Hydrogen GGR Demonstration Project
Project Report

BEIS Direct Air Capture and Greenhouse Gas Removal Technology Innovation Programme

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1.0 Executive Summary

Advanced Biofuel Solutions Ltd (ABSL), University College London (UCL) and Progressive Energy Ltd (PEL) investigated capturing carbon dioxide from the atmosphere while producing biohydrogen from waste and biomass feedstocks in the Biohydrogen GGR Demonstration Project. The project was made up of several work packages exploring the environmental impact of different approaches to carbon capture, the performance of biohydrogen GGR plants, the commercial environment for the technology and how to develop the process and bring it to market.

As it grows, biomass captures carbon dioxide from the atmosphere through photosynthesis. Heating the biomass in a low oxygen environment converts it into a synthesis gas (syngas) made up of carbon monoxide, carbon dioxide and hydrogen. The syngas reacts with steam to convert carbon monoxide to carbon dioxide and hydrogen. The carbon dioxide is removed through chemical or physical capture processes and transported to long term geological storage. The hydrogen is purified and used in heating or transport. The net effect of this biohydrogen GGR process is to produce a low carbon fuel while removing and sequestrating carbon dioxide from the atmosphere.

There are several pathways that can deliver biohydrogen GGR. This report considers the use of a fluidised bed gasifier and plasma tar reformer followed by wet and dry gas scrubbing to produce a good quality syngas. This is then shifted to biohydrogen using two different approaches:

- Conventional water gas shift reactors followed by carbon dioxide scrubbing using either the potassium carbonate (Benfield), amine (MEA), Selexol® or Rectisol® approaches. These systems are mature technologies with a high Technology Readiness Level (TRL).
- Sorption enhanced water gas shift (SEWGS) where the shift and the carbon dioxide capture take place in the same reactor. SEWGS is a relatively novel approach with a lower TRL.

The conventional approaches were modelled using information from the literature and performance data on real world systems held by the project partners. The SEWGS approach was modelled using data from the literature and the model was then validated against experimental work carried out by UCL.

The results of the modelling work are summarised in Table 1. It should be noted that the models did not optimise the carbon capture processes and real-world systems may deliver different results.

Table 1: ***Summary of Mass and Energy Balance (without process optimisation)***

		MEA	**BENFIELD**	**SELEXOL**	**RECTISOL**	**SEWGS**
Wood feedstock		110 ktpa 66 MWth	110 ktpa 66 MWth	110 ktpa 66 MWth	110 ktpa 66 MWth	110 ktpa 66 MWth
Hydrogen (98%v/v) production		10.95 ktpa 50.5 MWth	10.95 ktpa 50.5 MWth	10.80 ktpa 49.8 MWth	10.81 ktpa 49.8 MWth	11.40 ktpa 52.6 MWth
CO_2 sequestered		136.94 ktpa	135.82 ktpa	134.00 ktpa	133.13 ktpa	137.68 ktpa
Net energy efficiency (%):		55.7%	54.3%	63.6%	63.2%	71.6%

Each approach can achieve similar levels of hydrogen production and carbon capture. However, the large thermal load required to regenerate the solvents in the chemical capture processes (MEA and Benfield) result in a lower net energy efficiency than physical capture processes. SEWGS offers potentially better efficiencies than other approaches because of good hydrogen conversion rates and low energy cost for sorbent regeneration.

A lifecycle assessment of each approach is shown in Figure 1. It is likely that real-world systems could be optimised to deliver better results than those shown in Table 1 but this is unlikely to affect the overall ranking of different processes.

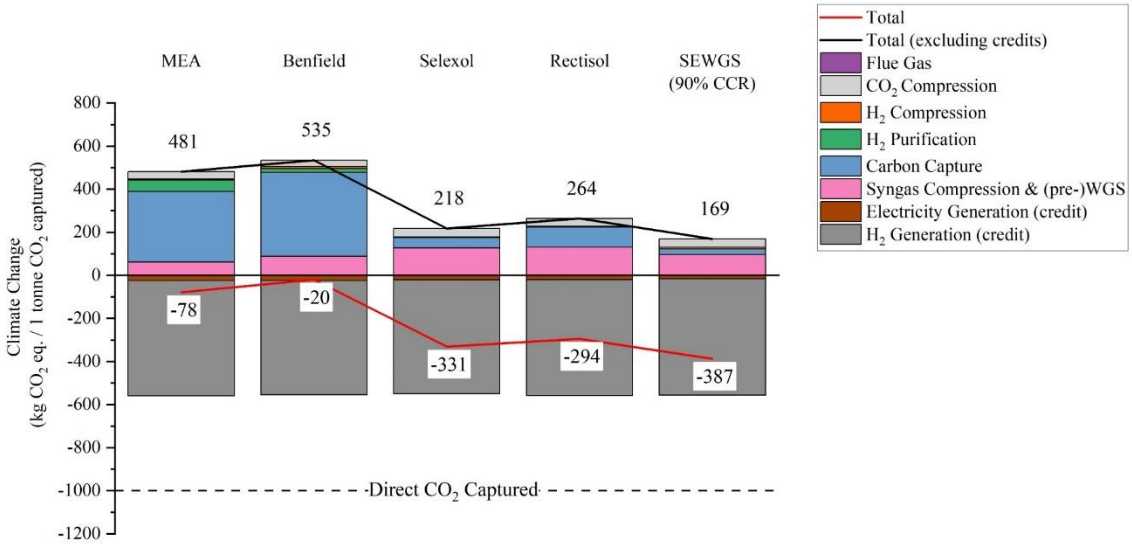

Figure 1: Comparison of climate change impacts for alternative carbon capture technologies (without process optimisation)

This shows that in all cases the greenhouse gas emissions associated with the heat and power used to capture carbon dioxide is matched by the greenhouse gas benefit of the biohydrogen produced. This means that each tonne of carbon dioxide captured results in a net benefit of more than one tonne. However, the benefit is larger for physical capture techniques. For SEWGS, the net benefit from capturing one tonne of carbon dioxide is 1.387 tonnes of carbon dioxide once the benefit of the biohydrogen is considered.

This result underlines the benefit of biohydrogen GGR. It results in greenhouse gas savings from the removal of carbon dioxide from the atmosphere and from the displacement of fossil fuels with biohydrogen. This benefit is greatest for SEWGS and provides a strong motivation to develop the technology.

Techno-economic models of physical, chemical and SEWGS biohydrogen GGR plants have been prepared. These show that first-of-a-kind plants have levelised costs of around £230 per tonne of carbon dioxide captured. However, this cost falls to around £130 per tonne as the technology matures, with SEWGS plants potentially capable of achieving £104 per tonne. The key inputs to the model are the costs of the wood feedstock and the value of biohydrogen.

ABSL is currently commissioning a plant in Swindon that converts household waste into biomethane. The design of a demonstration plant that extends to the Swindon plant to permit biohydrogen production has been developed. This will have two objectives:

- Production of biohydrogen with greenhouse gas removal on a full-time basis using conventional technologies, capturing more than 1,000 tonnes per annum of carbon dioxide.
- A SEWGS pilot facility in Swindon that has the capacity to capture 100 tonnes per annum of carbon dioxide. The pilot facility will be supported by a laboratory scale system hosted by UCL.

The designs have been developed to sufficient detail to enable equipment to be specified and vendors have been selected for each major package. Space has been allocated at the Swindon plant for the equipment and the interfaces with the existing syngas plant have been defined. A project plan for the delivery of the demonstration plant has been developed which shows:

- The detailed design being completed in Q3 2022.
- Equipment being delivered to site in Q4 2022.
- Commissioning being completed in Q3 2023.
- The two plants operating for at least one year until Q4 2024.

The overall cost of the project is currently forecast at £4.6m.

Biohydrogen GGR has an important role to play in helping the UK meet its net zero commitment. However, the technology will only be deployed if there is support for both the low carbon biohydrogen fuel and the negative emissions produced by the process. The UK Government has a desire to support both elements, but deployment will be constrained until a detailed support mechanism is put in place.

The biomass gasification technology required to deliver biohydrogen GGR is at a demonstration stage and SEWGS using a biomass-derived syngas is at the pilot plant stage. Funders will be wary of accepting the technology risk required to bring commercial biohydrogen plants to market and capital support from Government may be required for them to be deployed at scale.

The commercialisation of the technology will rely on Government intervention, but good progress is being made under existing policies. ABSL is developing a commercial plant based on biomethane production at the Protos site in Cheshire. This is located close to the Hynet carbon cluster, and the intent is to sequestrate carbon dioxide produced by the plant. The facility has the capability to convert to biohydrogen production as policy develops. The plan is to roll out a series of plants based on the Protos facility, with a target of ten plants in operation by 2030 capturing more than one million tonnes of carbon dioxide per year.

2.0 Science and Engineering

2.1 Process Description

Biohydrogen is a low carbon fuel made from sustainable feedstocks. Those feedstocks are composed of long chain hydrocarbons where the carbon has been captured from the atmosphere through photosynthesis. The biohydrogen production process reforms these hydrocarbon chains into biohydrogen and carbon dioxide. The biohydrogen is then used in heating, transport or electricity generation. The carbon dioxide can be captured and put into long term sequestration.

The overall impact is to convert a low-grade resource (such as waste wood or RDF) into a low- carbon fuel while capturing carbon dioxide to generate negative carbon emissions. The technology has the potential to remove greenhouse gases from the atmosphere more cost effectively than competing approaches.

This report focuses on the production of biohydrogen through gasification. The process is summarised in Figure 2.

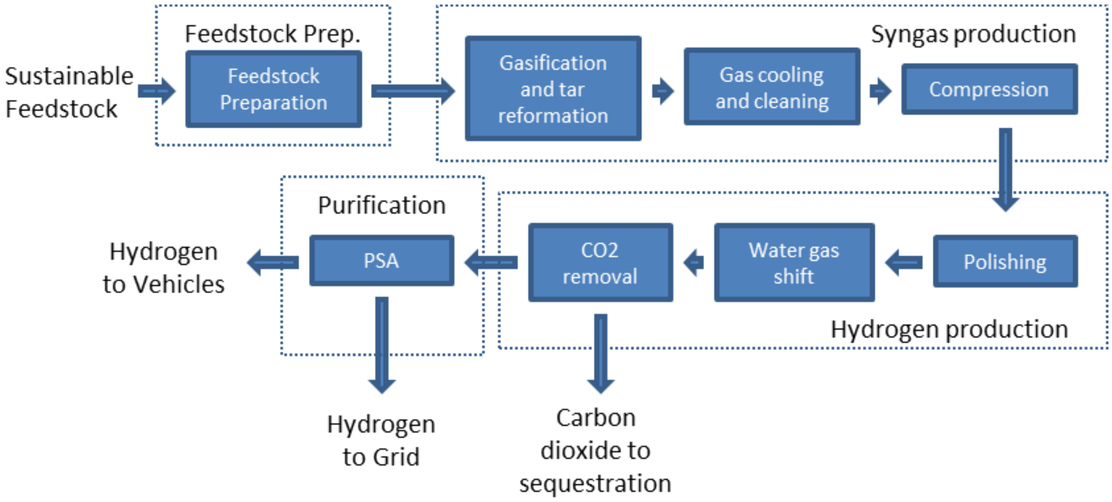

Figure 2: Biohydrogen Greenhouse Gas Removal Process

The process is made up of the following steps:

- Feedstock is made up of waste and biomass residues such as household waste, waste wood, straw, sawdust or sugarcane bagasse. It is prepared for the process through shredding, sorting and drying.
- There are several options for syngas production. They all rely on heating the feedstock in the presence of limited amounts of oxygen. This generates a crude synthesis gas which is made up of hydrogen, carbon monoxide, carbon dioxide, tars and ash. The tars and ash must be removed for the syngas to be processed further. This is achieved through some combination of further heating, wet scrubbing and catalytic conversion. The clean syngas is then compressed.
- The carbon monoxide in the syngas reacts with water to produce carbon dioxide and hydrogen in a process known as the water gas shift. Conventionally this is carried out over an iron or copper catalyst under carefully controlled conditions to optimise the amount of hydrogen produced. In sorption enhanced water gas shift (SEWGS), the carbon dioxide is removed as it is produced to drive the reaction to produce large amounts of hydrogen.
- The output from the water gas shift is a mixture of carbon dioxide and biohydrogen. The carbon dioxide is removed through either a chemical process, where a compound that reacts with carbon dioxide is used, or a physical process, where the carbon dioxide is dissolved or absorbed by a material. In either case the carbon dioxide is then released, compressed and passed to a sequestration network.
- The biohydrogen that is released from the carbon dioxide capture system will normally contain significant levels of contaminants such as carbon monoxide or methane. The gas is

cleaned using a pressure swing adsorption (PSA) device. The output from this is a high quality biohydrogen stream.

In a SEWGS system, the water gas shift and carbon dioxide steps are combined in a single vessel. This has the advantage of producing a high purity biohydrogen stream that may not require a PSA purification step if the target market for the hydrogen is heat. Purification will always be required if the biohydrogen is intended for use in fuel cell electric vehicles.

The baseline approach for the project considered a fluidised bed gasifier, plasma assisted tar reformation, a conventional two-stage water gas shift, potassium carbonate chemical scrubbing for carbon dioxide removal and a PSA for purification. The impact of using alternative chemical and physical carbon dioxide scrubbing techniques is considered together with a SEWGS approach.

2.2 Heat and Mass Balances

General approach

The chemical engineering team at UCL has developed a sophisticated set of models to predict the performance of different pre-combustion CCS technologies, as well as the balance of plant on a fully integrated biohydrogen system. These models, which have been developed on Aspen Plus simulation software, were validated with a combination of extensive operating experience and data from the ABSL Swindon pilot plant (with relation to gasification and gas cleaning sections), and literature data for the carbon capture systems and hydrogen purification packages. Details of model assumptions and design criteria for the gasification and syngas cleaning are provided in published works from the team (Materazzi et al., 2019). Details related to the syngas–to-hydrogen production model are provided in the next section. For this work, the facility is designed and modelled to convert approximately 110,000 tonnes per annum of Grade C waste wood (with 10% moisture) into approximately 372 GWh of grid-quality hydrogen.

CCS and hydrogen production models

A variety of carbon dioxide capture processes have been evaluated as stand-alone units, fed with the same synthesis gas (16,900 kg/h at 0.175 barg and 30 °C): two physical processes, Rectisol® (methanol), Selexol® (dimethyl ethers of polyethylene glycol, DEPG), and two chemical processes, amine (monoethanolamine, MEA 30%) and Benfield-type (K_2CO_3 30% wt/wt) in aqueous solutions. A SEWGS system is also modelled for comparison. The SEWGS model employs potassium promoted hydrotalcite as solid sorbent material for carbon capture. The five processes are then integrated in the global biohydrogen system for a whole system comparison.

In addition to the equipment required for CO_2 separation (absorption and desorption columns, pumps, heat exchangers, pressure reduction tanks, etc.), the models also included:

- A syngas compression stage, with outlet pressure depending on that of CO_2 separation column for different solvents chosen. This value was selected based on available literature data and not on optimum values.
- A two-stage, fully integrated water gas shift step for conversion of the CO into CO_2 upstream of the separation (for SEWGS, this reduces to a single high temperature step, followed by the SEWGS).

- A refrigeration system for the methanol process to maintain an optimum temperature in the absorption column and a downstream recovery system to limit losses of the absorbent.
- Condensation and drying steps to reduce the water content in the CO_2 produced to less than 50 ppm to prevent acid corrosion in the transport pipes.
- A 35 bar CO_2 compression station linked to a gas cooling system (final temperature < 40°C) in order to comply with the specifications of the CO_2 transport network (ISO27913).
- A methanation reactor to further reduce CO content in hydrogen rich syngas post CO_2 capture.
- A PSA unit for hydrogen purification to 98% (gas-grid quality) with associated gas engine for tail gas combustion and electricity production.
- A hydrogen compression station to deliver heat-grade hydrogen at 45 barg.

CO_2 capture and solvent regeneration packages

The difference in operation between physical or chemical solvents is primarily the use of thermal energy in the regeneration column (reboiler heat), which is typically an order of magnitude higher for chemical solvents compared to physical ones.

Both thermodynamic (equilibrium) and rate (kinetic) models were used to simulate the CCS packages. A rate-based model is used to simulate the absorption column to have an accurate estimation of solvent required to meet CO_2 purity requirements of greater than 95%. A thermodynamic model based on stage-equilibrium calculations is used for simulation of the regeneration column. This is done to provide a conservative estimation of thermal energy required to regenerate the solvent and also for the easy convergence of the calculations compared to the complex rate-based model. A CO_2 recovery of ~90% is fixed while modelling all five technologies. Additional details of all unit operations and key modelling assumptions for this work are reported in

Table 2 below.

Unit block		**Key assumptions:**			**Ref:**
Compressors		Isentropic efficiency: 0.75 Mechanical efficiency: 0.95			Coulson et al. 1999
Pumps		Mechanical efficiency: 0.80			Coulson et al. 1999
Water Gas Shift		**First Step:** Catalyst: Fe/Cr Inlet temperature: 350 °C Model: Gibbs equilibrium, adiabatic		**Second Step (liquid solvents only):** Catalyst: Cu-Zn Inlet temperature: 250 °C Model: Gibbs equilibrium, adiabatic	Materazzi et al. 2018
CCS		**Sorbent**	**Absorption Column:**	**Regeneration column:**	
	MEA	Monoethanolamine 30% in water	Pressure: 3 bar Inlet temperature: 55 °C N° stages: 20 Capture rate: 90.24%	Pressure: 1.5 bar Inlet temperature: 110 °C N° stages: 30 CO_2 purity: 96.00%	Theo et al. 2016; Park et al. 2002;
	BENFIELD	K_2CO_3 30% in water	Pressure: 9 bar Inlet temperature: 70 °C N° stages:15 Capture rate: 90.99%	Pressure: 1.5 bar Inlet temperature: 115 °C N° stages:30 CO_2 purity: 95.98%	Theo et al. 2016; Mondal et al. 2012

	SELEXOL	Dimethyl ethers of polyethylene glycol (DEPG)	Pressure: 36.5 bar Inlet temperature: 25 °C N° stages:10 Capture rate: 90.15%	Pressure: 1 bar Inlet temperature: 55 °C N° stages: 1 (depressurisation tank) CO_2 purity: 95.79%	Theo et al. 2016; Park et al. 2015
	RECTISOL	Methanol	Pressure: 36.7 bar Inlet temperature: -35 °C N° stages:10 Capture rate: 89.99%	Pressure: 1 bar Inlet temperature: 20°C N° stages: 1 (depressurisation tank) CO_2 purity: 92.16%	Sadegh-Vaziri et al. 2015, Chen et al. 2013
	SEWGS	K-promoted hydrotalcite	Pressure: 24 bar (adsorption), 1 bar (desorption) Capture rate: 90.11%	Productivity: 2.5 molCO₂/kg h Total Steam requirement: 0.28 S/C CO_2 purity: 93.54%	De Winter 2014
Methanation		Catalyst: 30% Nickel / Al2O3 Inlet temperature: 250 °C Model: Gibbs equilibrium, adiabatic			Materazzi et al. 2018
PSA		Inlet pressure: 20 bar H2 recovery: 95%, H2 purity: > 98% Splitting factors: literature data			Sircar et al. 2000
Gas engine		Efficiency: 40% electricity, 50% thermal energy			Coulson et al. 1999

Table 2: Summary of key assumptions for CCS plant models

Summary of EMBs

The mass and energy balance is the vehicle used to report the plant's performance including Net Energy Efficiency (NEE), cold gas efficiency (CGE) and biomass-to-hydrogen efficiency. When reporting NEE, we have considered the process on an end-to-end basis, from waste wood received into the plant to hydrogen and CO_2 generation ready for off-take, accounting for all electrical and thermal loads on the site (including solvent regeneration and gas compression), and all materials rejected from the facility. The parameters used to calculate NEE, such as net thermal input and electricity consumption, are readily available from the Aspen models. The biomass to hydrogen conversion efficiency which is a key consideration in the plant's performance is a measure of the efficiency of the feedstock conversion process and reports the amount of energy in the pure pressurised hydrogen product expressed as a percentage of the energy in the wood feedstock. This is similar to the conversion efficiency of the gasification plant, known as cold gas efficiency (CGE), which relates the energy of the cold, clean syngas with that of the original feedstock (on gross heating value basis). CGE is maintained constant for all the five cases examined, while other efficiencies are directly related to specific hydrogen recovery and carbon capture rates (CCR) of the plant.

		MEA	BENFIELD	SELEXOL	RECTISOL	SEWGS
Wood Feedstock	[A]	110 ktpa 66 MWth	110 ktpa 66 MWth	110 ktpa 66 MWth	110 ktpa 66 MWth	110 ktpa 66 MWth
Syngas to CCS plant	[B]	125.8 ktpa 53 MWth	125.8 ktpa 53 MWth	125.8 ktpa 53 MWth	125.8 ktpa 53 MWth	125.8 ktpa 53 MWth
Hydrogen (98%v/v) Production	[C]	10.95 ktpa 50.5 MWth	10.95 ktpa 50.5 MWth	10.80 ktpa 49.8 MWth	10.81 ktpa 49.8 MWth	11.40 ktpa 52.6 MWth
Carbon Capture Rate	[D]	91.2%	91.1%	90.4%	90.2%	91.4%
CO_2 sequestered	[E]	136.94 ktpa	135.82 ktpa	134.00 ktpa	133.13 ktpa	137.68 ktpa
Net Electricity Consumption	[F]	8.39 MW	7.77 MW	9.53 MW	8.86 MW	8.94 MW
Net Th. Energy Consumption	[G]	16.31 MWth	19.30 MWth	2.78 MWth	3.98 MWth	-1.05 MWth
Biomass-to-Syngas Conversion Efficiency (CGE):	[B]/[A]	80.3%	80.3%	80.3%	80.3%	80.3%
Biomass-to-H_2 Conversion Efficiency:	[C]/[A]	76.5%	76.5%	75.4%	75.4%	78.6%
Net Energy Efficiency (%):	[C]/ [A]+[F]+[G]	55.7%	54.3%	63.6%	63.2%	71.6%

Table 3: Summary of Mass and Energy Balance (without process optimisation)

The Biomass to Hydrogen conversion efficiency for all technological options investigated is higher than 75%. This is mostly due to the use of a two-stage water gas shift section which maximises the production of hydrogen (and CO_2) at the expense of CO and water. Furthermore, all CCS technologies analysed are very selective towards CO_2, thus minimising product losses within the process. The net energy efficiency (NEE) of the process is projected to vary between 55.4% for CCS Benfield and 71.6% for SEWGS. The high efficiency of SEWGS is due to the reduced steam requirement for combined WGS and CO_2 release, which results in excess thermal energy (~1 MWth) available from the plant.

It is also evident from study that the addition of a CO_2 capture plant results in an additional energy demand, proportional to the amount of CO_2 captured; both electricity and heat are needed to run the CO_2 capture plant and the dehydration and compression section. However, the analysis of individual contributions for energy input, shows that thermal energy is the most dominant factor, especially for chemical separation techniques. This was found in the range of 4-4.2 MJ per kg CO_2 removed from the gas stream when using chemical solvents, in line with data from the literature (Padurean et al. 2012). Minimum variations are associated with the use of different chemical concentrations and operating conditions, as well as the presence of additives in the solvent. On the other end, the value of electrical consumption is similar for all technologies, due to the presence of compressors for delivering hydrogen and CO_2 products at pressure in all cases investigated.

It is important to note that the real-world performance of CO_2 separation technologies may be significantly better than that shown in Table 3. For example, licensors of chemical separation technologies claim that they can reduce the thermal energy for capture to around 2.5 MJ per kg CO_2 using optimised solvents and selecting appropriate operating pressures and temperatures, however, substantiation of such specific performance figures is not readily available via the literature. This improved performance is unlikely to have an impact on the relative performance of the approaches assessed in this report.

The efficiency values in all cases are very favourable if compared with that of other bioenergy technologies (e.g., post-combustion CCS), and in line with those of other biohydrogen plants based on biomass feedstock (Ni et al., 2006; Antonini et al., 2021). Incidentally, the quantity of CO_2 captured (more than 135,000 tonnes per year) is significantly higher than that from other Waste-to-Fuel technologies, such as biomethane or liquid fuel production, meaning that the environmental benefit of biohydrogen production is significantly greater where CCS is available. This is because there is no carbon in the fuel product in the biohydrogen case.

2.3 Lifecycle Assessment

The evaluation of the environmental performance of potential near-future Greenhouse Gas Removal (GGR) technologies needs to consider a life cycle perspective taking into account all environmental burdens occurring during the entire life cycle of a product or service. In this work we performed an ISO 14040 and 104044 compliant, attributional Life Cycle Assessment (LCA) of the sequestration of one tonne of CO_2 within a biohydrogen plant. Calculations are performed with the proprietary software Gabi and the Ecoinvent life cycle inventory database v3.6.

Specifically, the study had the following two objectives:

1. Compare the relative performance of alternative technologies for pre-combustion carbon capture, to identify those that are environmentally advantageous.
2. Quantify the overall greenhouse gas removal potential of a 110 ktpa wood biohydrogen plant.

Allocations and functional unit

For both objectives, the functional unit chosen for this work is one tonne of CO_2 captured by the plant. We believe that this is the most appropriate Functional Unit for assessing the relative environmental performance of technologies for greenhouse gas removal. It must be noted that different Functional Units, focusing for example on hydrogen production or quantity of waste converted, may yield different results.

The thermochemical plant described above provides more than one function. Besides capturing carbon, the system produces biohydrogen and generates electricity, which are two valuable products that qualify for credits. In accordance with the ISO standards 14040 and 104044 we apply the system expansion approach which entails crediting the system with the avoided environmental impacts associated with the products that are displaced by electricity and biohydrogen. We assume that electricity replaces that available in the UK grid mix, and that biohydrogen is used for residential heating, displacing an equivalent amount (in heating potential) of natural gas.

For the purpose of inventory data collection, we adopt the distinction between foreground and background systems. Data for the Foreground system (i.e. the biohydrogen plant) is obtained from detailed mass-and-energy balances generated via Aspen Plus simulations, as described in the previous section. The Background system (chemicals, electricity and thermal energy consumption) is modelled using commercial LCA databases including Gabi Professional 2021 and Ecoinvent, version 3.6.

LCA results

In Figure 3 we compare climate change impacts of the carbon capture technologies investigated for the capture of one tonne of CO_2. Climate change impacts that are positive in sign represent direct and indirect greenhouse gas emissions. Direct emissions are released on-site, for example from a gas engine. Indirect emissions are associated with the supply chain and end-of-life treatment (where applicable) of chemicals and energy in UK. The climate change impacts that are negative in sign represent avoided greenhouse gas emissions associated with the displacement of natural gas and electricity. We report with a black line the total climate change impacts as sum of direct and indirect emissions, with a red line the total impacts including avoided emissions, and with a black dotted line the amount of CO_2 captured (i.e., the Functional Unit).

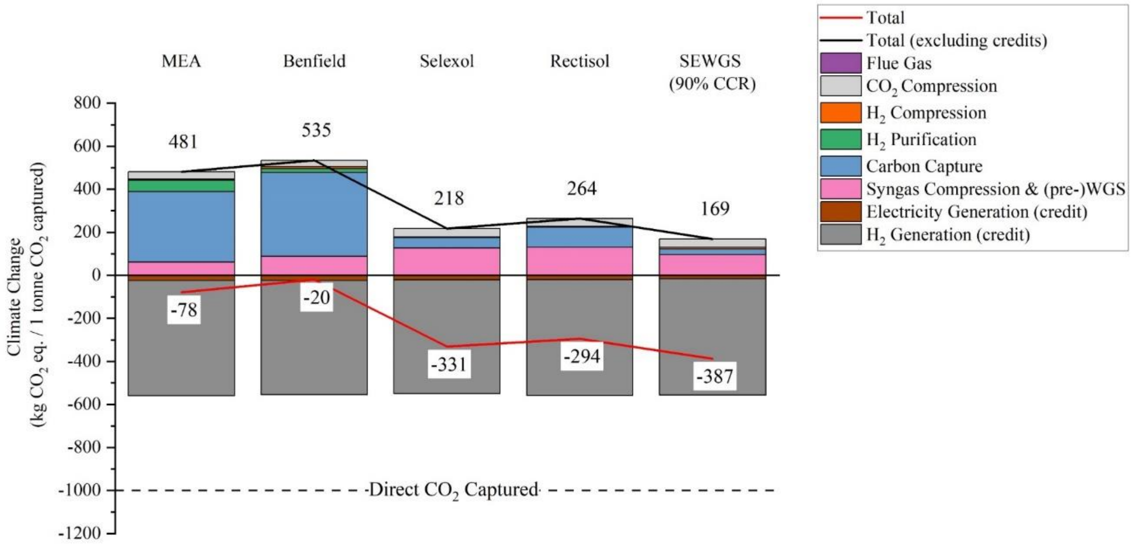

Figure 3: Comparison of climate change impacts for alternative carbon capture technologies (without process optimisation)

Therefore, taking MEA as an example, Figure 3 indicates that for each ton of CO_2 captured and sequestered, 481kg of CO_2 equivalent are emitted to the atmosphere. However, this value reduces to -78kg if credits for hydrogen and electricity are taken into account.

As expected, carbon capture technologies based on physical adsorption/absorption (i.e. Selexol®, Rectisol® and SEWGS) outperform those technologies based on chemical absorption (MEA and Benfield). Direct and indirect carbon emissions for physical technologies range from 169kg CO_2-eq. for SEWGS to 218 and 264 kgCO_2-eq. for Selexol® and Rectisol®, respectively. They are significantly higher for chemical technologies, totalling 481 and 535kg CO_2-eq. for MEA and Benfield. The emissions from the carbon capture phase are dominated by the consumption of thermal energy that is required to regenerate the solvent, representing nearly two-thirds of all carbon emissions. The remaining emissions originate from the purification of the hydrogen-rich stream and from the compression of the captured CO_2 stream.

As noted in the preceding section, the real-world performance of different carbon capture systems can be optimised to deliver significantly better greenhouse gas performance than those shown in Figure 1. However, this is unlikely to affect the ranking of technologies.

Avoided carbon emissions enable gauging the relative environmental benefits associated with the co-products, that is biohydrogen and electricity. Our analysis shows that that the avoided emissions are similar in value for all carbon capture technologies investigated, and comparable or even higher than the sum of direct and indirect emissions. Avoided emissions are dominated by credits for H_2 generation.

Sensitivity analysis on SEWGS for different CCR

In Figure 3 we report results of an interesting scenario analysis for SEWGS. We consider two alternative options for SEWGS with capture rates of 95% and 99%, which we compare with the baseline scenario of 90%. The chart shows that direct and indirect carbon emissions remain nearly unchanged when increasing the capture rate from 90% to 99%. The scenario with 95% capture rate yields the lowest carbon emissions because the increase in thermal energy for regenerating the sorbent is more than compensated by the increase in carbon captured. Interestingly, this analysis demonstrates that the SEWGS technology could potentially increase the carbon capture rate whilst maintaining similar environmental and carbon performance. This is a notable advantage compared to the other commercial technologies, where it was demonstrated that higher CCR comes often with excessive parasitic loads and operational inefficiencies.

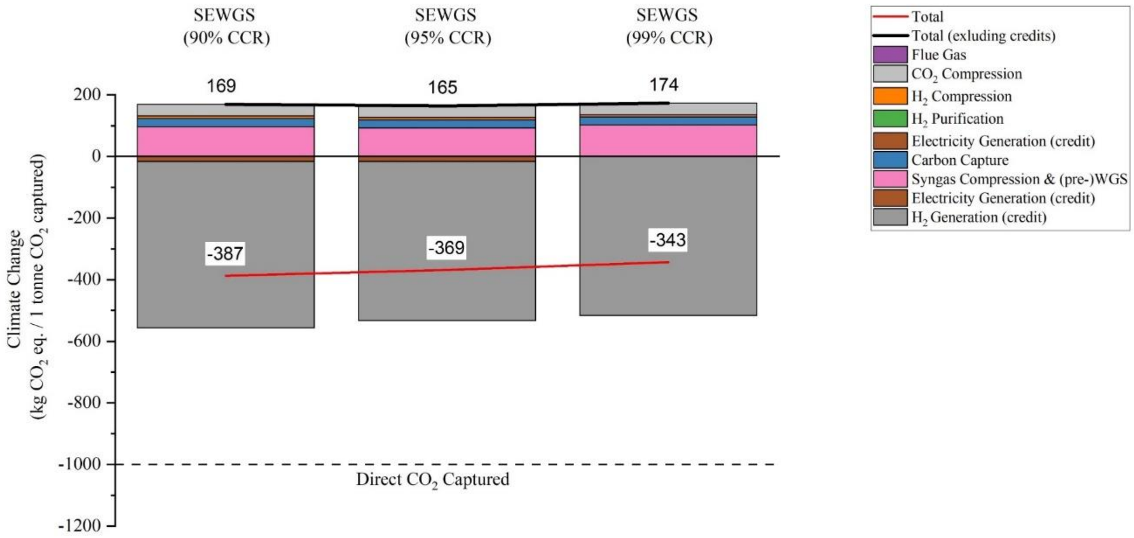

Figure 4: Scenario analysis for the climate change category for alternative SEWGS configurations. CCR: Carbon Capture Rate.

Other environmental categories

In Figure 5 we extend the comparative analysis of carbon capture technologies to environmental categories other than climate change. The reported environmental impacts correspond to the net sum of direct, indirect and avoided emissions. For graphical purposes, we express the impacts in relative terms, using as reference the highest impact in each category. The comparative analysis supports the results obtained for the climate change category in showing that the chemical technologies underperform across the majority of environmental categories. On the other hand, SEWGS consistently generates the lowest environmental impacts across the full spectrum of categories.

In most categories direct and indirect emissions of chemical technologies are dominated by the carbon capture phase, which encompasses consumption of electricity, thermal energy and solvents. This is particularly relevant for Benfield because of relatively high environmental impacts associated with the supply and end-of-life of its solvent: potassium carbonate. For physical technologies, the hot-spot analysis reveals higher contributions from the consumption of electricity to compress the syngas to the required operating pressure; this represents around half of direct and indirect emissions in SEWGS and Selexol®, and around a third in Rectisol®. The contribution from the syngas compression phase is lower in Rectisol® because of higher contributions associated with the supply and end-of-life of the solvent (i.e. fossil methanol). For all technologies, the avoided emissions are particularly significant in several categories, including acidification, marine and terrestrial eutrophication, particulate matter, photochemical ozone formation and fossil resource use. In these categories, the avoided emissions are comparable or even higher than the sum of direct and indirect emissions and are primarily attributable to the generation of H_2 that displaces natural gas for residential heating.

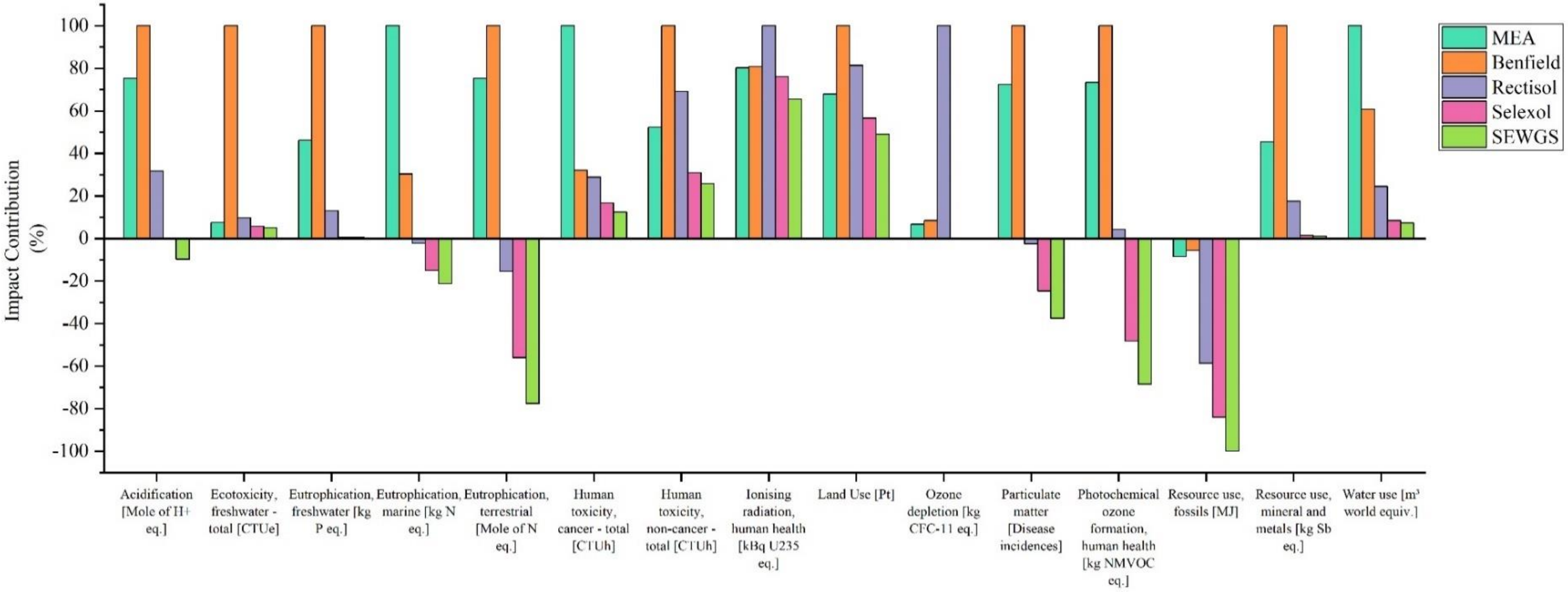

Figure 5: Comparison of carbon capture technologies for all environmental categories except climate change

Greenhouse gas removal (GGR) potential of full biohydrogen plant

In Table 4, we quantify the actual carbon sequestration capability of a biohydrogen plant at commercial scale (66MWth input). The table shows that a commercial scale biohydrogen plant would be able to remove from the atmosphere approximately 12-14 tonne CO_2 per hour (around 90-110ktpa CO_2) when physical carbon capture technologies are used, or around 7.6-8.6 tonne CO_2/h (around 60-70ktpa CO_2) with chemical technologies. It must be noted that all these values do not include credits for produced hydrogen and renewable electricity. These are added separately in *Table 5* to show the additional benefits of avoided emissions associated to all technologies adopted for CCS.

	MEA	BENFIELD	SELEXOL	RECTISOL	SEWGS
Net GHG removal (kg CO_2/h)	8,675	7,632	12,959	11,880	14,273
Avoided emissions (kg CO_2/h)	10,287	10,118	9,879	9,977	10,239
Overall GHG impact (kg CO_2/h)	18,962	17,750	22,838	21,857	24,512

Table 5: Net carbon sequestration for a commercial scale bio-H_2 plant

2.4 Discussion

Current approaches to fossil hydrogen production and methods for carbon capture

Hydrogen is conventionally produced in a two-stage process beginning with reforming of light hydrocarbons via an endothermic reaction with steam over a nickel catalyst – for example with a first stage comprising Steam-Methane Reformation (SMR):

$$CH_4 + H_2O \rightleftharpoons CO + 3H_2 \qquad \text{Eq. 1}$$

followed by a classical water-gas shift (WGS) reaction in which the carbon monoxide produced in Eq. 1 is reformed in two or more stages over iron/chrome and copper catalysts respectively in a mildly exothermic reaction with steam:

$$CO + H_2O \rightleftharpoons CO_2 + H2 \qquad \text{Eq. 2}$$

Separation of hydrogen and CO_2 is readily accomplished by a variety of proven separation technologies, discussed below. SMR is, however, no longer the optimal process choice for hydrocarbon reforming given the emerging costs and life cycle impacts of CO_2 emissions. With SMR the energy required to drive the endothermic reaction is generated externally to the process by combustion of carbonaceous fuels with air: the resulting flue gas (including CO_2) being discharged to the environment.

Contemporary requirements to eliminate discharge of CO_2 to the atmosphere drive process selection away from SMR and towards Autothermal Reformation (ATR) of natural gas; the essential difference with ATR being that the energy required for the reaction is obtained by internal “combustion” with pure oxygen rather than external with air: the carbonaceous product of “combustion” (CO) being retained within the process stream:

$$4\ CH_4 + O_2 + 2\ H_2O \rightarrow 10\ H_2 + 4\ CO \qquad \text{Eq. 3}$$

whereafter WGS is used to generate further hydrogen by oxidising the CO to CO_2 as in Eq. 2.

Separation of H_2 and CO_2 is an established art and can be achieved by a number of commercially available technologies which are based upon either reversible physical or chemical reactions. Hence these technologies may be classified as being either predominantly based upon reversible chemical reactions with a solid or liquid reagent or else a reversible physical adsorption in a solid matrix or liquid solvent. Generally, the processes that are based upon reversible chemical reactions are driven predominantly by using temperature swing[1], in which CO_2 capture takes place at a certain temperature, with regeneration of the adsorbent or solvent at higher temperature. Processes based upon physical adsorption depend predominantly upon pressure swing and exploit high gas pressure for capture, and lower pressure for adsorbent or solvent regeneration[2].

The observations regarding CO_2 capture technologies are of particular relevance for facilities based upon gasification of biomass or of waste-derived fuels, in which the gasifiers generally operate at atmospheric pressure. In short, with biomass gasification there is a conceptual advantage in using CO_2 scrubbing techniques driven by temperature swing rather than pressure swing because there are ample sources of thermal energy (waste heat) for use in temperature swing systems, whereas pressure swing involves significant economic disadvantages associated with gas compression and re-compression. From this we can deduce that if SEWGS can be shown to be effective at low or moderate pressure then we will have validated an important principle in establishing the economic and life cycle advantages in the application of this technology to biohydrogen production[3]. This has the potential to be an innovative enabling technology development that could improve the economic viability of future biohydrogen production.

TRL's of biomass gasification, water gas shift, different capture technologies, PSA, SEWGS

The production of biohydrogen entails the use of three essential process operations:

1. synthesis gas production via gasification of biomass or biogenic wastes,
2. syngas water gas shift
3. CO_2 capture from shifted syngas

It is pertinent to note that gasification, WGS and CO_2 capture are considered to be mature technologies (technology readiness level or TRL 9) in today's petro-carbon energy environment. It would be a mistake, however, to assume that these can be simply "cut and pasted" into the emerging world of bioenergy and that an optimised system would result. Firstly, although the generation of synthesis quality syngas produced by gasification of fossil fuels is at TRL 9, the relative novelty, small scale, and marginal commercial significance of biomass gasification have not to date attracted sufficient development effort to the technology[4]. With the emerging demand for both biohydrogen and BECCS (especially from a single facility) there is now a real incentive to bring biomass / RDF gasification generally from around TRL 7 to TRL 9.

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[1] e.g. Benfield , Amine systems.

[2] e.g. Selexol, Pressure Swing Adsorption, Rectisol.

[3] Design experience reveals that syngas compression can constitute the preponderant operating cost as well as a significant negative factor in achievement of threshold GHG performance of facilities using bio-syngas.

[4] The notable exception being the HT Winkler process developed in the former GDR where atypical economic drivers made it worthwhile to pursue this for the production of methanol from syngas.

WGS of syngas is an established industrial process at a TRL of 9 and can be transferred from its traditional petrochem setting to the processing of syngas derived from biomass or RDF. Nevertheless, the small scale and low operating pressures of biomass gasifiers make it necessary to question this sort of cut and paste technology transfer. Designers of bioenergy facilities need to find innovative design solutions to address the challenges of low-pressure operation and small scale. To this end, SEWGS is interesting since work undertaken in this project suggests that it can be effective at low pressure and utilise a combination of depressurizsation and waste heat from the gasifier for sorbent regeneration, and perhaps also reduce the total equipment count. This type of subtle optimisation has the potential to transform the economic and life-cycle viability of a biohydrogen facility. A favourable outcome of Phase 2 of this project could show that it would be worth the effort to bring SEWGS up to a TRL of 9 in order advance the state of the art for biohydrogen with BECCS.

With CO_2 capture from shifted syngas there are mentioned above several qualified technologies already at TRL 9, and they can be transferred for use in the emerging bioenergy economy. Similar cautions apply, however, and it is necessary to make informed choices based upon the characteristics of the host plant including the availability and cost of heat for sorbent regeneration, gas compression, CO_2 product specifications and capture efficiency requirements. With the inexorable increase in cost of CO_2 emissions coupled with the potential offset value of BECCS, capture efficiency emerges as a key process sensitivity, and hence the optimisation criteria for CO_2 scrubbing in a biohydrogen application may differ markedly from those in which these technologies have traditionally been used. Again, work in this project is seeking to elicit the extent to which SEWGS has the potential to augment the effectiveness of bulk CO_2 separation from the hydrogen product.

Impact of UCL analysis on future developments and selection of technology

The early development work by UCL on this project indicates that SEWGS may offer a number of conceptual advantages in biohydrogen systems, e.g. the ability to operate at low-moderate pressure with steam-aided regeneration of the sorbent, and reduction in plant complexity / equipment count, coupled with the lowest life cycle GHG impact per tonne of CO_2 removed compared with any of the existing scrubbing techniques investigated. Successful demonstration of SEWGS in Phase 2 of this project would constitute a technical innovation that would augment the future roll-out of biohydrogen facilities.

Best approach to move biohydrogen GGR from current TRL to commercial plant-

The principle technical uncertainty with biohydrogen production rests with the syngas production system – the gasifier and associated sub-systems. To be clear, not all biomass gasifiers are suitable for generating synthesis quality bio-syngas, so it is worth defining the differentiating characteristics that are required for producing hydrogen or sustainable transport fuels rather than a low heating value syngas for power production. These are:

- Syngas essentially free from nitrogen
- Syngas with low levels of organic contaminants (“tars[5]”)

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[5] Especially those containing organically bound sulphur and chlorine anecdotally reputed to be produced by indirect biomass gasifiers. It is practically impossible to remove these down to levels tolerable by catalysts.

In practice, the requirement for low levels of nitrogen mandates the use of oxygen as an oxidant rather than air; hence candidate gasification technologies comprise a short list that would include HT Winkler (Gidara), ABSL's RadGas technology as deployed in the Swindon biomethane demonstration plant, Enerkem and possibly Foster Wheeler Finland (now Sumitomo Heavy Industries). Most biomass gasifiers operate with air rather than oxygen because they have not been developed with chemical synthesis as an objective.

So, what are the technical hurdles that need to be crossed in order that biomass gasification could be seen as technically proven by potential investors – i.e. to move the TRL from its current level 7 to TRL9? Given that all candidate gasification technologies for biohydrogen production are based upon fluidised beds we would venture to suggest that such is the state of technical immaturity in the sector that there is no discernible adoption by technology developers of what might be identified as "best practice," or even commonly accepted design principles in each of the following key technology areas; pertinent because they have been the invariable sources of failure with these technologies to date:

1. Fuel specification, fuel conditioning and fuel feeding to the process
2. Remediation of entrained tars that are inevitably produced in the gasification reactions
3. Dealing with carry-over of ashes, alkali metals[6] and their compounds.

There are additional syngas processing challenges, but they are not specific to bio-syngas and have been overcome in existing petrochemical syngas clean-up technologies. It follows from the above that moving to TRL 9 would involve a convergence of technical understanding and development together with adoption of robust engineering design principles to address each of these three areas. (Interestingly, examination of the HTW technology suggests that Winkler did indeed develop robust design features to address the technical challenges in each of the technology areas mentioned above.)

As to how the TRL gap can be closed, it may be possible to offer market-based inducements in the hope that eventually the market will respond favourably; however, given the ambitious targets and pressing timescales evident in Government strategies for both hydrogen and BECCS, a more interventionist approach may be required. An indicative precedent for this is the way in which during the two decades following World War 2 the British Government oversaw the successful development and deployment of the 500MW generator sets that became the backbone of the nation's electricity infrastructure. A similar strategy might be possible today; in effect Government agencies commissioned the competitive development of what was seen as a core technology with a number of qualified suppliers.

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[6] The mineral content of biomass is unlike that of coal; the former being dominated by the presence of the alkali metals, the latter by the alkali-earth metals. The compounds of alkali metals have low melting points and can be temporarily gaseous at high temperatures and hence sublimate inconveniently in the cooler parts of the system.

3.0 Demonstration Plant

3.1 Engineering Design

The primary objective of the project is to develop the design of a plant that advances the development of greenhouse gas removal technologies. This objective will be met by a plant that:

- Produces biohydrogen with greenhouse gas removal on a full-time basis using conventional technologies, capturing more than 1,000 tonnes per annum of carbon dioxide.
- Develops SEWGS technology through a pilot facility that has the capacity to capture 100 tonnes per annum of carbon dioxide. The pilot facility will be supported by a laboratory scale system hosted by UCL.

Both facilities rely on the availability of good quality syngas from ABSL's demonstration plant in Swindon. This converts 10,000 tonnes per annum of household waste into a high-quality synthesis gas that is suitable for hydrogen production. The plant gasifier, which converts the waste, is shown in Figure 6.

Figure 6: Gasifier at ABSL Swindon plant

The conventional biohydrogen GGR process works as follows:

- Hydrogen rich syngas is taken from the Swindon plant.
- The gas is cooled in a gas/gas heat exchanger.
- The cooled gas is passed through a knockout drum to remove water.
- The dry gas is then passed through a pressure swing absorption unit to yield H2 and a tail gas.
- The purified hydrogen is analysed to check carbon monoxide levels to provide a quality assurance check.
- Hydrogen that passes this check is compressed to high pressure and metered into a tube trailer for export from site.
- Hydrogen that fails quality assurance is diverted to flare.
- The tail gas produced by the PSA is compressed and returned to the methanation equipment.

- Carbon dioxide in this tail gas is captured in the existing potassium carbonate scrubbing towers.

This process is shown in Figure 7.

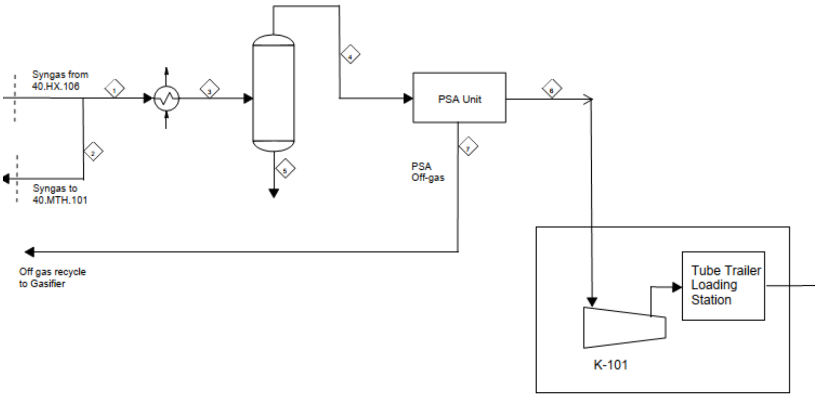

Figure 7: Conventional Biohydrogen GGR Process

The SEWGS process will operate as follows:

- SEWGS system comprises of five identical reactors which are used sequentially to provide continuous operation.
- Hydrogen-rich syngas is taken from the Swindon plant.
- The gas is cooled and passed through a knockout drum to remove most of free water.
- The gas is passed through a reactor that produces hydrogen and captures carbon dioxide.
- After a fixed period of time the syngas is diverted to the next reactor.
- The reactor is rinsed using steam and the pressure is reduced to atmospheric.
- Carbon dioxide vents from the reactor.
- The reactor is then purged with steam ready to accept syngas again.

This design is summarised in Figure 8.

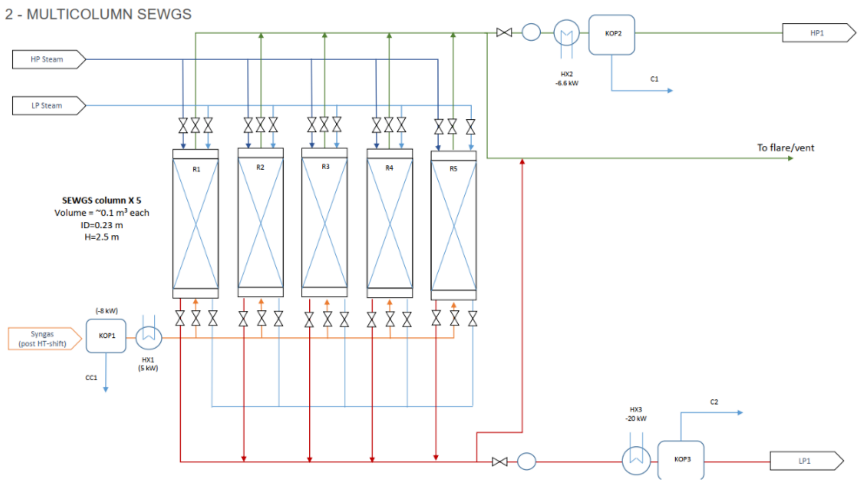

Figure 8: SEWGS Pilot Process

The conventional system will accept 600kg/hour of wet syngas and will produce 15kg/hour of fuel cell grade hydrogen together with 268kg/hour of carbon dioxide. The system is expected to operate for 7,446 hours per annum.

The SEWGS pilot system will accept 50kg/hour of wet syngas and will produce 2kg/hour of hydrogen together with 26kg/hour of carbon dioxide.

Both the conventional and SEWGS approaches rely on infrastructure provided by the ABSL RadGas demonstration plant in Swindon. This has the following characteristics:

- The plant processes grade C waste wood or refused derived fuel sourced from a landfill or material recycling facility within 20km of the plant.
- Power, gas and water and imported from the local grid.
- Fly ash produced by the process is sent to hazardous landfill and the effluent from the wet scrubbing of the gas is treated and sent to the sewer.

The Swindon demonstration plant provides an excellent setting for the biohydrogen GGR demonstration plant. It is one of the few facilities in the world that can produce a reliable, high-quality syngas from household waste. If the Swindon demonstration plant was not available, it would substantially increase the costs of the demonstration plant because it would require an expensive gasification plant to be constructed.

However, the Swindon plant has limited space that is available for the demonstration equipment. The project team have found space for biohydrogen equipment by designing an elevated platform for the PSA and SEWGS equipment and planning to relocate existing effluent tanks to create space for the syngas compressor. The proposed layout is shown in *Figure 9*.

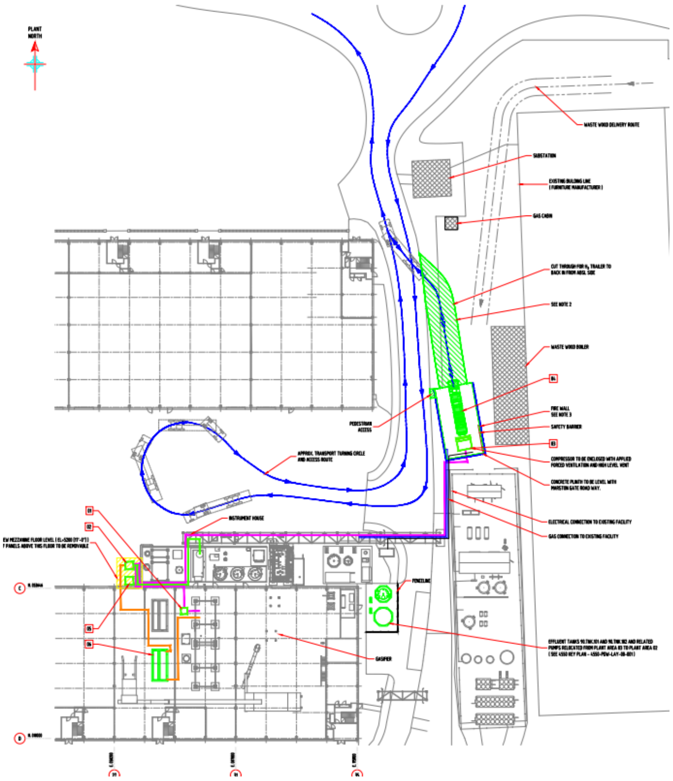

Figure 9: Proposed Biohydrogen GGR Demonstration Layout

The UCL laboratory scale SEWGS system will be hosted at the Manufacturing Futures Lab at UCL East in London. They will operate this system to support the development of the SEWGS pilot plant.

The other equipment will be operated by the Swindon plant’s operation team and controlled using the existing Valmet control system. The conventional system will run whenever a trailer is available to accept the biohydrogen, with a valve opening to divert syngas to the biohydrogen production line. The trailer is required because the Swindon plant’s environmental permit does not allow flaring of gas. This means biohydrogen can only be produced when there is an off-take for it and there isn’t sufficient space on site to store hydrogen except in tube trailers. The SEWGS system will operate for campaigns of several days followed by careful analysis of the results.

The equipment required for the conventional demonstration unit is:

- A simple cooler and knockout drum.
- A pressure swing adsorption unit supplied by Xebec.
- A hydrogen compressor supplier by NEL – the HS004.
- A syngas compressor supplied by Gas Compressors Ltd.

Italfluid has been selected as the preferred supplier of the SEWGS units. They specialise in the production of skid-mounted pilot plant equipment. In addition, they have experience of the manufacture of fossil fuel SEWGS equipment.

The estimated cost of the conventional system is £1.3m and the estimated cost of the SEWGS skids is £0.8m. The cost of detailed design, project management, integration and civils is £1.7m. This brings the total expected cost of the project to £4.6m including a £0.8m contingency.

3.2 Project Plan

The demonstration plant will be delivered by the Phase 1 project partners. Each will carry out the following roles:

- ABSL will manage the overall project and take overall responsibility for design, project management and operation of the system.
- UCL will act as the technical lead on the SEWGS system and will build and operate the laboratory scale SEWGS system.
- PEL will act in a technical advisor role, reviewing documents and providing constructive criticism.

The core team will be complemented by the following subcontractors:

- Wood will continue to act as technical lead on the conventional system.
- Otto Simon, an engineering service company specialising in medium-size systems, will carry out the detailed design.
- Valmet will design and implement the control system.
- Vendors will provide detailed technical information on their packages.

This team has worked together on the Swindon plant and have a very good understanding of its capabilities and how to work productively with each other.

The project will be split into the following work packages:

- Work package 1 will complete the detailed design and delivery plant for the system.
- Work package 2 will procure, fabricate and integrate the systems.
- Work package 3 will commission and operate the plant.
- Work package 4 will cover project management and reporting.

A summary Gantt chart showing key activities until the system starts production is show in Figure 10.

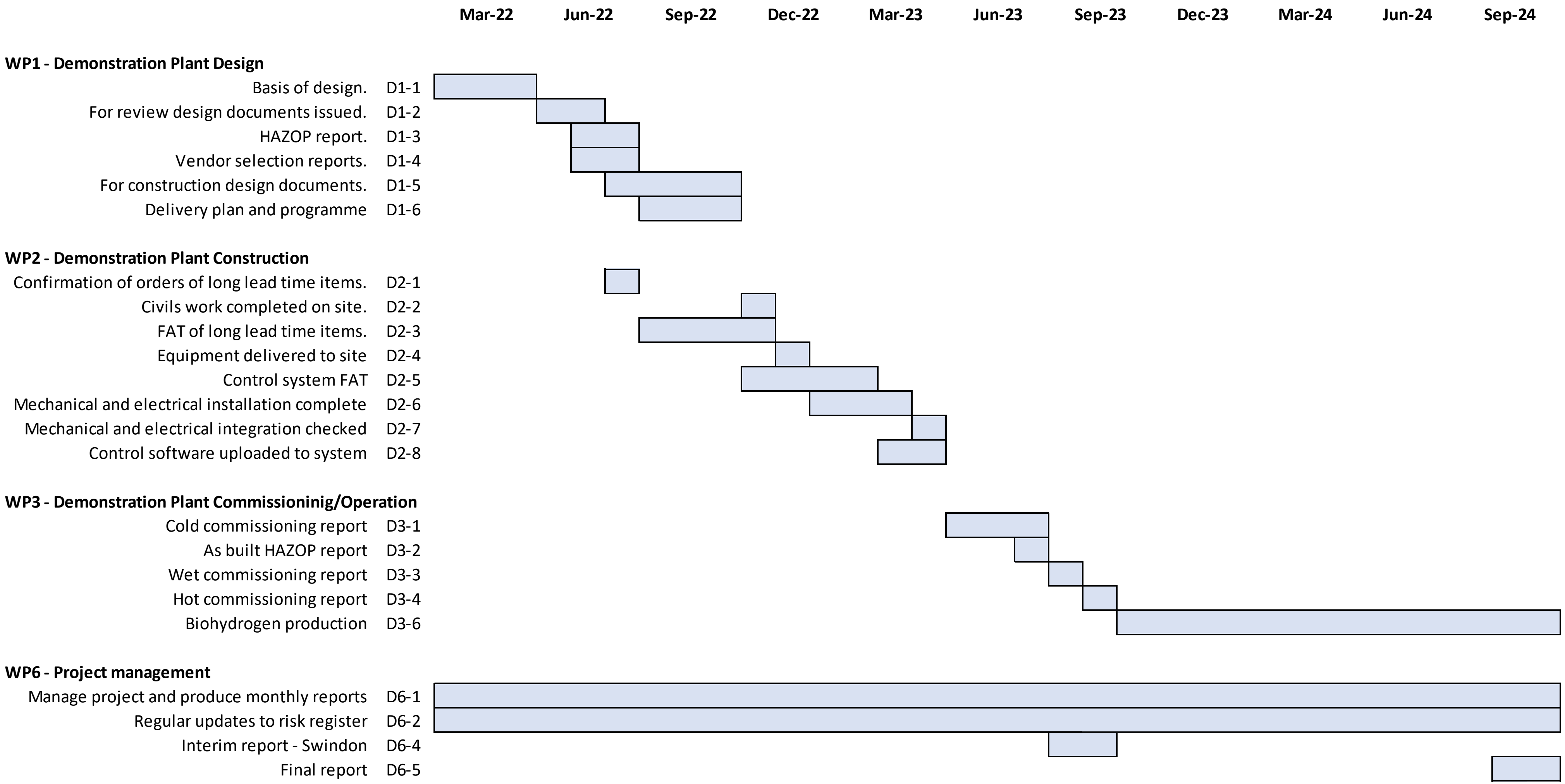

Figure 10: Summary Gannt chart to hydrogen production

The key risks for the project are:

- The project relies on the availability of good quality syngas from the Swindon plant. This is expected to complete commissioning in January 2022, eighteen months before it is required for the project. However, there is a low risk that syngas may not be available for biohydrogen production in the event of failure at the Swindon plant.
- The conventional biohydrogen production has a TRL of 6 and there is a moderate risk that there will be technical issues that delay the successful delivery of the project. The SEWGS system has a current TRL of 4 when using bio-syngas and therefore has significant technical risks. These risks are mitigated by allowing a reasonable project contingency.
- Biohydrogen will only be produced by the conventional system if there is demand for the product. Several nearby hydrogen filling stations have expressed interest but there is a low risk that there is insufficient demand, reducing the amount of carbon dioxide that can be captured. This risk does not affect the SEWGS system because hydrogen produced by it will be flared.
- The project plan allows for the current constraints imposed by COVID19 but further restrictions may result in project delays. This risk is considered low given that the project partners have extensive experience of working under COVID restrictions.

3.3 Benefits of Project

The project will deliver the following benefits:

- A conventional biohydrogen GGR demonstration plant that can capture 1,000 tonnes per annum of carbon dioxide.
- A pilot SEWGS biohydrogen GGR system with the capacity to capture 193 tonnes per annum of carbon dioxide.
- Detailed reports setting out the challenges and learning from both systems, particularly the SEWGS pilot system.

This will significantly advance the development of greenhouse gas removal technologies through the development of new technical knowledge on the design, construction and operation of both systems. In addition, it will provide a showcase for stakeholders in the technology that provides a practical example of the ability of biohydrogen to deliver the negative emissions that are essential to meet net zero objectives.

The project will only be possible through a risk sharing approach with Government. The risks around hydrogen off-take and the commercialisation model for greenhouse gas reduction mean that the project will not be able to secure private sector funding. Therefore, Government funding is required. However, the project relies on the use of private sector infrastructure and skills, such as the ABSL Swindon demonstration plant. It is unlikely this would be made available under an exclusive development contract. A risk sharing approach would allow Government to benefit from the Swindon plant infrastructure, resulting in significant cost savings against a fully standalone project.

The results of the projects will be disseminated through reports, company websites, academic papers and presentations to conferences. The plant will also be made available for filming and visits by stakeholders.

This will be one of the first projects to engage with the new UCL campus at the Queen Elizabeth Olympic Park through the Manufacturing Futures Lab (MFL), a multi-million pound laboratory created for cross-cutting, world-leading manufacturing research and education. The MFL will be an ideal location to showcase the SEWGS concept to the wider scientific community.

The technical results from the project will be used to validate process models. This is especially important for the SEWGS system. The plant will provide data that is essential to increase the TRL of SEWGS and provide a pathway for it to be deployed in commercial systems.

Overall, the project will use the excellent infrastructure provided by the Swindon facility to provide a cost-effective demonstration of a technology that is essential to the UK's climate change commitments.

4.0 Commercialisation

4.1 Commercial Environment

Support for hydrogen

UK Government hydrogen aspirations

The UK Government Hydrogen Strategy, published in August 2021, sets out an ambitious programme for hydrogen to replace the unabated use of fossil fuels in heating, power generation and transport; with zero emissions at the point of use. An important condition is that production of hydrogen should have acceptably low GHG impacts.

Technologies for getting there

Elemental hydrogen does not occur naturally, but it can be produced by splitting water or light hydrocarbons such as methane, using electricity and / or heat[7]; e.g. by electrolysis of water, or steam-methane reforming, e.g.:

$$\text{Heat (SMR)} \qquad CH_4 + H_2O \rightleftharpoons CO_2 + 3H_2$$

$$\text{Electricity (Electrolysis)} \quad H_2O \rightleftharpoons O_2 + H_2$$

To date the practical effects of the Second Law of Thermodynamics have served to make electrical energy significantly more expensive than heat energy, hence manufacture of low-carbon hydrogen from hydrocarbons is with existing technologies economically more attractive, even when the costs of associated CCS are included.

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[7] See table 2.2 of the UK Hydrogen Strategy for a list of technologies under consideration - https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1011283/UK-Hydrogen-Strategy_web.pdf

Biomass gasification constitutes a potentially attractive route to renewable hydrogen production via the production of bio-syngas; essentially a mixture of CO and H_2 which can then be reformed via the WGS reaction (Section 2.0, Eq. 2 above), to yield a mixed stream of H_2 and CO_2, or potentially by a future SEWGS equipped facility to yield a pure stream of H_2 directly.

Role of biohydrogen

With the roll-out of the UK hydrogen strategy, hydrogen will become a fungible commodity, with biohydrogen being indistinguishable at the point of use from hydrogen produced by other means. The potential value of biohydrogen lies in:

- relatively low cost of manufacture
- low carbon intensity
- avoiding the inefficient use of renewable electricity
- providing an efficient platform for BECCS
- resource efficiency / self-sufficiency via use of low-grade fuels

Support for BECCS

UK Government GGR aspirations

The vital role to be fulfilled by BECCS has been identified in successive Climate Change Committee annual carbon budget reports to Government and is now seen as essential in achieving net carbon neutrality. The Government's Net Zero strategy identifies a 2030 target capacity of 5Mt/a of engineered GHG removals, that is to say negative emissions. BECCS is the most likely source of savings towards this target, being at least to begin with, an extension of existing economic activities such as capture of CO_2 from the flue gases of biomass power or Energy from Waste facilities.

Technologies for getting there

Implementation of CCS generally comes at a cost, moreover a cost to the economy that is unprecedented in its nature, hence if we are to limit the negative economic impacts of BECCS it is essential to use cost-effective measures in its implementation. Essentially the technology options can be grouped into pre-combustion or post-combustion capture.

Biohydrogen (with pre-combustion capture) has the potential to provide a platform for the most advantageous implementation of BECCS because the costs of CO_2 capture would be incidental to the process rather than a dominating addition; neither would export of CO_2 from a biohydrogen plant compromise the output of the host plant. By contrast, with post-combustion capture (PCC) from a flue gas stream of an EfW or steam-cycle biomass power station there could be <50% reduction in power output occasioned by the energy demands of the capture plant itself.

Role for biohydrogen BECCs

With the emerging importance of negative emissions, it becomes increasingly important to optimise the BECCS potential of the nation's biomass resources, both with grown biomass and with biogenic wastes - the greater part of the UK's biomass energy potential is in its waste streams. Biohydrogen offers the opportunity to maximise the use of biomass energy potential through its intrinsically superior efficiency, whilst simultaneously and incidentally producing associated carbon dioxide as a discrete output. It follows that there would be a strategic benefit in the pursuit of the activities required to take biomass and waste gasification up to a TRL of 9.

What is required from Government?

Financial support – grant and revenue

The report on Work Package 3 of this project includes a discussion of market enabling measures that could be implemented to overcome barriers to deployment of biohydrogen facilities and to the development of a functioning market for BECCS; in both cases by development, inter alia, of tried and tested mechanisms based upon Contracts for Difference. Publication of the UK Hydrogen Strategy indicates that Government thinking on development of a hydrogen market is quite sophisticated and well developed, although it doesn't overtly identify biohydrogen as a particular case, and it is apparent that BEIS is at an advanced stage in designing an industrial CCS support scheme. It is important to recognise though that support mechanisms need not only to support emerging commercial operations in the early stages of both biohydrogen deployment and BECCS, but also the barriers to capital investment in the necessary assets and infrastructure – notably measures to overcome investor reticence where key technologies such as biomass gasification are not yet at TRL 9.

Regulations – standards (e.g. hydrogen blending, emissions trading scheme for waste)

Key to the development of a commercial hydrogen market will be adoption of universally recognised standards for biohydrogen together with quality systems by which conformity can be assured. Considerable work on this has already been accomplished, with government consultation on the subject closing in October this year.

The UK Hydrogen strategy recognises the potential market for hydrogen that could be initiated by blending hydrogen into existing gas networks where ongoing work with for example the Hydeploy[8] projects shows that up to 20% by volume could be feasible within the constraints of existing appliances; however, valuable as this may be in providing early demand in a nascent hydrogen market and an incremental step towards GHG reductions, it is clearly incompatible with the ultimate goal of carbon neutrality by the year 2050.

4.2 Commercial Plant Economic Performance

The economics of biohydrogen GGR are driven by the following factors:

- The technical performance of the biohydrogen GGR plant.
- The costs of or revenues from the sustainable feedstock used in the plant. Biomass residues such as straw will normally have costs. Waste feedstock will normally attract a gate fee to help offset the costs of BECCS.
- The revenue from the biohydrogen. This will depend on the use of the biohydrogen – at present transport biohydrogen is more valuable than heat biohydrogen – and on the value the market assigns to the greenhouse gas savings from using biohydrogen.
- The operating costs of the biohydrogen GGR plant such as staff, power, maintenance and consumables.

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[8] https://hydeploy.co.uk/ and https://hydeploy.co.uk/winlaton/

- The capital cost of the biohydrogen plant.

These were quantified in Work Package 1 of the Project to produce a techno-economic model of the plant. This was used to estimate the costs of capturing one tonne of carbon dioxide through biohydrogen production.

The following inputs were used in the model:

- The technical performance of a plant was based on the heat and mass balances developed by UCL discussed in Section 2.2. These models are based on a plant that is converting 110ktpa of waste wood into 376GWh of biohydrogen and 137ktpa of carbon dioxide.
- Waste wood was assumed to have a cost of £30/tonne. The market price is tracked on https://www.letsrecycle.com/prices/wood/ and has varied between a £20 gate fee and £30 cost over the last year. However, £30 /tonne represents a standard charge under a long term off-take agreement.
- Revenue from biohydrogen is valued at £20/MWh. Any large-scale biohydrogen off-takes are based on replacing natural gas for heat. The long-term value of natural gas is around £20/MWh at present and it is challenging for biohydrogen to achieve any premium on this amount at present.
- The operating costs for a biohydrogen plant using the Benfield process is estimated at £16.9m per annum. This is based on a detailed operating cost model developed in Work Package 2. Costs for Rectisol or SEWGS plant are lower because they have a lower heat demand.
- The capital cost of the plant is £165m based on a detailed cost model developed in the project.
- The cost of capital used in the levelised cost calculation is 12%. This is a typical hurdle rate for first of a kind plants.

The results of the levelised cost calculation using these assumptions for Benfield, Rectisol and SEWGS plant are summarised in *Table 6.*

Levelised Cost	**Benfield £/tonne**	**Rectisol £/tonne**	**SEWGS £/tonne**
Operating costs	124.5	108.3	99.9
Feedstock	24.3	24.8	24.0
Capital cost	155.2	158.3	153.1
	304.0	291.4	276.9
Hydrogen revenue	(55.4)	(55.7)	(56.9)
	248.6	235.7	220.0

Table 6: Baseline Levelised Costs

This shows that levelised cost for carbon dioxide captured in a Benfield plant is £249/tonne, falling to £220/tonne for a SEWGS system. This shows why SEWGS has not been adopted widely to date. A 12% cost reduction does not justify the technical risk of adopting a novel technology.

In the longer term it is expected that capital cost will fall, hydrogen prices will rise, and costs of capital will fall. The levelised costs, assuming a 15% reduction in capital cost, an 8% cost of capital and £50/MWh hydrogen price, are shown in *Table 7.*

Levelised Cost	Benfield £/tonne	Rectisol £/tonne	SEWGS £/tonne
Operating costs	196.0	153.1	136.0
Feedstock	24.3	24.8	24.0
Capital cost	87.4	89.1	86.2
	307.7	267.0	246.2
Hydrogen revenue	(138.4)	(139.3)	(142.2)
	169.2	127.8	104.0

Table 7: Nth of a kind costs

This shows that the costs of SEWGS carbon capture fall to £104/tonne over time. This is 40% lower than the cost of carbon savings through the Benfield process, demonstrating that the benefits of SEWGS are greater as hydrogen prices increase.

Overall, biohydrogen offers a very cost-effective route to capturing carbon dioxide. It is a significantly more efficient process than either direct air capture or post-combustion capture because the carbon dioxide is being captured from a gas mixture with a high carbon dioxide concentration. In addition, it has the benefit of generating a low carbon fuel in combination with delivering negative emissions.

4.3 Business Plan

A key feature of waste and biomass gasification is that the syngas that it produces can be converted into multiple fuels. In particular, a plant can have the flexibility to vary its output between biomethane and biohydrogen. This provides a route to commercialisation that allows plants to be developed as biomethane plants and then convert to biohydrogen production as demand for hydrogen grows.

ABSL is currently developing a plant at the Protos site in Cheshire that will convert 133ktpa of waste into biomethane while capturing more than 100ktpa of carbon dioxide. The plant is located close to the Hynet carbon sequestration network and the project is part of the Hynet phase 1 carbon cluster. This project is being jointly developed with Greenergy, a leading transport fuel supplier. It is expected to reach financial close in early 2023 and the target date for the plant to enter operation is Q4 of 2025.

The design of this plant is based around biomethane production initially, but it allows for conversion over time to biohydrogen. The move to biohydrogen will increase the amount of carbon dioxide that can be captured.

Plants that focus solely on biohydrogen will be developed as the hydrogen market develops. This should follow the finalisation of the Government's hydrogen business model when support will be available for low-carbon hydrogen to encourage its adoption. Support for the negative emissions generated through the sequestration of biogenic carbon dioxide will also encourage the production of biohydrogen as the amount of carbon dioxide that can be captured is higher for biohydrogen production than for biomethane production.

The business plan for development of the technology in the UK is:

- Complete commissioning of the Swindon demonstration plant and develop the capability to demonstrate biohydrogen GGR technology.

- Develop the Protos plant with Greenergy with a focus on biomethane production to demonstrate that the technology can be deployed at scale.
- Develop follow-on facilities focussed on biomethane and biohydrogen production.
- As the hydrogen market develops, the biomethane plants will move to biohydrogen production.

By 2030, ABSL expect to be operating ten plants across the UK capturing more than 1 million tonnes per annum of carbon dioxide.

There is significant interest in the development of greenhouse gas removal technologies in overseas markets. The US is very focussed on carbon capture as are some markets in Europe and the Far East. The deployment of the technology in the UK will provide a global showcase and will unlock opportunities to export UK expertise in the area to overseas markets.

The key precursors for the deployment of the technology are:

- Successful technical development through the Swindon and Protos plants.
- Support for biohydrogen and development of hydrogen markets.
- The roll-out of carbon sequestration networks.
- Support for negative carbon emissions.

When these conditions are met biohydrogen GGR will offer a cost-effective route to achieving negative emissions and will be able to make a substantial contribution to meeting the UK’s net zero commitment while developing a technology with major export potential.

5.0 References

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