DACC and GGR Innovation Programme Phase 2

Project Code 4696/11/2020

Biohydrogen Greenhouse Gas Removal Demonstration

Final Report

Contents

Revision History			
Revision	**Date**	**Author**	**Reviewer**
Draft	21/02/2025	Andy Cornell	Justin Hampton Penny McDermid

Approved by

Andy Cornell
Project Director
andy.cornell@absl.tech
07724 741 127

Advanced Biofuel Solutions Ltd
Unit A4 Marston Gate,
Stirling Road,
Swindon,
SN3 4DE

1.0 Summary

Gasification is a key technology for achieving net zero. ABSL is at the forefront of the development of this technology and operates the only commercial demonstration plant in the world to transform household waste into a low carbon fuel while capturing carbon dioxide. More than £60m has been invested into that Swindon commercial demonstration plant over the last ten years.

Gasification is a challenging technology and there have been several large-scale projects that have failed, losing their investors hundreds of millions of pounds. ABSL aims to avoid this large-scale failure by taking an incremental development approach that builds on experience gained with a pilot plant used to build and commission the small-scale Swindon commercial demonstration plant. The experience at a small commercial scale will allow technical, operational and commercial issues to be resolved to enable the successful delivery of large-scale systems.

The lessons learnt from the Swindon facility have a wider application to all innovative technologies. Most technologies fail during the move from pilot scale to commercial because they fail to resolve the scale up challenges further set out in this report.

Figure 1 – The Swindon Facility

The Biohydrogen Greenhouse Gas Removal Demonstration project relies on four sections:

- A gasification section that converts a one tonne per hour of waste feedstock into a high-quality syngas.
- A catalytic section that converts the syngas into hydrogen, methane and carbon dioxide. Around 0.9 tonnes per hour carbon dioxide is then captured and liquefied. The plant can capture 6,500 tonnes per annum of carbon dioxide.

- The hydrogen production section that purifies the hydrogen for use in fuel cell electric vehicles.
- A sorption enhanced water gas shift (SEWGS) section.

The gasification and catalytic sections (collectively referred to as the Host Plant) were constructed and cold commissioned before the start of the DESNZ GGR project. The hydrogen production section was designed and constructed within the DESNZ GGR project and relies on the gasification and catalytic sections. The SEWGS section is designed and built within the DESNZ GGR project and located at UCL.

The project objectives were to:

- Successfully commission and operate the gasification and catalytic sections of the plant,
- Design, construct, commission and operate a hydrogen production section to purify syngas from the catalytic section,
- Design, construct, commission and operate the SEWGS system at UCL.
- Capture more than 1,000 tonnes of biogenic carbon dioxide.

The results from the project were:

- The syngas production section was commissioned and generated good data on syngas quality but never achieved reliable operation,
- A lack of reliable operation meant that it was not possible to hot commission the catalytic section of the plant,
- The hydrogen production section was designed and fabricated but a key component, the PSA, was not delivered to site,
- The SEWGS equipment was designed, and fabrication commenced but was not completed.

UCL are committed to completing the SEWGS section of the project over the coming months. ABSL is attempting to raise funds to complete the gasification, catalytic conversion and hydrogen production sections of the plant but the probability of success is low.

The results from the project are disappointing and a large part of this report analyses the challenges faced by the project and identifies possible solutions for future projects.

The project was highly ambitious for the following reasons:

- It attempted to operate a commercial scale plant on a full-time basis in normal operational environment. This required innovation in an operational environment that actively discourages innovation.
- The technology is highly complex with far more process steps than other technologies such as anaerobic digestion or direct air capture.

- The safety environment is very challenging because of high temperatures, medium voltage power and hazardous materials.
- Commissioning a demonstration plant is expensive with the monthly costs of operating the plant exceeding £0.6m, and the time required to complete commissioning is uncertain. This means that securing investment is very challenging.

No complex gasification project has been delivered successfully because they all faced similar challenges that they have failed to overcome.

Funding was a major challenge throughout the development of the Swindon facility. The original forecast cost for the construction and commissioning of the gasification and catalytic sections was £27m and the costs to date exceed £60m. ABSL was consistently seeking new funds which resulted in pauses, a failure to plan, loss of key staff and tensions in relationships with subcontractors. A more accurate estimate of costs and securing sufficient investment to meet that estimate at the beginning of the process would have greatly improved delivery.

The plant faced many technical issues which the team gradually resolved. Most of these issues were caused by equipment failing to meet its design specification. For example, even a system as simple as a flare only allowed a gas flow 50% lower than the design intent. These problems were exacerbated by the poor quality of the mechanical and electrical integration of the plant. It took a long time to find underlying faults and manage their resolution.

Figure 2 – Gasifier Top Section

The project expected to encounter technical issues. However, these were not the major problem. Project management and operational issues had a much bigger impact. The key problems were:

- It was not possible to recruit people with experience of managing or operating complex, innovative process engineering projects. The pool of people with these skills is very small.
- The overall project scope was too ambitious and overwhelmed the project team.
- It was very difficult to organise the team to allow the engineering leads to work collaboratively. Innovative engineers are rare and used to challenging colleagues rather than working alongside other innovators.
- Budgetary pressures led to procurement decisions based on price rather than quality. This is a false economy in a complex engineering project because the resultant delays inevitably cost more than the amount saved.
- There was far too little focus initially on the competence of the operational team. This turned out to be the biggest problem the project faced. Operations works on a 24/7 basis which makes recruitment very difficult. Furthermore, there aren't any operators with experience of complex gasification processes. The operations team continually made mistakes during the commissioning of the plant, resulting in delays and damage to equipment. It took three years to identify a training plan and shift pattern that could be effective.
- The operations team needed 24/7 onsite support during commissioning rather than remote support on a call out basis. However, it is difficult to incentivise commissioning process engineers to work on a 24/7 shift rota.
- Initially, there weren't enough supervisors for the maintenance teams resulting in poor productivity. This was resolved by appointing a maintenance supervisor and maintenance planner.

The key problems for the hydrogen production and SEWGS sections of the plants were delays in the fabrication of equipment. Key suppliers on both sections suffered from financial challenges that paused fabrication. The supplier of the PSA for the hydrogen production section also had major problems demonstrating PED compliance. This PSA had not shipped at the conclusion of the project. UCL are committed to complete the SEWGS system and are considering options to complete fabrication.

The gasification line was successfully commissioned but did not achieve reliable operation. The gasifier operated for more than 5,000 hours in total but only around 100 hours of these were in gasification. At the conclusion of the project ABSL had identified solutions for the technical issues that had prevented long term gasification but was still working on improving operator confidence.

The quality of syngas produced by the plant is summarised in the following table. The main issue with the gas is the impact of air leaks into the gasifier, resulting in dilution with nitrogen. Despite this, the syngas was suitable for the catalytic conversion section of the plant. The source of the leaks was identified shortly after the final run. It was caused by failed packing around a knife valve.

Parameter	August	November	Design
Mass Flow	600kg/hr	800kg/hour	1,000kg/hour
Calorific Value	6.5MJ/kg	6.5MJ/kg	8.5MJ/kg
CO	24%	24%	37%
CO2	22%	18%	16%
H2	23%	24%	38%
H2O	4%	2%	6%
CH4	2%	4%	1%
O2	0.2%	0.3%	0.3%
N2	23%	28%	1%
HCN	324ppm	908ppm	200ppm
C6H6	716ppm	1,900ppm	500ppm
COS	70ppm	78ppm	50ppm
NH3	39ppm	8ppm	3ppm

Figure 3 – Syngas Composition: C2H2, C3H8, NOx, HCl, SOx, Phenol, Toluene, Naphthalene, HF all within specification

The catalytic conversion and hydrogen production sections could did not produce any results because the gasification was not operating reliably. The SEWGS section did not produce any results because construction was not complete.

ABSL worked on the development of a full-scale commercial plant in parallel with this project. This plant was based in the northwest of the UK and was a 15-times scale up of the Swindon plant. Petrofac carried out a FEED and SFW, Hatch, Wood and CECO were appointed to supply key technology packages. Microsoft agreed to purchase GGRs produced by the plant and Trafigura agreed to purchase the biohydrogen. The expected capital cost of this facility is £567m and the hydrogen it produces would meet the low carbon hydrogen standard. The MRV methodology for the facility would follow the approach used at Swindon to demonstrate ISCC compliance.

Unfortunately, this proposal was not able to secure capacity in the Hynet carbon sequestration network. DESNZ did not support the proposal in either of the Track 1 and Track 1 Expansion allocation rounds because of lack of operational data from the demonstration plant and a lack of credibility in ABSL's plan to secure the £567m of funding required for the project.

This response from DESNZ underlines the challenge facing ABSL. Stakeholders require the demonstration plant to operate reliably for a significant amount of time before they are willing to allocate resources to commercial scale plants. All of ABSL's experience supports this requirement, and there is clear evidence that all complex engineering projects fail if they aren't based on proven processes. Unfortunately, funders require clear evidence of future commercial viability to support demonstration projects, but it is difficult to provide this evidence for decarbonisation markets that are dependent on Government support.

ABSL has not been able to raise funds for the continuation of Swindon plant commissioning at the conclusion of the project and it is very likely that it will be broken up. This means that the value of the project is in the learning that can be used to improve the likelihood of success of future demonstration plants. New technologies will be essential to achieving net zero commitments and the successful delivery of demonstration plant projects is needed to bring them to market.

2.0 Background

Gasification is a key technology for achieving net zero. It allows the transformation of waste and biomass resources into low carbon fuels while capturing carbon dioxide. This achieves three objectives:

- The environmentally friendly disposal of waste and biomass residues with minimal GHG emissions. Other pathways lead to the emission of carbon dioxide or methane to the atmosphere and pollution of land or water.
- The production of low carbon chemicals or fuels to offset fossil equivalents that increase greenhouse gases in the atmosphere through their production and use.
- The capture of biogenic carbon dioxide. This can be sequestrated to generate negative emissions or combined with green hydrogen to increase low carbon fuel production.

The focus of this project is on the capture of biogenic carbon dioxide. However, the primary advantage of gasification is that it contributes to three essential decarbonisation objectives which makes it more efficient and cost effective than other pathways.

Gasification of coal and other fossil fuels is a mature technology. The Gas Light and Coke Company was established in 1812 to convert coal into town gas to heat and light London. Town gas continued to be used across the UK until it was replaced by natural gas in the 1960's and 70's. Coal gasification was also in Germany and South Africa to produce transport fuels and in China to produce natural gas. The Great Plains Synfuels Plant in the USA has operated since 1984 and gasifies coal to produce natural gas, fertilizers, solvents and phenol.

Figure 4 – Fulcrum Biofuels Facility

The gasification of biomass is more challenging. There have been numerous attempts to gasify wastes and biomass to produce fuels or electricity with few being successful.

Projects have been well funded and led by credible organisations but have been defeated by the challenges of the technology. A good example is Fulcrum's waste gasification facility in Nevada. The project attempted to convert around 15 tonnes per hour of household waste into a wax that could be refined into sustainable aviation fuel. The project was shut down in 2024 after spending several hundreds of millions of dollars without operating successfully.

ABSL's strategy is to take an incremental approach to developing biomass gasification. The company operated a pilot plot from 2009 to 2015 to develop and then prove the technology. The learnings from this pilot plant were used to develop a demonstration plant in Swindon. The objective of the demonstration plant is to learn how to operate a plant that can operate on a full-time basis in a fully commercial environment. This requires the following challenges to be overcome:

- How to structure and train plant operators on a process that is still under development.
- The development of detailed operational procedures.
- How to organise and train a maintenance team.
- The development of a programme of preventative maintenance.
- Building a critical spares holding.

- Compliance with environmental and safety regulations.
- Developing relationships with an ecosystem of contractors required to operate and maintain the plant.
- Overcome technical issues with plant equipment.
- Develop a plant control and safety system.
- Create a strategy to monetise the IP generated by the development.

These challenges interact with one another and cannot be solved sequentially. For example, it isn't possible to finalise operational procedures until equipment is fully operational, but it isn't possible to bring equipment into operation without procedures. Similarly, a control system needs testing under real world conditions before it can be finalised.

Resolving these challenges takes several years and this is the underlying cause of the failure of so many gasification projects. The monthly operational cost of large-scale gasification projects means that it is incredibly expensive to learn how to operate them. Investors invariably run out of funds or patience before the facilities are fully commissioned.

The strategy at Swindon was to commission and operate a small-scale facility with a relatively low monthly operating cost. The learnings from Swindon can then be used as a template for the larger scale plants.

The Swindon facility will demonstrate the capture of biogenic carbon dioxide. This is the primary objective of the GGR Innovation Programme. This project funded the addition of a hydrogen production line to the Swindon plant which would increase the amount of carbon dioxide the plant can capture in normal operation.

3.0 Design and Development of Demonstration Plant

3.1 Project Description

3.1.1 Overview

A block diagram of the Swindon demonstration plant is given on the following page.

The plant accepts one tonne per hour of waste material and transforms it into biomethane and/or biohydrogen while capturing 800kg/hour of carbon dioxide. It is designed to operate continuously with an annual availability of 85%.

The facility is split into four sections:

- The gasification section transforms the prepared feedstock into a high-quality synthesis gas that is free of tars, ash and contaminants.
- The methanation section increases the hydrogen content of the syngas and then converts it into methane while capturing carbon dioxide.

- The hydrogen production section takes the hydrogen rich syngas and purifies it to produce hydrogen that meets the transport fuel cell standard.
- The ancilliaries section is made up of packages that support the other sections.

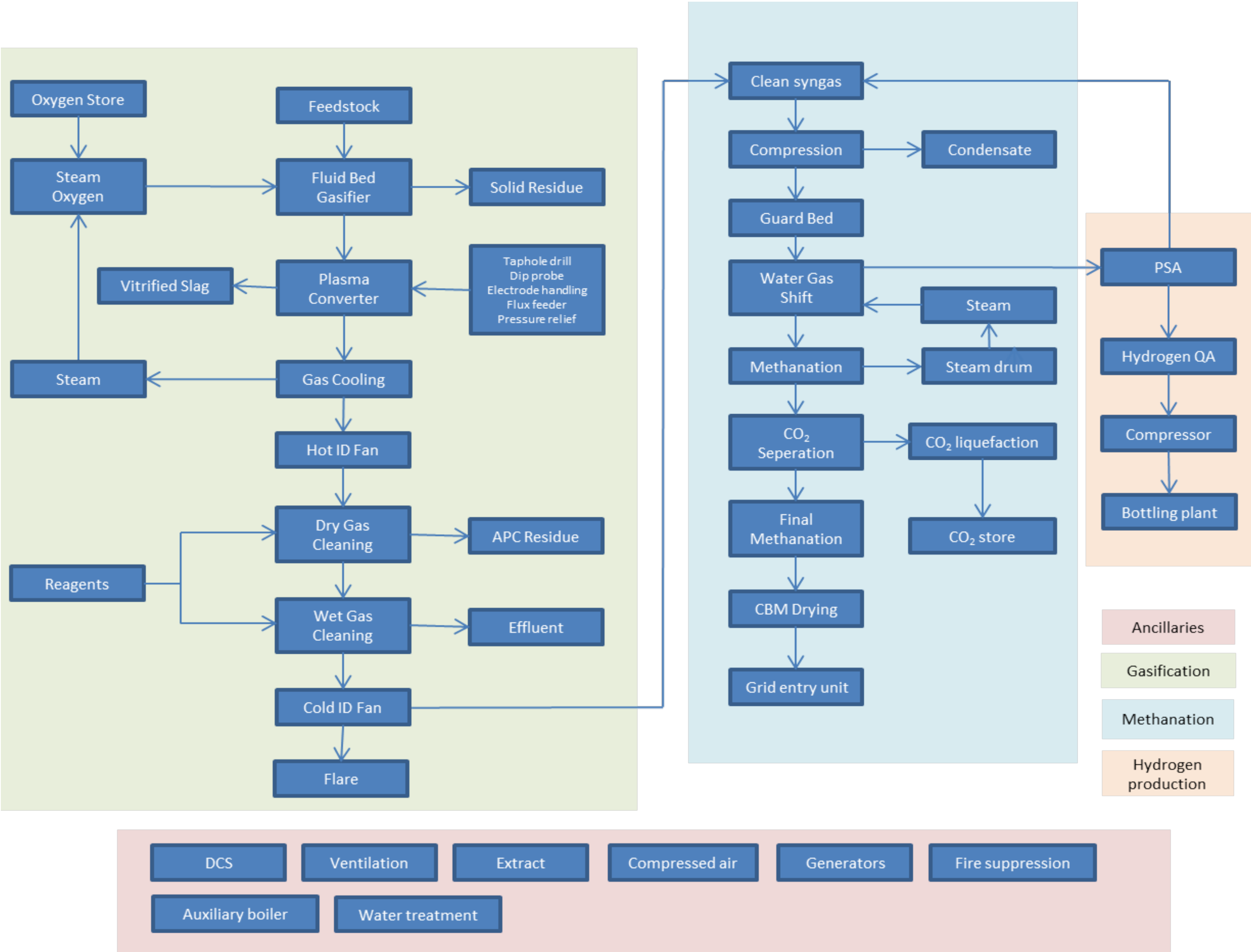


Figure 5 – Swindon Demonstration Plant

Summary description of the gasification, methanation and ancillary sections of the plant:

- Pre-prepared waste is brought to the plant in moving floor trailers.
- The dried feedstock is metered into an oxy-steam fluidised bed gasifier to produce a crude synthesis gas (syngas). Large incombustible material is removed from the gasifier and sent to inert landfill.
- Tars in the syngas are reformed using a direct current electric arc furnace. This also vitrifies the ash components of the syngas. The vitrified ash is collected and then exported from site for use as an aggregate.
- The gas is cooled in a waste heat boiler. Ash is collected from this system and sent to hazardous landfill.
- The gas is filtered and scrubbed to remove any remaining ash, acid gases and alkali gases. The scrubber uses acid and alkali consumables and produces an effluent that is discharged to drain.
- The cool, clean syngas is compressed.
- The compressed gas is catalytically converted into biohydrogen and/or biomethane.
- Carbon dioxide in the gas is removed using a chemical scrubbing system and then either stored for onward sale or injected into a transport and sequestration network.
- The biohydrogen or biomethane produced is metered into the gas grid for onward sale.

Figure 6 – Photograph of Swindon facility

This flow sheet is based on a pilot plant that operated between 2009 and 2015 at one tenth the scale of the Swindon demonstration plant. The demonstration plant project commenced in 2015, detailed design was completed in 2017, and equipment started to be delivered to site in 2018. The project paused for two years while further funding was secured and restarted in 2020. Mechanical and electrical integration was completed in 2022, and hot commissioning started in 2023.

3.1.2 Hydrogen Production

The extension of the Swindon plant to produce fuel cell grade hydrogen was funded by this project.

As shown in figure 1 the hydrogen production system is made up of:

- A pressure swing absorption (PSA) system accepts shifted syngas from the water gas shift reactor. The non-hydrogen components of the syngas are absorbed leaving a stream of high purity hydrogen. The non-hydrogen components are sent to the syngas compressor. The high purity hydrogen stream is sent to the compressor.
- A gas analyser tests the high purity hydrogen stream to ensure that it meets the D grade ISO 14687 specification.
- The hydrogen compressor increases the pressure of the hydrogen stream to 175barg.
- The bottling plant takes the compressed hydrogen and meters it into hydrogen cylinders.

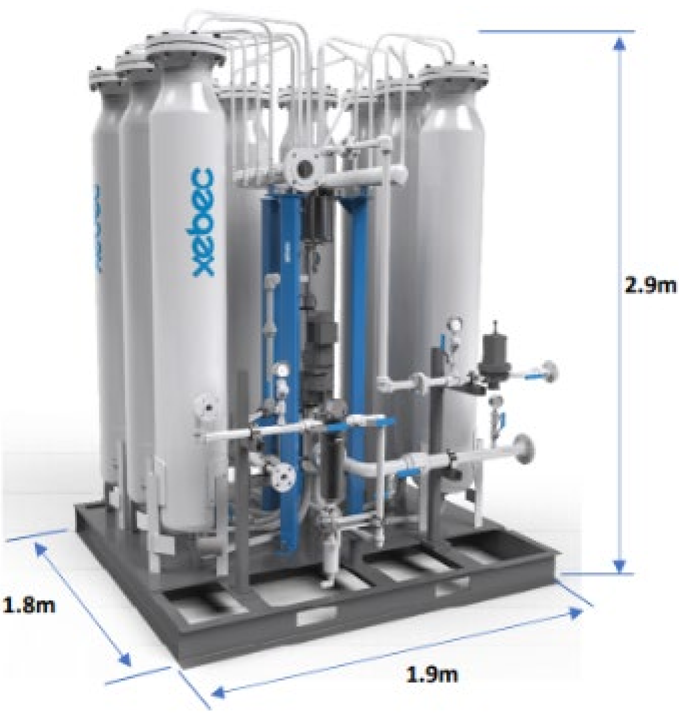


Figure 7 – Pressure Swing Absorption System

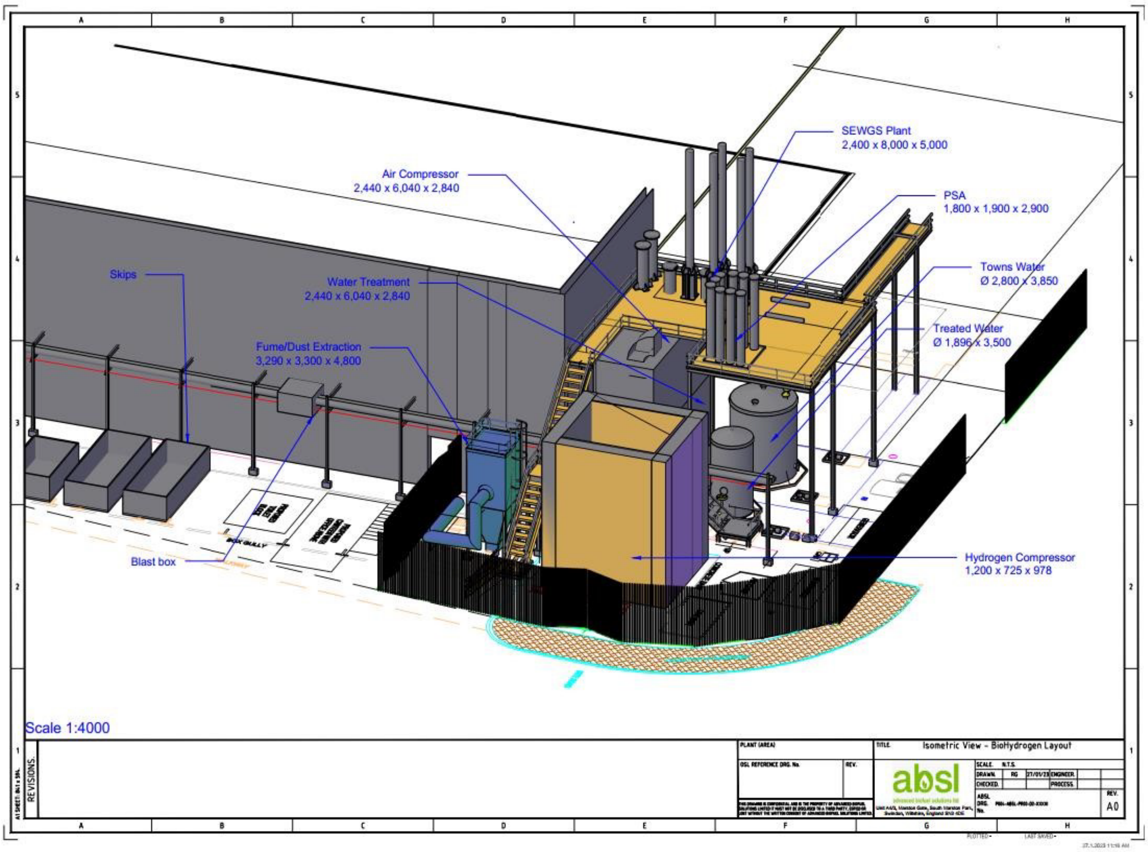


Figure 8 – Initial Hydrogen Design

The project commenced in June 2022; long lead time equipment was ordered in December 2022. Most equipment has been delivered to site and installed.

3.1.3 SEWGS

Sorption Enhanced Water Gas Shift (SEWGS) combines hydrogen production and carbon capture in a single unit. The thermodynamic equilibrium in the shift reaction can be enhanced to give more hydrogen yield by adding a CO2 absorbent into the shift reactor. Carbon dioxide is then captured as a solid carbonate as soon as it formed, shifting the reversible water-gas shift reactions beyond their conventional thermodynamic limits. Regeneration of the sorbent releases pure CO2 suitable for sequestration. SEWGS can yield higher CO2 capture ratios at lower energy efficiency penalties and at lower costs in comparison with more mature technologies based on solvents. SEWGS has been tested at pilot scale in Europe in multi-vessel PSA type using hydrotalcite-based materials as sorbent. SEWGS reaction on a packed bed has been studied extensively by the UCL group as part of this project, and simulation studies have demonstrated the advantages of the SEWGS in the Swindon gasification plant (https://doi.org/10.1016/j.fuproc.2024.108032). However, the large number of pressurised vessels and high temperature operation increase technical risks and costs. Therefore, the team has been exploring the idea to operate SEWGS in a fluidised bed, by operating two interconnected vessels only in combined temperature/pressure swing mode. A fluidized bed reactor has several advantages over a packed-bed reactor such as full mixing of an optimal contact between the gas and the particles, and can provide relatively uniform temperatures across the catalyst and facilitate a lower pressure drop compared to a packed-bed reactor.

The Scope of this project was the design, realisation and operation of a twin-fluidised bed reactor for testing SEWGS at pilot scale at the new Manufacturing Futures Lab (MFL) at UCL East campus. Simulated syngas would be fed from bottled gases, with the aim of generating two separate streams of H2 and CO2.

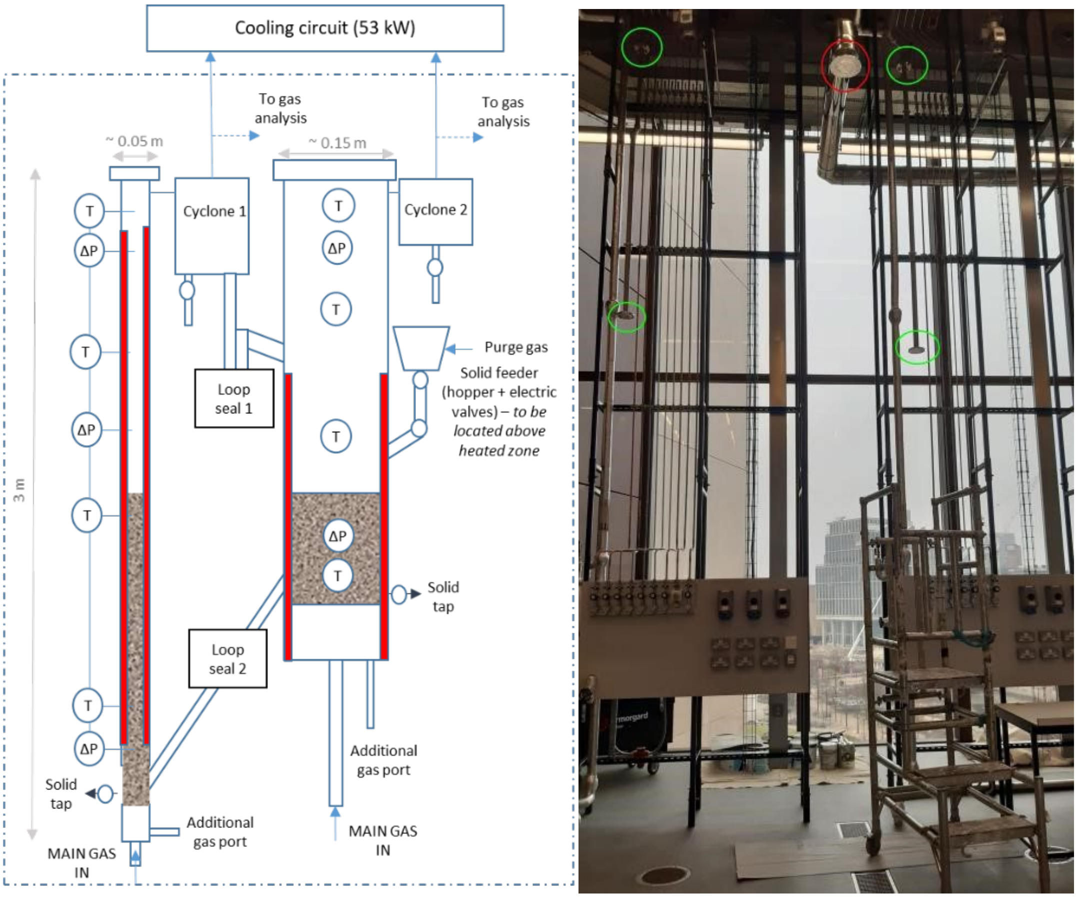


Figure 9 – SEWGS System

3.1.4 Discussion

3.1.4.1 Complexity

As discussed in Section 2.0, biomass gasification is a challenging technology.

Figure 5 illustrates the underlying problem. The Swindon plant is complex. There are 22 distinct technology packages with separate suppliers for each of them. Some of those packages, such as the plasma converter, are also complex and require the integration of ten or more subpackages. The process requires handling of solids, liquids and gases at high temperatures and pressures and many of those materials are hazardous.

A typical anaerobic digestion plant might be made up of around ten technology packages. These are far simpler than the packages used in the Swindon plant. Furthermore, there are vendors who will sell end to end anaerobic digestion plants and deal with the system integration issues. There aren't any vendors who supply an end-to-end gasification solution. Overall, anaerobic digestion plants are far simpler that gasification plants.

Simpler gasification facilities will use an air blown gasifier to feed crude syngas into a boiler that raises steam that is used to generate electricity in a steam turbine. These are made up of thirteen or so packages, some of which have equal complexity to the Swindon plant, but they avoid the complexity of tar reformation, gas cleaning and catalytic conversion of syngas. Projects require the integration of several licensors, and there aren't many organisations with extensive experience of this integration. Many simple gasification facilities fail during commissioning because of the lack of a reference plant.

The main alternative to gasification for the capture of biogenic carbon dioxide are post-combustion capture systems used in conjunction with combustion technologies such as incinerators. A post combustion capture plant is complex with around 20 technology packages. Existing combustion plants can be retrofitted with carbon capture equipment, reducing the scale of the challenge. However, post combustion capture of biogenic carbon dioxide has only been demonstrated at pilot scale. At present. there isn't a demonstration plant to develop operational experience of the technology.

Another alternative to gasification is direct air capture (DAC). This has the advantage of simplicity – plants will only require 5 or 6 technology packages. The key challenge for DAC is the huge energy requirements to capture carbon dioxide at concentrations of only 400 parts per million.

A gasification plant has more complexity than most other industrial processes. The closest analogue is a crude oil refinery. However, refineries have been developed over decades and there is a huge industry built around the development, construction, commissioning, operation and maintenance of them. None of this ecosystem exists for gasification plants.

The only viable development pathway for gasification technologies is a gradual approach that moves slowly from pilot plant through demonstration plant and then commercial facility. The attempts to short circuit this process set out in Section 2.0 were highly likely to fail because a full-scale commercial plant does not provide the correct environment to bring a complex first of kind technology into operation. The Swindon plant is essential to bringing gasification technology to commercial readiness.

3.1.4.2 Safety and Environmental Regulation

The operation of gasification plants include the following hazards:

- Hot, asphyxiating, explosive and poisonous gases such as hydrogen, carbon monoxide, hydrogen sulphide and ammonia.
- Hazardous and flammable solids such as fly ash and waste wood dusts.
- Hazardous liquids used in gas cleaning such as amines, sulphuric acid, sodium hydroxide and sodium hypochlorite.
- Medium voltage electricity.
- Stored energy in the form of compressed air and molten slag.

Gasification projects must follow best practice to mitigate safety risk to employees and visitors to the plant. This required the project to:

- Carry out a HAZOP on the plant and where necessary LOPA and ALARP studies.
- Carry out functional safety assessments.
- Ensure that safe working procedures are followed by plant operators.
- Ensure that risk assessments are carried out for maintenance activities and that lock out tag procedures are followed.
- Assess training requirements for all staff and ensure that training is carried out.
- Maintain records to demonstrate that safety requirements are met.

These requirements must be met by all projects. However, the hazards around gasification mean that compliance is especially important.

The Swindon plant's environmental performance is monitored and regulated by the Environment Agency. The facility is the only gasification plant in operation in the UK because other, simpler gasification plants are regulated as waste incineration facilities under the IED. ABSL has worked hard with the EA to develop an appropriate regulatory framework, and this has led to modifications to the guidance on operating gasification facilities.

3.1.4.3 Innovation in an Operational Environment

The process conditions and technical approach to gasification were established in the ABSL pilot plant. A large amount of innovation was required to scale up this pilot plant to demonstration scale and further innovation has been required to operate the process on a full-time basis in a commercial environment.

Figure 10 – Syngas Compressor

The key areas where innovation has been required are:

- Equipment packages used in the plant have not met their design specification. For example, sensors used to detect waste wood gave false negatives and positives resulting in blockages in the gasifier feed system. Innovation has been required to identify solutions. Various types and locations of sensors were tried until a solution was found.
- Equipment settings and control methodology have resulted in failures. For example, the initial configuration of the variable speed drives used for ID fans overloaded the motor coupling and sheared it. The coupling was repaired, and new settings tried until the correct balance of responsiveness and protection was found. Innovation was required to identify solution to many similar problems.
- In some cases, the increased scale of the demonstration plant created technical challenges that hadn't been encountered in the pilot plant. For example, the larger scale means that it takes longer to heat up the system. Nitrous oxide is generated during this heat up phase which condenses in downstream pipework as nitric acid, corroding and weakening it. Modifications to equipment and operating procedures have been developed to mitigate this problem.
- Operating the plant requires detailed instructions and procedures and producing these requires innovation. This is particularly challenging because operators do not have a comprehensive understanding of the process. For example, the control of the plasma furnace requires electrode height and

current to be set to the correct levels. These are obvious to anybody with a deep understanding of plasma physics and slag chemistry but writing a simple set of rules to allow an operator to set this is challenging.

Many problems that have arisen during the commissioning of the Swindon plant have required innovative solutions.

Innovation is extremely challenging in an operational engineering environment. Engineering focuses on finding reliable solutions to problems that are normally based on approaches that have been proven in the past. Most engineers are very uncomfortable when confronted with novel challenges. In addition, safety regulations and operational procedures strongly discourage innovation because it is inherently less safe than either using an established approach or simply not doing anything.

It takes a long time to build an organisational culture that can innovate safely. This is not an issue at pilot plant scale because the level of risk is far lower. At a demonstration plant scale, the high levels of safety risk explained in the previous section can cause months of delay.

An example of this on the biohydrogen project was the demonstration of compliance with the pressure equipment direction (PED). PED compliance is essential to ensure that hazardous gases are contained. However, demonstrating compliance for a new equipment used in a new process takes a long time. ABSL eventually agreed an approach to demonstrate compliance. A design review then identified several changes to the biohydrogen system. This required revisions to the PED compliance plan that took several more weeks to agree.

Unfortunately, it is unavoidable that ensuring safety acts as a drag on innovation. It is important that this is considered in the project plan.

3.1.4.4 Scale

Gasification requires high temperatures. The gasifier operates at 800°C, tar reformation takes place at 1,100°C and the catalytic conversion reactions take place at 500°C. The thermal losses from the reactors used for these processes are inversely proportional to their size. The losses from small vessels are larger than from small vessels. This is why a large man will handle cold weather better than a baby.

This was a significant problem in the pilot plant. The vessels used for catalytic conversion of the syngas lost heat rapidly and would struggle to keep temperatures above the light off temperature for the reaction. This was eventually resolved by using heated jackets for the reactors.

This scaling issue influences the sizing of a demonstration plant. A gasification demonstration plant must be large enough to allow the very high temperature tar reformation reactions to take place and then maintain sufficient gas temperatures to prevent the alkali salts condensing and fouling ductwork. This is a key driver for scaling of the demonstration plant.

Catalytic processes are frequently demonstrated at very small scales – 100's of kilograms per hour – and then scaled up 100's of times for commercial facilities. Gasification requires larger scale demonstrations to give useful, scalable information. This increases the cost and complexity of demonstrating the technology.

3.2 Process Modelling

3.2.1 Host Plant

The demonstration plant model was produced in Aspen and based on results from the pilot plant and data from equipment vendors. It is summarised in the following Figure.

	Inputs kg/hour	Outputs kg/hour
Feedstock	900	
Oxygen	400	
Solid residue		160
Gas treatment chemicals	40	
Effluent		805
Water	655	
Carbon dioxide		850
Substitute natural gas		200
	1,995	1,995

Figure 11 – Swindon Plant Mass Balance

This mean that the plant expects to capture 850kg/hour of carbon dioxide. At the expected availability of 85%, this equates to 6,300 tonnes per annum.

The actual results from syngas production section of the plant are compared to this modal in Section 4.0.

3.2.2 Hydrogen Production

The hydrogen production model was produced in Aspen based on information from equipment vendors. It is summarised in the following Figure.

	Inputs kg/hour	Outputs kg/hour
Shifted syngas	573	
Effluent		262
Hydrogen product		15
Tail gas returned to syngas line		296
	573	573

Figure 12 – Hydrogen Mass Balance

Unfortunately, delays to the project meant that it wasn't possible to validate this mass balance with real world data.

3.2.3 SEWGS

The fluidised bed SEWGS model was produced in Aspen by UCL team. It is summarised in the following Figure.

	Inputs kg/hour	**Outputs kg/hour**
Simulated syngas (dry)	30	
Water vapour	10	
Effluent (condensed water)		20
Hydrogen product		2
CO2 product		18
	40	40

Figure 13 – SEWGS Mass Balance

Unfortunately, delays to the project meant that it wasn't possible to validate this mass balance with real world data.

3.3 Development

3.3.1 Host Plant

The key events for the host plant are summarised in the following table.

Date	**Event**
Q4 2015	DfT funding agreed
Q1 2016	Planning permission granted Environmental permit application duly made Basis of design, PFDs, P&IDs, 3D drawing completed NIC funding agreed
Q2 2016	National Grid funding agreed Landlords consent granted Enquires for major equipment issued
Q3 2016	Environmental permit issued Orders placed for waste heat boiler and methanation
Q4 2016	Orders placed for gasifier, gas cleaning, network entry Enquiry issued for mechanical and electrical integration
Q1 2017	Orders placed for plasma furnace, control system, liquefaction Civils work contractor appointed Hazop commenced
Q2 2017	Hazop completed Order placed with ADI for mechanical and electrical integration Detailed design completed

	Waste heat boiler delivered to site
Q3 2017	Civils work completed Gas grid connection complete
Q4 2017	Discharge consent agreed Off-take agreement in place
Q1 2018	Final equipment delivered to site Recruitment of operational team commenced
Q2 2018	Suspension of work due to withdrawal of funding by owners
Q4 2019	New funding agreed with DfT, new shareholder and Swindon LEP Contracts novated to new company ADI returned to site Plasma furnace refractory installed
Q1 2020	Operations team recruited Plasma furnace assembled New plasma furnace duct designed Fuel preparation, dry filter, wet filter, compressor, liquefaction equipment inspected by vendors and snag list drawn up
Q2 2020	Blast proof control room installed COVID Impacts on construction Base control system installed to allow control wiring checks Problems with operational team performance and issues around recruitment
Q3 2020	Snag list agreed with ADI Issues with PED compliance because of quality of ADI documentation Major delays to plant control system – revised set of documents sent to Valmet Delays to oxygen and carbon dioxide system Pre-commissioning checks carried out
Q4 2020	Continued issues with COVID restrictions Commissioning of plasma power supply and compressor deferred because of issues with international travel Carbon dioxide and oxygen tank installation complete
Q1 2021	Cold commissioning work commenced Snags cleared Continued work on control system Major procurement problems caused by COVID and new Brexit regulation Several staff replaced
Q2 2021	Cold commissioning complete and wet commissioning commenced Control system delivered to site and onsite testing commenced

Q3 2021	Wet commissioning of syngas line completed Leak testing carried out UKCA accreditation complete Permit pre-operational conditions met
Q4 2021	Gasifier hot commissioning commenced without electric arc furnace Hot ID fan failed at coupling to motor Ukraine war led to large increases in power and carbon dioxide pricing – increasing plant operational costs.
Q1 2022	Gasifier operated on virgin wood resulting in tar fouling of downstream equipment Gasifier nozzles modified to improve throughput and reduce blocking with sand Several weeks spent cleaning tar from system First arc struck on plasma furnace toward end of the month Ongoing issues with operator competence
Q2 2022	Gasifier and plasma furnace operated Continued problems with tar fouling from Q1 operations Plasma power supply failed Bed media system issue with erosion and blockages Deputy plant manager hired to improve team performance
Q3 and Q4 2022	Electrode breaks prevented plasma operation Furnace eventually heated up to operating temperature New operation team structure implemented with shift leaders focused on team management and assistants focused on plant control
Q1 2023	Successful furnace dip and gasifier operated on oil Unable to tap furnace – Hatch brought onsite to provide support Hot ID impellor failed and replaced
Q2 2023	Gasification line operated for several weeks in combustion mode Problem with poor quality electrodes identified Oxy-steam issues identified Problems identified with feed system, ash removal and alkaline scrubbers New operations director recruited – several initiatives to improve team performance
Q3 2023	Annual shutdown Dig out of plasma furnace
Q4 2023	Syngas successfully produced for around 1 hour New electrodes performing very well Oxy-steam gasification demonstrated Furnace successfully tapped New electrode performance well

	Plant manager role split into operations and maintenance
Q1 2024	Wood carried out inspection of methanation equipment and produced snag list Gasification runs identified problems with syngas leaks, syngas cooling, pressure control, feed system and syngas cleaning
Q2 2024	Feed system issues resolved Long term operation in oxy-steam combustion proven Operator experience developed
Q3 2024	Syngas cooling issues resolved Several gasification runs lasting several hours Flare modified to allow full throughput Annual plant maintenance including update to tapping system
Q4 2024	Several gasification runs at higher throughput as flare issues resolved Problem identified with bed media system preventing longer term operation – solution now developed Source of leak found – solution identified Regular gasification runs Plant shut down due to funding issues

Figure 14 – Host Plant Key Events

The original plan for the Swindon plant expected the following timeline:

- One year for detailed design,
- One year for fabrication,
- 6 months for on-site integration,
- 6 months for commissioning.

The actual timeline, ignoring the 18-month gap causing by funding issues, was:

- One year for detailed design.
- 18 months for fabrication.
- Two years for on-site integration.
- Two years spent on commissioning to date with a further year of work expected.

This totals 6½ years versus the original estimate of 3 years. The reasons for this delay are explored in Section 3.4.

3.3.2 Hydrogen Production

The timeline for the hydrogen production section of the plant is set out in the following table.

Date	**Event**
Q2 2022	Contract signed with BEIS Detailed design work with Wood, Italfluid, OSL commenced

Q3 2022	Hazop completed
Q4 2022	Process and civils design completed for PSA system PSA and control system ordered Issues are around size and cost of Swindon SEWGS system
Q1 2023	Agreed to switch from Swindon SEWGS to UCL SEWGS with BEIS Detailed design complete Orders placed for all major equipment Civils work complete
Q2 2023	LOPAs and ALARPs complete Platform delivered to site
Q3 2023	Platform installed PSA delayed because of issues with PED compliance Concerns around explosive risk around hydrogen compressor
Q4 2023	Hydrogen compressor lifted to position on platform DSEAR HAC complete
Q1 2024	Mechanical and electrical integration work commenced Control system hardware delivered to site Short lead time equipment ordered
Q2 2024	Further delays to PSA because of PED issues Delays to onsite mechanical work because of PED compliance Mechanical work delayed because of arguments around cost with contractor FAT of control system carried out
Q3 2024	FAT of PSA carried out and unit ready to ship All equipment delivered to site except PSA Mechanical and electrical work completed on site
Q4 2024	Project paused due to funding concerns

Figure 15 – Hydrogen Section Key Events

The project will be closed during March 2025. At the point of close, the PSA will not have shipped. All other equipment will be installed on site. No commissioning work will have been carried out and the hydrogen equipment will not have been tested. The reasons for this failure to complete the project successfully are explored in Section 3.4.

3.3.3 SEWGS

Given the low TRL of SEWGS and the complex design of pressurised dual-fluidised beds, there is no vendor of such technology. Several companies (Strata Technologies, Vinci, Integrated Lab Solutions and Helical Energy) were contacted at the beginning of the project, but only Helical Energy (HE) were able to commit to the delivery of the unit. HE had some previous reference projects employing similar designs at university of Manchester and Cranfield. HE was involved during the entire design of the facility.

Finch Consulting Ltd were appointed to carry out the entire HAZOP and DSEAR of the facility.

The SEWGS facility design has been fully completed, including P&IDs, 3D drawings, control philosophy and component specifications. Finch undertook a detailed HAZOP study on this with the following highlights:

- The P&ID was deemed to be of sufficient detail, quality, and accuracy for this phase of the design, and adequate as the basis for conducting the HAZOP Workshop. The HAZOP made several recommendations for P&ID changes or design changes (e.g. instrument/alarm changes) which in turn require P&ID changes. Therefore, the P&ID's should be reviewed once the recommendations have been implemented to ensure the drawings are accurate to the system as it is.
- Utility systems (such as instrument air, process water, steam, hydraulics etc.) were not assessed separately, but were assessed at the point of use in the main Nodes.
- No intolerable risks were identified. This is under the assurance that there is strictly no access to the laboratory area by non UCL staff during rig operation.

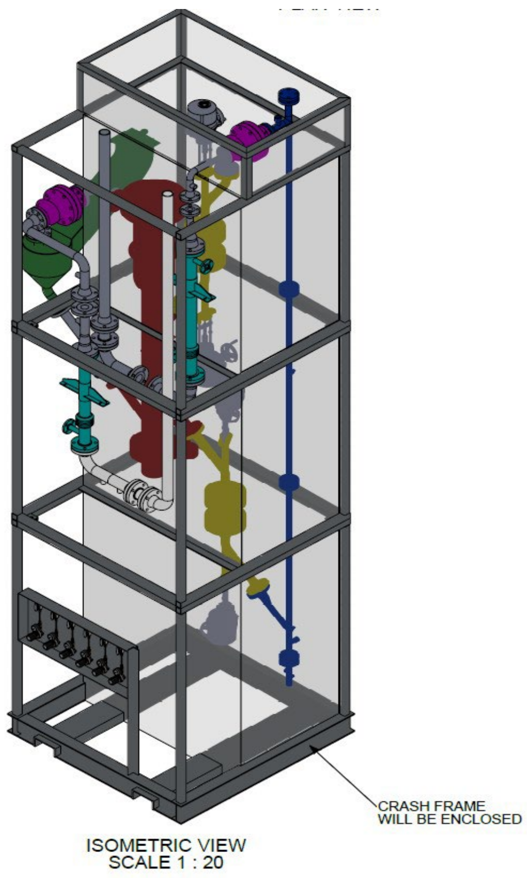


Figure 16 – SEWGS System

At the close of the project most of the components of the SEWGS system have been procured but it hasn't been integrated, commissioned or tested. UCL still intend to operate the system, but this will be done outside of the project. The reasons for delays to the SEWGS project are set out in Section 3.4.

3.4 Challenges and Solutions

3.4.1 Host Plant

3.4.1.1 Project Funding and Organisation

The original budget for the host plant was £27m and the actual expenditure to date is more than £50m. Whilst this was outside the scope of the DESNZ GGR project, the host plant was essential to provide the syngas for Hydrogen and CO2 capture. The expected time to bring the host plant to full operation was three years compared to the current expectation of 6½ years. This underestimate of the difficulty of the project is one of the key challenges to its successful execution. Funders, employers and other stakeholders did not understand the cost and time required for the project. This meant that the project had a structure that was not aligned with the project requirements resulting in tensions as costs overran.

The problems caused by this misalignment were:

- ABSL ran out of cash on several occasions and had to pause while new funding was secured. In the last month, the company was not able to secure funding and the host plant project ended without having achieved a successful conclusion.
- The Swindon plant has a planning horizon of 12-18 months. Critical spares have long lead times and planning for major maintenance activities takes months. The uncertainty around funding meant that it was impossible to plan effectively, nor to achieve an acceptable level of spares holding.
- The project team planned for a 4-year project rather than a 6-year project. Key staff left over the course of the project which created skills gaps and issues around succession.
- Suppliers and off-takers were given unrealistic expectations around the timescales for their interaction with the project. This led to tensions in those relationships which impacted on project performance.

This issue could be resolved by producing a more accurate project plan and budget at the outset. However, this would be extremely challenging to achieve given the uncertainties around the time and costs of delivering innovation projects. There was always a concern that the project was operating without sufficient contingency, but no-one envisaged that it would cost more than 50% more than the budget. It is only recently that it has become possible to accurately forecast the full costs of commissioning. Previous, there wasn't enough understanding of the commissioning plan to cost it accurately.

It is also worth noting that it is unlikely that the project would have secured funding if it had given an accurate view of timescales and costs at the outset.

3.4.1.2 Technical Issues

The technical challenges encountered during the host plant project can be split into several categories:

- Issues caused by the failure of an equipment package to meet its design specification. For example, the grade of graphite used in electrodes used in the plasma furnace was below the specified level resulting in frequent electrode breaks.
- Issues caused by the project team not configuring equipment correctly. For example, the ID fan coupling broke because its variable speed drive was set up wrongly.
- New process phenomena not encountered on the pilot plant because of changes to design or the increased scale. For example, silica oxide fumed from the plasma furnace because the increased scale meant that heating up the system took much longer than on the pilot plant.

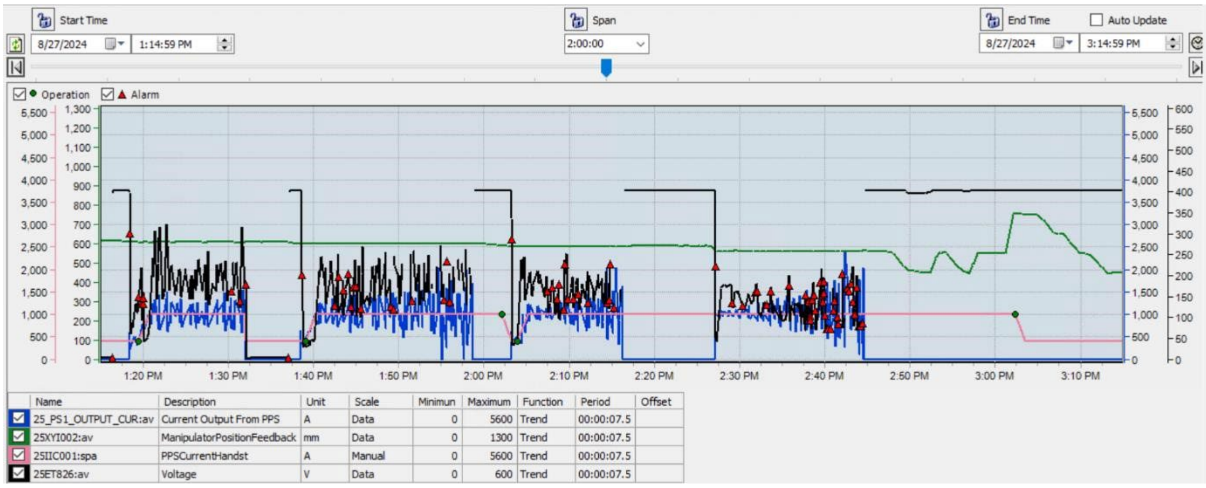


Figure 17 – DCS Trace used to Fault Find Plasma Power Supply Issues

The first two issues could be mitigated in the detailed design phase by engaging more closely with contractors to critically review designs and double checking how equipment should be configured. However, as explained in Section 3.1.4.1, gasification plants have many complex equipment packages. There was a detailed review of designs that identified most issues. This still left many that weren't discovered until the commissioning phase. This is not unusual and other gasification plants faced the same issues as set out in Section 2.

The key question is why there are so many issues that even if 90% are identified and resolved in the design phase, the remaining 10% delay projects by years. ABSL has been shocked by the poor reliability of the equipment supplied by reputable vendors.

One problem is that vendors struggle with even small amounts of innovation. For example:

- The plant used a flare that was designed to process landfill gas or gas from an anaerobic digestion plant. These gases are mixtures of carbon dioxide and methane rather than the hydrogen, carbon monoxide and carbon dioxide mix produce by the Swindon plant. The vendor of the flare didn't account for gas composition properly in their nozzle design resulting in a flare that could only process 50% of design throughput.
- The designer of the heat exchanger used to cool syngas installed standard sootblowers for cleaning ash from the secondary pass without considering the impact of these sootblowers on system pressures. In operation the activation of the sootblowers tripped the plant because of elevated pressures. The pressure limits were clearly set out in the system specification but overlooked by the vendor.
- The bed media system in the gasifier transports mica from the base of the gasifier to the roof where it was injected back into the system. The chain conveyor used for this application rapidly eroded on bends. This was caused by the hardness of the bed media used in the Swindon plant. The problem would have been avoided if the vendor had understood the bed media specification.

Figure 18 – Flare/Control Room

A further problem is poor quality engineering. For example:

- ABSL procured electrodes from a UK supplier. ABSL specified a high grade of electrodes. The vendor failed to meet this specification resulting in electrode breaks. ABSL worked with them for six months to try and improve quality until eventually moving to a US supplier. The change in supplier resolved the issue immediately.

- The auxiliary boiler used to generate steam for start-up did not include the correct control system for start-up. This made the boiler difficult to start and eventually led to the failure of boiler and a delay of several weeks while it was repaired.
- The routing of pipework in the quench vessel meant that only some of the liquor passed through the cooling heat exchanger. This meant the quench would rapidly overheat and trip the gasification process. This was discovered during commissioning. The pipework was rerouted, and quench temperatures reduced significantly.

There isn’t a single system in the gasification line that hasn’t required some modification to meet the design intent.

There have been very few new process phenomena arising from the project. The process was developed and proven in a pilot plant. The main source of technical challenges in the demonstration plant has been persuading equipment to meet its design specification. These problems have been relatively simple to resolve once they were accurately diagnosed. The key challenge is correctly diagnosing the source of the problem in a complex process.


Figure 19 – Tapping the Furnace/Ash Build Up in Syngas Cooler

For example, the temperature of the syngas exiting the syngas cooler after the electric arc furnace was too high, resulting in system trips after several hours of operation. Possible sources of this problem were:

1) Syngas temperatures entering the cooler were too high.
2) The syngas composition or volume didn’t match the design condition, impairing cooler performance.
3) Fouling in the first, second or third passes of the cooler because of ash composition or volume.
4) Failure of soot blowers to remove ash.
5) Fouling on the wet side of the boiler.

6) Temperature of water entering the cooler.
7) Pressure of steam exiting the cooler.
8) Time required for system to reach equilibrium.

It was challenging to identify the actual cause because it took three weeks to bring the system up to temperature and then one week to cool it down to allow the inside of the boiler to be inspected. Furthermore, investigations were hampered by other problems with the system such as blockages to the feed or bed media system. Eventually, the problem was isolated to a fine dust fouling the second pass of the system and a solution was found.

Overall, the host plant project has suffered from many relatively minor technical problems that have taken a long time to resolve. These are primarily caused by the poor design of equipment supplied to the project exacerbated by insufficient quality control in the project team. Some technical issues remain but solutions have been identified for each of these.

3.4.1.3 Project Management Issues

The management of the host plant project has been extremely challenging. The problems were:

- The project team did not include any members with experience of delivering complex, innovative, process engineering projects. This is not surprising as there are very few people with these skills. It meant that the whole team had to learn through the project, leading to frequent mistakes. This issue was identified at the start of the project, but it was not possible to find people to fill the missing skill gaps.
- As explained in Section 3.4.1.1, the budget has never been adequate, and the target completion dates have always been very aggressive.
- This was a first of a kind plant and it was not possible to recruit people with experience of designing, fabricating, commissioning or operating a similar facility. This meant the project team had to be trained after recruitment. This long period of orientation slowed the project down.
- Recruiting engineers capable of innovating and developing new solutions was difficult. As discussed in Section 3.1.4.3, engineering does not encourage innovation and finding engineers that wanted to work in an area full of risk and uncertainty was challenging.
- The scope of the project was too wide. It would have been far more efficient to have built and commissioned the syngas production section of the plant first and then build methanation after syngas was being produced reliably. The wide scope resulted in resource being spread too thinly.

Figure 20 – Methanation Vessels

- The technical leadership of the project was not effective at working in a collaborative way. Innovative engineers are rare and are used to challenging colleagues. Typically, projects will be led by a single technical leader, a benign dictator who will make major decisions. This facility was too complex for a single technical leader, but it was very difficult to find a project structure that could accommodate multiple innovate technical engineers working in a collaborative manner. This resulted in the use of a single technical authority who was unable to keep up with the workload. The issues caused by this problem were:
    - The start-up plan for the electric arc furnace involved preloading the system with large quantities of metal and flux. It was subsequently discovered that this was highly unusual. The normal approach was to start with a small amount of material in the furnace then gradually build up a slag bath. This decision cost the project several months. It could have been avoided if third party advice had been sought earlier.
    - The project occasionally got distracted at resolving unnecessary problems. For example, several weeks were spent operating the gasifier on cooking oil. This could have been avoided if more effort had been put into making the gasifier underbed burner work more effectively.
    - The project team frequently failed to see the wood for the trees. There were so many minor problems that it could be very difficult to spot major issues. A good example of this issue was the back pressure caused by the flare. The whole project team were aware of pressure problems in the system. These were often blamed on poor fan performance, even

    when experts were brought in to review data. The problem with the flare was only diagnosed after several weeks of comparing actual system performance to the design. In hindsight the problem was obvious.
  - There were major problems with the plant control system.
- Budgetary pressure towards the end of the procurement phase resulted in the mechanical and electrical integration vendor being selected on price rather than quality. This resulted in an extremely lengthy snag list and problems securing PED compliance because of poor record keeping. Issues caused by poor installation were found years after the contractor had left site.
- It was attempted to carry out activities in parallel rather than in sequence. For example, cold commissioning checks were carried out on some areas of the plant while equipment was still being installed in other. This invariably end up wasting time rather than saving time. Splitting management attention over multiple activities resulted in them being carried out poorly so that they needed to be repeated. This reflects the challenges of carrying our normally simple tasks in a new environment. Commissioning engineers who could easily cold commission a power plant struggle to understand the gasification process flow without management supervision.
- A conventional project management approach was very inefficient during the hot commissioning phase of the project. Equipment failures or unexpected results would often delay planned activities resulting in idle resource. A more agile approach that adjusted plans dynamically allowed a better use of resource.

The clear lessons to be drawn from these issues are:

- Do not commence a project unless there is consensus that the budget and programme have sufficient margin.
- Innovation projects require the advice of people with experience of delivering similar projects. This is an essential component of project success.
- The project team will require a long induction period to develop a sufficient understanding of the innovative technology.
- The scope of the project should be minimised. Phase the project to be delivered in small steps. This will save time and cost in the long run.
- Develop a project structure that enforces collaborative working from multiple technical innovators. This will require project managers with strong diplomatic skills.
- Innovative processes have a lot of inherent challenges. Do not make them even more challenging by choosing price over quality.
- Operate in a sequential manner to keep project focused. Parallel work will often need to be done twice.
- Dynamic project management is essential in the commissioning phase of the project to react quickly to equipment failure and other issues.

3.4.1.4 Operational Issues

A problem with gasification projects, and more broadly with any complex process technology, is that projects are seen as a technical challenge with operational issues being a secondary problem. ABSL's experience is that the operational challenges are the main problem and that technical challenges are relatively easy to resolve. The Swindon plant could have adopted a completely different set of technologies and would have taken several years to commission. A competent, well trained and organised operations team with a complete set of standard working procedures and a functional control system would have brought the plant into operation within a much tighter timescale.

Figure 21 – Host Plant Gases Compound

There is an ongoing interaction between equipment performance, process conditions and operations. Operations needs to maintain and operate equipment; equipment needs to perform to determine process conditions and then the process conditions define the operating conditions. In turn, the operating conditions impact the performance and reliability of the equipment. This means that commissioning a plant is an iterative process that can only proceed very slowly.

The original operations structure was:

- A single plant manager and a single chief technical officer who was responsible for commissioning, operations, health and safety and technology.
- Five shifts of three plant operators made up of a shift supervisor, assistant shift supervisor and process technician. The shift supervisor was responsible for site safety. The shift supervisor and their assistant were responsible for controlling

the plant through the control system. All three were responsible for physical activities on site.

- Two maintenance shifts made up of two multi-skilled maintenance technicians. They were responsible for planned and reactive maintenance together with modifications to the plant.
- A technical team of one responsible for process engineering, commissioning and other technical activities.

The original team struggled for the following reasons:

- The recruitment of shift operators proved very difficult. This is because of a shortage of competent staff and the location of the plant – Swindon does not have any other process plants.
- There was insufficient resource for the management of training of the teams. Operators without any process industry knowledge required a high level of support. Furthermore, even operators with process industry experience did not understand oxy-steam gasification or electric arc furnaces and required specialist training.
- There wasn't a large team of process engineers to lead the commissioning of the system. The initial expectation was that the operations team would commission the plant. This was highly optimistic. The operations team could follow operating instructions for a well-defined process. They did not have the underlying process, mechanical or electrical knowledge to be able to commission. The technical team was under resourced.
- The maintenance team did not have sufficient resource for planning or managing procurement, stock level and workflow. The plant maintenance management system required configuration and ongoing management, and the maintenance team did not have the right skills to deal with this.

These issues led to very slow progress on commissioning the plant and dealing with the snag list from the construction phase. Operators would make major mistakes, damaging equipment, and equipment wasn't properly maintained. It caused safety issues around risk assessments for plant activities and the lock out procedure for maintenance.

Several new structures were tried to improve operating efficiency including increasing the shift team size to four and increasing the technical team size together with employing a maintenance planner, a training manager, a deputy plant manager and environmental and safety officers. Gradually, performance improved and progress was made on commissioning the plant.

At the conclusion of the host plant project two major issues remained.

Firstly, the operations team performance was still below the required standard. Some shifts were not able to deal with process interruptions which meant that minor problems that should be solved in an hour could bring down the plant for days. This could be partially addressed by better training but in some cases new staff needed to be hired. Replacing staff is a major issue because it takes six months to train a shift supervisor.

Secondly, commissioning planning and support was insufficient. Over the course of the project, six people had been given responsibility for building a commissioning plan and managing the delivery of commissioning. None of them had been wholly successful.

Figure 22 – Carbon Dioxide Distribution Manifold

Commissioning managers generally come from a control system background with a good understanding of instrumentation. The commissioning managers initially hired by the project had a good understanding of control systems but struggled to understand the process sufficiently to produce any commissioning plan. We then asked engineers with a good understanding of the process to produce a plan. These engineers were able to produce workable plans, but they were challenging to implement because no-one had previous experience of commissioning an oxy-steam gasification plant.

Commissioning any process is always challenging. Commissioning a novel complex process is extremely difficult. There are uncertainties around sequencing, timescales, resource requirements and the impact of mechanical failures that can only be resolved through practical experience. The lessons learnt from commissioning the Swindon plant are essential learning for future facilities. The gasification failures outlined in Section 2 all occurred during the commissioning phase because they did not have demonstration plant experience to draw on. The project underestimated the scale of the commissioning challenge and then took several years to develop a solution.

ABSL developed the following solutions to the two remaining major operational challenges:

- The plant should move to campaign operation with four shifts of three people. Running operational campaigns of 6-8 weeks followed by a month of consolidation and training will improve operator performance. Reducing the total operational headcount means that management time can be more focussed on improving performance.
- Commissioning management should be moved to the process engineering team, but they should be given time to increase their knowledge of commissioning best practice and produce a commissioning plan. The team should be expanded to allow them to support commissioning activities on a 24/7 basis.

If ABSL managed to secure additional funds these solutions would be implemented.

3.4.2 Hydrogen Production

The hydrogen production line developed under the DESNZ GGR programme was far simpler than the host plant and the project only completed part of the installation before it was terminated due to company liquidation. However, there were challenges during the design, procurement, fabrication and installation phase. These challenges and their solutions are set out in the following table.

Issue	Solution
The original design incorporated a tube trailer to store compressed hydrogen from the system. However, it was not possible to find a safe location to park the trailer. It wasn't possible to secure the area around the trailers to exclude sources of ignition.	The tube trailers were replaced with a bottling plant that filled gas cylinders with high purity hydrogen. These can be transported to end users.
The cost of equipment used in the project had increased significantly since the project proposal was submitted to BEIS. This was driven by equipment inflation caused by the Ukraine war.	Several value engineering sessions were held to identify possible cost savings. It was decided to remove the syngas compressor from the project scope and to reroute the tail gas from the PSA through the existing syngas compressor on site. This slightly reduced the throughput of the system but reduced costs significantly.

The detailed design of the SEWGS system intended for installation in Swindon was too large and too expensive.	The Swindon SEWGS part of the project was cancelled and replaced with a simple, smaller system at UCL.
The PSA was meant to be a mature solution supplied by an established vendor, Xebec. However, Xebec went into administration soon after we had placed a formal order with them. There wasn't any alternative supplier for the equipment.	ABSL continued to work with Xebec through the administration process. Eventually the company was purchased by Ivys and work on the PSA restarted. This led to a short delay to the project.
Xebec/Ivys had significant problems demonstrating PED compliance for the PSA. This was because their fabrication shop did not have suitable systems in place.	Xebec identified an alternative fabricator in the USA. ABSL helped them understand PED requirements and put suitable processes in place to demonstrate compliance. However, this delayed the shipping of the PSA by twelve months.
Leaks from the hydrogen compressor could self-ignite, creating a high temperature jet that would pose a hazard to people working around the compressor. In addition, the hydrogen in the compressor could ignite creating an explosion that would damage people and property. There is very little operational experience of operating hydrogen equipment, and the guidance was unclear on how to operate the compressor safely.	ABSL discussed the issue with industrial gases companies and industry bodies to try and identify best practice. There wasn't a consensus, and so ABSL modelled the impacts of leaks and explosions caused by the compressor. The inventory of gas in the compressor was very low but the modelling showed that it presented a significant risk. ABSL considered enclosing the compressor in a building that would focus any explosion safely upwards. Several different building designs were considered but none were cost effective. Eventually the compressor was relocated on to a platform high above other equipment and procedures were put in place to ensure operators could only access that platform when the compressor was not operating.
The mechanical integrator had to make several high integrity welds to connect the system to the host plant. They struggled to demonstrate that these were PED compliant.	ABSL has a large amount of experience of the PED from the construction of the host plant. The company worked with mechanical integrator and the notified body for the plant to agree a plan to demonstrate compliance. This required X rays of the welds and improvements to the integrators weld records.

The scope of work for the integrator was modified for design changes agreed during the plant HAZOP. These changes were relatively minor, but they led to a dramatic increase in price.	ABSL negotiated with the supplier for several weeks to reduce the price increase.
ABSL suffered from financial challenges across 2024 while delivering the project. This led to a loss of resources and risk of cancellation.	ABSL was transparent with DESNZ around these risks and both parties worked collaboratively to keep the project on track.

Figure 23 – Hydrogen Challenges and Solutions

3.4.3 SEWGS

SEWGS is a kind of pressure swing adsorption (PSA) process, where the produced CO2 is in situ adsorbed on solid materials at temperatures between 350 and 550°C during the WGS reaction in one reactor. The solid sorbent is then circulated to a higher temperature reactor, operated at atmospheric pressure, in which CO2 is released. The regenerated sorbent is then extracted from the bottom and sent back to the main reactor through intermediate loop seals.

During the design phase the project has gone through a number of difficulties, which have caused serious delay to the project:

1. Originally specified loop seals were deemed not suitable after detailed engineering, due to the physical inability to generate a sufficient differential pressure between the two reactors so HE developed an alternative, but more complex, solution using a lock hopper type design to satisfy the performance requirement.
2. A novel pilot scale lock hopper was built by HE to demonstrate the material flowability which proved successful. Costs borne by HE. The new design implied several cascading engineering changes to integrate the lock hoppers into the SEWGS facility.
3. Size of the transport column reactor was reduced from the original specification to allow for increasing superficial gas velocities that would enable higher flexibility in sorbent material choices. The change required a complete redesign of the transport column and internal re-appraisal of the vessel to satisfy the pressure vessel codes. This change also required modifications to the piping tie-in points, change to the electrical heating, revised thermal analysis to account for the modified thermal expansions and changes to the skid structural members
4. Nitrogen generator for start-up of the facility needs to be anchored to floor of the lab for safe operation, requiring additional support and thickening of the concrete slabs. The project was filed under UCL Estate and is currently ongoing with expected termination in April 2025.

3.5 Final Costs

3.5.1 Host Plant

The host plant was not funded by the project. The total costs of construction and commissioning to date are shown in the following Figure.

	£
Equipment	25.7
Design and delivery	11.0
Commissioning	15.6
Other	4.0
Total	**56.3**

Figure 24 – Host Plant Cost

Its forecast that the additional cost to bring the host plant into full operation is £15.0m. This would give a total cost for the host plant project of £71.3m. This compares to a total forecast of £30.2m in 2018. The key reason for this variance is the cost of commissioning the plant. This was expected to be around £2m over six months rather than more than £30m of 3 years.

3.5.2 Hydrogen Production

The hydrogen production expenditure is summarised in the following Figure.

	£
Third party costs	1.9
UCL	0.7
ABSL	1.5
Total	**4.1**

Figure 25 – Hydrogen Project Cost

The forecast cost to completion is around £5.0m. This compares to a budget of £4.7m.

3.5.3 SEWGS

Entire cost of the SEWGS facility is approximately £0.5m. Of these, approximately £0.3, have been invoiced to HE (mostly for design work, and few parts procurement).

4.0 Trial Results

4.1.1 Host Plant

The project focussed on the hot commissioning of the syngas production section of the host plant. The methanation section was cold and wet commissioned but syngas production never achieved the reliability required to hot commission methanation.

The syngas section is split into three subsections:

- The gasifier subsection that transforms the waste feedstock into a crude syngas.
- The electric arc furnace that removes ash and tar from the syngas.

- The balance of plant that cools the syngas and removes contaminants.

The number of cumulative operating hours is shown in the following figure.

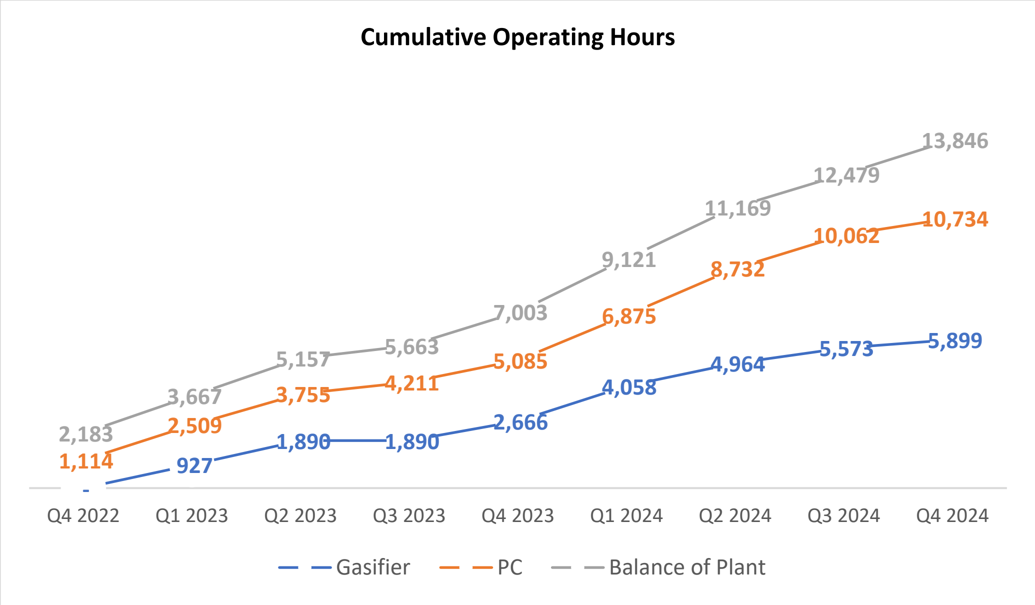


Figure 26 – Cumulative Operating Hours

The Figure shows when each subsection is operating at normal operating temperatures with all mechanical and electrical systems in operation. It does not show when the equipment is operating at normal process conditions. The 5,500 hours of combined operation of all three subsections shows that syngas production can work reliably and provided the data required to resolved all of the issues set out above.

The hours of operation in wood combustion mode are shown in the following Figure.

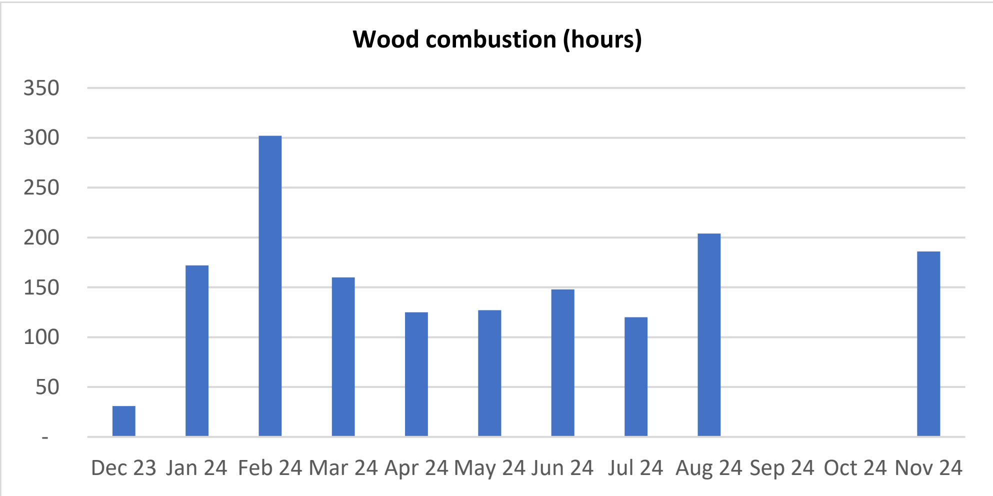


Figure 27 – Monthly Hours of Wood Combustion

Overall, the plant achieved around 1,500 hours of operation on waste wood. This demonstrated that the syngas line operated reliably with ash and other contaminants in the system and that operators could control the plant effectively.

Operating the plant in oxy-steam gasification mode was more challenging, as shown in the following Figure.

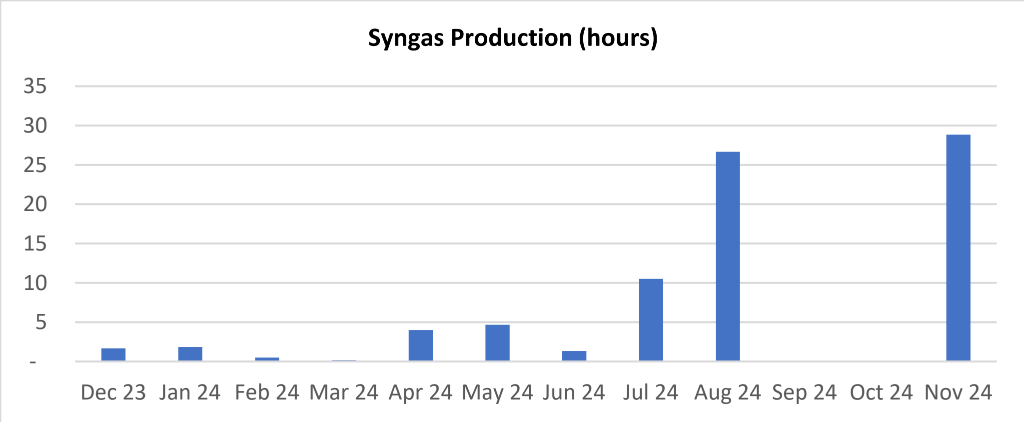


Figure 28 – Monthly Hours of Syngas Production

In total the plant achieved just below 100 hours of oxy-steam gasification before the project concluded. As set out above, the predominant issues that impacted on reliability were operator competence and the quality of operational procedures. In addition, there were the following technical issues and affected reliability:

- The system delivering feedstock into the gasifier would bridge and jam. This was resolved in March 2024.
- The syngas was not cooled sufficiently in the syngas cooler and quench. This was resolved in June 2024.
- The bed media system blocked. This was unresolved at the point of ABSL liquidation. A solution had been identified but not implemented.
- The ash handling system blocked due to faulty valves. Various improvements to the system have been made which should improve reliability.

In November, there were several runs of six hours that were ended by blockages where bed media is returned to the gasifier. The system was moved to combustion mode to allow these blockages to be cleared. Operators then struggled to return the plant to gasification mode, resulting in an outage lasting several days until the next gasification run.

The project team are confident that the technical issues preventing long term gasification can be resolved. The operation issues are more difficult to resolve but the plan set out in Section 3.4.1.4 had a good chance of success.

The quality of the syngas produced in the August and November runs is compared to the design specification in the following Figure.

Parameter	August	November	Design
Mass Flow	600kg/hr	800kg/hour	1,000kg/hour

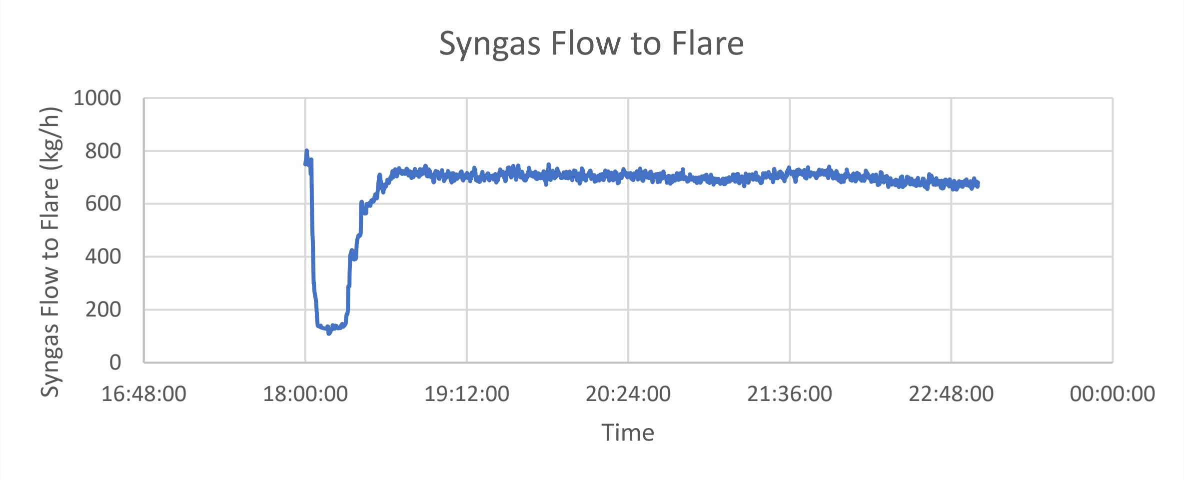
Calorific Value	6.5MJ/kg	6.5MJ/kg	8.5MJ/kg
CO	24%	24%	37%
CO_2	22%	18%	16%
H_2	23%	24%	38%
H_2O	4%	2%	6%
CH_4	2%	4%	1%
O_2	0.2%	0.3%	0.3%
N_2	23%	28%	1%
HCN	324ppm	908ppm	200ppm
C_6H_6	716ppm	1,900ppm	500ppm
COS	70ppm	78ppm	50ppm
NH_3	39ppm	8ppm	3ppm

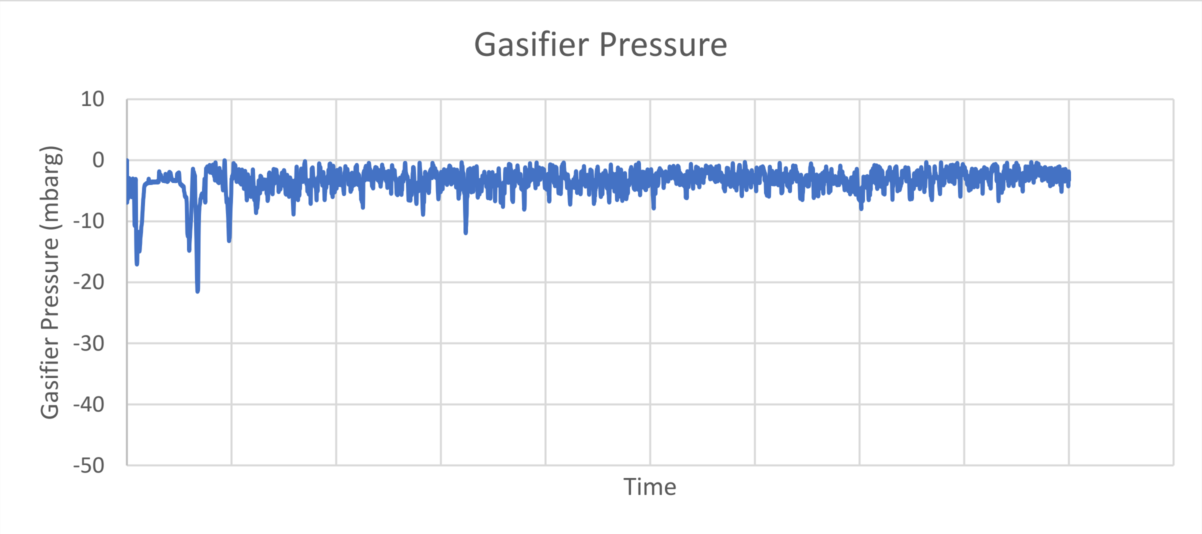
Figure 29 – Syngas Composition: C_2H_2, C_3H_8, NOx, HCl, SOx, Phenol, Toluene, Naphthalene, HF all within specification

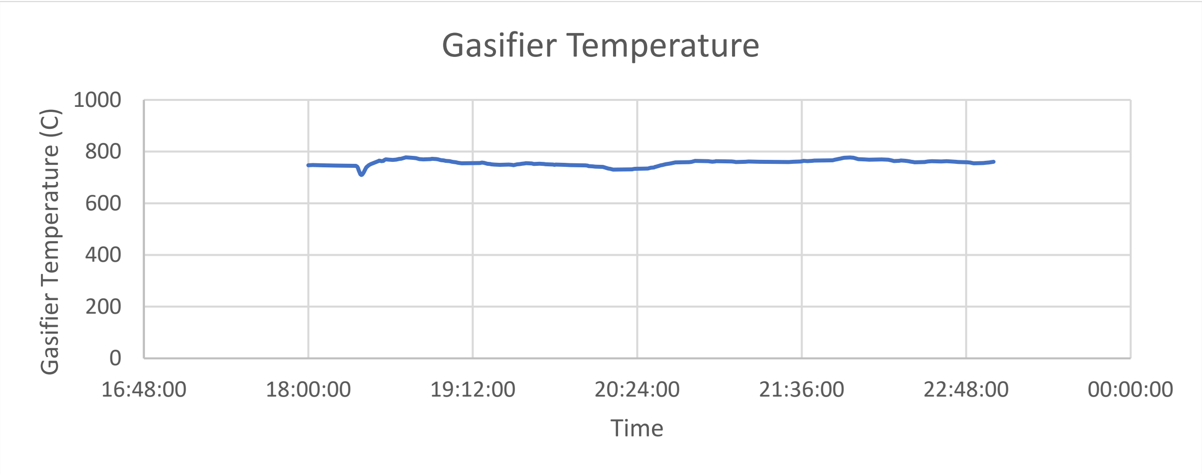
This table shows that the plant produced good quality syngas. The main issue that prevented the start of methanation commissioning was reliability issues. The following conclusions can be drawn from these numbers:

- There was a leak of around 200kg/hour of air into the system resulting in elevated level of nitrogen and combusting some of the hydrogen and carbon monoxide. This source of this leak was identified in November and a solution is ready to implement.
- The throughput of the system was restricted by the flare system in August. This issue was resolved in September but testing in November did not operate at full throughput to allow the results to be compared to August.
- Ammonia levels were high in August because the acid scrubber was not operating correctly. This was fixed for the November run.
- Cyanide, benzene and carbonyl sulphur levels were high because of the impact of the leak on gasification quality. The levels are acceptable to the methanation system. Improvements have been planned to the alkaline scrubber to address the cyanide and carbonyl sulphur issues.

The quality of the gasification during the different runs can be assess by looking at traces across the runs as shown in the following Figure.


Syngas Flow to Flare
Syngas Flow to Flare (kg/h)
1000
800
600
400
200
0
16:48:00
18:00:00
19:12:00
20:24:00
21:36:00
22:48:00
00:00:00
Time


Gasifier Pressure
Gasifier Pressure (mbarg)
10
0
-10
-20
-30
-40
-50
Time


Gasifier Temperature
Gasifier Temperature (C)
1000
800
600
400
200
0
16:48:00
18:00:00
19:12:00
20:24:00
21:36:00
22:48:00
00:00:00
Time

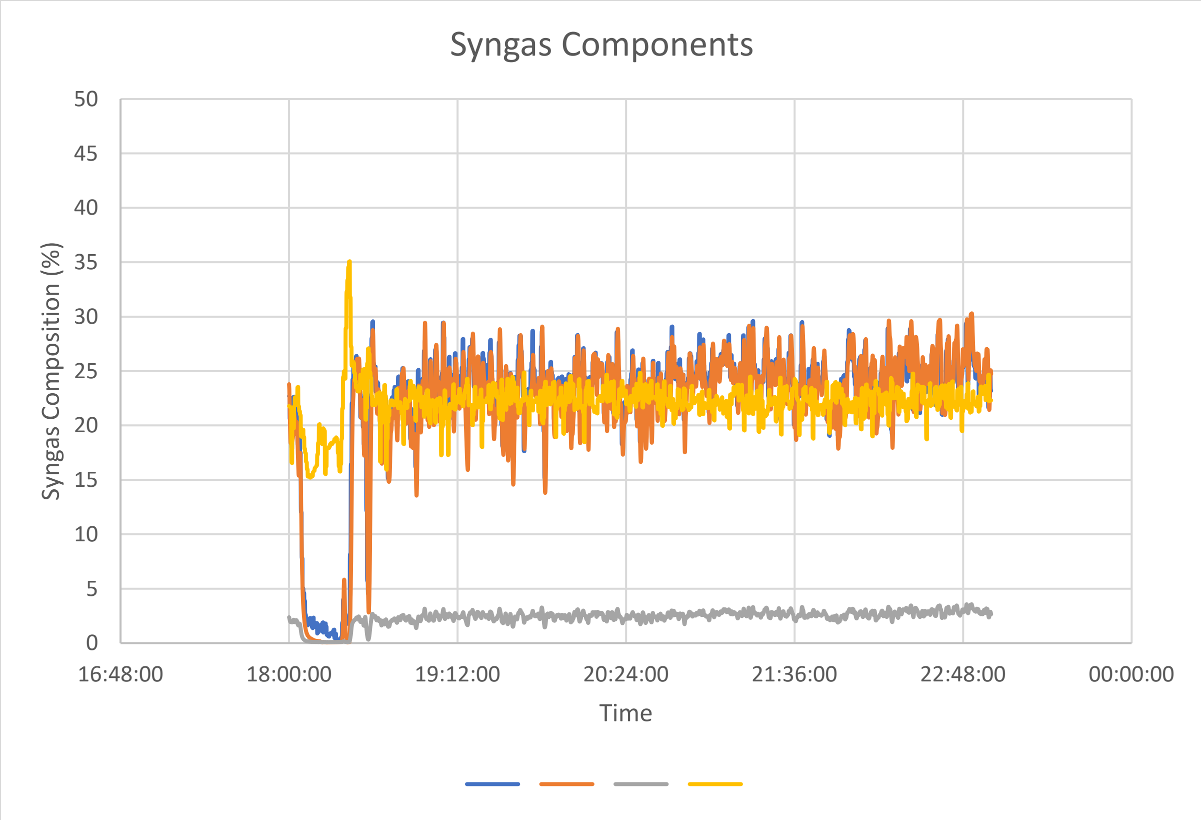


Figure 30 – Data from Gasification Run

These graphs show that was significant variation in syngas pressure and composition across the run. These improve over the course of the run, but the variation is still higher than would be expected. The underlying causes of the variation are:

- The air leaks into the system mean that combustion is taking place in the air space rather than the bed.
- The operating pressures are lower (more negative) than expected. This results in fines being pulled out of the bed and gasifying in the air space.

These issues can be resolved by reducing the leakage into the system and using operational experience to move to higher pressure operation.

All the information from the operation of the plant is stored in a data historian. This provides a valuable record of the gasification experience at the plant.

4.1.2 Hydrogen Production

The hydrogen production can only be tested and generate results once the syngas production and methanation section of the plants are operating reliably. Therefore, there weren't any results from the hydrogen production section of the project.

4.1.3 SEWGS

Project delays were substantial due to extended design phase and challenges faced with placing orders for the materials. UCL is now exploring the potential to complete the works using in-house capabilities and alternative funding routes, including a number of recent grants from UKRI. Estimated delivery time of the rig is July 2025 with first test completed in September 2025.

5.0 Project Review and Future Work

The project was a complex engineering project that relied on the development of infrastructure that sat outside the primary project activities. This made it extremely challenging.

The positives outcome from the Host Plant development work and GGR project were:

- The host plant progressed to the point that it was producing good quality syngas and had a credible plan to commission methanation and then biohydrogen production.
- The design of the hydrogen production section was complete and had been reviewed for safe operation. All the required equipment had been fabricated and was either delivered to site or ready to ship.
- The SEWGS plant design is completed and has been reviewed for safe operation. The system is in manufacture and UCL are committed to complete construction and commissioning.

The negatives for the organisation, Host Plant and GGR project were:

- The funding environment for low carbon technologies is extremely challenging and this has affected project partners and subcontractors, delaying the project and eventually terminating it. This is discussed in more detail below.
- The commissioning of the Swindon plant has taken far longer than expected and prevented the project achieving its key objective of capture biogenic carbon dioxide. The reasons for the delays are discussed in depth above.
- Demonstrating compliance with the pressure equipment directive has been challenging for the project team and subcontractors. Meeting PED requirements for innovative projects requires careful planning.

ABSL struggled to raise funds across 2024 and suspended work on the project in December 2024. This led DESNZ to terminate the project in April 2025. ABSL is highly likely to shut down operations and enter liquidation. Most of the project team have already been made redundant. There is a small possibility that the Swindon plant will be sold to a new owner who will complete the project. However, the most likely outcome is that the plant will be broken up.

The SEWGS equipment is owned by UCL. They intend to complete the SEWGS part of the project.

6.0 Solution Assessment

6.1 Commercial Solution

ABSL has been developing a commercial plant for several years and has completed its FEED. It is support by Microsoft for carbon credits and Trafigura for hydrogen. The underlying technology has been proven at ABSL pilot and demonstration plants and is supplied by large established companies such as Sumitomo, Hatch and Wood. As far as ABSL are aware, it is the most developed H_2BECCs project in the world.

6.1.1 Location

The project is located on Plot 4 of the Protos development in north Cheshire. The site is very close to the EET blue hydrogen project and the Encyclis waste to energy plant. It is close to the Hynet Carbon Sequestration Above Ground Interface servicing the Encyclis project and to the proposed Cadent hydrogen distribution network. There are several large energy consumers that are committed to converting to hydrogen such as Essar and Encirc Glass.

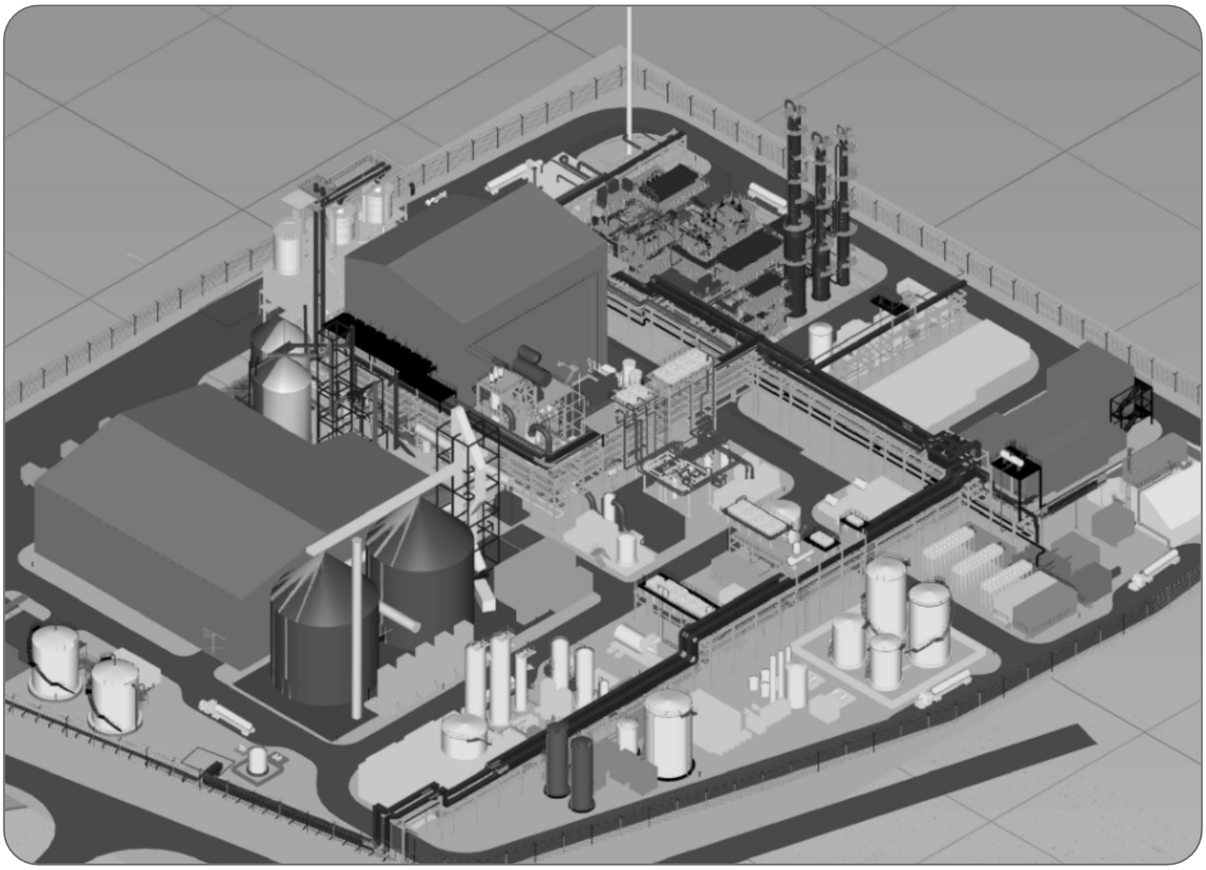


Figure 31 – Commercial Plant Design

The land is owned by Peel, and they have provided a letter of support confirming that they will enter into a lease for the site with ABSL if we are successful in securing carbon sequestration capacity.

6.1.2 Current Stage of Development

ABSL has been developing the project since early in 2021 and submitted CCUS Track 1 and Track 1 Expansion applications that were not successful. The current project status is as follows:

- An agreement has been reached with Peel on the site,
- Planning permission has been obtained although a revised permission is required to reflect changes to the project identified during the FEED,
- Key contractors have been identified
- Off-takers are engaged
- Discussions have been held with funders
- Petrofac completed a FEED in 2023

Overall, around £7m has been spent on developing the project to date. A large amount of work has been completed but further work is required to take the project to FID.

6.1.3 Process Description

The project is a H_2BECCs facility that gasifies waste wood to produce a clean syngas that is converted to hydrogen while capturing carbon dioxide. The key process steps are:

- A fluidised bed gasifier supplied by SFW converts the waste wood into a crude syngas.
- Tars and ash in the syngas are removed using an electric arc furnace supplied by Hatch.
- The syngas is cooled and cleaned using a cyclone and wet scrubbers supplied by CECO.
- The cool clean syngas is converted into hydrogen and carbon dioxide is captured using a process supplied by Wood.
- The hydrogen is purified using a PSA supplied by Linde.

Mature technology from established vendors is used in each of these process steps but the combination is novel.

The plant process 120,000 tonnes per annum of waste wood and produces 305GWh of low carbon hydrogen while capturing 150,000 tonnes per annum of biogenic carbon dioxide. Its uses 160GWh of power per annum for waste handling, gas cleaning, gas compression and carbon capture.

6.1.4 Negative Emissions

The project will deliver a GHG benefit of 200,000 tonnes per annum through the capture and sequestration of 146,000 tonnes per annum of negative emissions and 55,000 tonnes per annum of saving from the replacement of 305GWh of fossil natural gas with low carbon hydrogen.

The project has an LOI from Microsoft for the sale of carbon credits. Trafigura will purchase the low carbon hydrogen.

6.1.5 Flexibility

The is expected to operate for 7,446 hours per year with a one month annual shut down for annual inspections and one month of unplanned maintenance spread across the year.

It will produce 21 tonnes per hour of carbon dioxide in normal operation and will have the ability to turn down to produce 15 tonnes per hour. It is also possible for the plant to run in a combustion mode where it will process a small amount of waste to keep systems warm.

However, the ability to turn down or run in combustion mode will be constrained by contracts requirements to process waste. Therefore, any flexibility will be limited to times of sequestration network unavailability or other emergencies.

The overall scale of 15 tonnes per hour is driven by project economics and technical risk. Larger scales deliver better economics. However, the scale is a 15x scale up of ABSL's demonstration plant and this is seen as the largest scale up factor that will be acceptable to funders. Therefore, there is limited opportunity to show flexibility in the scale of the project.

6.1.6 Design Life

The design life is 20 years.

6.1.7 CO2 Flow Rates

The plant will export the following amount of carbon dioxide:

- 21 tonnes per hour,
- 14,000 tonnes on average per month,
- 154,000 tonnes per annum.

At least 95% of this carbon dioxide will be biogenic.

6.1.8 Project Downtime

The plant availability is:

- The plant has a one-month annual shutdown for planned maintenance.
- It is expected that there is a further four weeks of unplanned maintenance spread over the remaining 11 months.

This gives a total availability of 7,446 hours per annum.

The plant will take around one week to shut down and one week to start up.

6.1.9 Co-Product and Supply Chain

The plant will produce 305GWh of low carbon hydrogen from 120,000 tonnes per annum of grade C waste wood. The wood isn't suitable for reuse or recycling and will be diverted from energy recovery or landfill. ABSL has an outline agreement with

Evero for the supply of waste wood to the facility. Evero is an established processor of waste wood and operate two waste wood power plants in the northwest.

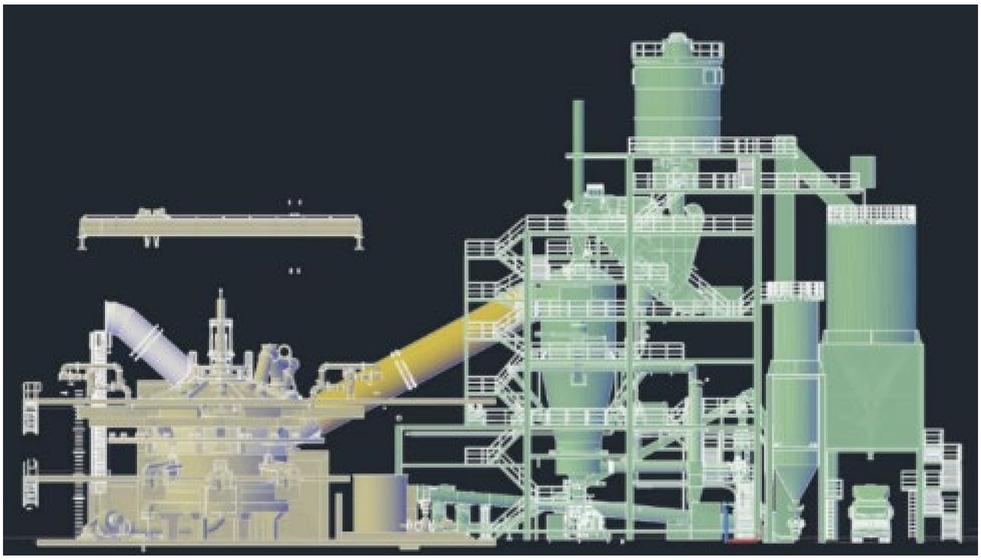


Figure 32 – Commercial Gasifier and Electric Arc Furnace

The hydrogen will meet the low carbon hydrogen standard with an expected carbon intensity of 18.5gCO_{2eq}/MJ.

6.1.10 Utility Supply Agreements

The main utility requirements for the plant are set out in the Process Description. The plant requires 22MW of power, up to 30MW of natural gas for warm up and 13.5tph of potable and raw water. These amounts were calculated by Petrofac during the FEED.

Peel is responsible for the provision of utilities to the site and have engaged with power, gas and water companies to procure these. This is clearly set out in the draft lease and the lease option.

6.1.11 Carbon Dioxide Stream

The plant is a hydrogen BECCs facility converting waste wood into hydrogen while capturing carbon dioxide.

The source of the carbon dioxide is the carbon in the waste wood processed by the plant. This is converted into carbon dioxide in the gasification and hydrogen production steps of the process. This produces a gas that is a mixture of carbon dioxide and hydrogen together with small amounts of nitrogen, carbon monoxide and other contaminants.

The capture process uses an amine promoted potassium carbonate scrub to capture carbon dioxide from the gas mixture. The solvent is then regenerated through heating and release of pressure. The carbon dioxide is then dried and compressed to 45 bar for injection into the Hynet transport and sequestration network. There is a small amount of on-site storage of compressed carbon dioxide to service the plant's requirements.

Prior to export, the carbon dioxide is analysed to ensure that it meet the Hynet carbon dioxide specification. If it does not meet the standard it is vented to atmosphere.

6.2 Capital Cost

The forecast capital cost for the commercial plant is £567m. The analysis of this amount is shown in the following Figure.

	£m
Material & Equipment	186
Third Party Services (TPS)	27
Field Construction & Site Installation	151
EPCM Cost	66
Insurance	11
Owners Costs	39
Contingency	87
	567

Figure 33 – Commercial Plant Capital Cost

These figures are based on a detailed FEED carried out by Petrofac in 2023. The basis of each estimate is:

- Material and equipment is based on quotes from each equipment supplier.
- Third party services are estimated by Petrofac using data from other projects.
- Field construction and site installation is estimated using quantities produced by Petrofac from the FEED and rates from their approved UK suppliers.
- EPCM cost is based on estimates from the FEED and standard Petrofac rates.
- Insurance is based on a third-party quotation.
- Owner's costs are based on actual costs incurred by ABSL and third-party quotes for future services
- The 20% contingency is Petrofac's estimate of the risk allowance required by funders to ensure there is sufficient cash to complete the project.

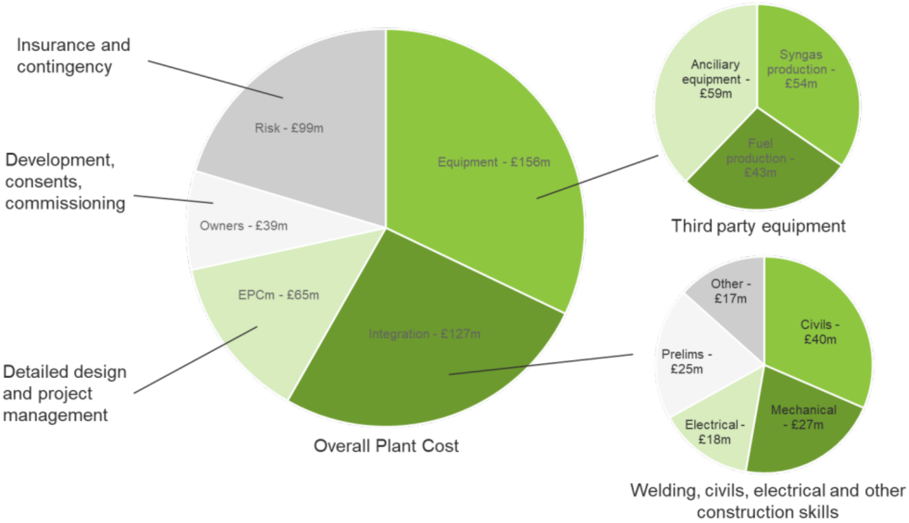


Figure 34 – Commercial Plant Capital Cost

Overall, the £567m is a robust estimate of the total cost of delivering a commercial plant.

6.3 Lifecycle Analysis

ABSL has produced a Heat and Mass Balance for a commercial plant summarised in the Figure below and showing expected GHG capture rate and mass and energy flows into the plant. This HMB is based on information provided by equipment vendors including Wood. The information was provided to University College London to produce an LCA. ABSL has also prepared an LCA for the biogenic hydrogen produced by the plant based on the Low Carbon Hydrogen Standard.

	Mass		Energy	
	In	Out	In	Out
	tph	tph	MW	MW
Syngas Production				
Waste wood at 20% moisture	15.81		66.98	
Air to dryer	21.58		0.03	
Exhaust from dryer		23.01		0.52
Oxygen - 93% purity	6.90		0.17	
Carbon dioxide to gasifier	1.94		-	
Boiler feed water	11.15		1.08	
Oversize from gasifier - inert		0.16		-
Vitrified slag - product		0.40		0.25
10 bar steam for H2BECCS		7.55		5.64
Fly ash from boiler/APCr		0.03		0.00
Gas treatment chemicals	0.85		-	
Effluent		6.20		0.18
Syngas to H2BECCS		20.87		52.97
Power			14.00	
Heat Losses				22.70
	58.22	58.22	82.26	82.26
		0.00		
H2BECCs Process				
Syngas	20.87		52.97	
Steam from syngas production	7.55		5.64	
High purity water	1.74		0.18	
Carbon dioxide to sequestration		21.24		0.14
Carbon dioxide to gasifier		1.94	-	
Hydrogen to battery limit		1.36		40.90
Power			7.00	
Combustion air	5.67		0.01	
Gases to atmosphere/thermal losses		11.29		0.26
Heat Losses				24.50
	35.83	35.83	65.80	65.80

Figure 35 – Commercial Plant Heat and Mass Balance

UCL assessed GHG emissions using carbon dioxide, hydrogen and tonnes of waste as the functional units. They used incineration as the counterfactual for waste wood and heating using natural gas as the counterfactual for hydrogen. Meaning that the impact of emissions of fossil carbon dioxide were ignored because that carbon dioxide will be emitted in the counterfactual.

The calculation in the hydrogen emissions uses a MWh of hydrogen as the functional unit. This only considers the biogenic fraction of the waste in line with the LCHS

Process inputs are:

- Diesel for transport of waste wood to a processing centre, to shred waste wood and transport it from processing centre to the H_2BECCs facility.

- Electricity used in the facility to convey waste and solid residues, pump water, compress gases, reform tars in the electric arc furnace and power other equipment.
- Natural gas used in start-up and to supplement steam produced by the cooling of syngas.
- Chemicals used in gas cleaning – sulphuric acid, sodium hypochlorite, sodium hydroxide, sodium bicarbonate.
- Activated carbon used for gas cleaning, electrodes consumed in the electric arc furnace.
- Water consumed in the facility for cooling, steam production and water gas shift reaction.
- Power used in carbon dioxide transport and sequestration network.

The impact of leakage of syngas, hydrogen and carbon dioxide were considered but are not material. Uncaptured carbon dioxide emitted to atmosphere is biogenic in nature - therefore does not result in climate change. The emissions from the materials and construction of the plant and transport sequestration are ignored in the LCHS but are considered in the UCL study, are not material.

UCL did not take information from Hynet on emissions associated with the transport and sequestration network, but they are not material. Data from an academic study was used to assess T&S emissions.

Waste streams from the process are:

- Effluent produced by the gas cleaning scrubber and boiler blowdown.
- Oversize material from the gasifier.
- Fly ash from the syngas cooling system.

The GHG impact of these input and waste streams is assessed using published carbon intensities. The only material input is the carbon intensity of electricity.

ABSL seeks to procure low carbon electricity to meet the plant's load. However, it's unclear whether this will meet LCHS (or other standards) rules around the attribution of the benefit of low carbon generation. Therefore, both GHG assessments are based on UK grid averages.

UCL carried out their assessment using published 2020 intensity of 283gCO_2/kWh and considered the impact of using the expected 2028 carbon intensity of 63gCO_2/kWh (the year the plant is expected to enter operation) the Hydrogen Emissions Calculator is based on the 2028 carbon intensity.

There is clear uncertainty around the 2028 grid intensity. The assumed value is based on National Grid Future Energy Scenarios, relying on the expected role-out of offshore wind. There has been significant progress on decarbonisation of the UK Grid since 2020 and it seem prudent to assume that this will continue.

UCL work gives the results shown In the following Figure based on 2028 UK grid carbon intensity.

Functional Unit	Emissions $kgCO_{2e}$	Net Emissions $kgCO_{2e}$
1 tonne waste	108	-1,710
1MWh Hydrogen	41	-427
1 tonne carbon dioxide	83	-369

Figure 36 – Commercial Plant LCA

Negative emissions for the waste case are due to the impact of sequestering biogenic carbon dioxide and substituting fossil natural gas with hydrogen. Negative emissions in the hydrogen case are due to sequestration of biogenic carbon dioxide. Negative emissions in the carbon dioxide case are due to substituting fossil natural gas with hydrogen. In each case the overall negative emissions are 200,000 tonnes.

Emissions from the process are low compared to alternative approaches. Hydrogen figures equate to 11.4 gCO_{2e}/MJ, well below LCHS requirement of 20gCO_{2e}/MJ. However, there are methodological differences between UCL LCA approach and LCHS. UCL also carried out an analysis using LCHS giving GHG emissions of just below 20gCO_{2e}/MJ in 2028.

The result of the ABSL analysis is that 2028 GHG emissions of the hydrogen produced by the plant is 18.5gCO_{2e}/MJ. The key sensitivity for this result is UK grid carbon intensity (which will decarbonise over time and eventually intensity will drop below the 63$kgCO_{2eq}$/MWh required for the hydrogen produced to meet the LCHS). UCL expect the carbon intensity of hydrogen to fall to 0.67gCO_{2e}/MJ by 2050, in-line with the carbon intensity of green hydrogen.

UCL also looked at other, relatively minor, environmental impacts from the process including acidification, ecotoxicity and eutrophication.

Overall, the process is strongly net negative in all scenarios and as the UK grid decarbonises will deliver low carbon hydrogen and a large amount of carbon credits for engineered negative emissions.

6.4 Process Risks

ABSL recognises the importance of taking a risk-based approach to project management. Regular sessions are held to identify risks and quantify their probability and impact. Risks are placed onto a risk register which is regularly reviewed, following the approach set out in ISO 31000.

Each risk is assigned a category and owner responsible for managing that risk.

Mitigating activities are identified for all significant risks and the post-mitigation probability and impact for the risk is evaluated. Progress on mitigating each risk is tracked at risk review meetings.

The risks are tracked in the Project Risk Register.

Each of the other project parties prepare their own risk register to ensure they are managing risk. Petrofac produced a risk register during the FEED.

The risk register covers each of the risk identified in the question. The major risks for the projects based on the post mitigation score are below.

Financing

ABSL and its advisors engaged with financial institutions to discuss project funding. There is very little appetite to funding gasification plants because of the perceived technology risk.

The largest concern to funders will be the contract for delivery of the plant. They would prefer a structure that assigns risk for delay, cost and performance to the contractor. However, contractors are unwilling to offer lump-sum, turnkey contracts in the UK because of risks around civils, mechanical and electrical costs. Therefore, ABSL worked on a target cost structure where project risks are shared between the owner, funders, insurers and the contractor. There is a risk that it will not be possible to find an arrangement that is acceptable to funders.

Given ABSL's issues with securing funding for the demonstration plant, it seems like a real challenge to secure funding for a commercial plant.

Delays.

The project programme is made up of several activities running in parallel that may constitute the critical path. These activities rely on third parties such as banks,

and the planning authority who may be delayed. The risk will be mitigated by experience in the Swindon demonstration plant, careful project management, early engagement with counterparties and allowing sufficient margin in the project budget. The programme is based on significant engagement with different project partners and time allowed for each activity is realistic.

Operating Cost Escalation

Operating cost model is based on Petrofac FEED output and supplier engagement. Increases in estimates during development reduce the probability of financial close. Increases in costs during operations may affect the ability of the plant to meet the expectations of funders. The risk is mitigated by continuing to engage with suppliers to fix unit costs and to refine models of plant performance.

A key area of risk is the cost of maintaining the plant. This has been estimated using information from vendors, costs for other waste to energy plants and experience from the Swindon demonstration plant as a basis. However, it is difficult to achieve high levels of certainty for the cost of maintaining a new process. ASBL will continue to work with O&M contractors to increase the level of certainty.

Power Grid Connection

The project has an average expected power load of 22MW and a peak requirement of 25MW. This will be met by a 20MW high voltage connection and 5MW low voltage connection. If power requirements increase during the ongoing design of the plant, there might not be sufficient availability to meet demand. This risk can be mitigated by focusing on managing power demand and incorporating power generation into plant design.

Carbon Sequestration Allocation Process

The project relies on the export of biogenic carbon dioxide into a T&S network. This requires agreement from Government. ABSL has not succeeded in either the allocation rounds to date and there is a substantial risk that it will not be successful in future.

If the project is successful in entering the negotiation phase of the allocation process, it will only be able to reach financial close if it can negotiate a strike price that is acceptable to funders. There is a risk that the required price does not meet DESNZ value for money requirements. ABSL has benchmarked its financial performance against other technologies and believes that it is competitive. This risk will be mitigated by focusing on cost management and value engineering during the design process.

Operational Risks

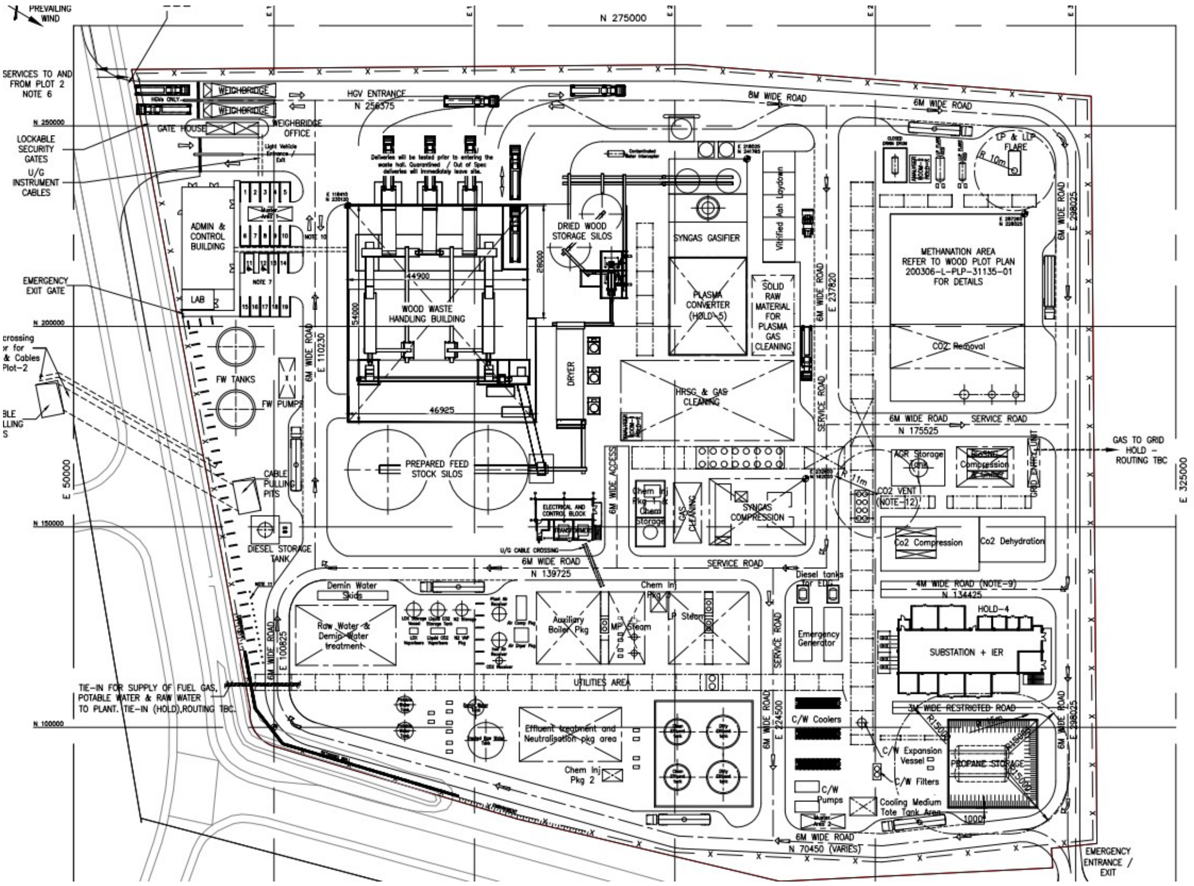


Figure 37 – Commercial Plant Plot Plan

ABSL has a large amount of operational experience from the Swindon plant, recorded in the plant operational records. The key risks are:

- Waste receipt and conveying systems are prone to blocking because of tramp material such as wires or concrete blocks. Mitigation: allowing maintenance periods for this equipment to clear blockages.
- Control of the gasifier is complex, particularly during start-up when it is moved between air combustion, oxy-steam combustion and oxy-steam gasification. Mitigation: using a well-tested control system and good training of operators.
- Use of the flare will be limited by the environmental permit, typically to 10% of the year. There is a risk that this will be exceeded, particularly during the early years of operation. Mitigation: through engagement with the EA to ensure that set a reasonable limit and use of operational procedures that minimise flare use.
- Catalysts used in the plant are highly sensitive and can be damaged by contaminants. Mitigation: holding a stock of spare catalyst and incorporating systems that can reduce the catalyst if it’s oxidised.

The availability of data from the Swindon plant is a very important risk management tool for the project.

6.5 Monitoring, Reporting and Verification Methodology

ABSL has significant experience operating an MRV system. Its Swindon demonstration plant will produce fuel that qualifies for Renewable Transport Fuel Certificates, requiring the plant to produce Proof of Sustainability that meets the rules of the Renewable Transport Fuel Obligation and RED II. ABSL operates a system for measuring and reporting sustainability of the fuel the plant produces that is compliant with ISCC rules that demonstrate RED II compliance. This is audited annually by Control Union.

Figure 38 – Lifting Plasma Furnace Roof into Place

ABSL has also reviewed current MRV standards for engineered negative emissions and produced a report for DESNZ on how these could be applied to the project.

There is a large amount of overlap between the ISCC MRV requirements and standards for negative emission MRV. Both cover feedstock sustainability, co-products and GHG assessments. Negative emissions standard also covers additionality and permanence of the carbon removals not necessarily covered in the ISCC standard, although the ISCC does cover carbon storage and utilisation as part of RED II.

Relevant MRV standards from the ERM report identified in the question are:

- Puro Earth standard covering gasification of wood waste in a H_2BECCs plant but scored as neutral in two areas (Feedstock Production and Co-products) by ERM.

- Gold Standard only applies to capture of carbon dioxide from fermentation plants.
- Draft ACR standard would apply to H2BECCs projects but needs improvement.

None of these standards are currently completely acceptable and ABSL believes work is needed to create credible standards that meet the tests set out by ERM. ABSL is comfortable that it can put a robust MRV protocol in place that meets the requirements of current and future standard as set out below.

Feedstock Production

Project feedstock is low grade waste wood. Any MRV standard will require the project to demonstrate that feedstock is sustainable and calculate the GHG emissions associated with it.

Low grade waste wood is only suitable for energy recovery and assessed as sustainable under RED II. This can be demonstrated through waste transfer notes and proofs of sustainability from the supplier. Under ISCC regulations auditors will visit the waste wood processor to check procedures for assessing GHG emissions associated with the feedstocks and will visit a sample of collection points to verify the wood is genuinely waste.

Similar protocols can be used to demonstrate that feedstock is sustainable for a carbon credit MRV protocol.

Waste wood entering the facility will be measured using a weighbridge and reconciled to waste transfer notes.

Feedstock is a waste and so it will not be necessary to assess GHG emissions associated with its production. Emissions associated with collection, processing and transport of feedstock to the plant will need to be assessed. These are relatively simple to measure through calculation of diesel used.

Overall, the MRV for feedstock production can follow the approach currently used by the ISCC for renewable fuels.

Hydrogen Production and Carbon Capture Plant Emission Date

Flows of materials in and out of the facility will be easy to measure and validate:

- Facility will accept waste wood over the weighbridge.
- Exports of hydrogen and carbon dioxide through fiscal meters.
- Power, water and gas measured using fiscal meters.
- Consumables measured using goods received notes and plant stock management system.
- Effluent discharge to drain metered.
- Other waste streams measured through waste transfer note.

These flows are easy to measure and audit using the same techniques used in the ISCC audits of the Swindon plant.

Results can be used to calculate the GHG emissions from the process using conservative, commonly accepted carbon intensity values. The only material assumption used in the GHG calculation is carbon intensity of the electricity. The plant will either use grid electricity and UK average grid carbon intensity or it may purchase low carbon electricity through private-wire power purchase agreement. The MVP rules will determine what carbon intensity will be used in the GHG calculation.

Allocation of GHG Emissions

The key challenge of the MVP is how to allocate emissions between carbon dioxide exported by the plant and hydrogen it produces. The approach suggested by Puro is to allocate the emissions to the fuel co-product which ABSL agrees with.

As shown in the GHG analysis, the hydrogen produced by the facility should meet the low carbon hydrogen standard even if all the GHG emissions are allocated to hydrogen. This means the hydrogen can be sold as low carbon hydrogen. The amount of negative emissions generated by the plant will be the amount of biogenic carbon dioxide exported to the T&S network.

Biogenic Content

Waste wood processed by the plant has approximately 95% biogenic content. However, it will be necessary to demonstrate actual biogenic carbon in the carbon dioxide exported by the plant and to use this to estimate the biogenic hydrogen content.

The commonly accepted approach to calculate biogenic content in mixed waste streams is C14 analysis where relative concentrations of carbon isotopes are used to determine biogenic content. The method is mandated for use in waste ICC plants and recommended in the Renewable Transport Fuel Obligation. The facility will use C14 analysis to determine the biogenic content in the exported carbon dioxide and hydrogen.

Additionality

It is relatively simple to show additionality of carbon sequestration from the process. The waste wood processed in the plant would have been incinerated or sent to landfill. Either counterfactual would have resulted in the carbon with the waste being emitted to atmosphere. Therefore, the carbon dioxide captured be the plant is an incremental reduction in carbon dioxide emitted to atmosphere.

7.0 Route to Market

7.1 Target Market

The RadGas process can produce a range of low carbon fuels including biomethane, sustainable aviation fuel, biomethanol and biohydrogen. Biohydrogen is the preferred output for the following reasons:

- Biohydrogen contains no carbon and so RadGas plants producing biohydrogen generate more greenhouse gas removals than those producing other fuels.
- Production of biohydrogen is simpler than other fuels. The process requires fewer reactors and lower thermal losses.
- The conversion efficiency to biohydrogen is higher than the efficiency of other fuels.

Therefore, this section considers the risk and barriers for production of biohydrogen. A plant that produces biohydrogen and GGR is referred to as a hydrogen bioenergy with carbon capture and sequestration (H_2BECCS) facility.

H_2BECCS facilities operate in two target markets:

- Low carbon hydrogen.
- Negative emissions or greenhouse gas removals (GGRs).

These are considered in more detail below.

7.1.1 Low Carbon Hydrogen Market

The key features of the low carbon hydrogen market are:

- It is immature with high levels of uncertainty around the timing and quantum of supply and demand.
- It is driven by Government regulations on the emission trading scheme and support for low carbon hydrogen.
- There are many organisations looking to switch to hydrogen for heat and transport to meet decarbonisation targets. However, switching will involve capital costs and disruption which act as a barrier to adoption. Furthermore, risks around the availability and cost of low carbon hydrogen also discourage its adoption.
- There is very limited low carbon hydrogen production at present. There are only small amounts of green hydrogen being produced and no blue hydrogen. There are projects underway that will significantly increase blue and green hydrogen production.
- Blue and green hydrogen production is supported by Government backed business models. Currently there isn't any support for biohydrogen.

- Transport of hydrogen to end users is challenging. It can be transported by road, but this is expensive and requires many vehicle movements. Transport by pipeline is more cost effective but requires the consumer to be close to the point of production. Public hydrogen networks are under development but are unlikely to be widely available until the late 2020's. This means that it is preferable for production and consumption to be in close proximity for an offtake to work.
- Overall, it is highly likely that there will be high levels of demand in future but currently it is difficult to find counterparties willing to enter into long term hydrogen off-take contracts.

7.1.2 Greenhouse Gas Reduction Market

The key features of the GGR market are:

- It is immature with very high levels of uncertainty around pricing, supply, demand and regulation.
- It is driven by Government policy and corporate decarbonisation objectives. Governments recognise that they need GGRs to offset residual emissions and achieve net zero objectives. Corporates that are committed to decarbonising require GGRs for similar reasons.
- Currently, platforms such as Puro trade GGRs generated from afforestation, biochar or timber products. These offer sequestration of 10's or 100's of years and trade at around €30-€150/tonne. Companies such as Boeing, Microsoft or Swiss Re will buy credits to offset their positive emissions. Long term geological storage with sequester carbon dioxide for 1,000's of years and should trade at a significant premium to shorter term solutions.
- The UK Government has consulted on support for GGRs through contracts for difference or a guaranteed price. It intends to introduce a scheme to help provide certainty to the market.
- The regulation of the market is currently carried out by voluntary bodies such as Puro, CDP or the Greenhouse Gas Protocol. There isn't an agreed set of standards to give confidence to the market. Some companies will use unregulated negative emissions to claim they are low carbon, bringing the market into disrepute. There may be a role for Government to help set standards.
- Voluntary standards currently focus on land-based carbon sequestration but there is a growing awareness of engineered solutions.
- Companies such as Microsoft are willing to enter into long term offtake agreements to help develop the sector because they recognise its importance in delivering net zero.
- GGR trading is virtual and so does not suffer from the same delivery logistics issues as low carbon hydrogen.

- Overall, it is possible to secure offtake agreements and Government regulation appears to be heading in the right direction. However, there are high levels of uncertainty around the value of GGRs.

7.2 Risk and Barriers to Deployment

7.2.1 Feedstock

The RadGas technology can accept a range of wastes and biomass residues. The RadGas pilot plant operated on wastes as varied as refuse derived fuel, waste wood, bagasse, corn stover and auto shredder residue. However, flexibility in commercial plants is limited by the feedstock preparation equipment, planning permission and contractual structures. It is expensive and disruptive to change the feedstock used in the process. Plants will enter into a long-term contract with a feedstock supplier able to guarantee supply.

The largest source of biomass in a country with a high population density such as the UK is household waste, and this is the target feedstock for RadGas plants in the UK. Total waste arisings in the UK are around 50 million tonnes, enough to support more than 300 RadGas plants. Availability of waste isn't a constraint on plant growth for the foreseeable future.

ABSL plants will compete for waste with conventional waste to energy plants that mass burn household waste to raise steam that is used to generate electricity. These have a large share of the market at present but face challenges around environmental impact and carbon capture. Furthermore, the electricity they produce competes with low carbon electricity produced by wind and solar. The RadGas process produces low carbon hydrogen which has a higher intrinsic value than electricity.

Figure 39 – Waste Feedstocks

Overall, waste is not seen as a constraint on growth in the short or medium term. It does set a long-term limit on the number of RadGas plants deployed in the UK.

7.2.2 Hydrogen Off-take

The hydrogen market is outlined in Section 7.1. The Climate Change Committee estimate that at least 160TWh of hydrogen is required for the UK to reach its net zero target. This would support more than 500 RadGas plants if sufficient feedstock was available. Therefore, demand is unlikely to constrain RadGas growth in the long term.

In the short term, the key challenge is finding hydrogen off-takers. Converting to hydrogen requires capital investment and business disruption. In addition, transporting hydrogen is complex and expensive which means that it is preferable to produce hydrogen close to the point of use. This creates an organisational challenge in developing biohydrogen plants close to hydrogen consumers and carbon sequestration networks. In the medium term, this issue will be resolved as large-scale hydrogen networks are deployed to link producers and consumers. In the short term, Government support can help connect the market through grants and price support to help.

Biohydrogen is competing with blue and green hydrogen. It delivers lower cost hydrogen than green hydrogen and has a superior GHG performance to blue and green hydrogen because of the negative emissions associated with carbon sequestration. The volumes of biohydrogen are likely to be small compared to overall demand because of feedstock constraints but it should be able to compete well with other low carbon hydrogen solutions.

7.2.3 Carbon Dioxide Offtake

The plant captures biogenic carbon dioxide and transfers it to transport and sequestration networks. This creates negative emissions (GGRs) that can be used to offset positive emissions from elsewhere in the economy and help deliver net zero objectives.

There is a large amount for demand for negative emissions from the voluntary corporate market. This is driven by organisations that have made net zero objectives and use negative emissions to achieve them. Examples include British Airways, Microsoft, Coca Cola and Engie. Currently this demand is being met through nature-based sequestration such as afforestation and simple engineered solutions such as biochar production.

Governments have also recognised the importance of negative emissions to their net zero objectives.

The GGR market is global and negative emissions are traded virtually with no need for physical delivery. That means that the overall demand is many millions of tonnes and does not constrain demand for RadGas.

There are several competing approaches:

- Land based solutions such as afforestation or development of peat bogs will sequestrate carbon dioxide for 10's of years.
- Short term engineering solutions such as biochar or renewable building materials will sequestrate carbon dioxide for 100's of years.
- Engineered solutions that sequestrate carbon dioxide in geological storages will store it for more than 10,000 years.

H_2BECCs offers long term geological storage. Competing technologies are:

- Direct air capture used artificial methods to capture carbon dioxide directly from the air and then inject it into transport and sequestration networks. The concentration of carbon dioxide in the air is very dilute (400ppm) which means capture is expensive.
- Post-combustion technologies strip carbon dioxide from a flue gas from a biomass power stations. The concentration is low (5-10%) and capture requires very tall towers and large volume of capture solvents. This makes capture expensive from an energy and economic point of view.
- Pre-combustion technologies oxy-steam rather than air to oxidise materials. This reduces gas volumes and makes capture more cost effective. H_2BECCS is a pre-combustion technology but it can target other products such as biomethane, biomethanol or power generation. Hydrogen is a product that offers more utility than electricity and higher level of carbon dioxide sequestration than products that contain carbon.

H_2BECCs can compete economically with each of these approaches and will be able to capture a good market share of the GGR market. Carbon dioxide off-take will not constrain RadGas demand.

7.2.4 Sites

Plants will require a suitable site. The key requirements are:

- 6 hectares of useable land plus at least 3 hectares of laydown for use in construction.
- Good connections to utilities including power, gas and water.
- Proximity to a hydrogen off-taker or network for export of gas.
- Proximity to a carbon dioxide transport and sequestration network.
- Industrial setting with support from local authority for GGR plants.
- Landlord willing to offer long term site option to allow project development.

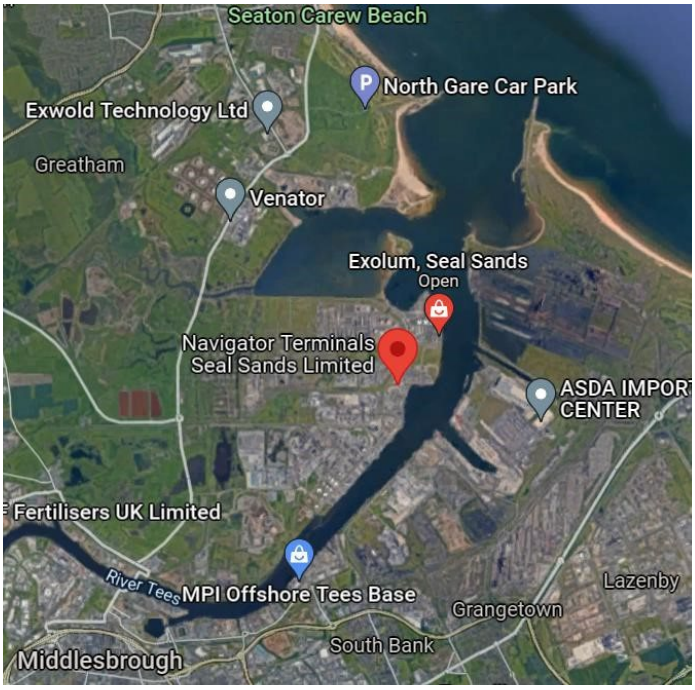


Figure 40 – Sites around Teesside

ABSL has identified one site in Northwest England and two in Northeast England that are suitable for RadGas H_2BECCs plants. These are in carbon clusters to provide access to carbon sequestration and hydrogen users. Further sites are available in each cluster. Further clusters are being developed in Scotland, South Wales and the Solent and over time carbon dioxide transport networks will be rolled across the UK.

Site availability will be limited initially with tens of sites being available in the original clusters. Once the number of clusters increase there will be hundreds of potential sites. Site availability could act as a constraint on growth.

7.2.5 Supply Chain Capacity

Plants rely on a wide range of organisations for project development, design, construction, commissioning and operations. The key suppliers and contractors are:

- The primary engineering contractor who will design and deliver the plant.
- The suppliers of key technology packages including the gasifier, plasma furnace, catalytic conversion, carbon capture and the plant control system.
- Specialist contractors who will carry out activities such as loading catalysts, testing oxygen lines or installing refractory lining.
- The Operations and Maintenance Contractor for the plant.
- Regulatory bodies such as the Environment Agency and Health and Safety Executive.

Generally, there are many organisations able to carry out these roles with capacity to deliver multiple plants in parallel. However, capacity is more constrained for the delivery of specialist equipment such as the gasifier or plasma furnace and suppliers would struggle to deliver multiple projects concurrently. Over time, suppliers will increase capacity if there is sufficient demand, but this will take several years.

H2BECCs is competing with other advanced biofuel projects for supply chain capacity. Similar resources are required for SAF production, carbon capture and low carbon power generation. This places further constraints on capacity in the short term.

Supply chain capacity will constrain the deployment of H_2BECCs in the short and medium term. At present it is difficult to see how more than one facility could be delivered per year. Over time this will increase to four per year. In the long term it will no longer constrain delivery of plants.

7.2.6 Technology Readiness

Pre-combustion capture technologies have a relatively low technology readiness level. The key driver for oxy-steam gasification is how it simplifies the capture of carbon dioxide and so the motivation for developing the technology has only arisen over the last 10 years as the focus on dealing with climate change has increased.

Currently, there aren't any operational commercial H_2BECCS plants. There are several pilot plants that have demonstrated the key technologies required for a H_2BECCS plant such as gasification, tar reformation and the water gas shift reaction. Furthermore, there are some H_2BECCs demonstration plant in development, construction or commissioning. As far as ABSL is aware, its Swindon plant is the closest to demonstrating H_2BECCs in a commercial environment.

Plants will only be able to secure supply chain support and funding if the technology has been demonstrated at a reasonable scale on a full-time basis in a commercial environment. The successful operation of the Swindon plant is an essential step to enable the deployment of the RadGas technology.

Technology readiness will constrain deployment of the technology until the Swindon plant is operational.

7.2.7 Funding

RadGas plants have a capital cost of £550m. ABSL has engaged with a wide range of strategic and institutional investors to develop and understanding of the availability of finance to meet this cost. JP Morgan and Jefferies, two respected banks, have advised ABSL on funding for plants.

A large amount of capital was available for projects that deliver low carbon infrastructure. Funds are particularly interested in technology platforms that can be deployed in multiple plants. This is true for debt and equity financing.

However, the climate for financing low carbon technologies has become very negative over the last year. It would be very challenging to fund a facility through project debt and equity. ABSL is seeking partners with strong balance sheets to resolve this problem.

7.3 Commercialisation Plan

ABSL's plan for commercialisation is:

- Continue the commissioning and operation of the Swindon plant until it has operated reliably for six months.
- Continue to market the technology to companies that are developing low carbon fuel and carbon capture projects. These might produce hydrogen, methanol, methane or SAF. ABSL has a prospect list of around 20 organisations that are developing projects and has an ongoing dialogue with five projects.
- Licence the technology to these projects and then support them through the development, design, construction and commissioning phases.

Unfortunately, ABSL is struggling to fund this plan and so is unlikely to be able to implement it.

The key challenges to securing finance are:

- Concerns around the technical risks around bringing the Swindon plant into operation.
- Risks that the low carbon fuels and GGR markets will not develop.
- Issues with the economics of the ABSL process and concerns that the capital and operating costs may be too high.