D1.10 BIOCCUS Phase 2, Final Report – Public Domain Version

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1 Introduction

This is the public domain version of the final report from the BIOCCUS (Biomass Carbon Capture, Utilisation and Storage) Phase 2 Demonstrator project, funded through the Net Zero Innovation Portfolio (NZIP) under the Department of Energy Security & Net Zero (DESNZ). The report provides an overview of the project and describes some of the key findings and activities where commercial sensitivities can be respected.

BIOCCUS is a GGR (Greenhouse Gas Removal) technology designed with the aim of maximising negative emission potential, combining two established GGR concepts, namely biochar and BECCS (Bio-Energy with carbon capture and storage). BIOCCUS is a biomass pyrolysis-based cogeneration system with biochar production and carbon capture, utilisation and permanent storage. The technology uses undried and un-processed waste wood (i.e., not pelleted) from sustainably sourced domestic timber to produce electricity and heat in addition to biochar and commercial grade carbon dioxide (Figure 1).

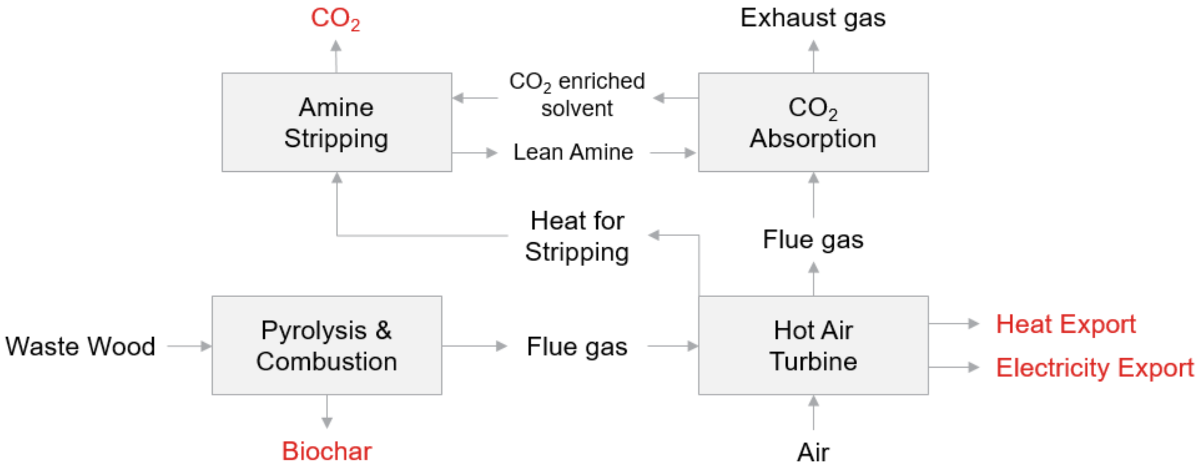

Figure 1 - The BIOCCUS Concept

1.1 System overview

The first process in the BIOCCUS plant is biomass pyrolysis, which is performed with reduced oxygen to produce syngas and biochar. Syngas is then combusted producing flue gas with 13-17% carbon dioxide. The enthalpy from the flue gas is used to drive the Hot Air Turbine (HAT) and its associated generator, via two heat exchangers, to produce the electricity and heat outputs from the system. The removal of carbon dioxide from the flue gas uses a temperature swing absorption process, utilising the heat recovered from syngas combustion to regenerate the solvent.

The key benefit of the system is that it will provide value from all four outputs, giving a low cost for carbon dioxide sequestration. Due to its modular nature, it can be easily and quickly deployed within the community, at farms or near greenhouses addressing the need for decentralised heat and electricity requirements. Community scale carbon capture, utilisation and storage (CCUS) systems allow the development of the CO_2 capture and utilisation supply chain in industry without having to wait for the development of the important but complex and expensive CO_2 transport and storage infrastructure. The BIOCCUS system is also well integrated so that it maximises heat recovery to improve energy performance and overall efficiency.

1.2 Demonstrator site selection

During the Phase 1 project, an agreement had been reached with Icknield Farm in Oxfordshire to build a new facility on a plot of land for the plant installation. The land was occupied but was due to become vacant. Upon project commencement, a site visit was arranged in early June. Prior to this visit, the landowner notified the project lead that the plot was not available, but there was an existing building that was available and could be used for the project. This existing building was inspected but was judged to be not suitable for the project partly due to the height restriction but also the general condition.

At this juncture, alternative sites were explored and enquiries made to several estate agents for property to lease. A suitable property was found in Haywards Heath, an existing grain store, with adequate height and footprint and suitable infrastructure. After a site visit, an offer was placed to hire the facility for 2 years, with an option to extend to 5 years. This offer was agreed in principle and the lease signed.

1.3 Demonstrator plant specification

The specification for the demonstrator plant is shown below in Table 1. Low and high flow relates to the amount of Flue Gas Recirculation (FGR) used - 17% and 58% respectively. This is a parameter which was explored in the testing phase and is expected to be within this range. Most values are like those presented previously in the Phase 1 concept study. The amine cycle heat requirement is significantly reduced for the demonstrator project, the reason for this is that due to budget restrictions, the amine system was scaled down to treat one quarter of the flue gas, hence the heat required for solvent regeneration was reduced. This has a knock-on effect to some of the outputs; the Net heat output is increased, and the CO_2 output is reduced.

Table 1 - BIOCCUS Demonstrator Plant Specification

Parameter	Low flow	High flow
Inputs		
Feedstock flow rate (10% moisture) – kg/h	328	378
Syngas heat production (based on HHV) – kW_{th}	1166	1344
Amine cycle heat requirement – kW_{th}	110	102
Outputs		
Biochar output – kg/h	67	77
Net electrical output – kW_e	48.7 – 54.3	
Net heat output – kW_{th}	242 – 459	
CO_2 – kg/h	90 – 110	

2 Demonstrator plant layout

The final overall plant layout is shown below in Figure 2.

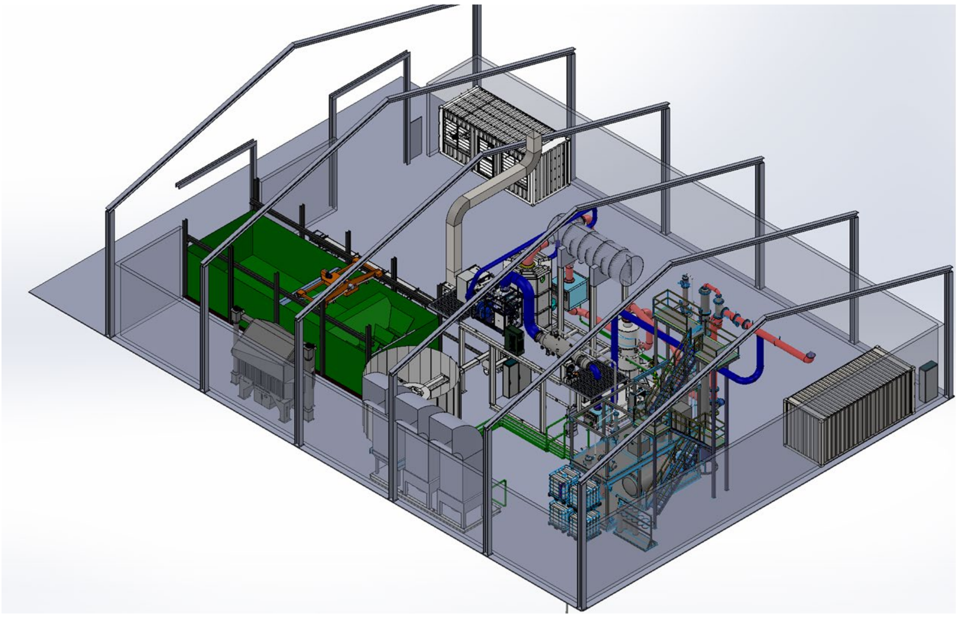

Figure 2 - Overall plant layout

All the major sub-systems and components were successfully installed into the facility. The installation progressed as each of the major sub-systems became available. The CO_2 system was assembled on-site, but all the other major sub-systems were installed on skids at the partner locations and delivered to site when ready for integration with the other systems.

2.1 Analysis

This section of the report describes the process flow assessments that were undertaken. The analysis of the demonstrator plant was performed with two separate models; the first focussing on the power cycle, capturing the thermodynamics and heat transfer in the combustor, heat exchangers and hot air turbine. The second model analysed the CO_2 capture system, defining the system flows and separation effectiveness.

2.1.1 Power cycle analysis

For the power cycle analysis, the analysis focussed on updating the heat exchanger layout and assessing the sensitivities within the system while the demonstrator plant design was being finalised.

The modelling was performed in three phases:

- A combustion modelling exercise to calculate the flows and flue gas composition and to provide an initial 1D performance matching study to provide initial heat exchanger specifications

- A 3D CFD (Computational Fluid Dynamics) study to calculate heat transfers and pressure drops from the proposed high temperature and medium temperature heat exchangers
- A system modelling study to assess performance at differing combustion calibrations in Modelica (Figure 3)

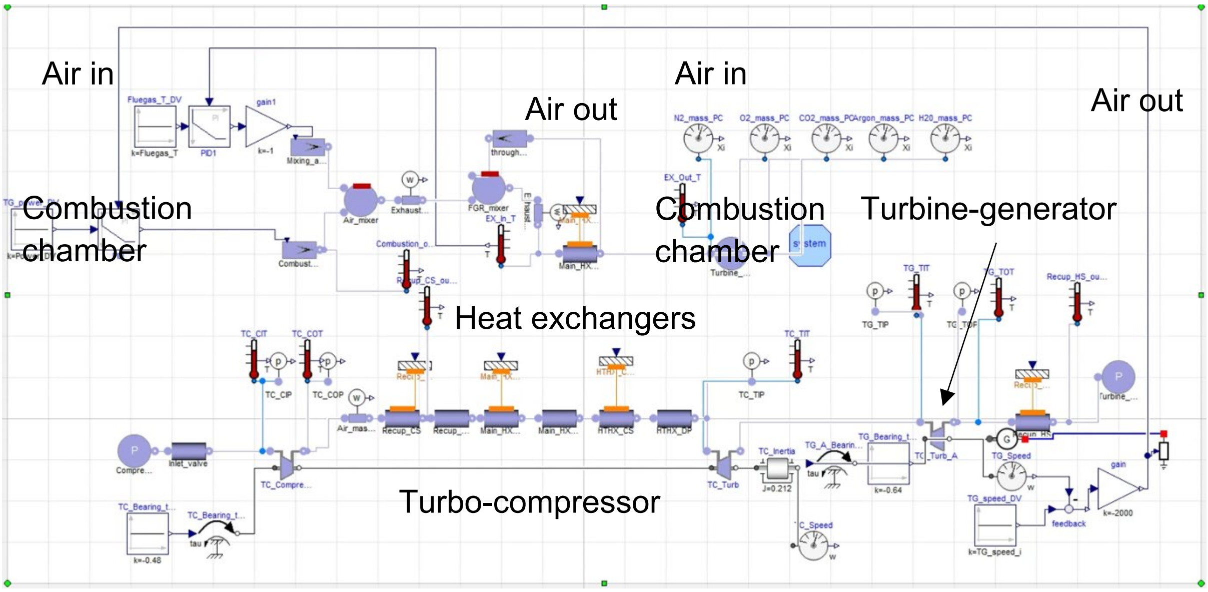

Figure 3 - Screenshot of system 1D performance modelling using Modelica

The results from this study were used to:

- Understand the range of air flow and flue gas flow requirements
- Specify the performance of the two heat exchangers
- Verify that the flue gases were still compatible with the amine cycle
- Verify that the heat produced by the power cycle still matched the needs of the full-sized amine cycle

2.1.2 CO_2 separation cycle analysis

A ChemCAD model was used for the modelling of the demonstrator plant CO_2 separation system. To meet the project budget requirements, the initial aim was to size the system to process a quarter of the flue gas produced by a single-module pyrolysis and heat recovery plant. This initial sizing was implemented into the model by adjusting flow rates and component sizes from those determined in the Phase 1 concept design study.

Once an initial hydraulic design of the columns was completed, the supplier of the internals was engaged to discuss packing options and typical performance. The column diameters, sized according to the flow rate and hydraulic performance of the packing layers, were confirmed by the supplier as being representative of larger size systems, and hence a suitable demonstration of the technology.

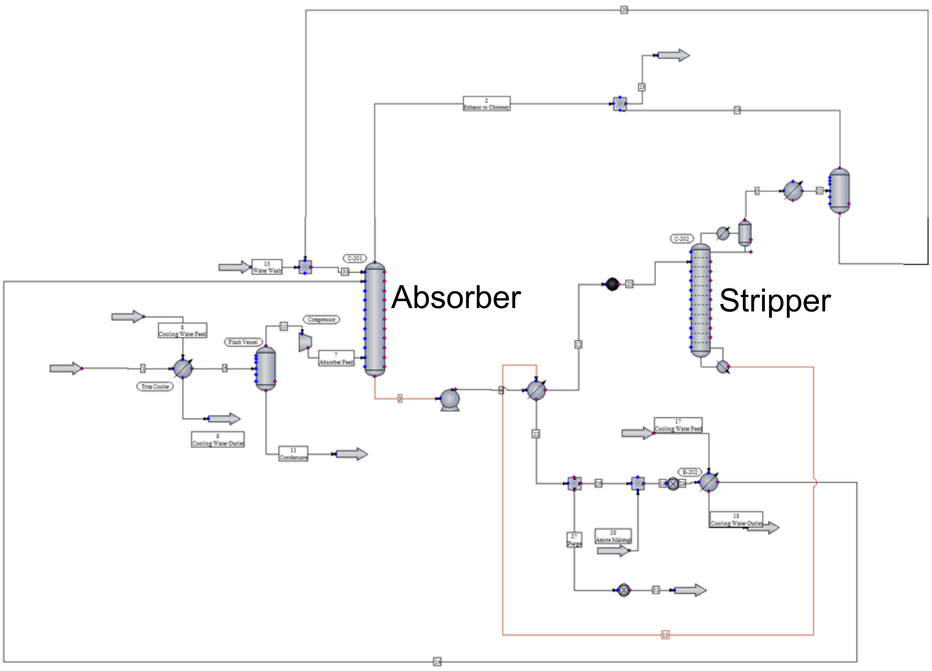

Figure 4 - CO_2 System ChemCAD Model

As the column design was maturing, more information became available relating to the height within the column occupied by the liquid distributors, support grids and other equipment. The original bed heights needed to be adjusted to fit the columns into the building. The model was used to perform a sensitivity study to understand the trade-offs from downsizing the columns but the decision was made to reduce the bed heights to fit the columns within the building, and not to downsize any further for cost optimisation. The data generated from the test phase could then be used to validate the model outputs and enable further adjustments to the design for future iterations of the system to be made with confidence.

2.1.3 Heat & Mass Balances

The final heat and mass balances from the two analysis models were produced. Two analyses were run for the power cycle with the extremes of predicted performance of the high temperature heat exchanger (both calculated using CFD). The overall heat & mass balance for the Power Cycle model is within 3%, which has negligible impact on the results. For the CO_2 separation system model, the overall mass balance for inlet and outlet streams balances to 0.03%.

2.2 Pilot plant installation

This section gives an overview of the demonstrator plant installation at the project site. The photos included in Appendix A2 show the installation of some of the major sub-systems and components. The installation progressed as each of the major sub-systems became available. The CO_2 system was assembled on-site, but all the other major sub-systems were installed on skids at the partner locations and delivered to site when ready for integration with the other systems.

2.3 Design & development challenges

Many challenges were encountered in the design and development of the demonstrator plant, predominantly relating to finalising the design, supplier selection, and managing the manufacturing and installation timing with so many sub-systems and components. More details relating to three of the key challenges are outlined below:

2.3.1 CO_2 system sizing

Towards the end of the Phase 1 project, it became apparent that the budget restrictions for the Phase 2 projects would not be sufficient to build the full single-module facility. Therefore, the plan for Phase 2 was to downsize the CO_2 separation system to handle a proportion of the flue gas from a single pyrolysis and heat recovery module, to demonstrate its effectiveness while maintaining the overall project budget. The early analysis and design work performed in the project confirmed that a quarter-size CO_2 separation system would be used and the initial feedback from suppliers suggested this would be containable within the budget and be representative of a full-sized single-module system.

2.3.2 Planning and permitting timeframes

The local authority (Mid-Sussex District Council) granted planning permission for a change of use to the facility being hired for the project. This decision was expected to be made by the Officer within 6 months of the start of the project. However, due to some local objections, the decision was changed to be made by the Planning Committee, which added two months to the original timing. The Officer's report was then not ready in time, so it was pushed back a further month. A wide-spread power cut in the area led to another month delay. Following a brief discussion of the proposal in the Planning Committee, permission was belatedly granted. The building lease was then able to be finalised with the landlord and the project could start the installation. During this delay, parts were either held back at the partners locations or stored at Ricardo's facility until access to the site was possible.

The Environment Agency issued a permit for the demonstrator plant, following an application submitted in late 2022. The initial timeframes for determining this permit were provided, but indicated that it would only be granted after the end of the project. Raising this issue with DESNZ managed to expedite the process and successfully led to the permit being granted prior to the testing phase.

2.3.3 Commissioning dependencies

A significant challenge in demonstrating this technology are the dependencies between the major sub-systems. This was identified when defining the commissioning plan earlier in the project, with a critical part being that the CO_2 system required the combustion and heat recovery systems to be operating well in order to run.

To reduce the criticality of these dependencies, electrical heating elements were added into the steam generator design. This enabled the steam system and amine system to perform hot commissioning without a reliance on production of flue gas from the pyrolysis plant and also removed the reliance on the hot air turbine to generate power and provide heat to the down-stream steam system. This decision enabled significant progress to be made in the commissioning of the plant before the installation was completed, and allowed testing of some of the sub-systems to progress when unplanned maintenance was required on other sub-systems.

2.4 Pilot system costs

The project spend followed a similar profile to that outlined in the original proposal. There was a slower ramp-up on the procurement, but within 9 months this had caught up. Note that the project ended up over-spending the original budget with these costs being covered by the partners. The breakdown of actual costs is shown below in Figure 5, where the labour cost includes elements relating to the system design, manufacture, install, commission and test.

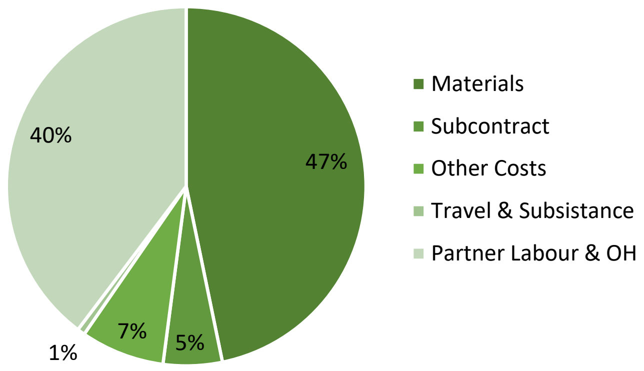

Figure 5 - Cost breakdown (Actual)

3 Test results

3.1 Introduction

This section summarises the results from the pilot plant testing phase of the BIOCCUS demonstrator project. The initial objectives of the testing phase were to evaluate the following for a range of feedstocks:

- Biochar quality
- CO_2 quality
- Emissions
- Heat and power generation

In addition, the data gathered during the testing phase was able to evaluate the parameters listed below:

- Electricity usage of all consumers and parasitics
- Staffing requirements and useability for non-experts
- Water consumption and drainage requirements
- Effectiveness and robustness of heat exchanger cleaning systems
- Compressed air usage
- Part load capability
- Noise
- Maintainability / Servicing requirements

3.2 Test Plan & Approach

The data that was collected mostly satisfied the objectives listed in the previous section. The resulting biochar from each feedstock variation was tested to analyse its chemical properties and suitability for future uses. The carbon content of the biochar was tested to allow for evaluation of the GGR performance of the system. This testing was performed by the University of Nottingham. Samples were sent after each feedstock trial with results available a few weeks later. The quantity of the delivered feedstock was recorded and stored electronically, as per the wood acquisition / delivery procedures. Daily checks were performed on the feedstock and the amount of feedstock used was monitored to minimise downtime between feedstock variations.

3.3 Feedstock trials

During the testing phase, five different feedstocks/combinations were tested to compare the biochar quality produced by each one:

- Woodchip
- Grass blended with woodchip
- Slabwood (outer bark sections)
- Whole ash trees (from the ash dieback management programme)

- Strawberry & raspberry plant residues and growing media (coir)

Results are shown qualitatively in Table 2 below. Good quality biochar was achieved from all feedstocks as the carbon stability was above 70% for all. Biochar stability is the proportion of carbon in biochar that remains after oxidation - a defining property of biochar and determined by the stability of its carbon structure.

The carbon content for the woodchip, grass blend and ash dieback all achieved the targets. The moisture content was above the target for all feedstocks, however the target water content was derived from alternative systems without a wet sump for biochar extraction, therefore there is an expectation that the water content from the BIOCCUS system will be generally higher, as shown from analysis.

Table 2 - Biochar test results

Parameter	Units	Min	Target	Max	Woodchip	Grass / Wood Blend	Slabwood	Ash dieback	Strawberry & raspberry
Total-C	wt-%	80	85						
H	wt-%			3					
O	wt-%			10					
H/Organic-C ratio	-			0.7					
O/Organic-C ratio	-			0.4					
Stability	%	70	90	100					
Water content	wt-%			1.5					
Feedstock Cost					▼▼▼	▼▼	▼▼	▼	▲

3.3.1 Woodchip

Woodchip was supplied from a local sawmill to ISO P31s standard, Table 3 shows the composition specification.

Table 3 – ISO P31s woodchip guidance specification

	Grade	Max Length	Coarse Fraction	Main Fraction	Fine Fraction
ISO17225-4:2021	P31s	120mm	45-120mm	3.15-31.5mm	<3.15mm
Current	Limits	All	<6%	>60%	<10%

This feedstock was chosen for commissioning and initial test running due to the repeatability and ease of resupply.

This feedstock structure initially proved too fluid for the loading bay augers, leading to occasional blockage of delivery conveyor. This issue was subsequently resolved by tuning the timing of the loading bay augers and conveyor.

3.3.2 Woodchip and grass mix

Woodchip and grass were tested at an approximate ratio of 10% grass cuttings to 90% P31s woodchip. The grass cuttings were delivered fresh and stored in the loading bay for 3 days prior to mixing. In this time, decomposition had started and significant heat was generated low down in the pile. Due to the decomposition, matting had taken place, and therefore an even distribution of grass and woodchip was very difficult to achieve.

The matting also caused a bridging/tunnelling effect, where the feedstock is delivered vertically to an auger and within the dryer, therefore stopping the flow of feedstock without constant operator intervention. If the feedstock were mixed thoroughly on delivery, or turned over regularly prior to mixing, this may have mitigated the issue.

3.3.3 Slab wood woodchip

The wood chip derived from slab wood (generally larger proportion of sap wood and bark) performed similarly to the woodchip previously tested, from an operational perspective. The biochar result however shows a lower carbon quantity and much greater level of oxygen content.

3.3.4 Ash dieback

The woodchip derived from trees felled due to the Ash dieback disease was noted for quick combustor heat up (good propagation of fire post starting) and stable temperatures. Again, the feedstock delivery was comparable to the previous types of woodchip tested.

3.3.5 Strawberry/raspberry roots with coir mix

Strawberry root/coir mix processing was challenging to use in the condition delivered. It was successfully processed when blended with some woodchip, but it did not stay as a homogeneous mixture when being transported through the augers. Stable combustion temperatures were hard to achieve and the CEMS (Continuous Emissions Monitoring System) reading showed high HCl (Hydrogen Chloride) due to plastic contamination (irrigation pipes) and NOx (Nitrogen Oxides) emissions were higher, as expected.

3.4 Partial load operation

Much of the testing was carried out at partial load to help understand and characterise the system and to develop robust operating procedures. Prolonged running at part load was not necessarily considered in the design stage, but with progressively more running at part load, it became clear that the stability and repeatability was good, especially in the range of 400-500°C combustor outlet temperature.

3.4.1 Key observations

During combustor warmup and until the outlet temperature (TT-P2021) exceeded approximately 250°C, a gas plume was visible at the stack, primarily caused by condensation in the exhaust ducting. With the correct balance of air flow to and from the combustor, the visible smoke levels were minimal.

Stable running of the combustor was achieved in the 250°C to 500°C range with automatic feedstock control and minimal operator intervention. This was dependant on feedstock delivery reliability, which was heavily influenced by the feedstock in use.

The ID (Inlet Depression) fan targets a depression in the combustor of 100kPa. This approach did not give a particularly stable outlet flowrate due to the incremental delivery of feedstock to the combustor. Stability of the flue gas flowrate into the amine system was affected, but this could be improved with further dampening of fan control terms.

3.4.2 Plant Performance

Stable and repeatable part load running of the combustor, dryer and feedstock handling systems was achieved for several months of the testing phase.

If considering just the CO_2 capture efficiency from the flue gas of the amine plant, data from a part load operating point showed that a CO_2 capture efficiency of 87% was demonstrated which was relatively close to the initial target (at full load conditions) of 90%.

3.4.3 CO_2 Quality

Using the CEMS measurement system an initial indication of CO_2 quality was obtained. The data represents a single log (5s sample time) during stable running conditions. Comparing to the target CO_2 specification shows the output was within limits for critical parameters such as CH_4, NH_3 and SO_2.

3.4.4 Flue Gas Emissions

The CEMS kit incorporates two heated lines to allow sampling of the CO_2 after the dehydration column and the flue gas just before the stack. Comparing to the emissions limits set by the permit, CO, SO_2 and NO_x were all comfortably below the levels required.

4 Successes and lessons learnt

This section describes the key successes from the Ph2 demonstrator project and highlights the main lessons learnt.

4.1 Successes

The major successes achieved by the project are:

- First of a kind demonstration of biochar pyrolysis with CO_2 capture, across a range of different feedstocks
- Delivery of a complex technology demonstrator project, incorporating the design, procurement, installation and testing of multiple sub-systems. Including mitigating significant procurement delays to achieve the project end date only two months after the original plan
- Identification of a demonstrator site after the Phase 1 plans fell through, including successfully navigating planning permission for change of use, permitting and a building lease
- Safe installation and operation of the demonstrator plant, aided by regular internal and external QHSE audits. The project has an excellent safety record considering the inherent risks in the scope of work
- Commercial interest already generated and on-going discussions underway with potential customers.

All project milestones were achieved and all deliverables completed. The project successfully passed through three DESNZ Stage Gates with minor comments to address.

As part of the Dissemination, Exploitation and Communication activities, the project activities have been publicised and several marketing assets created. Customer and stakeholder open days have been hosted. Customer projects have been won by the partners with various leads generated for future projects.

4.2 Lessons learnt

Lessons learnt were captured and regularly reviewed. The list below presents some of the main lessons learnt from Phases 1 & 2:

Late changes to planning and permitting applications: The applications were driven by Ricardo with engagement of the partners and were submitted early in the project to minimise the impact on the project timing. However, late changes were identified following the initial submission. At this point, a key points summary document for both applications was created for review to ensure that further submission updates were minimised.

Local Authority Planning Application Support: The planning application received some objections from four local residents and the parish council. At the point of being notified that the decision would be made by planning committee, it was too late to ask for support to be registered on the portal, from the landlord, the local sawmill and others who were supportive of the plans. Future projects will consider the possibilities of local objections and will request support to be registered by those in favour.

HAZOP: The HAZOP (Hazard Operability) initially focussed on the CO_2 separation system, using a Ricardo team. Subsequently the HAZOP was expanded to cover the other parts of the plant, and regular on-line sessions were set-up with the project partners. For various reasons, these on-line sessions were sporadic and not as efficient as the Ricardo in-person sessions. Therefore, the wider HAZOP sessions were replaced with several all-day workshops to progress the work with the view to finalising the HAZOP for the whole plant by the end of November 2023.

Procurement: Supplier contact in Phase 1 was slow and in some cases resulted in wasted effort and time to establish a Non-Disclosure Agreement (NDA) that was subsequently not needed. To mitigate this, supplier information gained from Phase 1 was fed into Phase 2 to allow a faster start to the project. Following the listing of the press release (prior to the official project start), potential new suppliers were contacted using publicly available information. Where an NDA was felt necessary this process was initiated as soon as possible.

Component certification: The team was focussed on the delivery timing for the heat exchangers assuming there would be no issues with certification. In the event, certification issues and delays further held up the delivery which had a knock-on effect to the whole project timing. For future projects, we will create specific check points for certification status for all applicable parts of the system and ensure the manufacturer engages with the certification bodies earlier in the manufacturing and sign-off process.

5 Technology benefits & challenges

This section of the report describes the risks relating to the operation of the plant and its impact on the local environment. The annual GGR impact is then described in the context of the MRV methodology, before then using this as a basis to estimate the life-cycle impact.

5.1 Process risks

The process risks relating to the GGR mechanism are primarily addressed in the MRV methodology which evaluates the permanence of the storage and the life-cycle impact. These factors are addressed in the subsequent sections. The operational process risks of the technology are documented in the HAZID (Hazard Identification) which was produced for the project. Of the hazards identified, the majority relate to personnel risks which can be mitigated with suitable procedures. The primary process risk that could cause environmental harm relates to the use of amine and its acute toxicity for aquatic life. The mitigation relating to this risk relates to minimising the chances of spillage, through use of sealed containers, and surrounding the amine system with bunding so that, in the event of a spill, the amine is contained and can be cleaned and disposed of without entering the watercourses.

5.2 Safety considerations

The purpose of this section is to outline the safety considerations that need to be made for future installations of the plant. The HAZID produced by the project forms the basis for this assessment, with additional detail for a few specific areas outlined below:

DSEAR – An independent consultant was employed to perform a DSEAR (Dangerous Substances & Explosive Atmosphere Regulations) review of the plant and facility design. The conclusions were that no explosive zones were identified, with the only risk being potential combustion of gases in the flue stack under conditions where syngas was produced without sufficient oxygen for combustion, igniting on a hot surface further downstream. This risk is mitigated by the installed lambda sensor which will cause a shutdown in the event of insufficient oxygen, hence the combustion event would only be for a short duration.

SIL – The SIL (Safety Integrity Level) was determined by evaluating the hazards that are present in the plant in the context of a decision tree such as the one shown below in Figure 6.

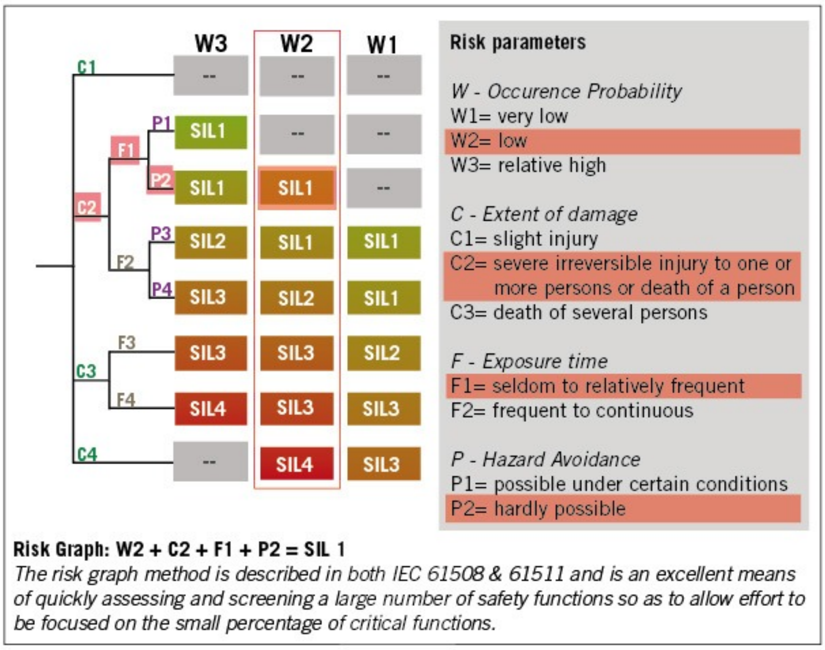

Figure 6 - SIL Decision Tree (Source: Prognost)

An internal review of the hazards identified the following items for consideration:

- Gas monitoring / detection system
- Biochar sump water level control
- Steam generator control
- Amine system column and reboiler pressure control
- Access hatches / safety switches on feedstock and biochar augurs
- Amine system column inspection hatches
- Fire detection and suppression system
- Amine system sump level control
    - Specifically the stripper and reboiler due to the elevated temperatures
- Hot Air Turbine shutdown system

The SIL rating for these is summarised below in Table 4.

Table 4 – SIL Ratings

Function	W	C	F	P	SIL
Gas monitoring / detection	2	2	1	1	--
Biochar sump water level	2	1	1	1	--
Steam generator	2	2	1	1	--
Amine system column & reboiler pressure	1	2	1	2	--
Feedstock and biochar augur access hatches	2	2	1	1	--
Amine system column inspection hatches	1	2	1	2	--

Fire detection and suppression system	2	2	2	1	SIL1
Amine system column and reboiler sump level	2	1	1	1	--
Hot air turbine shutdown system	1	2	1	1	--

PED – Certain elements of the BIOCCUS system come under PED (Pressure Equipment Directive). The relevant components and their certification requirements are listed in Table 5 below.

Table 5 - PED Requirements

Categorisation	Component	Modules
Article 4.3	Solvent filter, Trim cooler, Reflux condenser, Dehydration cooler	-*
Category I	Reboiler, Regenerative heat exchanger, Dehydration filter, Reflux drum, Knock-out drum	A
Category II	Dehydration column	A2, D1, E1
Category III	Mixing tank, Medium temperature heat exchanger	B (design) + D, B (design) + F, B (production) + E, B (production) + C2, H
Category IV	Absorber tower, Stripper tower, Air-to-steam generator, High temperature heat exchanger	B (production) + D, B (production) + F, G, H1

*required to be designed and manufactured in accordance with sound engineering practice and provided with adequate instructions for use.

A summary of these modules and how the design and production types apply is included below in Figure 7. The facility should be safe provided that these components are manufactured and certified according to these requirements and they are protected by pressure relief valves that are included within a Written Scheme of Examination. This was confirmed to be the case by engagement with a Notified Body during the demonstrator plant project.

The steam generator also falls under Steam Boiler regulations (BG01, BG03) which require a person to be always on-site to perform an emergency shutdown if required.

Hazard Category	With no QA system – Serial Production	With no QA system – Unit Production	With QA ISO 9000 system or equivalent – Serial Production	With QA ISO 9000 system or equivalent – Unit Production
	Modules			
I	**A** Technical documentation and internal production control			
II	**A1** Technical documentation and internal manufacturing checks with monitoring of the final assessment		**D1** Technical documentation and production quality assurance	**E1** Technical documentation and product quality assurance
III	**B** EC type examination + **C1** Conformity to type	**B1** EC Design examination + **F** Product verification	**B** EC type examination + **E** Product quality assurance	**B1** EC Design examination + **D** Quality assurance for final inspection, testing & production — **H** Full quality assurance for design, final production, inspection & testing
IV	**B** EC type examination + **F** Product verification	**G** EC unit verification	**B** EC type examination + **D** Quality assurance for final inspection, testing & production	**H1** Full quality assurance with design examination and special surveillance of the final assessment

Figure 7 - Conformity Assessment Modules (Source: Intertek)

Fire protection – The facility would also require sign-off by the local Fire Service, including completion of a fire risk assessment from both the operator and the Fire Service. For the demonstrator plant, a fire detection system was installed as well as a gas monitoring system to detect hydrocarbons above the feedstock storage area. A fire suppression system would likely to be needed to be able to satisfy and mitigate the risk of fire during continuous operation.

In summary, if the protection measures are in place as outlined in the previous paragraphs, the level of risk should be reduced to as low as reasonably practical, which should enable safe operation of the technology in a commercial environment.

5.3 Environmental & social impacts

This section outlines the environmental and social impacts of the technology, based on the demonstrator plant project. The primary environmental impact is on air quality due to the flue gas produced by the plant, this was addressed in the permitting application. Due to the process, an environmental risk assessment was not required as part of the planning consideration. The primary social impacts are traffic and noise, both were assessed within the planning application. Hence, conclusions from these assessments for the demonstrator plant provide helpful indications for future installations of the technology.

5.3.1 Environmental impact – Air Quality

The primary environmental impacts of the technology relate to air quality, due to the syngas combustion and associated flue gas emissions. The primary focus of the air quality assessment performed for the demonstrator plant was the impact on the human receptors close to the demonstrator plant site, in the nearby business units. The pollutants relevant to the air quality assessment included the pollutants attracting an emission limit according to the Environmental permitting technical guidance PG5/1(21) and pollutants emitted as the result of amine-based carbon capture process, including ammonia, amines and their degradation products (e.g. nitrosamines).

The relevant pollutants considered within the air quality impact assessment were:

- Carbon monoxide (CO)
- Particulate matter (dust)
- Nitrogen Oxides (NOx)
- Total Volatile Organic Compounds (TVOC)[1]
- Hydrogen Chloride (HCl)[2]
- Formaldehyde
- Ammonia
- Amines
- Nitramines
- Nitrosamines
- Acetaldehyde

Figure 8 and Figure 9 show contour maps of the annual mean process contributions (PC) for NO_2 and PM_{10}. The emission rates used for this assessment were based on the Environment Limit Values as a worst-case assumption.

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[1] TVOC is assumed to be benzene

[2] Only applicable when melamine faced woods are in the fuel

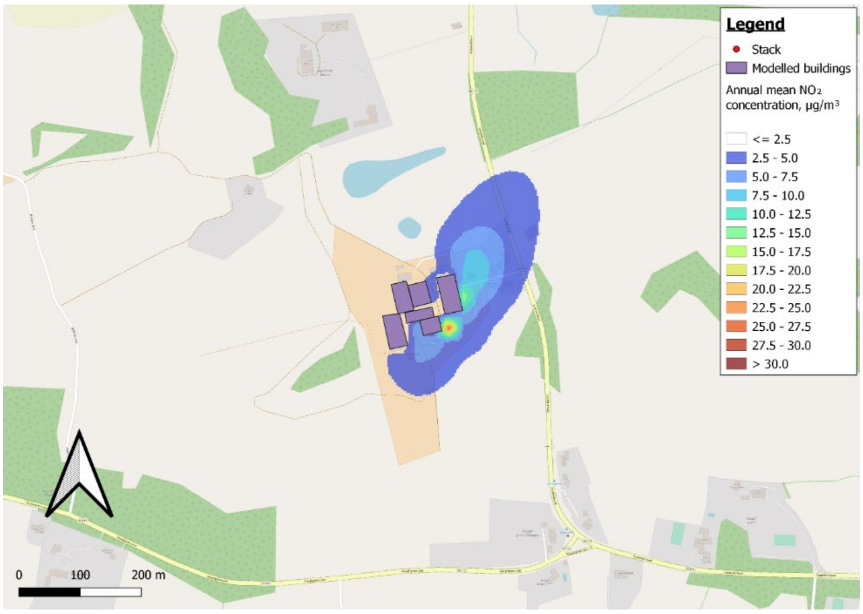

Figure 8 - Contour map of modelled process contribution to annual mean NO2 concentrations, 2015, (µg/m3)

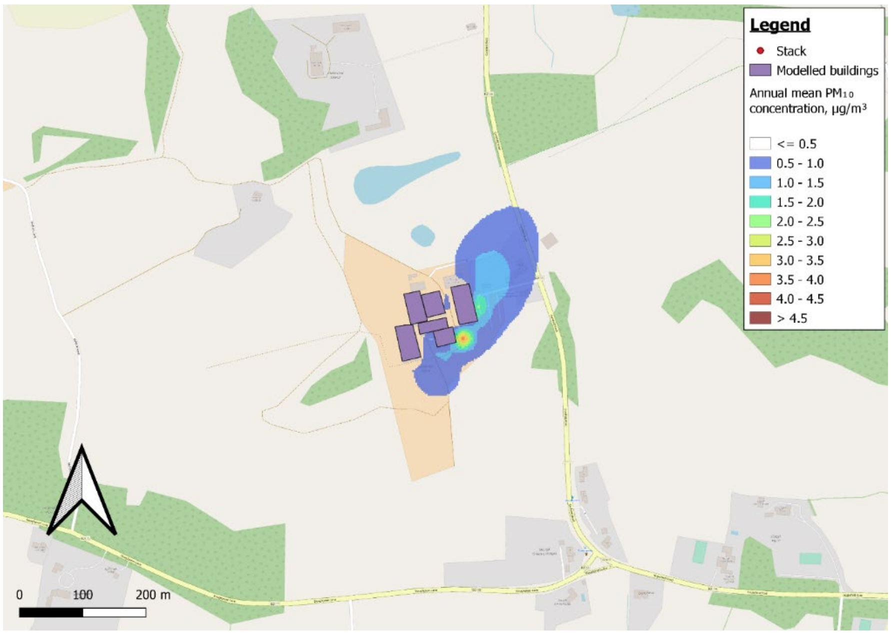

Figure 9 - Contour map of modelled process contribution to annual mean PM10 concentrations, 2015, (µg/m3)

From Figure 8 and Figure 9, it can be seen that the location of maximum impact in both cases does not occur at a relevant location for long-term human exposure. Instead, this maximum was predicted to occur immediately to the east of the stack.

The maximum long-term process contribution (PC) across the modelled human receptors was above 1% of the long-term standards for benzene, NO_2, PM_{10}, formaldehyde, and nitrosamine, while the maximum short-term PC across the grid is above 10% of the short-term standards for NO_2 and piperazine. All other pollutants were less than the 1% or 10% of the relevant short term and long-term standard.

The results of dispersion modelling indicated that Process Contributions and resultant Predicted Environmental Concentrations of all pollutants at human receptors were of negligible significance, except for benzene and NO_2 with a minor to moderate significance. However, this occurs at only four out of the 41 receptors. Furthermore, the predicted environmental concentration at these receptors is well below the air quality objective (AQO) and environment assessment level (EAL) (less than 70%). Given that several worst-case assumptions were adopted in this assessment, it is expected that overall, the effects of the proposed technology at this and other sites are likely to be of negligible significance.

5.3.2 Social Impacts - Noise

The assessment of the impact of noise from the demonstrator plant was assessed according to BS4142:2014. The building location is shown in more detail in Figure 10.

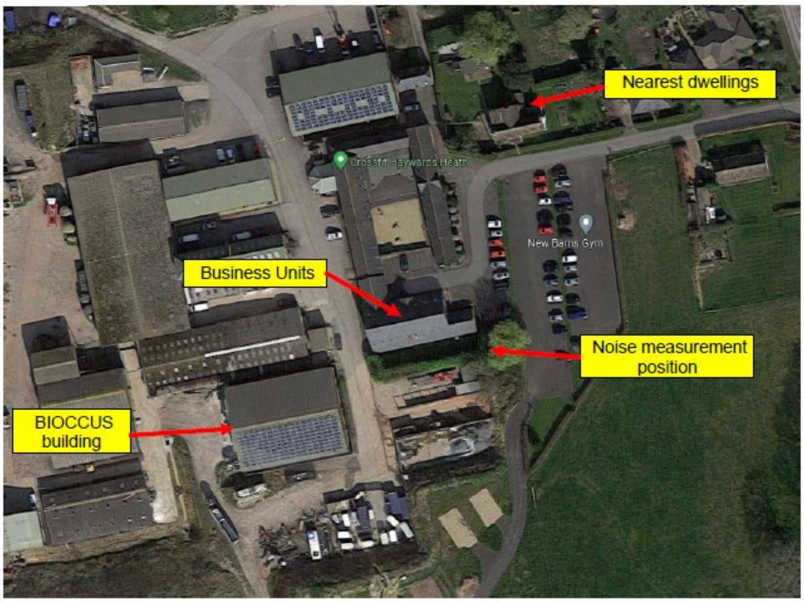

Figure 10 - Plant building location

There are two items of noisy plant in the building, the hot air turbine and the biomass drier, both of which were estimated to have noise emission levels of ~80dB(A) at 1m in the design phase. The plant noise emission was used to determine the reverberant sound pressure level inside the building by first using the typical acoustic absorption of the building internal surfaces to calculate the room constant. The internal noise level was then used to determine the external noise level at the building façades.

The exhaust outlet of the drier was located on the south façade and is therefore screened from the nearest receptors. Noise from this outlet as well as the calculated noise level at the eastern façade, was used to estimate noise levels at the business units and nearest residential receptor. The calculated noise levels are summarised below:

- Predicted noise level at Business Units: 37dB(A)
- Predicted noise level at nearest dwelling: 19dB(A)

Internal noise levels at the Business Units would therefore typically be 25dB(A), assuming slightly open windows. This would be significantly below the recommended internal guideline of 40-45dB(A) for offices.

At the nearest dwelling the typical background noise LA90,15min was measured as 32-35dB during the proposed operating hours. The predicted external noise level of 19dB(A) is significantly below the background noise level resulting in a 'low impact' according to BS4142. Based on the internal noise guideline LAeq,16hr 35dB of BS8233 for daytime living rooms, the predicted external level of 19dB(A) would be imperceptible inside the dwelling, even with slightly open windows.

During the testing phase, the measured noise emissions inside the facility were 89dB for the dryer and 92dB for the Hot Air Turbine, both ~10dB higher than the original estimates in the design phase. Applying a linear uplift to the impact on the surroundings would suggest an internal noise level at the Business Units of ~35dB(A) – still below the internal guideline of 40-45dB(A). At the nearest dwelling, the external noise would still be below the measured level of background noise.

Therefore, while the noise inside the building was higher than anticipated, and would require ear defenders for long-term exposure in certain parts of the facility, the predicted noise levels from the demonstrator plant and future instances of the technology are not likely to cause disturbance to occupiers of the nearby business units at nearby dwellings, provided future site layouts have similar proximity to the nearby buildings.

5.3.3 Social Impacts – Transport

A transport statement was also produced to assess potential impacts of the demonstrator project. The predicted level of traffic generation was assessed as being unlikely to be noticeable and comparable to the hourly fluctuation of traffic flows on the streets surrounding the site. The assessment demonstrated that the project would not have a demonstrable adverse impact on the local highway network or road safety. It is anticipated that future instances of the technology would also have no adverse impacts on the transport network.

5.4 Monitoring, Reporting & Verification

This section outlines the proposed Measurement, Reporting and Verification (MRV) methodology for the BIOCCUS technology. In order to enable accounting of reductions under the UK's Nationally Determined Contribution (NDC) in the future, the proposed methodology is fully aligned with approaches used for certificates traded on international carbon markets and national GHG inventories to be reported under the UNFCCC. Such approaches focus on direct GHG emissions (Scope 1) caused by the project in question and do not cover a full Life-cycle-analysis (LCA).

The BIOCCUS technology leads to GGR and carbon sequestration through the following means:

- Waste wood is used as biomass input, meaning the biomass is not grown with the purpose of being used for the BIOCCUS technology
- All power and heat required for the process are generated from the waste wood input, meaning no consumption of grey electricity from the grid or fossil fuel combustion for heat generation
- The process generates more electricity and heat than it consumes. These can be fed into the grid / sold to external customers where they can displace grey electricity and heat generated from fossil fuels
- The process yields biochar, which is rich in carbon. Where the biochar is applied to soil and remains there, nearly 80% of the carbon will remain bound in the soil indefinitely, i.e. not return to the atmosphere
- The process allows the capture of nearly all of the remaining CO_2 allowing to further process it to commercial grade CO_2 which can be used for purposes like drinks production and food packing. While the carbon is emitted to the atmosphere again when drinks are consumed, the production of the commercial grade CO_2 in the BIOCCUS process happens using the renewable electricity and heat generated from the waste biomass input. It thus can displace commercial grade CO_2 generated using fossil-fuel based electricity and heat.
- Even more CO_2 could be sequestered from the atmosphere in the future by using long-term storage approaches, e.g., using the captured CO_2 for cement curing, meaning it will remain bound in the material. Such approaches are at present not included in the methodology.

The above-mentioned benefits can only be achieved under two conditions which are non-negotiable: The biomass input has to be biomass waste and the biochar has to be used for soil enhancement and remain in the soil.

5.4.1 Baseline scenario and methodology

The methodology should be generally applicable to GGR technologies and thus covers the following outputs:

- Biochar
- Power exported to the grid
- Heat to be sold to external users

- Commercial grade CO_2

At present, existing methodologies for carbon market certificates (voluntary as well as under the Clean Development Mechanism (CDM)) do not cover a process with all of these outputs. Methodologies[3] exist for the various products, including

Methodologies based on LCA approaches, like the Puro.Earth Biochar Methodology (Edition 2022, Version 2) were not considered as the MRV approach to be developed in this report focuses on Scope 1 emissions.

- Biochar production and application (Verra methodology VM0044, EBC-Guidelines for the Certification of Biochar Based Carbon Sinks)
- Power and heat generation from renewable sources (CDM Tool 05, CDM Methodology ACM0002 Grid-connected electricity generation, CDM Methodology AM0036 Use of biomass in heat generation equipment, CDM Methodology ACM0006 Electricity and heat generation from biomass)
- Capture of CO_2 from exhaust gases (CDM methodology AM0063 Recovery of CO_2 from tail gas in industrial facilities to substitute the use of fossil fuels for production of CO_2, CDM Tool 05 (power generation), CDM Tool 03 (heat generation))

The methodology suggested in the following section builds on these existing methodologies and the principles therein. Where available, CDM methodologies were used, as these, being developed under the United Nations Framework Convention for Climate Change (UNFCCC), are considered to have the highest acceptability at the international level. Where no CDM methodologies were available, methodologies from voluntary markets were considered, again preferring the most widely recognised standards.

A key point to note is that both the ECB Guidelines and VERRA only permit waste biomass to be used in the project with the baseline scenario either decomposition or non-energy combustion of the waste biomass. Where a project uses purpose-grown biomass or biomass with a competing use (e.g., power/heat generation) these methodologies are not applicable.

The BIOCCUS demonstrator project is focused on demonstrating and evaluating the integrated processed of biochar production and capture of CO_2, including the generation of power and heat from the pyrolysis syngas. The demonstrator project does not cover the compression of CO_2, but this would usually be considered part of the production of commercial grade CO_2. Neither does it cover the transport and use of CO_2 nor the application of well as biochar.

For this reason, the methodology has an assessment scope limited to the sourcing and production stages of biochar and commercial grade CO_2 as indicated in Figure 11. The baseline and the monitoring methodologies related to biochar and

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[3] Full references to all methodologies are presented in Annex 1.

commercial grade CO_2 will cover these two stages in detail and only refer to potential approaches and key considerations for the application and distribution stage.

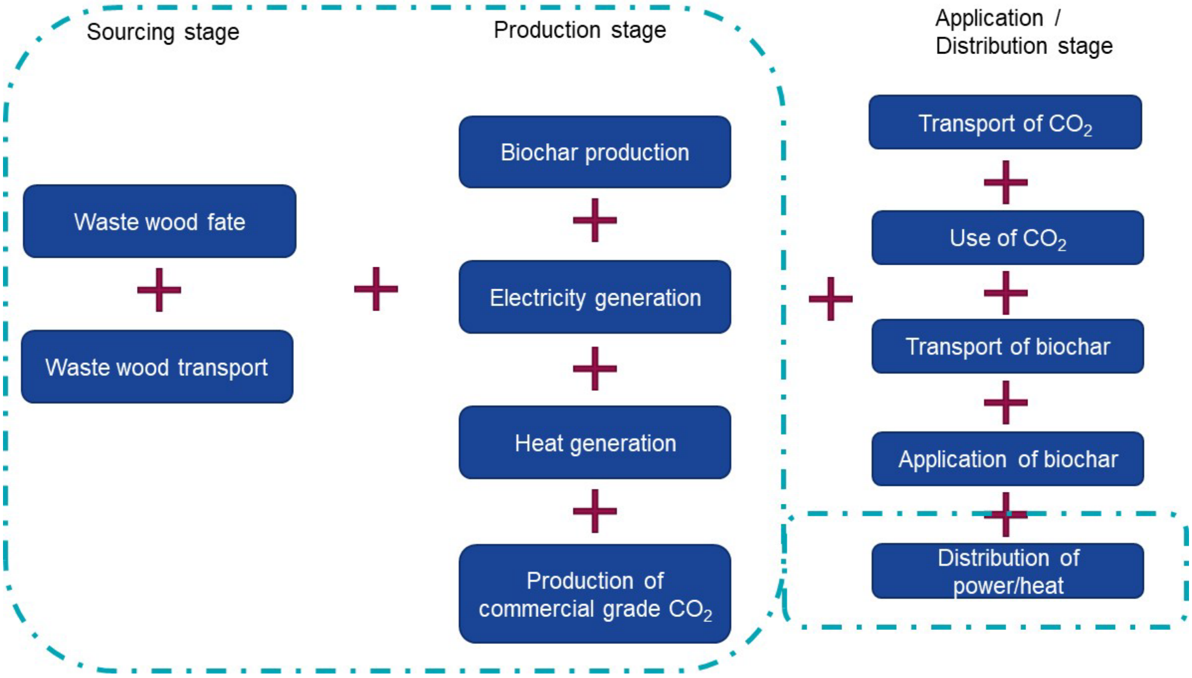

Figure 11 - Emission relevant activities (suggested assessment boundary in blue)

The annual mitigation impact ($MI_{tot,y}$) for the year y is calculated as the difference between the baseline emissions and the project emissions of that year.

$$MI_{tot,y}\ [t\ CO_2] = BE_{tot,y} - PE_{tot,y}$$

where

$BE_{tot,y}$	Baseline emissions in year y [t CO_2]
$PE_{tot,y}$	Project emissions/removals in year y [t CO_2]

The baseline scenario summarises the general assumptions of what would happen in the absence of the project. The baseline methodology represents the approach for quantifying the GHG emission levels under the baseline scenario.

As a starting point, a separate baseline scenario has been identified for each of the four production outputs: biochar, electricity to the grid, heat to external consumers and commercial grade CO_2. These are presented in Table 6. For the purpose of developing the baseline, biochar is considered as the main product of the process. It is assumed that without the BIOCCUS project, this biochar would not be produced, and the waste wood used as biomass input to the biochar production would be used as mulch and left to decompose or combusted. With regards to power, heat and commercial grade CO_2 it is assumed that these are each produced separately using non-renewable sources.

In line with the standards this methodology is based on, the assessment scope does not include the full life-cycle emissions of the production outputs, e.g., GHG emissions related to the production and distribution of fuels, GHG emissions related to process steps leading to the generation of a CO_2-rich exhaust gas, e.g., from the energy needs of steam-methane reforming for hydrogen production for the purposes of a Haber-Bosch process, N_2O emissions from the application of synthetic fertilizer to agricultural soils based on ammonia generated in that process.

Table 6 Baseline scenarios for the products

Product	Baseline Scenario	Methodology assumptions
Biochar	No biochar is produced, waste wood is left to decompose with the carbon contained set free eventually.	No GHG emissions from the baseline as only waste biomass is eligible according to Verra methodology VM0044, EBC-Guidelines for the Certification of Biochar Based Carbon Sinks
Power exported to the grid	Consumption of power from the grid	Emissions from the generation of power and transmission/distribution losses
Heat provided to external consumers	Generation of heat in a boiler consuming natural gas, located where the heat is consumed	Emissions from fuel combustion for heat generation, no emissions from the distribution of heat as heat is consumed at the location it is generated.
Commercial grade CO_2 production and compression for bottling	Capture of CO_2 generated as by-product from an industrial production process (e.g., steam methane reforming) consuming power (from the grid) and heat (generated in a boiler consuming natural gas), compression of CO_2 using power from the grid	Emissions from the generation of power and transmission/distribution losses Emissions from fuel combustion, no emissions from the distribution of heat

The production of biochar, electricity, heat and commercial grade CO_2 can lead to emissions of CO_2, CH_4 and N_2O from a number of different activities under the baseline. Depending on the assumptions made, emissions from certain gases might not occur or might be negligible under certain activities. This methodology has only considered the CO_2 emissions and has omitted any other gaseous greenhouse gas emissions as they are dependent on the downstream usage.

5.4.2 Application of the monitoring methodology

The monitoring methodology was applied to the BIOCCUS demonstrator project, located on Holmsted Farm near Haywards Heath. In line with the permit, 4000 operational hours were assumed per year. Table 7 presents four scenarios of the demonstrator site as well as the greenhouse gas removal achieved under each scenario (assuming biochar is applied to agricultural soil and remains there).

Table 7 presents the annual greenhouse gas removal in tCO_2-eq estimated by using the methodology developed in this report for a number of scenarios applying the BIOCCUS technology.

Scenario 1 is based on the full load performance of the demonstrator plant and the measured carbon content of the biochar operating on woodchip.

Table 7 Scenarios used for estimating GGR from the BIOCCUS technology

Scenario	Description	Assumptions	GGR (per annum)
1	BIOCCUS Ph2 demonstrator project	Outputs considered: Biochar, electricity. No client for the excess heat CO_2 is separated to prove its quality but not sold. The plant is operated 4,000 hours per year	762 t CO_2-eq
2	BIOCCUS demonstrator plant with CO_2 and heat use / export	Outputs considered: Biochar, electricity, heat, commercial grade CO_2 Commercial grade CO_2 is produced from 25% of the exhaust gas and sold. The plant is operated 4,000 hours per year	1,001 t CO_2-eq
3	BIOCCUS demonstrator plant with full-size CO_2 system	Outputs considered: Biochar, electricity, heat, commercial grade CO_2 Commercial grade CO_2 is produced from 100% of the exhaust gas and sold. The plant is operated 4,000 hours per year	998 t CO_2-eq
4	Four-module plant, maximum operating hours	Outputs considered: Biochar, electricity, heat, commercial grade CO_2 Commercial grade CO_2 is produced from 100% of the exhaust gas and sold. A four-module plant sized for commercial applications The plant is operated 8,000 hours per year	8,004 tCO_2-eq

5.5 Life-cycle Assessment

The considerations for the Life-cycle Assessment for the technology is mostly captured in the previous section on MRV which calculates the net GGR on an annual basis, including consideration of the associated emissions relating to feedstock transport. The only significant factor not considered are the associated emissions relating to the construction of the plant. These are estimated for the demonstrator plant below:

Table 8 - Estimated CO_2 emissions from pilot plant construction[4]

One-time construction of plant	Quantity	Unit	Carbon intensity of materials (tCO_2eq per unit)	Carbon Emissions (tCO_2eq)	Source
Ceramic	15	t	0.244	3.66	1
Mild steel	15	t	1.77	26.55	2
Stainless steel	25	t	6.15	153.75	2
Cable	6.5	km	64.65	420.225	3
Deliveries (Road)	100000	km	0.00019	19	2
Deliveries (Sea)	30000	t.km	0.00001	0.3	2
Total				**623.5**	
Plant Lifetime	20	years			
Annualised Construction Impact				**31.2**	

Quantities of ceramic (kiln bricks used in the combustor), mild steel and stainless steel are based on estimated quantities for the whole system. The demonstrator plant includes approximately 6.5km of cable for the power, instrumentation and control of the plant which has the largest contribution to the construction emissions, when considering the average cable size to be comparable to the analysis in the source data. Deliveries (Road) is estimated as 500 trips to deliver parts, from the various suppliers, with an average distance of 200km. Deliveries (Sea) primarily relates to the heat exchangers that were manufactured in Southeast Asia.

In addition to this, the MRV calculations have not considered any downstream emissions associated with the transportation of the biochar, for its use as a soil improver. Some of the biochar produced to date has been issued locally for trial purposes, with an estimated transportation distance of 50km. Using the same assumptions regarding carbon intensity per tonne/km as in the MRV methodology, the estimated emissions associated with biochar transportation are 11.2 tCO_{2eq} per annum.

Hence for the demonstrator plant, based on Scenario 1 in Table 7 and the estimations above, the net annualised GGR capacity is 720 tCO_{2eq} per annum. Over a plant lifetime of 20 years this equates to 14.4 $ktCO_{2eq}$ life-cycle impact.

The LCA for the commercial-scale, four-module plant has been estimated based on the information above. The calculations relate to the MRV Scenario 4 in Table 7. The construction impact, at a high-level, could be estimated to be four times the values calculated in Table 8. This is on the basis that the plant would contain four pyrolysis and heat recovery modules. The CO_2 system is 16x larger than the pilot plant, in terms of flue gas processing, but this would only be 4x the pipe diameters and the metal thicknesses are likely to remain the same. Based on these early assumptions,

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[4] Source 1: https://media.marshalls.co.uk/image/upload/v1611237240/Environmental-Characteristics-BTB3.pdf
Source 2: https://www.winnipeg.ca/finance/findata/matmgt/documents/2012/682-2012/682-2012_Appendix_H-WSTP_South_End_Plant_Process_Selection_Report/Appendix%207.pdf
Source 3: https://www.pvcforum.it/pvc_library/18-LCA%20-%20EPD/UPC%20-%20Cables%20final%20report.pdf

the annualised construction impact is estimated to be 124.8 tCO_{2eq}. It is reasonable to assume the downstream emissions for transportation of CO_2 are zero as the target customers are those that have a use for the CO_2 on their site. The biochar transportation emissions may increase as the larger quantities produced may not be able to be sold locally. Hence the associated emissions from biochar transportation could be based on an average transportation distance of 100km, and would increase by a factor of four due to the larger quantity of biochar produced. This results in an estimated impact of 89.6 tCO_{2eq} per annum.

Taking these estimations into account, the net annualised GGR capacity of a fully commercial, four-module system, is estimated to be 7790 tCO_{2eq} per annum. Over a plant lifetime of 20 years this equates to 156 $ktCO_{2eq}$ life-cycle impact.

5.6 Cost vs benefit and technology scaling

The Ph2 pilot is based on a single-module pyrolysis and heat recovery unit, with a downscaled CO_2 capture system. While a single-module system is of interest to some customers, most have been discussing either a twin module of a four module system, with a single CO_2 system sized to process the flue gas from that number of modules. Hence, the cost vs benefit information that is most relevant for future deployment relates to MRV Scenario 4 in Table 7.

As the technology scales, the cost reductions are achieved primarily through scaling of the CO_2 system (a single-system sized for the output of all four modules) and costs that do not increase linearly such as those related to the control system, emissions monitoring, installation and procurement of several components with a common design. The operating costs also reduce for a four-module system due to anticipated staffing levels.

Based on these estimates, a commercial, four-module system provides a strong commercial proposition given the payback period is competitive with conventional CHP technology. The levelised cost of CO_2 removal is also very positive due to the revenues generated by the co-products.

6 Business plan & Route to Market

This section outlines the business plan and route to market for the BIOCCUS technology after the completion of the demonstration project. Specifically, this will address the plans and opportunities to deploy the whole technology solution to customers, i.e. those who require or desire all outputs of the system. The individual sub-systems also have their own development paths which the partners are pursuing individually or in collaboration, as appropriate. For example:

- Woodtek has already deployed the pyrolysis system developed during this project to some customers
- Bluebox and Woodtek are pursuing pyrolysis plus heat recovery opportunities for various customers
- Ricardo is pursuing development opportunities for the CO_2 capture system, as a retro-fit opportunity for existing gas or biomass systems

The business plans for each of these will not be discussed in detail in this report, however as they are pursued, they reduce the uncertainties and dependencies in the exploitation of the whole BIOCCUS technology.

6.1 Target customers

The ideal customers are those that require heat and power on-site, as well as one or both of biochar and CO_2. This means the primary list of customers are:

- Concrete manufacturers – CO_2 can be used in the curing process, biochar in construction products (in the future)
- Commercial greenhouses – CO_2 can be used to aid growth, biochar can be mixed with compost
- Biomethane-to-grid sites (anaerobic digestors) – biochar can be used to improve yield and stability. CO_2 separation and collection may already be implemented from the biomethane plant
- Wastewater treatment sites – similar uses to anaerobic digestors

Secondary customers who may be interested in exporting CO_2 and/or biochar are:

- Local authorities (driven by net-zero targets)
- Timber and furniture production facilities
- District heating schemes

In the case of commercial greenhouses, biomethane-to-grid sites and wastewater treatment sites, the GGR performance of the system may rely solely on the biochar production. The greenhouses will use the CO_2 directly for yield boosting and the biomethane-to-grid and wastewater treatment sites will export the CO_2, where at present the likely use would be in the food and drinks industry.

The reasons for selecting food-grade CO_2 as a requirement for the system was to ensure there was an immediate market need for the technology. As CCUS deployment grows worldwide, applications for carbon dioxide utilisation will also grow. Some, mostly direct, CO_2 applications are existing well-established applications (e.g. greenhouses, slaughterhouses, fire extinguishers, enhanced oil and gas recovery, etc.) while others are emerging markets aimed at ensuring permanent storage of the CO_2 (e.g. green cement, concrete curing, aggregates, etc.). These are shown below in Figure 9.

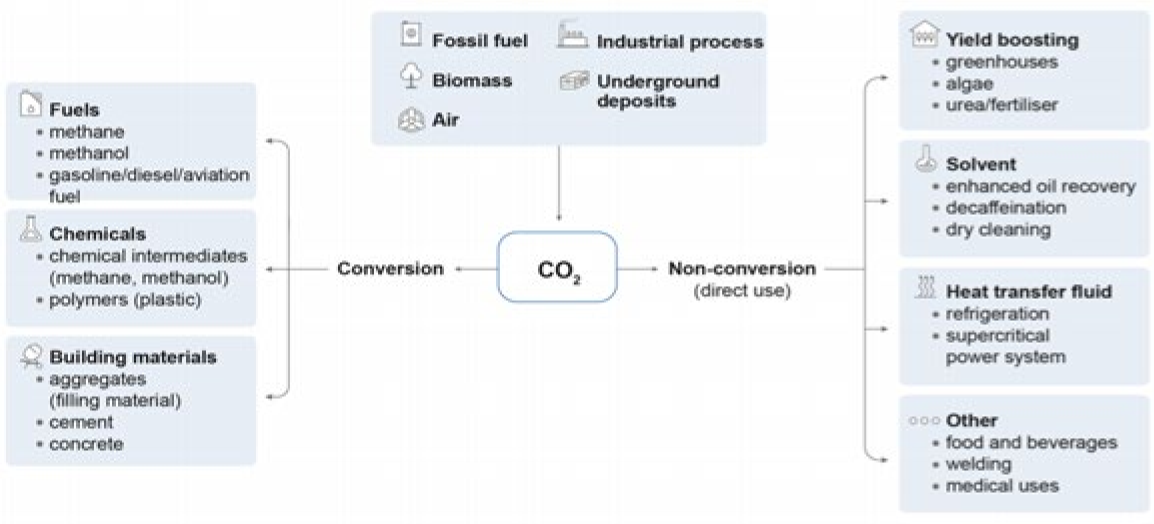

Figure 9 Existing and emerging carbon dioxide uses

By ensuring that the system is designed for direct CO_2 usage, the technology will be able to be rolled out rapidly, as it will not be reliant on the CO_2 market developing for use in building materials. As the building material CO_2 market increases, the system can easily be modified to produce CO_2 at the required (lower) purity, which will likely bring a further cost saving.

Finally, it should be noted that even in the scenarios where the CO_2 is used directly, there remains a net benefit in terms of greenhouse gas emissions. At present, the largest source of food-grade CO_2 is from ammonia production for fertiliser use. 45% of the UK's CO_2 is produced in this manner, and it is the sole source for Air Liquide products who have a 40% UK market share[5]. Ammonia production relies on natural gas. Due to inefficiencies and the associated N_2O and CH_4 emissions, the net impact of the production process is ~1.41 kg CO_2 released to the atmosphere, per kilogram of CO_2 used (Hoxha & Christensen, 2018), ignoring any emissions associated to its transport. On the same basis, use of CO_2 generated from a BIOCCUS system is effectively net zero due to its use of sustainably sourced biomass. Therefore, even though the greenhouse gas *removal* performance of the system is reduced if the CO_2 is used in these direct applications, there is still a strong contribution towards net-zero by reducing the generation of these emissions.

6.2 Impact from Ph2 project

The Phase 2 pilot project has provided tangible evidence of quality and quantity of the outputs of the system, which are critical elements for the business case. In addition, the project has delivered an impressive demonstrator plant, which is a valuable asset, and has been used already for many customer visits. An operational, physical plant, albeit still a demonstrator, is significantly more effective than a virtual design. Customers have been impressed by the quality of the engineering and it can alleviate any concerns regarding emissions, noise and operational requirements.

The other main impact from the project has been the validation of the business case with the target customers. Active discussions are being held with concrete manufacturers, commercial greenhouses and anaerobic digestor operators who have all confirmed their interest in the technology following visits to the demonstrator plant. The first deployment opportunities for the full system are now likely to be in a commercial greenhouse environment. Furthermore, there is significant interest from several local authorities, who were identified as second priority customers earlier in the project.

6.3 Potential carbon savings & job creation

The environmental impact has been calculated for high and low forecasts for the commercialisation of the technology, considering both the greenhouse gas removal (long-term storage) impact as well as the CO_2 reduction from the technology roll-out considering its displacement of heat, electricity and CO_2 generated from non-renewable sources. The sites and their uses of CO_2 are assumed to be the same as those identified from the market analysis, hence only a proportion of the future sales consider the CO_2 to be permanently stored (those located at concrete facilities).

Using the high and low forecasts, the GGR potential for the technology is estimated to be 310kt – 820kt CO_2/annum by 2030. The reduction in CO_2 emissions is estimated to be 340kt – 900kt CO_2/annum. Therefore, the total contribution of the technology towards net-zero is estimated to be 650kt – 1720kt CO_2/annum.

The job creation from this roll-out will primarily relate to employment of designers, systems engineers and manufacturing technicians in the partners, as well as those in the supply chain – particularly in the stainless-steel fabrication supply chain for the bespoke parts such as the CO_2 system columns and heat exchangers. Based on the value of these parts and future projects, it is expected that sales of a single system would support 10-20 jobs for approximately 6 months. Hence, by 2030, the job creation impact is estimated to be 50 – 250 full-time roles sustained.

6.4 Barriers and Risks

A summary of the barriers and risks identified relating to the commercialisation of the technology is presented below in Table 9, using a PESTLE approach to categorise the type of risk.

Table 9 - Summary of Barriers & Risks

Category	Risk	Probability	Impact	Criticality	Mitigation
Political	UK government policy prevents use of biomass in GGR technologies	VL	H	H	Recently published strategy supports use of biomass in such systems
Economic	Volatility in carbon credit pricing impacts investor confidence	L	H	H	Contribute to UK GGR Business Models Expert Group policy discussions
Economic	Uncertainty in Operating costs impact investment decisions	L	H	H	Use test programme to generate data on operational costs, as much as possible
Sociological	Lack of public acceptance, leading to objections in planning process	M	M	H	Consider local beneficiaries when discussing project feasibility with customers
Legal	Lack of freedom to exploit the technology due to existing Intellectual Property	L	H	H	Progress UK and International patent applications to provide freedom to operate
Legal	Lack of defined MRV methodology for operators to use	M	M	H	Engage with future industry-wide discussions and keep up-to-date with methodology developments (e.g. VERRA, Puro.Earth)

7 Conclusions

The project has successfully demonstrated the BIOCCUS technology, representing a first-of-a-kind integration of carbon capture through both pyrolysis and post-combustion CO_2 capture technologies.

The concept design from the Phase 1 project was realised into hardware, procured and manufactured. The project site was identified and a highly complex plant was successfully installed in a safe and efficient manner. The plant was then successfully commissioned and completed a testing phase that produced biochar from several different feedstocks and produced evidence that the system targets can be achieved following some design modifications.

The testing has demonstrated a GGR capacity of 144 $kgCO_{2eq}$/h (excluding transport/use of the CO_2 and transport/application of the biochar), with strong evidence to justify a GGR capacity of 762 tCO_{2eq}/annum in its current form. When commercially scaled, a single plant will have a GGR capacity of ~8000 tCO_{2eq}/annum.

The technology has been shown to have a very strong cost vs benefit assessment, with limited operational risks and adverse impacts on the surrounding environment – note that an environmental risk assessment was not required for the planning application. It also represents a strong commercial investment proposition for the target customer segments and has great potential to be exploited both in the UK and overseas.

Ricardo and the project partners are now in discussions with potential customers as a result of this successful demonstration.

A1 References

Transport Environment. (2021, October 11). Europe’s policymakers lag behind truckmakers on CO2 emissions.

A2 Installation Photos

Figure 12 - Feedstock Dryer

Figure 13 – Combustor (with High Temperature Heat Exchanger inside)

Figure 14 - Absorber Tower (left), Stripper Tower (right)

Figure 15 – Reboiler

Figure 16 - Mixing Tank

Figure 17 - Dehydration Column

Figure 18 - Air-to-steam generator

Figure 19 - Feedstock storage & top-loader

Figure 20 - Intermediate Rotary Feedstock Hopper

Figure 21 - Flue Gas Scrubber

Figure 22 - Medium Temperature Heat Exchanger (right) & Economiser (left)

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