Direct Air Capture and other Greenhouse Gas Removal technologies competition

REVERSE COAL

Phase 1 Final Report for BEIS

Department for Business, Energy & Industrial Strategy

Lapwing Energy

Glossary

Abatement	Stopping or reducing (current) emissions
Batter	A sloped side to an excavation, used to prevent edge collapse
BEIS	Department for Business, Energy and Industrial Strategy
Biochar	Biological charcoal - a solid form of highly concentrated carbon made by pyrolysis
Buffer Zone	Space between an area used for one purpose and an area used for another purpose.
Carbon	Solid, non-oxidised CO_2. 1 tonne of solid carbon x 44/12 = 3.667 tonnes of CO_2
Carbon Credit	Certificate or permit representing one tonne of carbon dioxide or the equivalent amount of a different greenhouse gas that has been verifiably sequestered
CCS	Carbon Capture and Storage
CEA	Controlled Environment Agriculture – principally glasshouses and vertical farms
CO_2/CO_2e	Carbon dioxide / Carbon dioxide equivalent
Coppice	An area of woodland in which the trees or shrubs are periodically cut back to ground level to stimulate growth and provide biomass
Coppicing	Cutting back to stimulate new growth
DACCS	Direct Air Carbon Capture and Storage
Decant Structure	An intake structure consisting of a vertical or inclined hollow tower (riser)allowing the free water to be pumped out of the tower or drain by gravity via a buried conduit
DEFRA	Department for Environment, Food and Rural Affairs
EA	Environment Agency
GGR	Greenhouse Gas Removal
Landraise	Our proposed process for restoring land to pre-drained levels.
Lapwing	The Lapwing Estate Ltd group, consisting of Lapwing Energy Ltd, Pollybell Farms Ltd and Lapwing Fine Foods Ltd.
MRV	Monitoring, Reporting and Verification
MWh	Megawatt-Hour
Overburden	Rock or soil overlying a mineral deposit, archaeological site, or other underground feature
PAHs	Polycyclic aromatic hydrocarbons
Paludiculture	The practice of farming on land with a high water table.
Peatland Code	A voluntary certification standard for UK peatland projects wishing to market the climate benefits of peatland restoration
Pyrolysis	The thermal decomposition of materials at elevated temperatures in an inert atmosphere
Reverse Coal	This combined carbon capture, processing and storage proposal.
Carbon Sequestration	The process of capturing and storing atmospheric carbon dioxide (CO_2)
SLR	A leading global engineering consultancy specialising in environmental solutions
SRCW	Short Rotation Coppice Willow
Syngas	Synthetic Gas: A mix of molecules containing hydrogen, methane, carbon monoxide, carbon dioxide, water vapours, plus other hydrocarbons and condensable compounds
Tonne (t)	Metric tonne (1,000kg)
Tailings Dams	An earth-fill embankment dam used to store by-products of mining operations
Topsoil	The top layer of soil that acts as a growing medium.
UoL / UoE	University of Lincoln / University of Exeter
UKCEH	UK Centre for Ecology & Hydrology
WWF	World Wildlife Fund

Executive Summary

The global agri-food sector is responsible for c.30% of greenhouse gas (GHG) emissions (13.7Gt CO_2e pa[1]) and 60% of lost nature around the world[2]. However, Lapwing believes there is a better way. To hit Net Zero, carbon emissions from every sector of the economy need to be abated and carbon sequestration implemented to remove both past and difficult to remove emissions whilst protecting our precious natural environment. Lapwing has developed "Reverse Coal", which both sequesters *and* abates significant quantities of carbon, *and* also produces food with measurable positive environmental and social impact:

- Carbon sequestered and secured in a concentrated permanent store
- Scaled abatement of emissions from lowland peat
- Biodiversity enhanced
- Water quality improvements
- Flood alleviation protecting communities
- Resilient production of healthy food, adapted to accommodate future climate change
- High skilled full-time jobs replacing zero hours seasonal contracts

Reverse Coal was born out of a necessity to develop a transition plan for Pollybell Farms (farming operator of The Lapwing Estate) to ensure food production could continue into the future without having an irreversible, negative impact on the environment but rather a positive one. Lapwing and Pollybell Farms have received recognition from the Rt Hon George Eustice MP, Secretary of State for Environment, Food and Rural Affairs, for our innovative land management techniques addressing climate change:

"For some [climate change] will mean maximising food production from the most productive soils, but in new ways such as Pollybell Farms, which covers 5,000 acres straddling Nottinghamshire, Lincolnshire and Yorkshire and has been developing a totally new way of addressing their low-lying peat land to ensure both resilience and environmental benefit. Many of the country's leading producers of fresh produce on our grade one fen soils are starting to think creatively about how they can manage their most valuable asset in a more sustainable way."

In addition, Lord Deben, Chair of the UK's Climate Change Committee has stated:

"Land use is going to change very urgently if we are going to meet our climate change demands. This is the time for radical change, close to revolution"

Reverse Coal delivers that "revolution"

[1] Willett, W., Rockström, J., Loken, B., Springmann, M., Lang, T., Vermeulen, S., ... & Murray, C. J. (2019). Food in the Anthropocene: the EAT–Lancet Commission on healthy diets from sustainable food systems. The Lancet, 393(10170), 447-492.

[2] WWF. 2018. Living Planet Report - 2018: Aiming Higher. Grooten, M. and Almond, R.E.A.(Eds). WWF, Gland, Switzerland

At the heart of this revolution is Biochar, an engineered GHG removal solution. The focus of this Phase 1 feasibility project has been to optimise our integrated approach. The premise of Reverse Coal is to utilise photosynthesis to remove CO_2 from the atmosphere via production of short rotation coppice willow (SRCW) on rewetted peatland. This simultaneously abates landscape soil emissions from agriculturally drained lowland peat – which accounts for 3% of total UK GHG emission[3], and sequesters carbon from the atmosphere through the SRCW.

SRCW is harvested as a crop and fed into high temperature pyrolysis, producing biochar, a solid form of approx. 86% carbon. Long term stable carbon sequestration is achieved by burying biochar. This is one of the most **concentrated** and most easily **verifiable** of all carbon mass-storage solutions offering up to 45,408t CO_2e stored per hectare.

Energy from pyrolysis is utilised in Controlled Environment Agriculture (CEA) to enhance food production. This solves the inherent dilemma of bioenergy crops: the loss of land from food production.

Lapwing Energy’s proposal for Phase 2 is to pilot a pyrolysis system at Pollybell Farms on The Lapwing Estate. The pyrolysis system will produce biochar from willow which will then be stored in a unique storage facility demonstrating that CO_2 can be permanently captured.

By demonstrating this process and its continuous operation we will have completed the necessary due diligence required by investors before scaling to the larger commercial scale.

Our Phase 1 feasibility study involved Lapwing Energy working with subcontractors, The UK Centre for Ecology & Hydrology (UKCEH), University of Lincoln (UoL), University of Exeter (UoE) and SLR Consulting to produce a systems approach for a biochar solution. This report summarises the work completed in Phase 1 and our proposal for Phase 2.

[3] The UK National Atmospheric Emissions Inventory. Lowland Peat UKCEH

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1.0 Reverse Coal Overview

1.1 Process

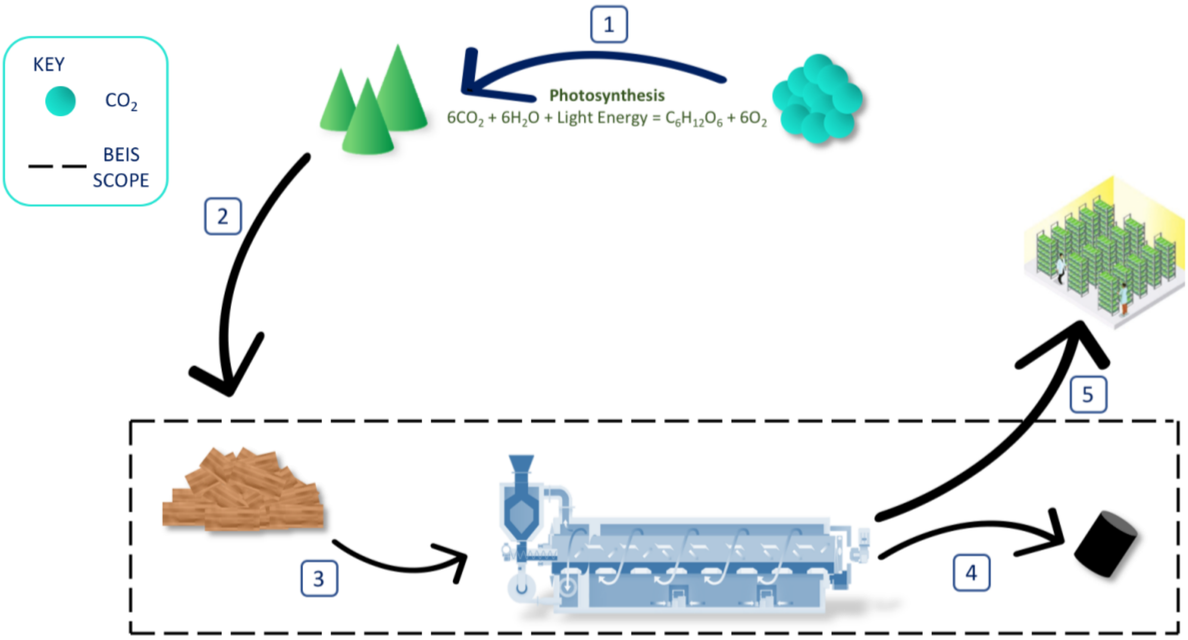

Figure 1.1 How REVERSE COAL removes carbon from the atmosphere + scope for BEIS Phase 2

1. Current agriculture practices on lowland peat are emitting vast sums of GHG emissions. By rewetting lowland peat, these emissions can be abated. Short Rotation Coppice Willow (SRCW) is a bioenergy crop that can be grown quickly on rewet peat. SRCW captures carbon dioxide from the atmosphere through photosynthesis.

2. When the SRCW is ready to be harvested, it is chipped and stored to dry, reducing its moisture content so it does not decay.

3. Once dried the SRCW is fed into the pyrolysis process which is a very high temperature kiln absent of oxygen. The SRCW thermally decomposes into a gaseous product, liquid and biochar. This biochar has a high carbon content.

4. The biochar produced is buried in a permanent storage repository that stabilises the biochar and prevent CO_2 emissions. This solution offers easy MRV (monitoring, reporting and verification) and prevents any collateral environmental impact.

5. The final part of Reverse Coal is to use the energy by-product in a CEA system, producing higher value foods, replacing the change in land use and subsequent displacement of food production.

1.2 Commercial

Lapwing Energy has focused on developing a commercially viable Greenhouse Gas Removal (GGR) and abatement project at the **megatonne** per annum scale which offers not only CO_2 removal but an investable business model that can be fully operational by 2030. We believe that being investable is essential to reaching the megatonne abatement scale. For this reason, our Phase 1 feasibility study has focused significantly on the commercial model to ensure that Phase 2 can be scaled and implemented successfully.

Within one project, Reverse Coal offers remarkable social value, making headway in addressing the following:

- Net Zero agenda
- UK Government's Peatland Strategy
- National Food Strategy
- Objectives of the Strategic Defence Review
- 'Levelling up' job creation strategy
- National Flood Resilience Review 2016

1.3 Commercial GGR Potential

The commercial-scale concept we have developed to be operational by 2030 offers:

- Carbon sequestration c. 100kt CO_2e p/a = 5Mt CO_2 removal over project life
- Carbon abatement c. 900kt CO_2 p/a
    - Contribution to UK's net zero target **1Mt** CO_2 p/a
- **£2bn Contribution** to HM Treasury in tax receipts from the project over the 50-year life.
- Over 1,100 jobs created with an average salary of £45,000pa (43% above UK national average)
- Two viable storage options which are orders of magnitude larger than natural solutions, both of which retain productive farmland:
    - The 'land raise model' to rebuild eroded fenland to original ground level. This offers biochar storage 3.2m deep in cells measuring 69x69m. This can store 22,704t CO_2e per hectare.
    - The 'quarry model' to backfill new quarry voids to original ground level which adapts the storage approach. With biochar storage at 6.4m deep, this solution can store 45,408t CO_2e per hectare.

Reverse Coal is highly scalable with the total area of degraded UK lowland peat able to support over 10 of the commercial-scale projects. Both the growing of willow and biochar storage can be easily adapted to match production in different locations. In principle the approach can utilise biomass produced from any land area, and store biochar in any quarry, deep mine or area of lowered ground surface (e.g. opencast mining) where optimised storage conditions can be implemented. Subject to further investigation, we anticipate that on-land biochar storage potential via the Reverse Coal concept could deliver a large proportion of the UK's CCS needs at low cost, and without taking that land area permanently out of productive use.

1.4 Phase 2

Our proposal for Phase 2 is to pilot a small-scale pyrolysis system at Pollybell Farms. The pyrolysis system will be fed chipped SRCW with the intention of producing biochar that has a high carbon content. The Biochar produced will then be transported to a secure permanent repository which will demonstrate how the carbon retained in the biochar can be kept for an indefinite period of time without releasing any CO_2.

To do this, we intend to operate over a 12-month period showing the continuous production of biochar and the process of filling the biochar storage facility. Over 12 months we will be able to show the resilience of both the system and storage facility across all seasons. We have calculated that we will pyrolyse c.1,300 tonnes of SRCW producing 138 tonnes of biochar, which will be stored in bulk deposits.

Phase 2 has been designed to test and enhance the assumptions made during this Phase 1 feasibility study.

Once operational, the pyrolysis demonstrator will be generating energy as a by-product (0.2 MW (Net) of electricity and 0.4 MW of recoverable heat per hour). For the purpose of Phase 2 the energy will be utilised by Pollybell Farms with the intention of powering existing cold stores and pack house, all of which are covered under agricultural permits. As the feedstock is not a waste but fresh SRCW, no waste permit for incineration is required.

The Phase 2 demonstrator is the smallest unit using the same pyrolysis technology as the larger-scale operation.

2.0 Science and Engineering Underpinning the GGR Solution

Section 2 outlines the science and engineering that underpins the full Reverse Coal concept. As mentioned previously Phase 2 is designed to be as similar to the full-scale commercial however there are aspects that cannot be replicated for the demonstrator. These have been identified and the reasons for their exclusion and replacement are included throughout this section.

2.1 Carbon Capture

Capture uses the natural process of photosynthesis in the fast-growing ‘woody’ crop. Considering optimal growing conditions will promote maximum growth and yields, this has led us to select short rotation coppice willow (SRCW) on the rewetted lowland peat. This allows us to abate current land emissions and continue productive use of that land.

Equation 2.1 Photosynthesis

$$\underset{\text{Carbon dioxide}}{6CO_2} + \underset{\text{Water}}{6H_2O} \xrightarrow[\text{Chlorophyll}]{\text{Light}} \underset{\text{Sugar}}{C_6H_{12}O_6} + \underset{\text{Oxygen}}{6O_2}$$

2.1.1 The Science

A literature review of potential bioenergy crops was undertaken as part of the Phase 1 feasibility report to assess their energy generation potential, likely yields and production requirements. This review concluded that SRCW was the most suitable bioenergy crop for this project for the following reasons:

- SRCW is one of the most used perennial bioenergy crops in Europe and the UK and can be coppiced every 3-4 years.
- Willow roots can tolerate periods of waterlogging and can regrow naturally in re-wetted fen peatlands following coppicing.
- It is grown commercially on wet peatlands for a range of traditional uses such as basket making. This means that the techniques, infrastructure and machinery needed are already proven and available.
- SRCW can also tolerate nutrient-rich and heavy metal contaminated conditions for phytoremediation[4]. One hectare typically generates yields of 10t per annum of willow woodchips (30t cut every 3 years).
- Our experimental analysis also showed SRCW to have a high energy generation potential[5] which helps drive down the price of sequestering carbon as we are able to generate a greater source of energy per tonne of feedstock, as well as biochar.

2.1.2 The Engineering

Techniques for growing and processing SRCW are well known and seen as relatively low risk. Extensive guidance on willow production has been published by Teagasc[6].

[4] Phytoremediation – The use of plants to extract and remove elemental pollutants in soil

[5] Gross calorific value of 16.9MJ kg^{-1}

[6] The Irish Government’s Agriculture and Food Development Authority – Short Rotation Coppice Willow, Best Practice Guidelines

As SRCW takes approximately 3 years to grow and be dried (after initial coppicing), for the Phase 2 pilot we will be purchasing 12 months supply of willow chip from a local supplier. This will speed up the Phase 2 start date and ensure a continuous supply. Benefits of outsourcing willow chip include testing existing supply chain capacity and resilience, in the event of any variances to predicted on-site yield beyond Phase 2.

The following processes apply to SRCW production relevant to Reverse Coal:

- Ground Preparation – Clearance of existing foliage/previous crop residue.
- Planting of willow – willow rods are inserted into the ground with a step planter.
- Growth – Monitoring & minimal weeding where necessary
- Cycle times – 3-year harvest. Ideal harvest time is after leaf fall and before sap rising & bird nesting: i.e. Dec to Feb.
- Harvest – A conventional forage harvester with stronger cutting blades.
- Transport – Via conventional farm tractors & trailers.
- Storage – Storage with mixing and drying capability, using existing grain barns.
- Loading – Transfer to the plant will be by conventional farm loader.

Figure 2.1.2 Forage harvester with hydraulic driven willow cutting head (photo by Lawrence Abrahamson)

2.1.3 Energy and fuel requirements

As SRCW is being purchased for Phase 2 and grown for the commercial model, it is never a waste product and therefore a life cycle assessment for its production has been included.

Our supplier was unable to provide a carbon/energy balance for their feedstock, therefore a best estimate was produced using existing literature. For Phase 2, we estimate that the delivery of 1,305.6t of SRCW has a carbon footprint of 11t CO_2.

2.1.4 Social Value

As SRCW is purchased for Phase 2, the wider social benefits of the change in land use to SRCW are only applicable to the commercial scale operation:

- **Abatement**. Significant CO_2 emissions are associated with drained peat farmland: 26t per ha pa (agricultural peatlands produce 3% of total UK GHG emissions). Through rewetting lowland peat for SRCW, it is anticipated these emissions will be abated.
- **Biodiversity**. Wetland SRCW planted in an agricultural dominated area form an additional habitat and can increase regional structural diversity. (Natural England have confirmed this is treated as a biodiversity net gain).

- **Water Resources**. Peatlands play an important role in landscape hydrology. Lowland peat can act as a reservoir storing and subsequently releasing flood water and maintaining stable water levels in adjacent areas. At present, areas of peatland are pump-drained in winter and subject to intensifying water scarcity in summer; our approach would help to mitigate both challenges, thereby reducing pumping costs, energy use and economic losses during droughts.
- **Flood Alleviation**. As SRCW is a wetland crop, the land can be used as a natural floodplain for retaining flood water during a storm event, in a way that would destroy most conventional crops. This has the potential to significantly reduce flood risk to adjacent urban areas, many of which have been flooded within the last 5 years. The Internal Drainage Board (IDB) and EA operate a highly managed system of pumps and dykes facilitating this novel form of natural flood management, and will be able to make use of the additional floodplain capacity as it becomes available.

2.1.5 Risks and Mitigations

As mentioned previously the techniques for growing SRCW are well established and relatively low risk. However, while outsourcing SRCW for Phase 2 removes any potential risk of growing willow ourselves, we have less control of our supply chain. Having an insufficient steady supply of woodchip has the potential to delay operations and impact the overarching goal of operating for 12 months. We have chosen a longstanding supplier with ample capacity to supply us and to mitigate the risk further, backup suppliers have been identified who can supply willow if our supplier fails to deliver.

2.2 Carbon Processing

Pyrolysis technology offers a solution for the thermal decomposition of biomass. Biomass is heated in the absence of oxygen, so it does not combust or release CO_2. The chemical compounds (i.e. cellulose, hemicellulose and lignin) instead thermally decompose into combustible gases, bio-oil and biochar.

- Biochar is a solid material that sequesters a large amount of carbon. Our experimental studies have found that biochar derived from SRCW has a high carbon-content of 86%. By burying and securely storing biochar it is considered a carbon capture solution that removes atmospheric CO_2 and locks it away in geological reservoirs.
- Bio-oil and syngas offer biofuels which can be used for power generation.

To optimise the biochar production against power generation involves controlling the pyrolysis conditions (temperature, residency time, reaction gas) which are known to alter the ratios and quantities of production of biochar, bio-oil and syngas.

For Phase 2, the pyrolysis demonstrator will be configured to the parameters we have identified to optimise the quantity of carbon in the biochar, power generation capability, and biochar stability. This is to ensure that this can be upscaled to a larger system, where cost-effective power generation as a by-product is critical to the commercial viability of this sequestration scheme.

2.2.1 The Science

Static batch biochar trials were conducted by UoL using willow coppice. Each experimental run used between 3-4 kgs of willow which was charred in static mode. Our original hypothesis was that to maximise CO_2 sequestration it was necessary to maximise biochar production, so research focussed initially on both low and high temperature pyrolysis.

However, we learned that low temperature pyrolysis produces a high quantity of bio-oil which whilst practical for storage, is very poor quality and would require substantial refining for energy use which is therefore not as commercially viable for the up-scaled plans.

In addition to this, the low temperature pyrolysis providers we spoke with were unable to give sufficient evidence of results from woodchip type feedstocks as the majority of suppliers were focused on using waste products such as tyres.

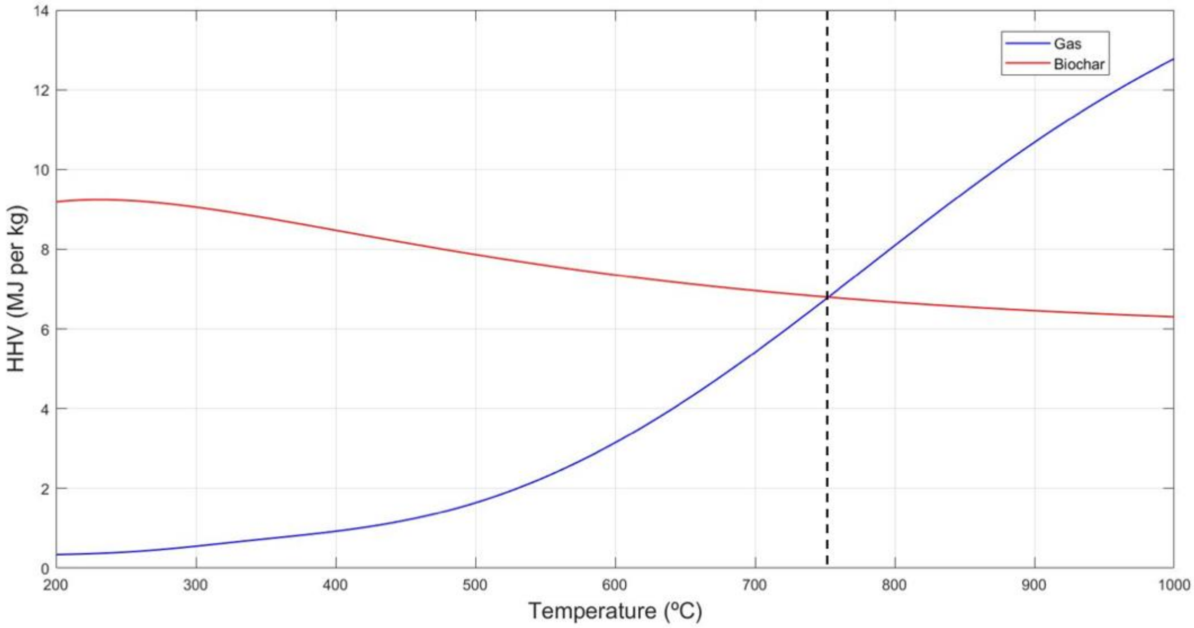

Figure 2.2.1 Pyrolysis model - Energy outcome (Gas & Biochar) vs temperature (Experimental research by UoL)

Experimental studies undertaken by UoL showed the optimum temperature for biochar and syngas production to be in the region of 760°C +/- 10%. The solution proposed optimises biochar volume per tonne and high energy production to reduce cost.

2.2.2 The Engineering

A review of pyrolysis providers was undertaken, which led us to identify a pyrolysis technology provider who offer high temperature pyrolysis technology. Their technology operates in the region of 750ºC which ties in with our experimental results. This company have experience of installing 200 kilns[7] in over 50 countries and were highly responsive to

[7] The chambers within which the pyrolysis process occurs

our requests for information. We believe their technology can produce our desired biochar and energy outputs and is the reason why we have chosen them for Phase 2.

2.2.3 Phase 2

For Phase 2 we will be installing a smaller pyrolysis unit which will be a ‘demonstrator’ of the larger system we plan to use for the commercial model.

Operating the pyrolysis system requires a trained team including operators and data collectors, supported by existing Pollybell and Lapwing staff. The plant will have a standard operating regime of 24 hours per operating day. For Phase 2 the plant will be operational 4 consecutive days a week, 40 weeks a year, aiming to operate for a total of 3,840 hours a year. This shift pattern has been designed to provide adequate breaks for day/night working.

We have identified a subcontractor who will design and install the necessary connections and the electric networks for the pyrolysis system and energy metering systems.

2.2.4 Energy and fuel requirements

The pyrolysis systems require an initial start-up fuel to heat the kilns. The fuel for the start-up will be liquefied petroleum gas (LPG). Once up and running the use of syngas for process heat removes the need for any further consumption of fossil-fuel based energy.

During phase 2, at the beginning of each week the kiln will require 235L of LPG for a cold start up as the kiln will not have been in operation for three days. Once up and running no more LPG will be needed as it will be in continuous operation for four days. LPG will be used from existing storage facilities on the farm.

2.2.5 Social Value

During Phase 2 the pyrolysis plant is projected to remove 436t of CO_2e per annum from the atmosphere. The energy generated from pyrolysis will also be utilised by Pollybell Farms for use in their existing packhouse and facilities reducing their demand for electricity from fossil fuels in the national grid.

Phase 2 will create two additional FTE (fulltime equivalent) roles at Lapwing in addition to supporting the decarbonisation of the business going forward and protecting existing jobs. Further to this, Phase 2 provides critical additional research performed by leading UK academics in this pioneering space.

Many of the social values associated with the pyrolysis plant are only fully appreciated from the commercial scale plant where the energy generated can be sold and used within CEA:

- **Energy -** The pyrolysis process not only generates enough syngas and heat to operate the plant itself, there is sufficient excess to export electricity and heat to secondary uses. In Lapwing’s case, this can be used to power CEA facilities that replace the food production capacity that would otherwise be lost through land use change from food production to biomass.

- **Energy Resilience -** The commercial-scale model will be incorporating 12 kiln units with 11 operational concurrently. This provides resilience, and capacity for planned staggered downtimes for maintenance.
- **Food Resilience** – CEA is insulated from the weather, and consequently wastage compared to traditional outdoor farming is reduced and seasonality negated.
- **Abatement – Food Production**. The increased range of products in CEA reduces the need for imported produce – such as salad products that are often brought to the UK by long-haul flight.
- **Employment & Skills** - New full time skilled jobs will replace zero-hours seasonal contracts.

2.2.6 Risks and Mitigations

The greatest risk is that the system fails to perform or achieve the outputs that we have predicted. The technology risk and potential downtime of the pyrolysis unit is mitigated through the use of a supplier that has 30 years in the industry. With a service centre located in the UK, we have local access to technicians and spare parts. We also intend to negotiate a service agreement to agree minimum performance levels throughout Phase 2. The Phase 2 demonstrator will provide the necessary due diligence before scaling to the commercial-scale pyrolysis systems.

2.3 Carbon Storage

2.3.1 Overview

Production of biochar is not the end of the process. Only once the biochar has been stored in a verifiable, stable and contained state for an indefinite period has 'Storage' been achieved. Our innovative solution combines proven experience from construction, mining and wastewater treatment and applies it to carbon storage.

The land of the Lapwing Estate is part of the Humberhead levels. Since they were drained 400 years ago, significant erosion has led to land loss of typically 4m from original ground level.

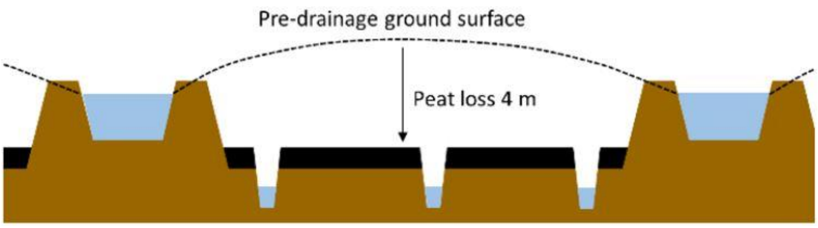

Figure 2.3.1 Proposal to rebuild land back to original level

Our proposal for the commercial-scale model is to rebuild that ground by reversing the field lowering that has resulted here from peat drainage, using a reversal of techniques from activities such as strip mining, seen across the Midlands in the 19th and 20th centuries. By removing the remaining peat and some subsoil, a layer of biochar can be placed and then covered with the subsoil and then the reinstated topsoil. This offers the capacity for substantial levels of solid carbon storage, and a corresponding CO_2 equivalent of 1 $MtCO_2e$ in only 45 hectares. This concentration exceeds all other on-land storage capacity that we are aware of and is far higher than the total carbon stock of any UK natural ecosystem (including the original deep peat).

2.3.2 The Science

Biochar and its burial as a carbon capture solution is a relatively novel concept however, the production of biochar has been around for thousands of years. There is a strong body of scientific evidence that supports its persistence and stability for terrestrial GHG removal. These studies[8] highlight that decomposition rates can vary significantly due to the experimental duration, feedstock, pyrolysis temperature and soil organic matter content. Feedstocks with higher carbon content were found to produce more stable biochar (i.e. wood derived biochar is more stable than crop or grass derived biochar). A literature review[9] of 74 biochar studies, found the mean residence time for biochar (monitored in laboratories) to be within a range of 8 to almost 4,000 years. Given this level of uncertainty we need to demonstrate that the biochar derived from SRCW combined with our proposed storage solution produces a very stable form of carbon in UK field conditions. This is fundamental to proving its long-term carbon sequestration potential.

Biochar & charcoal are the same carbon-rich solid produced from the pyrolysis of organic material. They have different names due to their different end applications. Charcoal is associated with heating or cooking whereas biochar is intended for use in agriculture.

Part of our Phase 1 feasibility study included undertaking experimental studies with SRCW derived biochar, assessing these uncertainties: the stability of biochar in peat (as a long-term carbon store), the potential risks of contaminant leaching into the environment (e.g. polycyclic aromatic hydrocarbons: PAH's) and the interaction of biochar with soil nutrients (e.g. nitrate and phosphate) and GHGs such as methane (CH_4), nitrous oxide (N_2O) and carbon dioxide (CO_2). Experimental studies by UKCEH investigated the stability of biochar under differing conditions and whether the pyrolysis temperature impacts the GHG emissions from peat and mineral soil-biochar mixtures. These studies show that the storage conditions for biochar are key to ensuring carbon sequestration, avoiding the risk of oxidation and subsequent CO2 re-emission. Appropriate design of a secure (and auditable) biochar storage facility has therefore been critical.

In summary:

- Biochar is more stable than un-pyrolysed SRCW feedstock
- Higher temperature production biochar (650^{o}C) is more stable than low temperature (300^{o}C) production biochar when stored in dry mineral and peat soils
- Experimental studies showed no risk of introducing toxic PAH compounds to the environment in peat or mineral soils amended with the SRC Willow biochar

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[8] Wang, J., Xiong, Z. and Kuzyakov, Y., 2016. Biochar stability in soil: meta-analysis of decomposition and priming effects. Gcb Bioenergy, 8(3), pp.512-523

[9] Gurwick, N.P., Moore, L.A., Kelly, C. and Elias, P., 2013. A systematic review of biochar research, with a focus on its stability in situ and its promise as a climate mitigation strategy. PloS one, 8(9), p.e75932

Our academic research has provided us with greater confidence in the long-term carbon sequestration potential of biochar derived from SRCW and its environmental impact when stored under Reverse Coal conditions.

2.3.3 The Engineering

The proposed long-term repository for both Phase 2 and the commercial-scale model manage the material characteristics by separating the biochar from interaction with atmospheric oxygen. Principally the biochar is mixed with water at the pyrolysis plant and transferred via a pump to the storage facility where it is fed into the ground, water removed and securely stored.

For the commercial scale, landraise repositories will comprise of an embankment on each side of the biochar, a flow control mechanism, and restoration soils. Quarry-based alternatives have also been designed. Once planted, the repository would need an annual inspection for signs of movement and dip checks between the bottom of the store and top of biochar water level to maintain a record of the saturation.

Reverse Coal proposes a novel, subsoil storage approach to biochar that can store 1 Mt CO_2e in 45ha (landraise, and the quarry solution 22ha) under highly stable conditions.

Compared to field application, our contained solution is more stable, more secure, involves lower transportation costs and emissions, and is far easier and cheaper to monitor and verify. Further long-term validation could be considered at any point in the future by employing a small diameter borehole rig to core-sample the repository.

2.3.4 Social Value

The carbon storage solution at scale brings significant wider benefits which will be developed through Phase 2:

- **Valuable Knowledge Base –** By placing biochar in storage solutions in Phase 2, we will be able to begin the process of collecting field scale biochar stability data which will be a valuable source of information for the future of carbon capture and storage solutions.
- **Water Quality –** sequestered biochar can act as a carbon water filter improving water quality and cleaning out nitrates or phosphates from the watercourse. The application of biochar to improve groundwater quality has attracted attention due to its potential to reduce toxic pollutants and contaminants in water. It has also been suggested as suitable for drinking water treatment processes and can avoid the production of carcinogenic by-products from chlorination. Application of wood-based biochar prepared from the fast pyrolysis process was successful in removing pollutants like arsenic, cadmium, fluoride, lead and chromium during the water purification process[10]. It has been widely demonstrated[11]

[10] Mohan, D., Sarswat, A., Ok, Y.S. and Pittman Jr, C.U., 2014. Organic and inorganic contaminants removal from water with biochar, a renewable, low cost and sustainable adsorbent–a critical review. Bioresource technology, 160, pp.191-202.

[11] Rajapaksha, A.U., Chen, S.S., Tsang, D.C., Zhang, M., Vithanage, M., Mandal, S., Gao, B., Bolan, N.S. and Ok, Y.S., 2016. Engineered/designer biochar for contaminant removal/immobilization from soil and water: potential and implication of biochar modification. Chemosphere, 148, pp.276-291.

that increasing pyrolysis temperature enhances the surface area and microporosity of biochar which increases the sorption capacity to remove contaminants.

- **Water Balancing –** rivers through this part of the Humberhead levels experience significant variances in flow – at times struggling to cope with high volumes, and at others struggling to meet abstraction licence quotas. Through careful management of levels using the decant structure, the biochar storage areas can become adjustable subterranean reservoirs. This can then become part of the system of flood risk mitigation for local towns and villages. In reverse, reservoir capacity can be used to reduce the abstraction requirements of the farm.
- **Farmland Retention** – both the land raise and quarry options involve removing topsoil and overburden, burying the biochar, and then replacing the overburden and topsoil. Apart from the environmental buffer zones above the dam structures themselves, the raised land can be returned to the current range of agricultural uses – including biomass production if desired.
- **Environmental Buffer Zones** – the land immediately above the dam structures can be covered with suitable short rootstock planting to both stabilise and contain the surface and also provide additional habitats for wildlife.

2.3.5 Risks and Mitigations

Currently the storage of non-waste biochar for the sole purpose of carbon sequestration is not covered by any particular regulation.

Legislation (LRWP 61[12]) in the UK only refers to the application of biochar to soil to benefit land, in which biochar is classed as a waste product. However, in the context of this project, our primary aim is to produce biochar and use it as a carbon sequestration solution. To clarify, waste is defined as "…any substance or object which the holder discards or intends or is required to discard..."[13]. Biochar would also be considered a waste product when either a) the identity of the material from which the biochar is produced is a waste or b) biochar is produced as a waste product in the pyrolysis process with the primary aim being that of generating bioenergy.

Within Reverse Coal, biochar is the product made from a virgin biomass resource (SRCW). The production of biochar is the primary aim of this pyrolysis process, and therefore just as in the production of charcoal for cooking purposes, biochar is not a waste product. Similarly, the storage of biochar is not a discarding of biochar, but the intended placement of the product for long term carbon sequestration.

As there are no existing standards to follow, we will need to seek permission from the Environment Agency to agree new standards for us to work to. To achieve this, we will work with the Environment Agency's National Bespoke Permitting Team, whose role is to deal with scenarios such as this. In the unlikely event that we are unable to obtain a permit, we will follow the waste biochar directive and divert to agricultural uses at the permitted spreading rates.

[12] Environment Agency. Storing and spreading biochar to benefit land: LRWP 61. 2019.
[13] Directive 2008/98/EC of the European Parliament and of the Council of 19 November 2008 on waste and repealing certain Directives

Legislation (LRWP 61) governing the application of waste biochar in the UK limits the storage of biochar to 10t and the application of biochar to soil at a maximum of 1t per hectare over any 12-month period. From an MRV perspective this application method is problematic as costs of verification will be high (using analytical methods to find trace inputs) as well considering that verification will need to be done at multiple locations if biochar is to be applied at scale. While this may confer some agricultural benefits, the application of biochar at this rate requires vast land areas, could involve high lifecycle CO_2 emissions, risks losses through wind and water erosion, and leads to small, hard-to-verify changes in soil carbon content. Similarly, the spreading of biochar increases the risk of pneumoconiosis (lung disease) from being exposed to airborne biochar particles.

The handling and storage of biochar presents a range of potential challenges discussed in the bullet points below, all of which are mitigated through containment and the application of water. We intend to pump biochar as this is the most efficient mode of transport due to its very low density and the cost/carbon cost associated with vehicular transport of biochar. Plus, this addresses the risks and issues listed in the bullet points below.

The Lapwing Estate sits within a highly managed artificial landform, drained 400 years ago to allow farming. The extensive network of ditches, pumps and control weirs operated by the internal drainage board allows the project to raise and lower groundwater levels as required. The location of the repository for Phase 2 has been selected for its proximity to the pyrolysis plant to minimise transport and enable regular inspection.

We have mitigated the following risks to acceptable levels in the solution proposed:

- **CO_2 loss** – Research by UKCEH showed that biochar slowly oxidises when exposed to air and may release some of the CO_2 that it is intended to sequester. This has been mitigated with a storage solution that retains the biochar under water, effectively halting decomposition.
- **Particle escape: airborne** – particle distribution size is dependent upon the process, but typically 20mm to dust. Small particles can be windblown, and therefore the biochar will be contained at every stage from production to storage. The contained storage solution is preferable to spreading on the surface of agricultural land as that poses greater challenges with monitoring and verifying its permanence.
- **Particle escape: waterborne** – biochar dust can escape in suspension, and therefore stored biochar will be placed in permanent containment devices. The contained storage solution is preferable to the application of biochar spread across land e.g. unbounded sub-surface treatments to agricultural land prone to wind and water run-off.
- **Flammability** – biochar is highly flammable (charcoal is a traditional fuel source), and there is a spontaneous combustion risk when handling, transporting and storing dry biochar[14]. The biochar produced will be sprayed with water within the pyrolysis plant as part of the cooling and stabilisation process – achieving a moisture content of 10%. This also increases its mass, which greatly increases the energy needed to raise its temperature to the point of ignition. The risks (and CO_2 emissions) of vehicular transport will be avoided by pumping biochar in solution to the burial site. Once in the

[14] Restuccia, F., Mašek, O., Hadden, R.M., Rein, G., 2019. Quantifying self-heating ignition of biochar as a function of feedstock and the pyrolysis reactor temperature. Fuel. 236. 201-213.

ground the biochar will be drained. The ‘biochar sludge’ residue will further drain over time, but the residual ‘biochar cheese’ retains a sufficiently high moisture content to mitigate the risk of combustion.

2.4 Net Carbon Capture

To summarise our Phase 1 findings, we have designed a GHG removal solution that:

- during Phase 2 can sequester 425t (net) of CO_2e in permanent storage repositories (gross value minus carbon cost of SRCW production).

- following the successful operation of Phase 2, at commercial scale we can sequester 100kt of CO_2e annually and abate a further 900kt of CO_2e pa through rewetting lowland peat and the establishment of SRCW whilst maintaining food production.

3.0 Phase 2 – Detailed Engineering Design

3.1 Detailed design overview

To clarify, the scope for Phase 2 is highlighted in section 1.1 and Figure 1.1.
Willow chip will be supplied on a weekly rolling basis to Lapwing Estate throughout Phase 2, where it will be unloaded onto an existing outdoor concrete pad, adjacent to the pyrolysis site. Willow chip will then be manually fed into the feed bunker by a tractor and front loader.

Pollybell Farms has a readily available tractor shed (25x40m) that will house the pyrolysis demonstrator. This will involve upgrading the site and discussions with planning authorities have indicated that the installation of a pyrolysis unit inside an existing agricultural building will not require change of use so long as the outputs i.e. the energy are used for an agricultural purpose and are part of the agricultural operation. Outside the existing building is suited to the location of the reception hopper and biochar storage.

3.1.1 Pyrolysis Design

Feed material is received *en mass* to the feed bunker where it is transferred to the plant by a screw conveyor. The feed bunker acts as the main interface point to the plant and will provide a constant supply of feedstock to the plant loading elevator. Feed material is progressively drawn through the bunker's walking floor screw conveyor before being transferred vertically upwards. Material is then discharged to the pyrolysis unit.

Feed materials enter the pre-dryer where the feed material will be in direct contact with the combustion flue gas of the pyrolysis kiln to remove some of the moisture content in the feed prior to the feed entering the pyrolysis heat tube. Feed material then enters through the rotary isolating valve and into the sealed feed bin. Material is drawn into the pyrolysis kiln heat tube by the feed screw, which is the master controller for the plant production rate.

The heat tube is heated from the outside by the kiln burner system. Combusted gas transfers heat into the feed material indirectly through the heat tube by radiation and convection. The exhausted flue gases are directed to the plant stack in the combustor and plant exhaust for discharge to atmosphere. The exhaust pressure is maintained through this system by the exhaust induced draft fan. The waste heat from the flue gas is utilised to evaporate the water in the wastewater process.

Internally to the heat tube, material is chemically transformed by pyrolysis as follows.

- Drying of any residual moisture content, releasing steam (H_2O);
- Volatilisation and pyrolysis of organic compounds;
- Steam reforming, methanation and water-gas shift reactions.

The products of this transformation are syngas – a dust-laden gas mixture containing predominantly steam, hydrogen (H_2), carbon monoxide (CO), carbon dioxide (CO_2) and methane (CH_4), as well as smaller quantities of higher hydrocarbons and paraffin, olefin and aromatic compounds – and a solid char.

Solid material is held up for the required residence time, typically 20 to 30 minutes, inside the heat tube by a scroll/weir at the discharge end. The residence time can be varied to suit the requirements of the feed material by variable speed drive on the heat tube motor. Material is then discharged through holes in the tube into the Staged Air Cyclonic Thermal Oxidiser (SACTO). Gas exits through the top of the chamber and proceeds to gas clean-up area to be cleaned, cooled and dehumidified prior to use in the engine and kiln burners.

Char material exits the discharge chamber of the kiln at approximately 600°C and requires cooling prior to final discharge from the process. This cooling is achieved in the three-stage cooling screw.

Heat is removed indirectly through thermal conduction from the char surface to the screw jacket, which is in direct contact with a counter-flow supply of cooling water. The cooled char is discharged through an airlock drum isolator.

Clean syngas produced will be used to generate electricity for use within the plant and for export. The gas will be combusted in an array of fully self-contained spark ignition engine each with a direct coupled alternator. The power produced will be three-phase and will produce on the order of 300 – 500 kW per engine depending on the quality of the feed.

Power generated by the gas engines shall be stepped up to 22 kV with a pair of transformers for export to the grid. A third transformer shall be provided to step down the power to 415V for use by the plant itself.

3.1.2 Storage Facility Design

For Phase 2, a mini storage facility will be constructed close to the pyrolysis plant. This will act as a proof-of-concept for both commercial models as all aspects are transferrable and scalable.

The biochar will be pumped from the pyrolysis site approximately 60m to the storage facility. This will require an electric pump which will run off excess electricity generated by the plant. The excavations will be in four stages spread over the 12 months operation period using existing farm equipment.

Once the Biochar has been cooled following discharge from the kiln, it will be transferred via a hopper to the pumping system. Biochar will be mixed with water and pumped c.60m away through a snap fit transfer pipe to the mini land raise storage solution.

3.2 Models used to inform design

Experimental research undertaken by UoL identifying the optimum temperature for biochar production and gas has been fundamental in informing the design of Phase 2.
Similarly reports by UKCEH on biochar stability have been key to informing the design of SLR's storage solution.

4.0 Project plan

4.1 Introduction

Pollybell Farms on the Lapwing Estate has been identified as the optimum site for operating the Phase 2 demonstrator. The benefits of Phase 2 at Pollybell Farms include:

- The expertise of the consortium involved on site.
- The close proximity to our willow chip supplier. This reduces the carbon footprint of sourcing feedstock and minimises supply chain issues.
- The available space for a mini-land raise demonstrator, plus 2,000 ha holding of agricultural land to spread biochar produced from Phase 2 at current regulations.
- Contribution to commercial Reverse Coal demonstrator. Phase 2 will be operating alongside ongoing rewetting and paludiculture trials as well as be able to offer energy to be used in Lapwing's CEA trials.

4.2 Delivery strategy

Lapwing has been fortunate to benefit from a strong cross disciplinary team, who have expertise in business, engineering and academia (Appendix 1). This team will be key to delivering Phase 2.

4.3 Costs

The project lifetime of Phase 2 is assumed to be 3 years before scaling towards the commercial-scale commercial project commencing. Indicative costs for the key components of Phase 2 show project net costs to be £3M over 3 years.

Appendix 1. Lapwing Energy Project Team

Lapwing's innovative approach is only possible through truly cross disciplinary research across business, engineering and academia.

Lapwing

Project Director – James Brown, 5th generation of the family to run The Lapwing Estate group. Qualified Chartered Accountant, MSc International Relations, BSc Economics and Politics, 14 years' experience at Lapwing. This project is James's vision and passion in how the global food system can be fixed through disruption.

Director – John Taylor has over 25 years' experience in sustainable farming. John is farming director for all Brown family farms. He is responsible for the paludiculture and land management trials at Pollybell.

Project administration and management. Katie Fretwell. Katie has 8 years' experience leading national projects through the management of a field-based team. Expertise in both agile and waterfall project management methodologies and experience of having led a multitude of technical projects across a range of sectors.

Research graduate – Jamie Smith has joined Lapwing to assist with research for the project. He graduated from University of Aberdeen with a BSc (Hons) in Geography.

Engineering project management – Jonathan White CEng FICE has joined the Lapwing team to assist with the engineering aspects of the project and the project management for phase 2 pilot. Jonathan has 25 years' experience across a broad range of sectors creating innovate engineering solutions.

University of Lincoln

Prof Simon Pearson FRSB (University of Lincoln). Founding Director of Lincoln Institute of Agri-Food Technology. He is a biosystems engineer with a track record in modelling and biosystems energy system design. A recent highlight includes energy system modelling that led to a world leading £14M low carbon glasshouse facility powered by anaerobic digestion and CHP now constructed in the UK.

Prof Duncan Botting (University of Lincoln). Visiting professor, former research director of ABB, sits on the BEIS Smart Systems Forum, works with the Energy Systems Catapult on the BEIS whole systems energy challenge as lead for INCOSE challenge group and is an IET Policy Panel member working with BEIS on offshore carbon/ wind/ hydrogen coordination planning.

Dr Amir Badiee – researcher for UoL's work packages. Post-doctoral Research Fellow at LIAT. He has been involved in multiple Agri-Tech and energy projects including the third generation of greenhouse cladding material design, soil moisture measurement using Cosmic Ray Neutron Sensor (CRNS) and multi-tier growing arrangement design.

Working in collaboration with UoL: **University of Exeter**

Prof Roger Maul (University of Exeter). He is Professor of Management Systems at the University of Exeter's Business School and Academic Director of the Initiative for the Digital Economy at Exeter (INDEX), which is based on London's South Bank and lead of the UKRI Circular Economy network on the carbon economy

UK Centre for Ecology & Hydrology (UKCEH)

Prof Chris Evans MBE. Over 20 years of peatland research aimed at mitigating the impacts of human activities on GHG emissions and carbon loss. He leads ongoing work on lowland agricultural peatlands for Defra and BEIS, and led work to include peatlands in the UK's national emissions inventory. He was a Lead Author two IPCC reports and is a member of the national committee of the Defra Lowland Agricultural Peat Task Force. He leads the £5.5m UKRI-funded Peatland GGR Demonstrator project, which is establishing trial sites for accelerated peatland restoration at Lapwing, in parallel with Reverse Coal. Chris was awarded an MBE in 2020 for services to ecosystem science.

Prof Niall McNamara. Expertise in the impacts of climate and land use change on soil carbon dynamics and ecosystem GHG emissions. This work ranges from ecosystem surveys (greenhouse gas budgets, soil carbon stocks) through to more mechanistic process orientated experiments (hydrology, drought, nutrients, warming). He has led UK and International work that has focussed on bioenergy cropping and biochar use. At CEH Lancaster, he is leader of the Plant-Soil Interactions Group.

Dr Sanchita Mandal - Soil biogeochemist at UK Centre for Ecology and Hydrology. She has been involved in the Reverse coal project since June 2021. Expertise in soil nutrient transformation, biochar soil interaction, biochar surface characterisation, contamination remediation using biochar and greenhouse gas emission mitigation.

Working in collaboration with CEH: **SLR Consulting Limited**

John Booth (AMICE, NEC reg. FRGS) is a Principal Engineer with 14 years of experience designing and delivering civil and mechanical engineering projects within the UK and abroad. John has provided innovative solutions which balance permitting, environmental and budgetary constraints across a broad range of infrastructure projects, with a particular focus on water management.