residuals	5,000	40*	Finished to >5 mm
Biomass Grade C	2,000	14**	Finished to 50 mm
Biomass Fines	1,200	13**	Finished to 3 mm
Blue Mac Lights	3,000	13**	Raw
RDF Lights	5,000	0**	Raw

***Table 1** Fuel Matrix for suitable fuel composition to the CSS gasifier.*

Biomass or AD residuals can be used interchangeably to complete the feedstock %
*****Materials that can be used to supplement low supply of biomass or AD residuals***

Originally CSS optimised the gasifier using a pelletised feedstock. Pellets show good flow through the gasifier, however, require significant preparation leading to high costs. Briquettes were trialled at significantly lower production cost. 100% SRF briquettes disintegrate in the gasifier and perform poorly, however integrating biogenic fuels, such as anaerobic digestion (AD) and biomass wastes, improve briquette "stickiness", resulting in performance improvements.

Table 2 below shows a summary of performance of different types of fuels trialled over this feasibility study; namely woodchip pellets (used as a counterfactual), SRF pellets, 100% SRF briquettes, and 60% SRF briquettes (blended with 40% biomass).

Type	Waste woodchip	SRF Pellets	RDF Briquettes	Blended Briquette
Fuel Input (kg)	240	212	207	215
Syngas Production (m3/ hour)	401	420	398	405
Syngas Average CV (MJ/Nm3)	5.55	5.07	5.6	4.82
Char Produced (kg)	17	22	37	32
Efficiency (%)*	59.06	57.33	56.23	57.79

***Table 2* Performance comparison of various feedstock trials to the CSS gasifier relative to a biomass (waste woodchip) counterfactual.**

Cold gas efficiency - does not include any heat that can be recovered from syngas cooling.

Trials with pellet and briquette feedstocks showed very little difference in syngas generation with a cold efficiency of approximately 57.33% and 57.79% respectively. The focus of the trials therefore shifted to optimisation for material flow characteristics and cost production of the feedstock.

Pellets show good flow through the gasifier, however the material can "hold up" in the top section of the gasifier; not reaching the gasification zone. Pellets may also pass too quickly through the reactor, being rapidly pushed through the gasifier throat resulting in non-gasified feedstock being discharged into the ash system. 16mm pellets show optimum flow characteristics if using a pellet feedstock.

Briquettes show no hold up or rapid carry through and combust uniformly, however the existing feed system has been developed for pellet feedstocks. Trials highlighted blockages may occur, therefore all future developments will use a shortened "puck" type briquette with an adjusted feed screw to prevent blockages.

Both pellets and briquettes command a gate fee for disposal, however pellets are more costly to prepare. CSS expects gate fees of £60/ tonne and £30/ tonnes for briquettes and pellets respectively; where the feedstock preparation system is installed "in-house".

ASH has developed a process design for the preparation of briquette feedstocks for the CSS gasifier. This is shown in the Process Flow Diagram (PFD) in Figure 3. The process design is predominantly fixed however the use of trommels, and separators allow the process to be modified should the feedstock availability (Table 1) change.

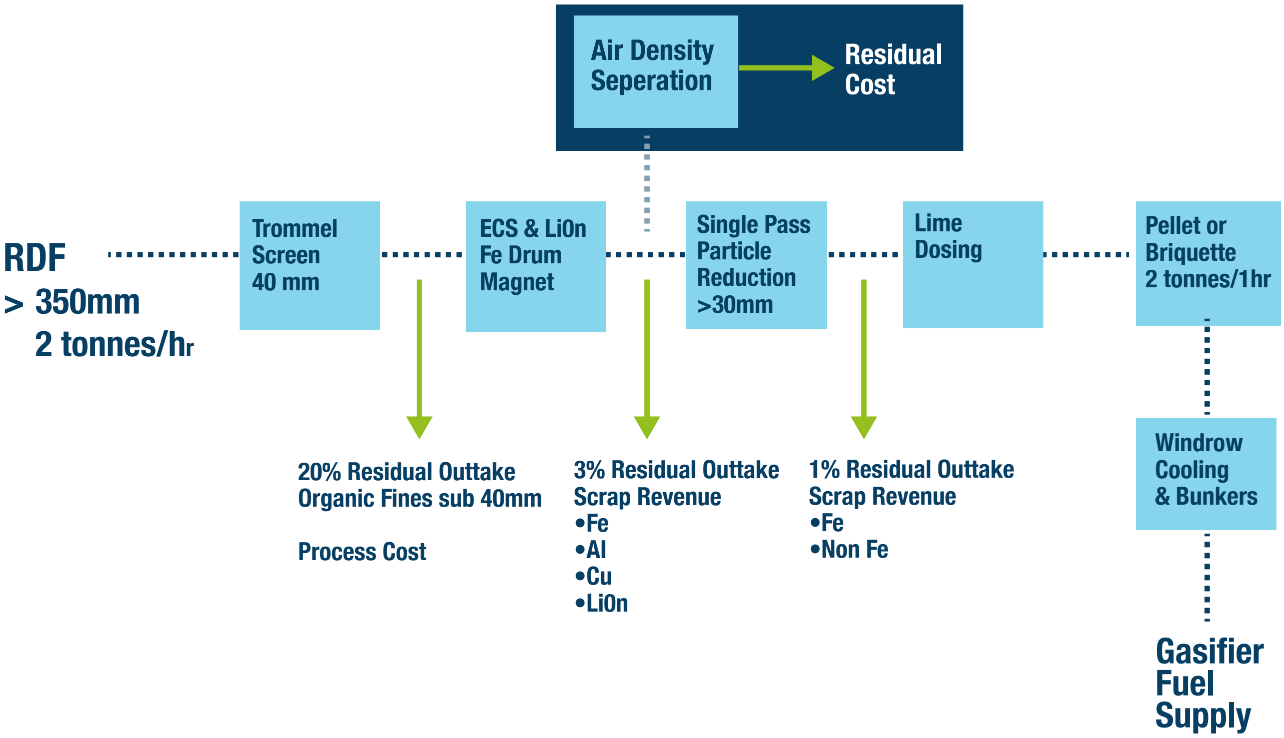

Figure 3 ***PFD of fuel preparation systems necessary to produce briquettes for the CSS gasifier.***

To summarise, the performance, flow characteristics, and market availability of a 60%/40% SRF/biomass briquette is optimum for a viable gasification project. CSS intends to use this feedstock for future development.

4.2 Design Optimisation of the CSS Gasifier

The CSS gasifier was originally designed and optimised using biomass pellets and waste woodchip. This underpins the feasibility of using gasification for the generation of syngas with high hydrogen content using a small-scale modular system.

Trials with SRF feedstocks are critical to validating SRF feasibility, with CSS' overall objective to achieve similar or better performance of syngas and hydrogen generation when compared to a biomass feedstock.

CSS also target other objectives including:

1. Trialling air enrichment processes to optimise the oxygen content fed into the gasifier.
2. Developing and improving the PSA system with back-flush systems to maximise hydrogen purity.

4.2.1 Initial SRF Trials and Feedstock Analysis

As outlined in Table 2, initial trials with SRF feedstocks showed comparable performance to biomass feedstocks. Figure 4 below, shows syngas generation for an SRF trial, with little fluctuation of product gases over time. Using SRF also showed no significant effect on Calorific Value (CV) of the syngas.

The trials did identify SRF increases differential pressure in the system. This effectively reduces syngas production, shown in the gradual downturn in generation over time. This is likely due to issues with gasifier agitation being optimised for biomass. Review of the gasifier agitator is planned for the Phase 2 demonstrator plant.

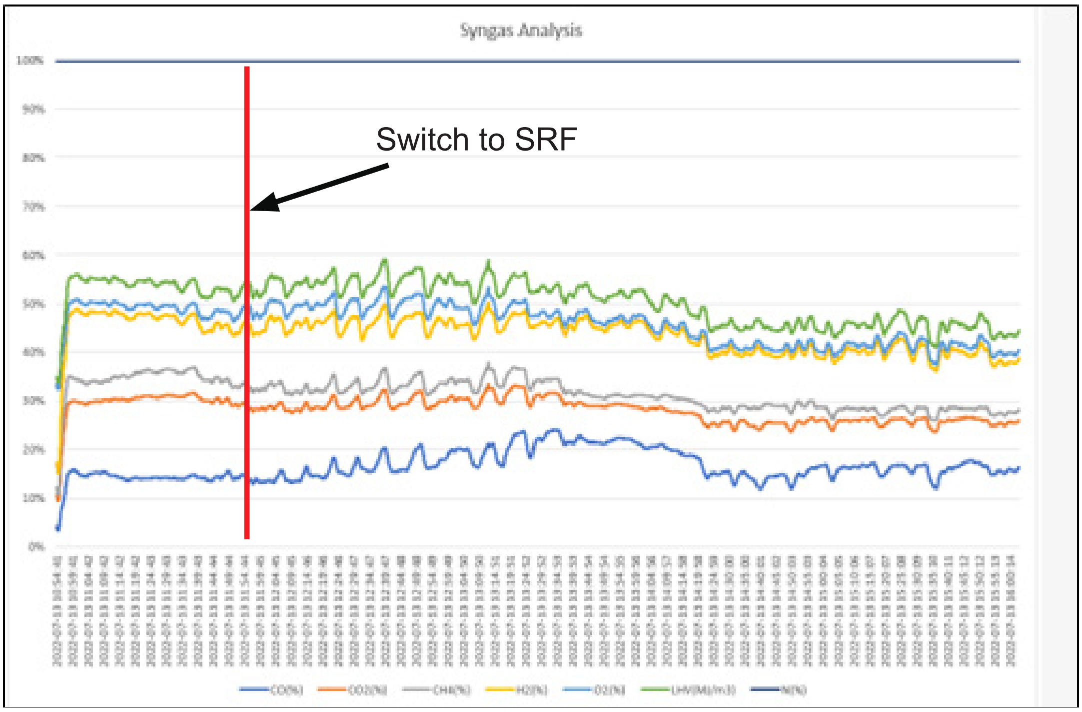

Figure 4 ***Syngas generation over time during extended trialling of SRF pellet gasification.***

Chemical analysis was also completed on the SRF with the following observations:

- Moisture content of SRF pellets is low compared to biomass. This may affect the water-gas shift reaction which produces significant amounts of hydrogen.
- Ash content is as expected for SRF (i.e. higher than biomass), therefore a higher feed rate is necessary compared to a biomass feedstock to ensure sufficient syngas generation. This also affects the amount of char produced.
- Species such as NH3 and HCl may be generated from SRF which may solidify and affect gas clean up.

The primary method of tuning the performance of the gasifier is through modulation of air supply. CSS has focused air injection to the front of the reactor throat when using SRF. This shows significant uplift in hydrogen generation from 11.69 wt% of generated syngas to 16.25 wt%, evidenced by on-line analysis shown in Figure 5 below.

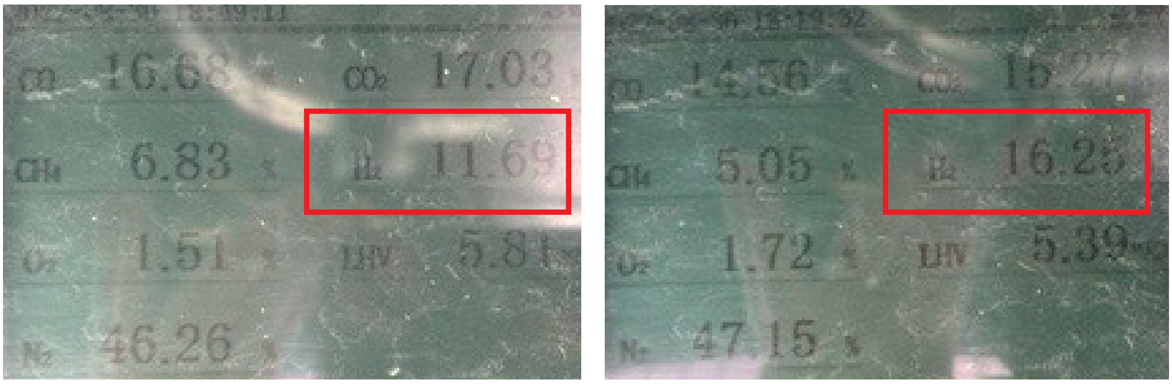

Figure 5 ***Syngas composition analysis before (Left 11.69) and after (Right 16.25) optimisation of air injection for SRF feedstock.***

Further optimisation was possible through the installation of eight additional thermocouples (TCs). TCs were originally only installed in the throat area of the gasifier. Additional TCs in the cone of the gasifier allows trending of temperature across different gasification zones and focus throat temperature to reduce methane production – in turn increasing hydrogen production.

A datalogger was also installed to record data directly from the control system which has eliminated manual readings; allowing proper trending of data over time. This will allow improvements to process automation.

CSS uses air enrichment to increase the Oxygen (O2) content of air injected into the gasifier. N2 levels in the injected air are reduced (and consequently syngas N2 levels) which increase syngas calorific value and reduces compression requirements. This results in:

1. Syngas still being capable of powering an engine with hydrogen removed.
2. %H2 in the syngas increasing so a smaller amount of syngas needs to be generated for equal hydrogen yield, resulting in size reduction of process unit and a reduction in capital costs.

CSS has completed enrichment trials by injecting bottled O2 into the gasification air stream. However, bottled O2 causes significant cooling of the gasifier throat which reduces hydrogen generation. Pre-heated O2 injection shall be trialled in subsequent demonstrator units.

Optimisation as described above has resulted in increasing syngas %H2 from 24.43 wt% to 26.21 wt% as evidenced in Figure 6 below.

Figure 6 ***Syngas composition analysis with O2 air enrichment at 60% (Left 24.43) and 65% (Right 26.21).***

CSS is confident that preheating the enriched air will further increase hydrogen composition in the syngas to 30 or 35 wt%.

4.2.2 PSA System Development

CSS uses a PSA system to extract hydrogen from syngas, releasing it as a pure product. At the onset of this feasibility study the PSA system was a prototype which has now undergone significant trialling and improvement.

To verify suitability of the generated syngas for the PSA, CSS took samples to identify contaminants which may poison the bed media (i.e., prevent its adsorption action). Sampling identified significant chlorine, sulphur, and hydrocarbon contaminants in concentrations able to poison the PSA bed.

CSS has therefore developed a adsorption unit to remove contaminants from the syngas stream before being passed through the PSA, with laboratory scale sampling data showing high performance of contaminant removal.

The PSA system was originally trialled using bottled syngas (pressurised to 7 bar) with pilot trials extracting hydrogen gas at 97% purity. The trials also highlighted the need for back flushing of the PSA beds (i.e. clearing the bed material). When clean, trials showed the PSA was capable of extracting 99% pure hydrogen.

Syngas releases from the process at 0.2 bar, therefore a compressor is used to connect the gasifier to the PSA system. Trials using unbottled syngas showed the PSA system could extract a 98% pure hydrogen gas stream. Figure 7 below shows the schematic of the final design for the PSA system including the purge systems.

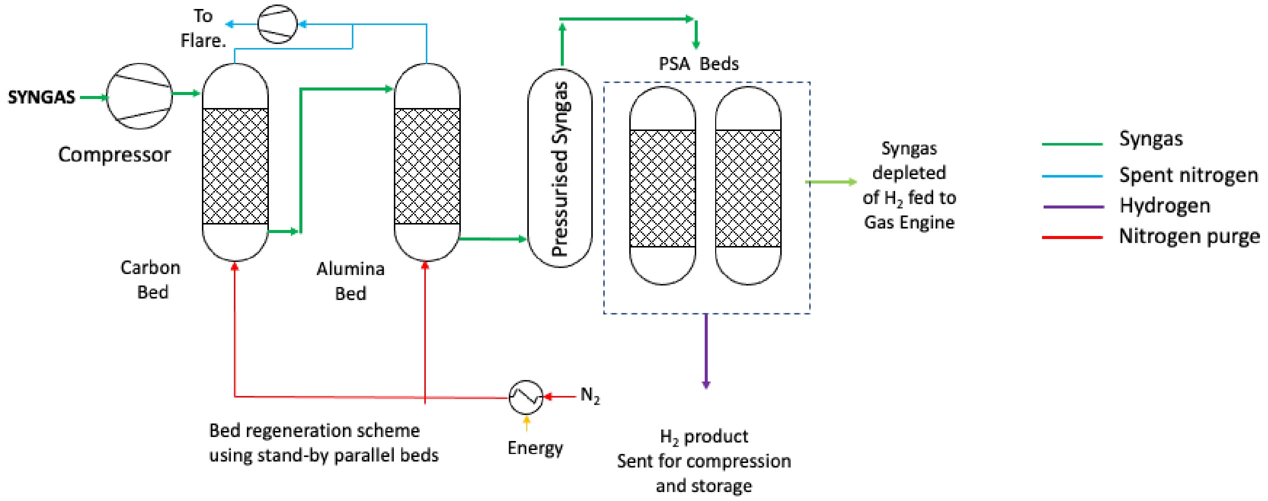

***Figure 7* Schematic of the compressor and PSA adsorption systems to produce pure hydrogen and "clean" syngas; including schematic of the nitrogen purge systems.**

Extended PSA trials were completed using SRF feedstock. SRF pellets showed successful generation of hydrogen generation from waste, although performance was slightly lower than biomass with a 98% pure hydrogen gas stream produced.

4.2.3 Process Residues

The gasification process results in char and water residue generation. Both residues currently do not have end-of-waste status and therefore must be disposed of appropriately as hazardous wastes.

CSS has taken samples of the water residue produced. The residue is highly contaminated with heavy metals, hydrocarbons, and other chemical compounds. For this reason, third party disposal continues to be the most financially viable solution, with viability expected to be reached when four combined CSS modular gasification units are in operation.

CSS has also sampled the char produced from the gasification process. Char is generally used to aid the agricultural viability of poor-quality land, and considered an important part of carbon sequestration [4]. CSS is currently reviewing the possibility for disposal through sustainable routes by achieving end-of-waste status. Landfill disposal therefore currently continues to be the most financially viable route at present due to the need for end-of-waste status for char.

CSS intends to further research and develop residue treatment systems.

4.3 Sensor Suite Development

The gasification process can produce variability in the syngas produced, with composition fluctuations occurring often and rapidly within an operational band. Instrumented control loops are used to manage this however this is difficult with traditional instrumentation due to the harsh environment of the gasification process.

QTECH has developed a Portable Mass Spectrometer (QMS) system and Electronic Nose (E-nose) to "sniff" for chemical compounds, directing process control to optimise hydrogen production. The objective therefore was to develop a smart system that is:

1. Capable of giving qualitative and quantitative identification of different combustible chemical species produced by the CSS gasifier.
2. Suitable for deployment in the process environment.

4.3.1 QMS & E-Nose Performance

Trials were conducted to assess the performance of the selected QMS and E-nose arrangement. Five test points were created to sample syngas at discrete intervals of the gasification process. This includes the gasifier outlet, multiple points in the scrubbing system, and the syngas storage vessel.

Figure 8 below shows an extract of results recorded by the QMS and E-nose system.

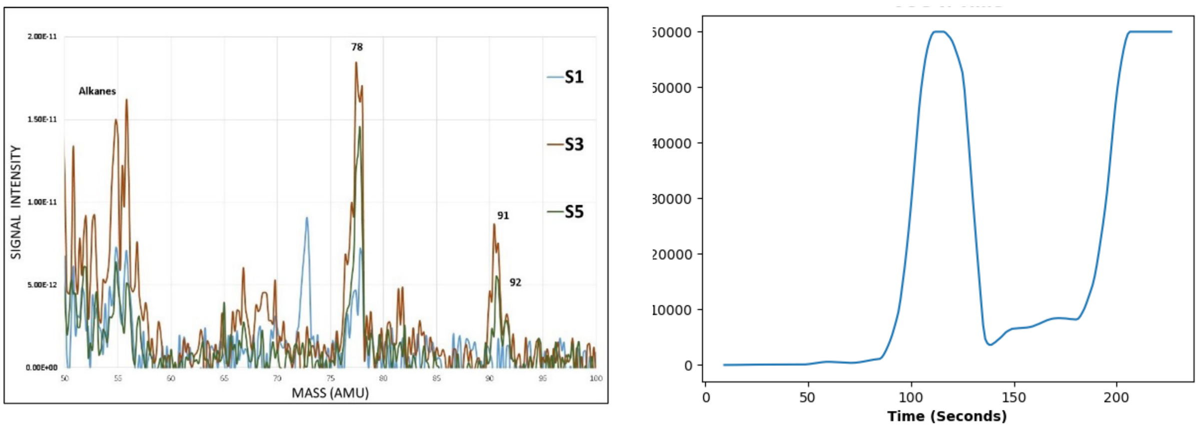

***Figure 8** - Mass Spectra (Left) showing gas concentrations with clear peaks at 40-50 AMU (alkanes), 76-79 AMU (benzene) and 90-92 AMU (toluene). E-nose Spectra (Right) showing volatile organic compound detection.*

As shown in the right-hand spectra the signals may become saturated (flatline). Therefore a “sniffing” approach will be adopted at commercial scale. Sniffing refers to periodic sampling rather than continuous.

Overall, the trials demonstrate use of QMS and E-noses are feasible for in-situ gas measurement; with low cost instrumentation capable of providing qualitative and quantitative syngas composition analysis whilst online. Trials have allowed detailed selection of E-nose sensors for commercial use.

4.3.2 AI Development

QTECH have designed an Artificial Intelligence and Machine Learning (AI/ML) which takes qualitative readings from the E-nose and QMS, converts this to a quantitative measurement, and compares this against a calibration curve. This will then drive the process control system.

The AI is based on a Gaussian Process Regression due to its performance during testing . It has been trained using a dataset of known gas cases quantified by the QMS. This process will be repeated with syngas samples to uncover patterns when multiple target compounds are present, and adjusted the AI behaviour.

Proof of principle for the AI control system has been tested in two ways:

1. **Open loop control:** using syngas samples from the gasification system to generate signals which the operator manually reacted to on a local display.
2. **Closed loop digital control:** taking an on / off control signal from the E-nose instrumentation to an Arduino microcontroller which was sent to a local controller.

These systems have currently only been tested within QTECH’s laboratory. Full integration into the CSS system will be done at commercial scale through:

1. **Open loop control:** by displaying the measurements of gas concentration directly on the gasifier control panel allowing operator control decisions.

2. **Closed loop control:** feeding the measurements to the gasifier control system allowing the microcontroller to make the changes in the system.

4.4 Hydrogen Storage and Distribution

PEC have completed an analysis of the hydrogen produced by the CSS process to assess compatibility for storage, considering the lower grade purity (i.e. below 99% hydrogen purity).

PEC's analysis indicated the conditions of the process are favourable to maintain the gaseous contaminants in the hydrogen stream (CO, CH4, O2, N2, CO2, H2) in a gaseous form, and therefore the CSS product stream can be stored safely in a hydrogen storage system.

The system will require the use of type I (all metal) storage systems, and type 3 (fully wrapped carbon composite) vessels for onboard hydrogen vehicles. However, prior to system installation a validation assessment is likely required by equipment suppliers; to be completed for a commercial unit.

5. Demonstrator Plant

5.1 Objectives

CSS has demonstrated the gasification process is suitable for use with an SRF feedstock to generate high quality hydrogen gas. However, a further demonstration plant is required to achieve the following objectives:

- Scale up the gasification process to 1 t/hr of SRF feedstock (current 500 kg / hr) and verify the production of 30 – 35 kg / hr of hydrogen.
- Finalise engineering designs for the gasifier, including the development of dual PSA lines to allow continuous operation.
- Complete a full engineering due diligence to identify process risks, including HAZOP, LoPA, and DSEAR study updates.
- Complete a full construction engineering package, including civil and structural design, and access & maintenance assessments.
- Develop construction health and safety plans for the safe construction of future turn-key solutions.
- Verify the cost model for the construction and operation of the plant.
- Verify the feasibility of the feedstock and its compliance to RTFOs.

This will help support the growth of the hydrogen economy by providing a small-scale hydrogen generation plant that will provide a local hydrogen source for areas without hydrogen infrastructure in place, whilst simultaneously providing a disposal route for almost 8,000 tonnes of waste per year.

5.2 Design of the Phase 2 Project

The Phase 2 demonstrator project is expected to be split into four discrete phases:

1. **Permissions and Engineering (2 – 3 months from mobilisation)** – Permissions must be granted to complete the installation of the demonstrator project including planning and environmental permits.

The engineering design of the Phase 2 project will remain consistent with the designs outlined in Figure 1, Figure 2 and Figure 7 at a higher scale as identified in the objectives. However, improvements based on this feasibility study shall be made as follows:

- Review of the fuel feed system to allow handling of larger fuel particles.
- Review of the mechanical agitation system within the gasifier.
- Integration of a pre-heated oxygen feed system using electrolysis.
- Engineering design of parallel syngas treatment systems (PSA / Adsorption).
- Review and development of residue treatment systems where feasible.
- Final selection of E-nose sensors and their arrangement, and integration of the sensor suite with an AI/ML for process control.
- Validation of suitable hydrogen storage systems.

2. **Gasifier fabrication (12 – 18 months)** – The full-scale gasifier will be fabricated and constructed by CSS.
3. **Procurement and Construction (12 – 18 months, concurrent with fabrication)** – Civil works, balance of plant procurement, and commissioning.
4. **Operation and Testing (6 months)** – Hydrogen generation with excess used for energy generation. Testing to include over 1,000 hours of continuous performance.

A demonstrator plant will include the construction of a single gasification system with associated PSA unit and syngas engine as shown in the schematic in Figure 9 below.

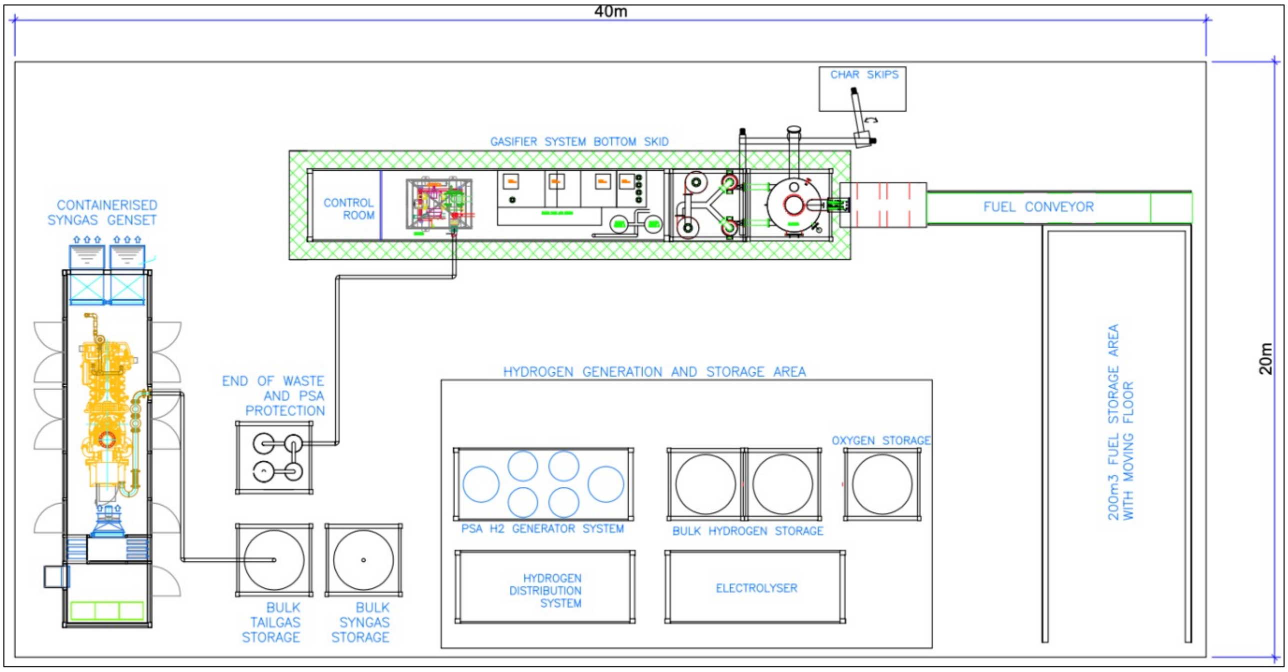

***Figure 9* General arrangement for the plant layout of the CSS gasification system proposed for a Phase 2 demonstrator.**

6. Benefits and Challenges

6.1 CAPEX / OPEX and LCOH

CSS has developed capital expenditure and operational expenditure models (CAPEX/OPEX) for a commercial scale CSS gasification unit as shown in Table 3 and Table 4 below.

Item	Price
Planning and permitting	
Engineering and Project Support EPCM	
RG1000 Gasification System	
Catalyst for CO reduction on Engine Exhaust to meet UK emissions standards	
Hydrogen & Oxygen PSA system - 1000Nm3/ hour of syngas at 35% hydrogen to produce 29kg/ hour	
Electrolyser - 250Nm3/ hour hydrogen and 125Nm3/ hour Oxygen for process	
Hydrogen compression, storage and distribution from PEC	
Perkins or Caterpillar CHP Generators (de-rated) 500kW net output	
Fuel Feed System (For basic twin hopper 24-hour storage system)	
Interconnecting Pipework and Services (budget)	
Shipping - 16 containers and cranes both ends (cost to be confirmed)	
Civil works	
Installation	
Commissioning and training	
Total Capital Cost	**£5,751,500.00**

***Table 3* Commercial capital cost estimate for procurement of the proposed 30kg**

No support fuel (e.g. LNG) is used by the CSS process; a significant benefit to the OPEX. The OPEX also includes a carbon cost based on emission costs as outlined by BEIS [5].

Item	Price
Gasifier Software License Fee and Remote Support	
Gasifier Maintenance	
Engine Maintenance	
Dosing and disposal costs	
PSA and Electrolyser Maintenance	
Feedstock Cost (Gate Fee)	
Labour Costs	
Carbon Costs	
General Overhead	
Total Operational Costs (/ yr)	**£562,750.00**

***Table 4* Operational cost estimate for the CSS gasification system.**

Using a conservative model, the CSS gasifier will produce 30 kg / hr of hydrogen. Over a plant life of 15 years with a flat depreciation rate of 5% per year gives a levelised cost of hydrogen (LCOH) of 12p / kwh (£120 £ / MWh and £128 £ / MWh with CCUS).

6.2 Greenhouse Gas Modelling

CSS has developed a greenhouse gas (GHG) emissions model to understand the environmental impact of the CSS solution. The model analyses the carbon emissions (CO2e) of the operational plant, incorporating emissions from transport, reagent production, and syngas combustion (referred to as CO_2 generation in this report).

Emission offsetting is also included in the model, with credit taken for electricity generation. Multiple cases have been developed to assess the impact of hydrogen generation and subsequent fossil fuel offset, and carbon sequestration through disposal of residual char.

Counterfactuals of SMR and biomass gasification are used, in addition to a landfill counterfactual based on modelling methodology by DEFRA [6].

The model does not include carbon emissions resulting from construction and decommissioning of the plant.

Table 5 below shows the estimated emissions for the CSS plant.

	Description	Carbon Emissions	Total Emissions
Case 1	No Char Credit, No Hydrogen Offset Credit	99	926.5
Case 2	Char Credit, No Hydrogen Offset Credit	50.3	470.3
Case 3	No Char Credit, Hydrogen Offset Credit	-145.2	-1358
Case 4	Char Credit, Hydrogen Offset Credit	-193.9	-1814.1
Case 5	SMR (Unabated) [7]	305	3,243,281.81
Case 6	Biomass Gasification with pre-combustion carbon capture [7]	101.9	270,163.22

Table 5 ***Performance of the CSS gasifier for multiple cases compared to SMR and biomass gasification counterfactuals.***

Reference counterfactual for emissions from landfill is estimated to generate 4,111.5 tonnes of CO_2 per year for the 7,920-tonne feedstock used in the CSS gasifier.

6.3 Comparison to Counterfactuals

Table 6 below shows a comparison of the key performance indicators for the CSS plant compared to SMR.

Item	Units	CSS	SMR
Hydrogen Flowrate	Kg/hr	30	8,994
Hydrogen Purity	%	95-98%	99.99%
Hydrogen Yield	%	61	66.6
Carbon Capture	n/a	Possible – pre-scrubbing, compression required	Possible – Post scrubbing, high energy requirement
Carbon Emissions	g CO_2 / kWh	<100	305
Total Cost	£M	5.7	144.1
LCOH	£ / MWh	120	39.60

Table 6 ***Comparison of CSS gasification technology to an SMR counterfactual.***

The CSS solution has clear benefits compared to SMR as summarised:

Small-Scale – The CSS gasifier takes up an area footprint of 800m2. This is significantly smaller than SMR which on average takes up 17,500m2. reduces land requirements and minimises planning permission risk.

Low Cost – The total cost of the CSS solution is less than 7% of a full-scale SMR site, making it affordable to a wider selection of investors / end-users.

Low Carbon – Lifecycle assessment shows the CSS solution emits a third of the SMR emissions. Crediting hydrogen usage indicates the project is carbon negative.

Waste Disposal – Each CSS gasifier can dispose of 7,920 tonnes of waste on a yearly basis.

The CSS solution key risks are outlined in section 9.3.

7. Development Plan

CSS Phase 2 development plan is to build a 1MW demonstration plant we have named as MicroH2-Hub, located at ASH Waste in Wrexham, which will be operational, producing 30kg of hydrogen an hour (225 tonnes per annum), for use in transport by September 2024.

The demonstration unit will exhibit the following key components:

Operational 1MW Plant – CSS will scale its 500kW plant design to 1MW. The 1MW unit is expected to be CSS' standard model, with 500kW for smaller sites where there is a lower demand for hydrogen and less available feedstock.

Scale-Up of PSA – CSS will scale the PSA to a 30 kg unit, intended to be 3 x 10 kg units to allow maintenance redundancy.

H2 Compression, Storage, and Distribution – A 450 bar compression and distribution system shall be installed to demonstrate vehicle filling feasibility.

Electrolyser – Integration of an electrolyser will supplement H2 production and generate O2 for air enrichment, utilising energy from the syngas engine.

Onsite Waste Processing Equipment – A scaled down fuel preparation plant including the shredding, drying and material sorting, shall be installed to prove waste processing capability for the gasifier feedstock.

E-Nose & AI – Full integration of the QTECH QMS and E-Nose systems shall automate and improve control of the gasifier.

Hydrogen Vehicle Conversion – Six HGVs shall be hybridised to run on diesel and hydrogen using ULEMco H2ICED® Dual Fuel Technology.

Commercial and Economic Modelling Including RTFO Scheme – CSS will ensure that compliance with the RTFO scheme is maintained by continued consultation with the Department for Transport over the proposed CSS feedstock.

8. Rollout Plan

8.1 Manufacturing Rollout

CSS has extensive experience in the delivery of gasification units in short timescales (8-15 months). The plant is split into discrete work packages to aid this:

- Gasifier Fabrication
- Hot Gas Filters
- High Temp Char Conveyors
- Heat Exchangers
- Blower
- Control Panel and Cabling
- PLC Works
- Compressed Air
- Container Skids
- Pipework
- I&C
- Valves

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 3 sub-contractors for each work package. This capability allows reliable fabrication and construction of up to six gasification units per year.

Commercial CSS units are expected to roll out after construction and operation of a demonstration unit (2025). During this time CSS shall engage potential buyers of future units as per the route-to-market plan.

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 gasifier units under license to significantly increase the capacity of rollout.

8.2 Route-to-Scale

CSS has developed an accelerated timeline to market as outlined in Table 7 below.

Stage	Scale	Oper. Year	Location	H2 Prod	Status	Funding Req.
1.1	Pilot	2022	CSS (Deeside)	n/a – short duration performance trials – 97% purity achieved.	Complete.	n/a
1.2	500kW	Mar 2023	ASH (Wrexham)	15kg per hour (biomass feedstock)	Project defined.	£1.5M
2	1MW	Feb 2025	ASH (Wrexham)	30kg per hour (SRF feedstock)	Project defined.	£6M
3	500kW plus Carbon Capture	Feb 2025	TBC	15kg per hour (SRF feedstock)	Project defined.	£5M
4	Multiple 1 MW plants	2025	UK/EU	30kg per hour (SRF feedstock)	Plant design to be finalised.	Comm. Rev.
5	License	2027	Global	30kg per hour (SRF or waste biomass feedstock)	Plant design to be finalised.	Comm. Rev.

***Table 7* Phased timeline of CSS' planned route to scale.**

9. Route-to-Market Assessment

9.1 Commercialisation

The capital cost of the CSS gasification plant is estimated at £5.7m as outlined in section 6.1. The CSS sales forecast only include sales of CSS technology (the gasification unit and PSA technology) This provides a cumulative revenue of £124m for CSS over the next 5 years and profit after tax of £29m.

CSS shall offer services and additional equipment supply in collaboration with industry partners on a cost-plus basis to provide turn-key solutions.

With this market position CSS have developed a 3-year business strategy model as illustrated in Figure 10.

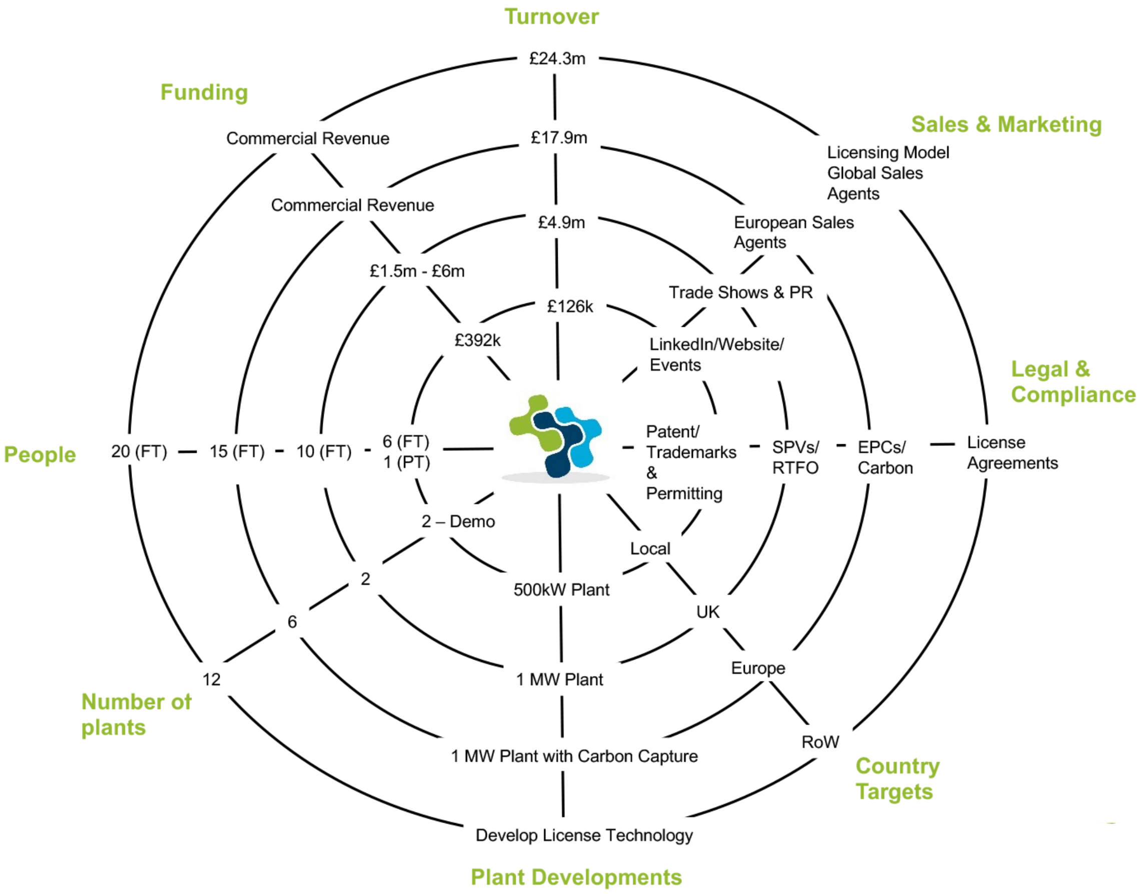

Figure 10 ***CSS 3-year business strategy model with today's position represented by the inner ring.***

The 5 key steps to commercialisation for CSS are as follows:

Funding – Crucial to scale up the system from 500kW to a 1MW demonstrator.

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

Carbon Capture Technology – CSS will continue to develop its carbon capture technology.

RTFOs – RTFO's significantly supplement the OPEX financial model. CSS will continue to prioritise conformity to ensure the project viability.

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

9.2 Route-to-Market

CSS' will primarily market its system to decarbonise heavy transport users partnering this with the ULEMCo H2ICED® dual fuel technology which requires a hydrogen purity of 95 – 98%. However, this would be a significant barrier to the market as dedicated hydrogen vehicles with a high quality requirement (e.g. PEC At 99.97% purity). Future development of the PSA system will be completed to achieve purity to allow rollout to a wider market.

CSS' target customers have the following key characteristics:

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

Commercial and economic analysis has shown the diversion of 10,000 tonnes of SRF can produce enough hydrogen equivalent to 1,100,000 litres of diesel -equivalent to savings of approx. £1.87m (based on £1.70 / L diesel) per annum.

Waste management companies and other industrial companies with high volumes of waste are therefore key targets for CSS. CSS will leverage the benefits discussed in section 6.3 with the USPs outlined below to target customers through existing relationships and connections, dissemination, and sales & marketing activity.

MicroH2-Hubs can run 24/7 and the cost to produce hydrogen is currently at £3.60/kg vs £5/kg on using renewables and electryolsis.

Payback for a MicroH2-Hub can be as low as 2.7 years with the inclusion of gate fees, energy and heat recovery, RTFO and hydrogen wholesale price.

Hydrogen from biogenic feedstock has lower CO2 emissions than grey hydrogen. Coupled with CSS future carbon capture technology the MicroH2-Hub will be carbon neutral.

MicroH2-Hubs are a modular configuration allowing for a smaller footprint, simpler planning & permitting process, and are easier to install.

MicroH2-Hubs can produce hydrogen, power and heat, and can utilise power internally.

MicroH2-Hubs are tailored to customers energy requirements and as and when demand grows modular plants can be added.

Market analysis has identified 3,000 potential waste management companies in the UK, giving a Total Attainable Market (TAM) of £7.9bn. Of these companies 301 have at least 10,000 tonnes of SRF available, giving a Serviceable Attainable Market (SAM) of £797m. The Serviceable Obtainable Market (SOM) of 91 companies with at least 40,000 tonnes of SRF available is valued at £241m.

Whilst completing a demonstrator project CSS will conduct further market research to engage prospective clients. This will supplement the growing interest CSS have had following dissemination and announcements of CSS BEIS funding.

9.3 Barriers and Risk

Key barriers and risks to the CSS project are outlined below.

- Dependence on market prices for gate-fees, electricity, and other fuels.
- Resistance to adoption of developing technologies.
- Investment competition.
- Launch of competitor or disruptor technologies.
- Previous high-profile gasification failures.
- Rising cost of raw materials and global supply chain issues.
- Waste is exported to Energy from Waste projects abroad.
- High cost of low carbon hydrogen relative to high-carbon alternatives.
- Demand uncertainty due to current limited use of hydrogen.
- Current reliance on ULEMCo or similar technologies for rollout.

9.4 Benefits to Other Sectors

CSS expects the following benefits for its supply chain:

- Support suppliers with orders of goods, materials and services and open up new markets for sales.
- Low cost solution to deal with waste that provides revenue support in the form of power, fuel and lower costs for waste disposal, storage and transport.
- Supporting end users so that they can adopt new hydrogen technologies, driving down emissions, and reducing costs.
- Modular units that can be added as demand grows, less pressure on cash flow and a lower CAPEX and OPEX to what's currently available in the market.
- Support the introduction of hybrid engines to adopt a transitional approach to converting trucks in a timed manner, reducing the risk of loss of hydrogen supply.

CSS expects further benefits to the UK economy by:

- Supporting the hydrogen economy with revenue, taxes, and jobs.
- Support businesses to reduce costs and improve their carbon footprint.
- Help to reduce carbon emissions and improve the environment.
- Reduce waste sent to landfill.
- Support the drive to reduce the cost of the production of hydrogen.

9.5 Job Creation

CSS expect for every constructed plant five jobs will be created as a direct result of operation, with an additional job created for distribution of the hydrogen per plant.

CSS expects to create five new full-time roles for a demonstrator project, and over the next five years 20 new full-time engineering and support roles, whilst enhancing our current employee's knowledge in the hydrogen sector. CSS are looking to bring in new skills in areas such as licensing, fuel preparation and RTFOs.

9.6 IP Strategy

The IP of the LCH2 Phase 1 project has been covered by a collaboration agreement where all partners have signed a collaboration agreement sharing all background IP and individual ownership of future IP.

For the Phase 2 project a new collaboration agreement will be signed granting full access to all background and future IP, with post project knowledge for gasification and hydrogen production exclusively owned by CSS.

QTECH will retain all IP on its QMS and E-Nose technology, ASH on waste fuel feedstock and PEC on hydrogen storage.

10. Dissemination

CSS has completed a number of dissemination activities over the course of this BEIS competition, this has included internal and external meetings, press releases, LinkedIn posts and internal and external meetings with Government bodies, Universities, funders and potential clients. CSS intends for future dissemination works to include:

- PR and journal articles.
- Hosting of online webinars.
- The sharing on websites and social media of this report.

11. Conclusions

CSS has completed a feasibility study under Phase 1 of the LCH2 competition and has successfully proven that the CSS technology is able to generate the expected hydrogen using an SRF feedstock. This has been done in accordance with BEIS' objectives for the LCH2 competition:

Feedstock Assessment – A full assessment has been completed on the available fuel stocks to CSS to identify the most suitable composition of fuel, the form the fuel should take (i.e. briquettes), and an outline of the process equipment necessary to prepare these.

Use of SRF – Trials have been completed to test the gasification process using SRF and have shown a consistent syngas generation comparable to a 100% biomass feedstock.

Air Enrichment Trials – Enrichment has increased syngas hydrogen content from 16.25 wt% to 26.21 wt%.

Continuous Gasification Trials – Extended trials with the gasifier have shown that syngas generation does not significantly change over time when using SRF.

PSA Trials – The PSA has been developed and proven to extract hydrogen at a purity of 98% on average.

Sensor Suite Development – Use of QMS and E-nose technology in syngas has been proven to be viable.

AI Development – An AI system has been developed and proven in principle for integration to a demonstrator unit.

Hydrogen Storage Viability – The generated hydrogen is not considered at risk for liquification due to contaminants when stored.

Lifecycle Assessment – The plant has been proven to have a higher LCOH compared to counterfactual, however shows significantly reduced capital costs and emissions, whilst also occupying a smaller land footprint.

CSS in collaboration with the wider consortium has achieved the 3 key objectives that it set to achieve at the start of the project, they were:

1. Demonstrate that it is technically and economically feasible to produce low

carbon hydrogen efficiently and reliably using SRF feedstock via gasification – CSS has successfully concluded that it is both technically and commercially feasible to produce low carbon hydrogen utilising SRF feedstock and this is evidenced throughout this report.

2. Assess that there is available feedstock, infrastructure, route-to -market and end-user demand - Having ASH as a project partner has given CSS significant insight into the waste sector confirming the available feedstock which was also backed up by market research in the UK waste sector. Waste companies typically have the right infrastructure to deal with the waste and to host a MicroH2-Hub. With increasing energy and transport costs the commercial model was attractive to ASH and provides an affordable solution for their requirements.
3. Ensure that the system is compliant with the RTFO scheme and environmental regulations – Led by ASH the project has had engagement with the Department for Transport and understands the requirements for compliance to the scheme and this will form a part of the Phase 2 project. Environmental regulations have been adhered to by CSS and ASH in both the gasification and waste sector and remain at the forefront of the technology for our Phase 2 project.

The project consortium has identified there are no major technical challenges that make the project unviable and have identified minor improvement works which can boost the efficiency of the project further. CSS intends to take all lessons learnt in this feasibility study to a demonstration Phase 2 project to objectively improve, develop and commercialise the MicroH2-Hub.

CSS would like to take this opportunity to thank BEIS for both the support and funding for our Phase 1 feasibility study and for the opportunity to apply for the next round of funding. Regardless of the outcome, CSS along with our partners have gained significant knowledge and experience in the hydrogen sector and will continue in ernest with the commercialisation of the MicroH2-Hub.

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