Direct Air Capture and Greenhouse Gas Removals Innovation Competition

REVERSE COAL

Phase 2 Final Report for DESNZ

Department for Energy Security & Net Zero

Lapwing Energy

Glossary

Abatement	Stopping or reducing (current) emissions
Anaerobic	An environment in the absence of oxygen
Biochar	Biological charcoal - a solid form of highly concentrated carbon made by pyrolysis
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
DEFRA	Department for Environment, Food and Rural Affairs
EA	Environment Agency
GGR	Greenhouse Gas Removal
Kiln	A high-temperature furnace used to thermally process biomass through pyrolysis
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
Oxidation	The addition of oxygen or removal of hydrogen
Paludiculture	The practice of farming on land with a high-water table.
Pyrolysis	The thermal decomposition of materials at elevated temperatures in an inert atmosphere
Carbon Sequestration	The process of capturing and storing atmospheric carbon dioxide (CO_2)
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)
UoL	University of Lincoln
UKCEH	UK Centre for Ecology & Hydrology

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, the Lapwing group 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 simultaneously protecting our precious natural environment. As part of this vision, Lapwing Energy has developed "Reverse Coal": a carbon capture, processing and storage system. The Lapwing vision both sequesters *and* abates significant quantities of carbon, *and* also produces food with measurable positive environmental and social impact. Benefits are:

- Carbon sequestered and secured in a concentrated permanent store
- Scaled abatement of emissions from drained 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

This is an alternative approach that ensures that food production can continue into the future with a positive impact on the environment, rather than an irreversible, negative one. Lapwing and Pollybell Farms received recognition from the Secretary of State for Environment, Food and Rural Affairs in 2022, 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, ex-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"*

[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

Reverse Coal delivers that "revolution"

At the heart of this revolution is circular thinking. The focus of this Phase 2 pilot project has been to prove this integrated approach. The premise of the Lapwing approach is to utilise photosynthesis to remove CO_2 from the atmosphere via production of short rotation coppice willow (SRCW) on rewetted peatland.

$6CO_2$	+	$6H_2O$	→	$C_6H_{12}O_6$	+	$6O_2$
Carbon Dioxide		**Water**	**Sunlight**	**Glucose**		**Oxygen**

By rewetting the peatland that SRCW is planted on, the emissions from the oxidation of drained lowland peat are simultaneously abated – which accounts for 3% of total UK GHG emission[3].

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 in a contained, waterlogged condition. This patented storage solution is one of the most concentrated and easily verifiable of all carbon mass-storage solutions offering up to 45,408t CO_2e stored per hectare.

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

By building a pilot plant at The Lapwing Estate as part of Phase 2, Lapwing Energy has been able to show that climate action and food production can go hand in hand. A pilot has been part of the necessary due diligence required by investors before scaling to the larger commercial facility.

Our Phase 2 pilot project would not have been possible without the backing of the Department for Energy Security and Net Zero as well as the Department for Environment Food and Rural Affairs, Natural England, The Lapwing Estate, UK Research and Innovation, IDRIC, and the Environment Agency. Reverse Coal has utilised the talent and knowledge of over 320 people from various industries to deliver this state-of-the-art pilot facility. This report summarises the work completed in Phase 2.

Dissemination of the Lapwing Reverse Coal vision at the 2024 Lapwing Open Day

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

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1.0 Reverse Coal Overview

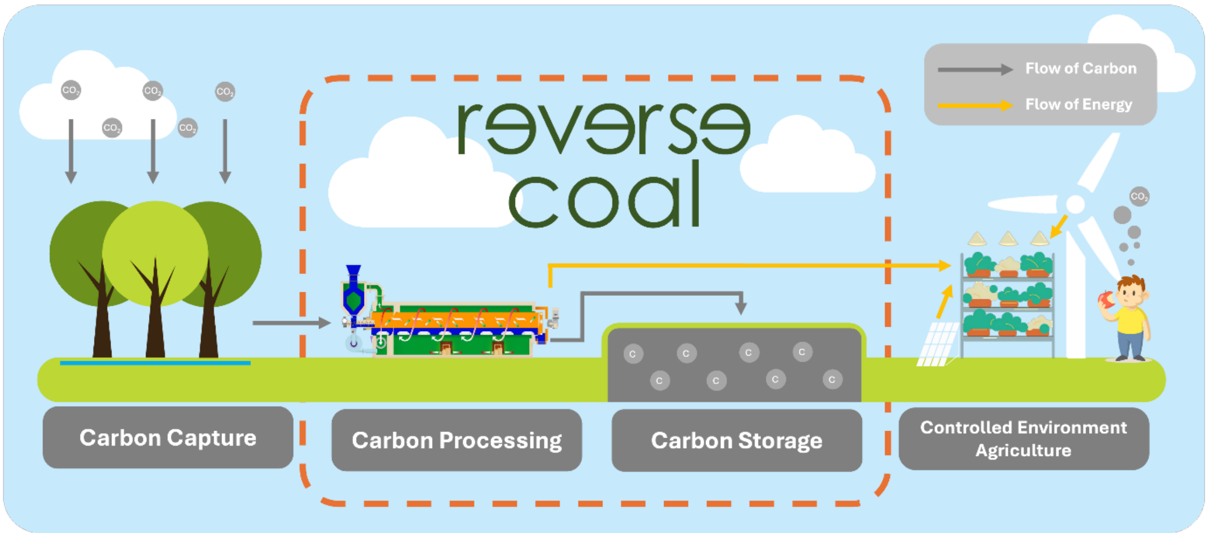

Figure 1.0.1 Reverse Coal Flow Diagram

The Lapwing Reverse Coal vision is for a holistic system change. The DESNZ Phase 2 project focuses specifically on the carbon processing and storage elements, and so these are the main focus of this report. Input and output elements of the wider vision are also referred to in this report to assist with context and clarity. All are essential components of a sustainable business model.

Lapwing Energy has developed a system technology integrating proven processes in an innovative approach. The Lapwing vision goes beyond carbon removal and is a disruptive new approach to land use. Driven by a need to rethink farmed landscapes particularly on lowland peat, Lapwing delivers a sustainable model for decarbonising agriculture whilst simultaneously creating a more resilient food production system.

Figure 1.0.2. Aerial shot of The Lapwing Estate

Current agriculture practices on drained lowland peat are resulting in GHG emissions in the region of 26 tonnes of CO_2e per hectare, per year (Prof Chris Evans, 2025). By restoring and rewetting the landscapes, almost all of these emissions can be abated, and peatlands can become carbon sinks. To avoid creating a resulting food security crisis, the displaced vegetable growth will be moved indoors. As this requires a steady supply of affordable power, bioenergy crops will be grown quickly on rewet peatlands to provide a sustainable supply of biomass.

1.1 Carbon Capture

Figure 1.1. Paludiculture crop trial site at The Lapwing Estate

Willow grows naturally across The Lapwing Estate. Studies have identified that Short Rotation Coppice Willow (SRCW) provides the optimum combination of speed of growth and calorific value, and will comfortably survive extended periods of soil rewetting. SRCW captures carbon dioxide from the atmosphere through photosynthesis and locks in the carbon as it grows. Once the SRCW is ready to be coppiced, it is chipped in the fields and hauled to site to be dried, prior to carbon processing.

1.2 Carbon Processing

Figure 1.2. Lapwing Energy's Pyrolysis Plant

Dried wood chip is fed into the pyrolysis process where it passes through a high temperature rotary kiln. The wood chip thermally decomposes in the absence of oxygen, breaking it down into syngas, biochar, and heat. Syngas is cleaned in the system for renewable power generation. Heat is recovered for actively drying wood chip. The biochar retains the stable carbon typically at 86% by mass.

1.3 Carbon Storage

Figure 1.3. Lapwing Energy's patented carbon storage solution

The carbon locked in the biochar is pumped and buried in a permanent storage repository that is flooded to stabilise the carbon and prevent re-emission. This facility offers high quality but straightforward monitoring, reporting and verification, giving full traceability to the carbon sequestered.

1.4 Controlled Environment Agriculture

Figure 1.4. Food production from CEA system

The final part of the Lapwing vision is to use the energy co-product in a controlled environment agriculture system, producing higher value foods, replacing the change in land use and subsequent displacement of food production. This delivers a closed loop system enhancing food production and at the same time decarbonising The Lapwing Estate.

1.5 Overview of Carbon Net Savings

Figure 1.5 highlights the relative carbon footprint of each step in the wider Lapwing vision:

- **Step 1** is the landscape abatement of emissions from lowland peat that dramatically impacts the total GHG impact.
- **Step 2** is the proven CO_2 removal 'technology' of photosynthesis, in this scenario SRCW.
- **Step 3** is the carbon processing (Reverse Coal) of the fixed carbon in the wood to biochar and then burial.
- **Step 4** is the utilisation of renewable energy in CEA reducing emissions of food production compared to the status quo.

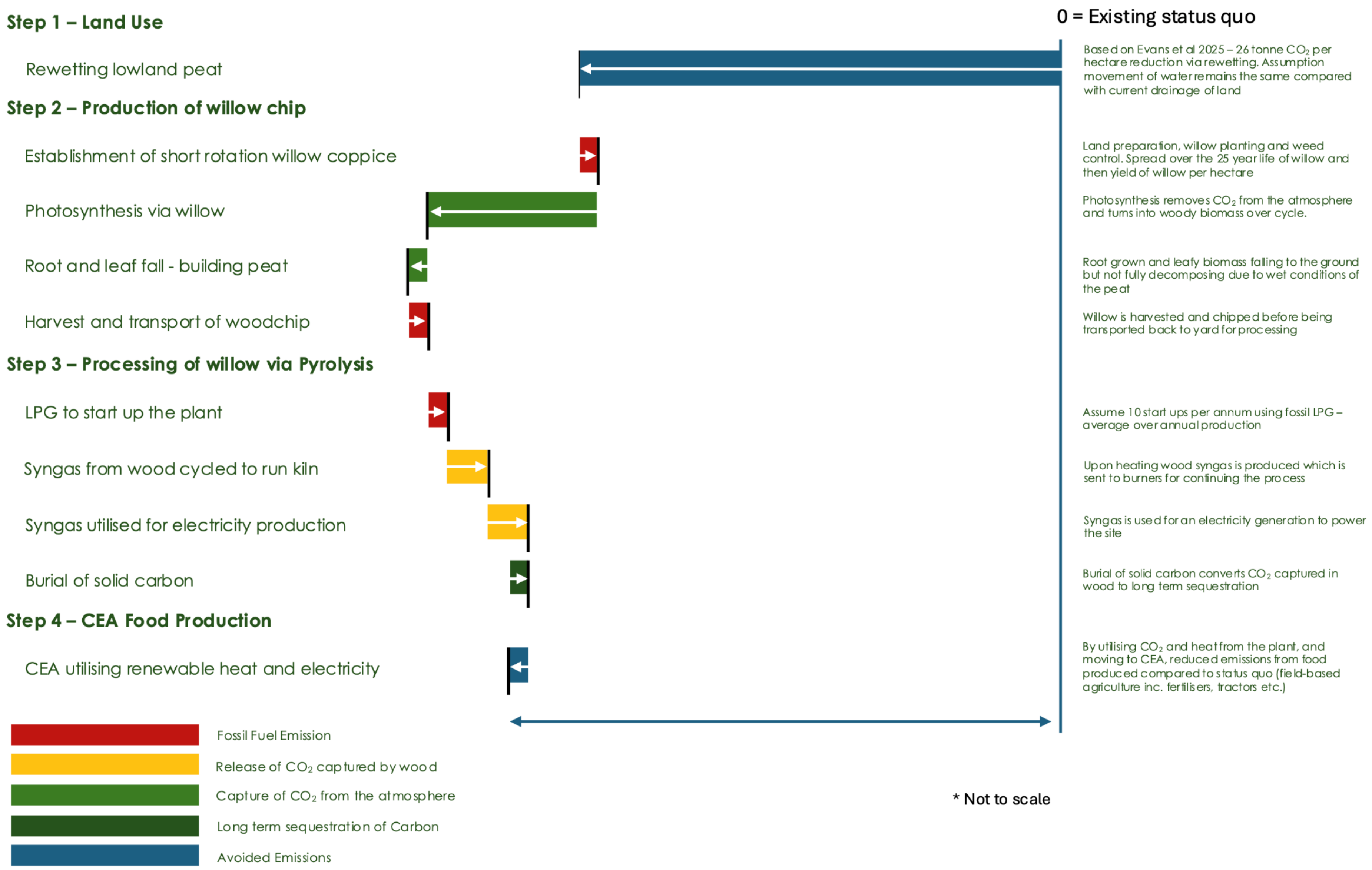

Figure 1.5. Waterfall flow of carbon savings through Reverse Coal

2.0 Reverse Coal Pilot Plant

The objective of Phase 2 of the Direct Air Capture and Greenhouse Gas Removals Innovation Competition is to construct, operate, test, refine and evaluate processes and technologies that can be used to remove GHGs from the atmosphere at scale. This section details the pyrolysis technology and carbon storage solution designed for Reverse Coal.

2.1 System Design

2.1.1 Design Overview

Lapwing Energy undertook a review of pyrolysis providers during the Phase 1 feasibility stage of the DESNZ Direct Air Capture and Greenhouse Gas Removals Innovation Competition: which identified high temperature pyrolysis as a preferred technology. Anergy's patented High Temperature Pyrolysis (HTP) technology operates in the region of 750^{o}C which ties in with Lapwing's experimental results that identified this to be close to the optimum temperature for biochar and syngas production.

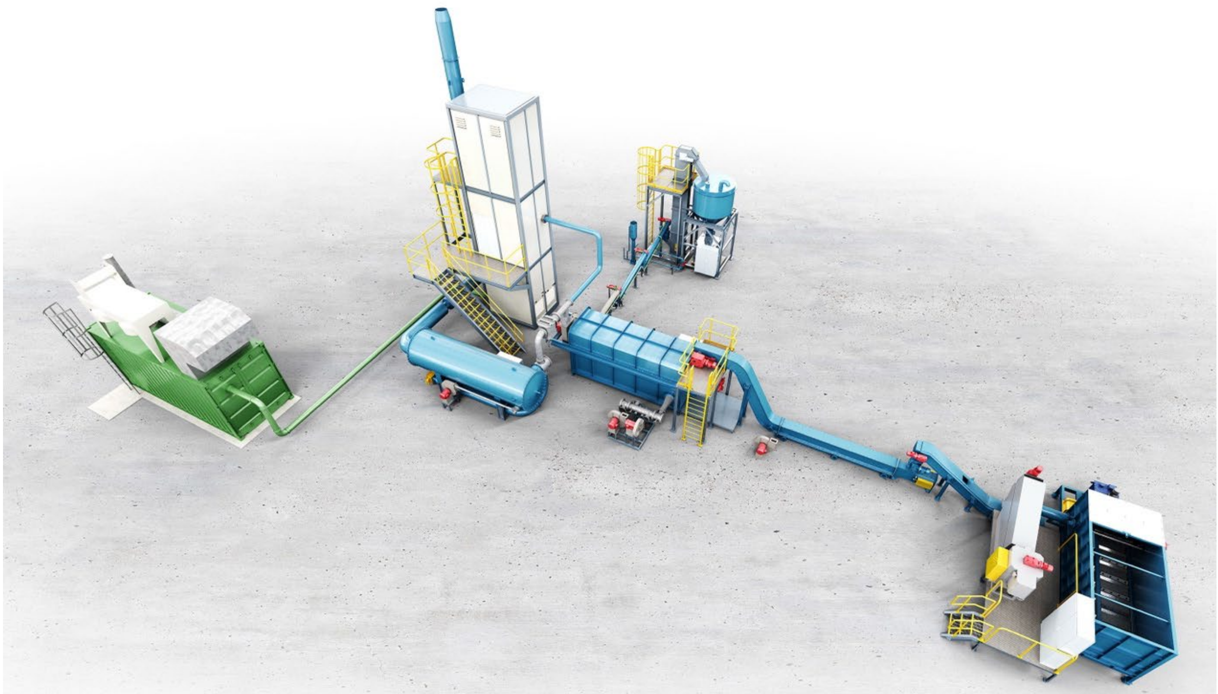

Figure 2.1.1. 3D Visualisation of the pyrolysis plant minus utilities (credit: Bilfinger UK)

For Phase 2, Lapwing engaged Bilfinger UK: an EPC contractor capable of delivering a turnkey solution in the UK. Bilfinger UK was engaged by Lapwing to provide the design, installation and commissioning of "the willows to biochar, power and heat demonstration plant".

Bilfinger UK scoped the various packages and delivered them through a range of specialist subcontractors and their inhouse delivery team. Sections 2.1.2 to 2.1.8 provide an overview of the core pyrolysis process.

2.1.2 AREA 10 - FEED HANDLING

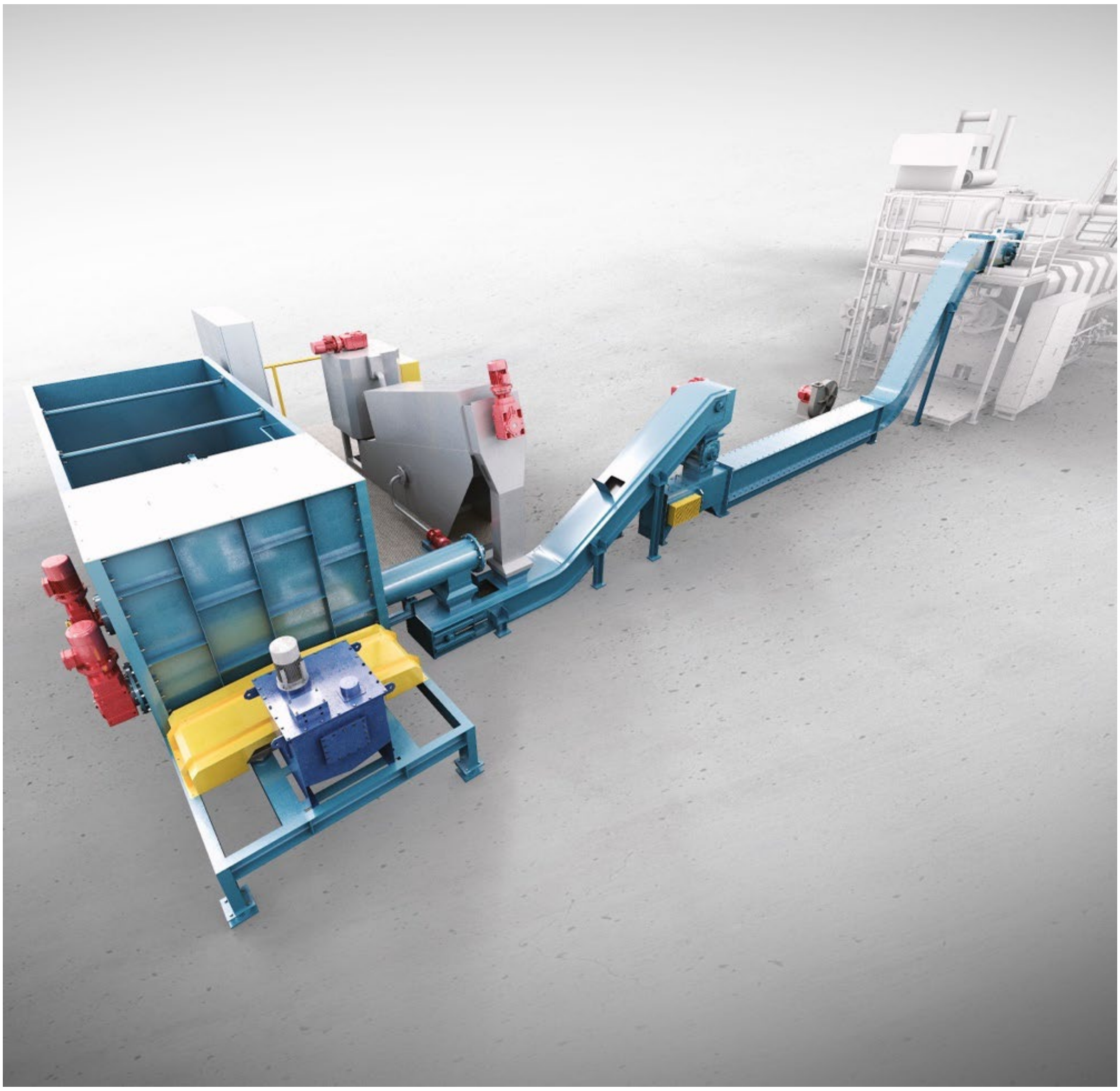

Figure 2.1.2. 3D Visualisation of Feed Handling system (credit: Bilfinger UK)

Woodchip, dried to 25% moisture, is loaded into the feed bunker by an operator. A 'walking floor' within the bunker transports woodchip to the end where it is collected by a screw conveyor. The conveyor system feeds the chip to the HTP kiln at a controlled rate of 340 kg/hr. Within the conveyor pre-drier, warm kiln exhaust gas is circulated through the woodchip to dry it further to 15% moisture. The conditioner filter next to the feed bunker processes the resulting 'liquor' from the GCU to remove solids and return clean liquor back to the GCU. To minimise waste production the solids are discharged from the filter into the woodchip stream, returning them to the process.

2.1.3 AREA 20 - PYROLYSIS SYSTEM

Figure 2.1.3. 3D Visualisation of HTP Kiln (credit: Bilfinger UK)

Woodchip enters through a rotary valve that seals against air flow. Within the HTP kiln the woodchip travels down within an inclined rotating tube made of specialist steel; the sealing mechanism ensures that no oxygen can get into the tube. Heat is provided to the tube by three external burners that are fed with syngas from the GCU. The heat causes the woodchip to break down ("pyrolyse") creating high carbon biochar solid and raw 'syngas'. The syngas is a mix of hydrogen, carbon monoxide, carbon dioxide, methane and water vapour.

Biochar exits (at 36 kg/hr) to the product handling conveyors and syngas (at 280kg/hr) to the GCU, while burner exhaust gasses are discharged to the stack. The recuperator skid uses the exhaust gases to pre-heat the air to the burners, increasing the plant efficiency.

The kiln residence time can be adjusted between 15 and 35 minutes. The standard kiln residency time for SRCW chip to our specification is 22 minutes

2.1.4 AREA 30 - CHAR PRODUCT HANDLING

Figure 2.1.4. 3D Visualisation of Char Product Handling (credit: Bilfinger UK)

Hot biochar is received from the HTP kiln into a series of three inclined screw conveyors. These are double walled and have a cooling water jacket fitted, as well as water spray to cool the biochar.

The bucket elevator lifts the biochar into the product storage bin, where load cells measure the weight and keeps the operator informed. When required the biochar is discharged through the rotary valve either into a pumped discharge system or to flexible bulk bags.

2.1.5 AREA 40 - GAS CLEAN-UP

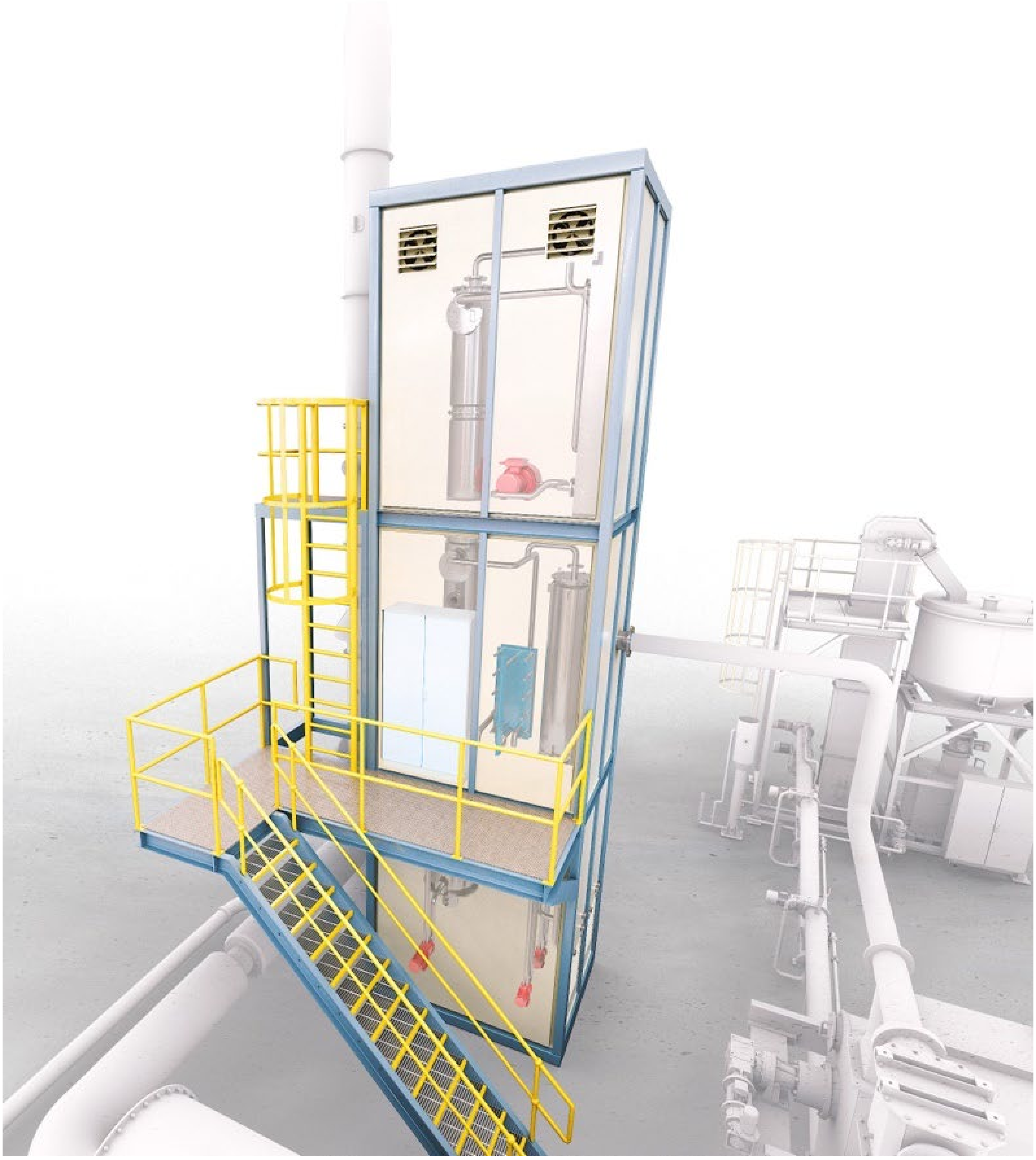

Figure 2.2.5. 3D Visualisation of Gas Clean-Up System (credit: Bilfinger UK)

The ‘Gas Clean Up’ unit is a process module that includes a three-stage cleaning system to process the raw syngas. This includes removal of particulates and acid gasses as well as drying and dehumidifying the final gas product. Doing this converts the raw syngas into a fuel suitable for the gas engine and the HTP kiln burners. The liquor produced in this process is treated in the filter conditioner to enable it to be reused and minimise waste streams.

2.1.6 AREA 60 - COMBUSTOR AND PLANT EXHAUST

Figure 2.1.6. 3D Visualisation of Combustor and Plant Exhaust (credit: Bilfinger UK)

The Staged Air Cyclonic Thermal Oxidiser (SACTO) consists of an insulated chamber with a burner mounted within. It is used to dispose of syngas that cannot be sent to the gas engine, typically during start up, shutdown and in case of emergency. The SACTO is maintained in a state to become automatically operational when required.

The SACTO is brought up to temperature during start up using LPG, and used until the syngas supply is sufficiently steady for the gas engine to use it. The SACTO then maintained in readiness for a shut-down (planned or emergency) and during operation to combust any excess gas if/as required if we reach our grid export limit (260kW pyrolysis, 400kW pyrolysis + solar).

The stack provides a safe and compliant exit route for combustion gasses from the kiln and, when required, the SACTO.

2.1.7 AREA 70 - POWER GENERATION

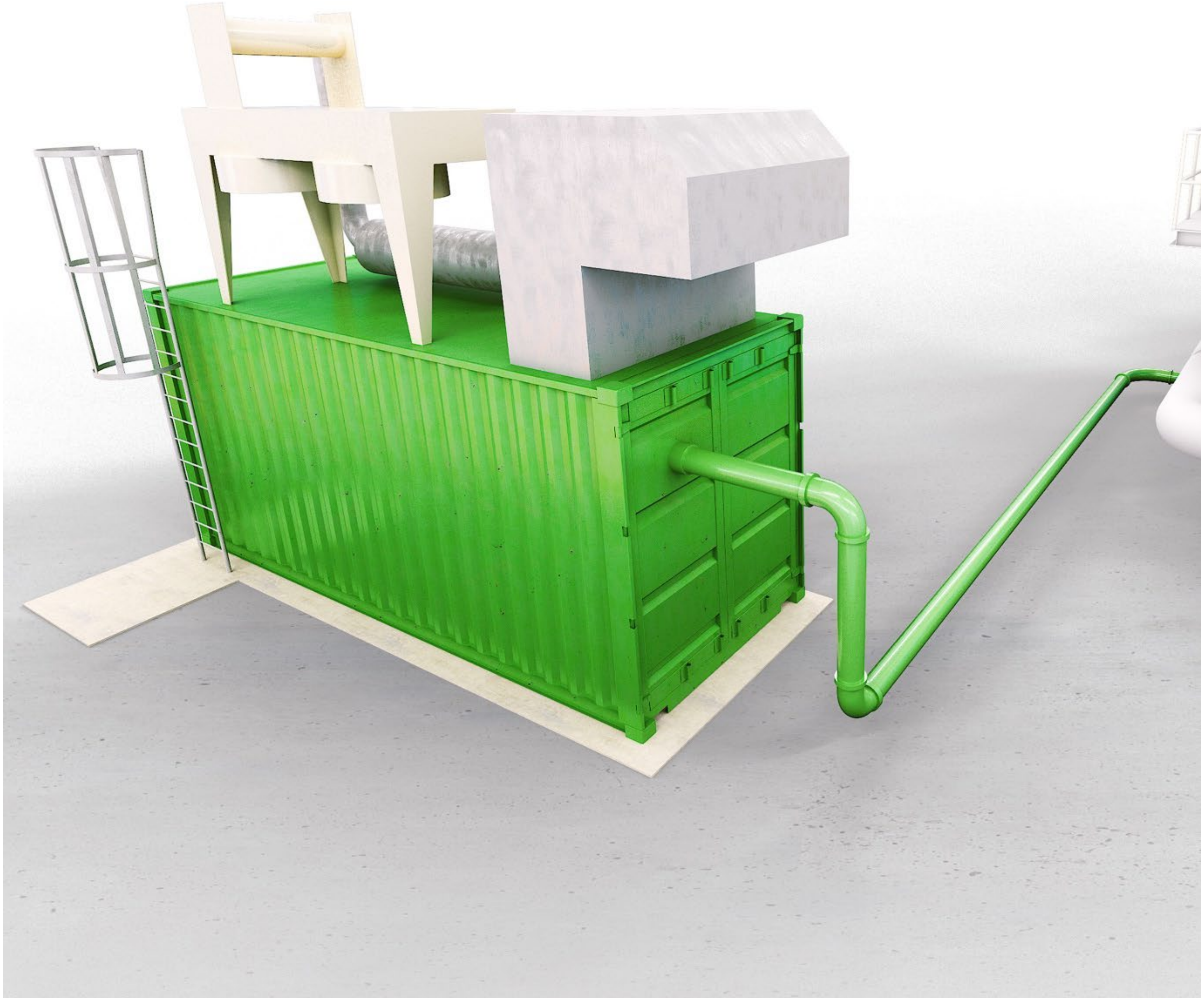

Figure 2.1.7. 3D Visualisation of Gas Engine (credit: Bilfinger UK)

The gas engine is a diesel vehicle engine that has been modified to run on clean syngas. When operating, this powers a generator to produce up to 320 kW of electricity. A small proportion of this provides the parasitic load required to run the plant, with the remainder exported to ultimately be utilised by existing farm operations.

2.1.8 AREA 00 - PLANT SERVICES & AREA 90 - UTILITIES

Included within the plant boundaries are a number of utility packages required for the operation of the Plant. These include:

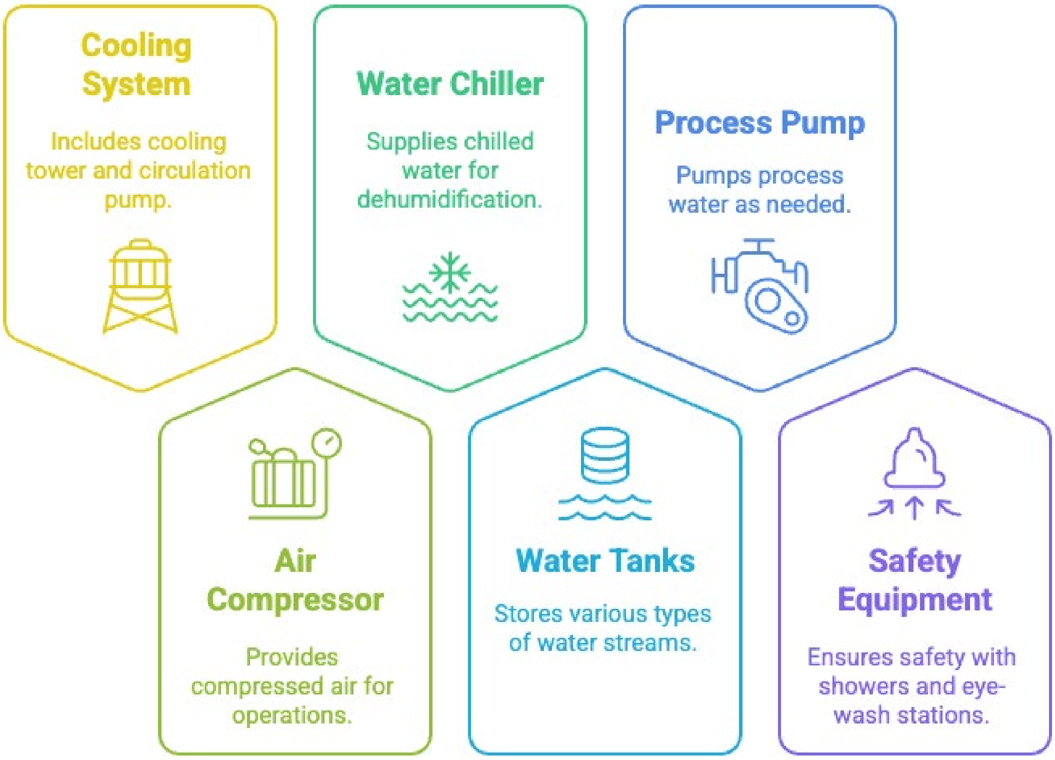

Figure 2.1.8. Utility packages that are required to safely operate the pyrolysis plant

2.1.9 Carbon Storage

The innovative approach to carbon sequestration developed under the Reverse Coal project centres on storing biochar produced via pyrolysis in long-term, secure underground repositories. This patented solution ensures stable and verifiable carbon storage while mitigating risks of carbon loss through oxidation or environmental exposure. The biochar storage facilities are designed to be submerged in waterlogged conditions, leveraging the benefits of geotextile filter bags to maintain separation from surrounding soils to prevent migration. This setup allows for biochar to act as a carbon filter, enhancing water quality while ensuring structural stability.

The application of biochar to land as a soil amendment is increasingly recognised for its potential benefits, such as enhancing soil fertility, improving water retention, and sequestering carbon. However, the current norms of biochar application are associated with a lack of robust traceability. Lapwing's carbon storage solution was developed to demonstrate straightforward, transparent traceability offering purchasers a high degree of confidence that they can return after many years to see the biochar remaining in the repository.

The demonstration repository, located at Oatlands Farm, showcases this approach. Initial trial repositories revealed key insights into optimal construction and storage processes, including methods to control groundwater, manage seasonal variations, and safely handle biochar's flammable nature.

With a capacity to store 1 mega tonne of CO_2 equivalent in just 45 hectares, the model offers a highly efficient storage method – storing mainly carbon as opposed to other approaches which include higher proportions of other elements. Post-storage, the facility is designed for restoration to agricultural use, ensuring minimal long-term disruption to land use.

Some of the key benefits of this approach include improved water management, with potential for biochar repositories to serve as adjustable subterranean reservoirs, and contributions to water quality through biochar's filtration properties. While challenges such as regulatory frameworks and long-term maintenance remain, these repositories serve as state-of-the-art facility.

Geotextile bags, adapted from sludge dewatering technologies, form the core of the storage design. These bags serve multiple functions: they securely contain biochar while allowing water drainage, prevent contamination between biochar and surrounding soils, and reduce human handling during the storage process. Their semi-permeable design facilitates water flow, maintaining biochar in saturated, anaerobic conditions, which reduces CO_2 emissions and mitigates oxidation risks.

The bags are integrated within dam structures, creating a scalable and stable storage solution that aligns with proven practices in the mining and waste sectors. Additional design features enhance the structural integrity and environmental resilience. These include soil mass overlay to counter buoyancy, increase bearing capacity, and strategic placement away from vulnerable geomorphological features. Discussions with Murlac secured the procurement of custom sludge dewatering filter bags, optimising storage for Phase 2 of the project.

Figure 2.1.9. Biochar pumping trials highlighting flowing waterbed method

Key findings from trialling the geotextile bags for biochar storage highlighted the efficacy of the “flowing waterbed” method. Biochar, dropped into a controlled water flow, forms islands that erode uniformly, ensuring a consistent mixing. This approach outperformed alternatives by preventing blockages and was able to adapt to variations in biochar particle size. The system’s design includes components like Akron flow control valves and a dual-pump setup, ensuring precise water flow and safe biochar transport.

2.1.10 Design Coordination

The Design Coordination phase was a collaborative process and outlined the early stages of project development, focusing on the infrastructure, and operational strategies. This foundational stage was critical for establishing the project’s technical, operational, and logistical frameworks.

Design Coordination meetings (Lapwing, Bilfinger UK, SLR and BSCG) aligned project goals with practical implementation. The primary objective was to coordinate the design of the pyrolysis plant, integrate it with the operational requirements of Lapwing, and ensure adherence to the principles of the Construction (Design and Management) Regulations 2015 (CDM2015) to minimise risks.

Optimal Plant Placement: The team identified the Oatlands Farm site as the ideal location separating energy generation and woodchip handling from the organic crop operations at Little Carr Farm. The selected layout of the pyrolysis plant minimises space usage while allowing future scalability by sequentially adding similar units. It was identified that an additional kiln could be located in parallel and share key equipment from the pilot plant.

Figure 2.1.10.1. As-built site plan of Oatlands (credit: Bilfinger U

2.1.11 Models

During the Reverse Coal Phase 1 feasibility study, the University of Lincoln (UoL) conducted static batch biochar trials using SRCW. 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. This therefore requires substantial refining for energy use so 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, which can vary greatly from batch to batch.

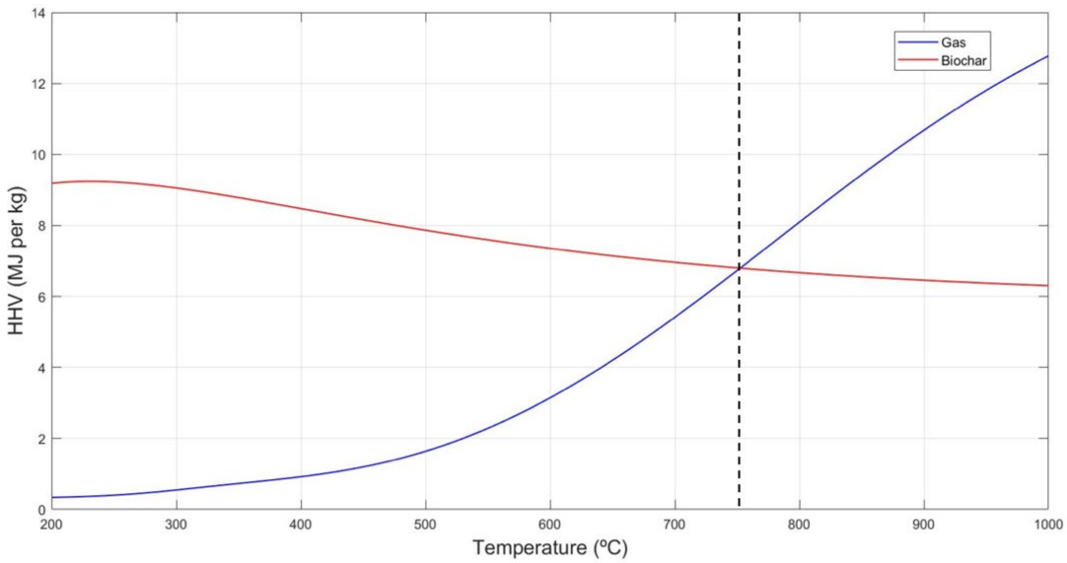

Figure 2.1.11.1. Pyrolysis model - Energy outcome (Gas & Biochar) vs temperature (Experimental research by UoL)

Experimental studies undertaken by UoL showed the optimum temperature for biochar and syngas production to be in the region of 760°C +/- 10%.

Anergy's pyrolysis technology can optimise biochar volume per tonne and high energy production to reduce costs. This is primarily due to their high temperature pyrolysis system and efficient gas clean up know how. A Sankey Diagram was developed to model the end to end energy flows, which has been the foundation to the IChemE contract between Lapwing and Bilfinger UK.

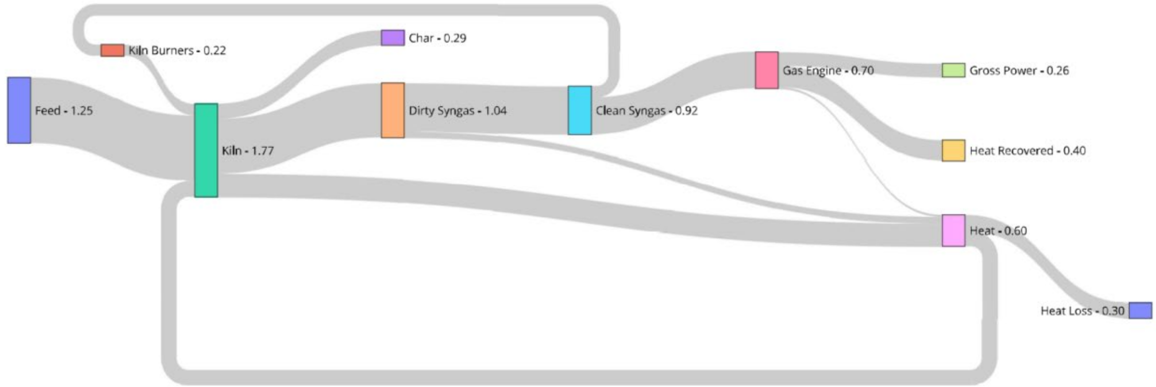

Figure 2.1.11.2. Sankey Diagram for willow chip through Anergy HP870 Kiln (credit: Anergy Ltd)

During Phase 2 of Reverse Coal, UoL developed a digital twin of the pyrolysis system to model various scenarios and optimise the real-world system. The digital twin model developed is capable of:

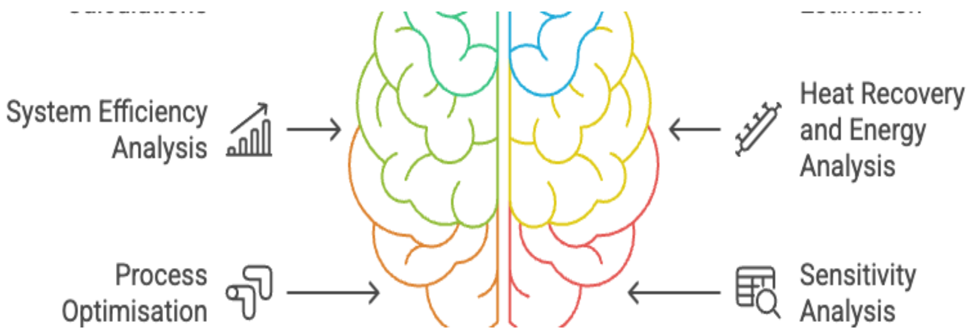

Figure 2.1.11.3. Capabilities of UoL's digital twin model

As part of another research project ‘Climate SAFE’ (funded by DEFRA under the Farming Innovation Programme), in collaboration with Lapwing, UoL has developed an Energy Hub Model to look at the integrated energy system with controlled environment agriculture (CEA) for food production.

The validation and optimisation framework established by the University of Lincoln forms a comprehensive basis for evaluating the performance of the pyrolysis system. Their framework employs a multi-layered approach that integrates laboratory testing, digital modelling, and system-level analysis to ensure the technology achieves its intended environmental, energy, and economic outcomes.

All modelling components have been validated using current design parameters and are ready to receive and process live operational data. Validation through the Sankey methodology will assess the system’s performance across critical indicators, including biochar yield, electricity output, heat recovery, and carbon emissions. These activities will help maximise the impact of the pyrolysis system, positioning it as a key solution in advancing low-carbon agriculture and long-term carbon sequestration strategies.

2.2 Reverse Coal Pilot System Development

2.2.1 Site Preparation

The Lapwing Estate offered the Reverse Coal project the use of the Oatlands Farm site. The buildings and hard standings at Oatlands date from the 1960s and were as a result in 'well used' condition. Most recently they have been used for storage of farm vehicles and equipment, and up until 2015 they were used for vegetable processing. The sheds are structurally sound and largely watertight, with floors in generally good condition. By utilising existing buildings, Reverse Coal avoided the need for any bespoke new build construction plus the carbon expenditure (in particular on steel & concrete) which would be attributed. Some adaptation and refurbishment has been necessary to house the pilot plant. As an agricultural project, if Reverse Coal can demonstrate that disused sheds can be repurposed, it presents a model that can be replicated across other farms that have similar infrastructure.

Oatlands Farm has four large sheds, hard-standing areas and surrounding field space. The site offered the ability to compartmentalise the pyrolysis process, and to keep the processes of power generation and possible future vertical farm operations (non-organic) segregated from the certified organic food hub of Little Carr.

Figure 2.2.1.1. Oatlands Farm in 2022 (Left to right Sheds 1,2,3 & 4)

Figure 2.2.1.2. Refurbished Oatlands Farm in 2024

Following discussions with the plant manufacturers, sheds 3 & 4 were refurbished with Yorkshire panelling to improve air flow around the plant and to reduce buildup of dust around hazardous areas (explosive atmospheres). The yard was cleaned and repaired to prevent contamination and deterioration from woodchip being delivered.

2.2.2 Plant Manufacture

Bilfinger UK led the manufacture of the pyrolysis plant. Bilfinger UK divided subsystems between their subcontractors. Anergy manufactured their patented HTP kiln design (Section 2.1.3) and were selected to also provide the feed handling, char product handling, gas clean-up, combustor and plant exhaust (sections 2.1.2; 4; 5; & 6). Bilfinger procured the gas engine (2.1.7) from Quantum and utility packages (2.1.8) from a range of other vendors.

Anergy's project management team is in Singapore, whilst their manufacturing site is in Chennai, India and technical leadership in Australia. Lapwing and Bilfinger UK visited the Chennai factory during the manufacturing period and attended factory acceptance tests (FATs) of key equipment.

Figure 2.2.2.1. HTP Kiln being manufactured in Anergy's factory in Chennai, India

Figure 2.2.2.2. Char bin trial assembly in Anergy's factory in Chennai, India

Anergy developed a more modular approach to the manufacturing of the pilot plant, with each subsystem built and tested in isolation. This approach was introduced following Anergy's previous experience with the aim to reduce the commissioning presence and time on site.

Figure 2.2.2.3. Anergy's team carrying out electrical work on the HTP Kiln electrical panel in Chennai, India

2.2.3 Pyrolysis Plant Installation

Bilfinger established site at Oatlands Farm under CDM regulations on the 3rd of June 2024 and commenced the installation phase of the project. The installation process was split into two phases reflecting the staged delivery of equipment predominantly arriving by sea from Anergy's factory in Chennai.

Figure 2.2.3.1. Delivery of the Phase 1 equipment on site

The first phase of equipment included:	The second phase of equipment included:
- Chiller - Cooler - Gas Engine - Stack base - Product Handling Bin - Pyrolysis Kiln - SACTO - Char elevator and conveyors - Ductwork and piping	- Waste water treatment plant - Recuperator - GCU - Stack - Feed Bunker

Figure 2.2.3.1. Phased delivery of pyrolysis plant equipment

The first phase of equipment arrived on site on the 10th of June 2024, followed by the second phase on the 7th of November 2024.

Figure 2.2.3.2. Installation of the pyrolysis plant at Oatlands Farm

Bilfinger's modular approach allowed areas to be positioned and fixed as and when they arrived. Snagging of equipment and electrical installation led to the Installation completion milestone being achieved in March 2025.

2.3 Challenges

The nature of R&D inherently involves challenges, and Reverse Coal has been no exception. The Lapwing team encountered numerous "showstoppers" throughout the delivery of the Pilot Plant, and this section highlights some of those challenges and the approaches taken to overcome them.

2.3.1 Grid Connectivity

Reverse Coal is a carbon processing and storage project, but the business model relies on the saving from exporting self-generated electricity to the wider Lapwing business. For this reason, a grid connection is key to enable use of the local grid to transfer electricity and manage fluctuations in supply and demand.

The intention has always been to use the electricity generated within existing farm operations to support the decarbonisation of The Lapwing Estate. With Little Carr Farm, the organic hub, only 1km away from the Oatlands site, the plan has been to use the existing grid infrastructure. With a high-voltage line running between the sites, Lapwing engaged with the local Distribution Network Operator (DNO) National Grid, to understand how the existing infrastructure could be used.

Figure 2.3.1. Gas Engine on site

Under the guidance of Lapwing's electrical contractor, Lapwing submitted a G99 Application in August 2023, for the connection of the gas engine to the grid. The local DNO returned a quote of £85k to upgrade the existing transformer, but still offered an export capacity of zero! National Grid then explained that a further c.£300k would be needed to install new cables to facilitate an export. This clearly exceeded Lapwing's original £30k budget!

Lapwing met with the local DNO in November 2023 and proposed an alternative solution to reduce the transformer size to fall under a set threshold size, and combine the projected pyrolysis plant output with the underutilised export capacity allocated to Lapwing Energy's existing floating solar farm at Little Carr. This enabled the upgrade cost to be reduced from nearly £400k to less than £50k.

Ultimately the challenge was understanding the parameters that the local DNO operate to and therefore the right questions to ask to get to a workable solution.

2.3.2 Power Surges

After the new transformer was installed in October 2024, a lightning event in December 2024 triggered a series of what were believed to be power surges at Oatlands Farm, damaging electrical equipment. This included the newly installed fire alarm system, plus printers, lights, heaters, CCTV and WIFI connections . Fortunately, the core pyrolysis plant was isolated at the time ahead of commissioning, preventing potentially catastrophic damage. However, this incident posed a major challenge in safely and securely integrating the facility into the grid infrastructure.

To prevent damage from further 'surges', Lapwing's electrical contractor installed surge protection. However further 'surges' continued, causing further damage to most of the above items – which had been replaced following the first surge. National Grid attended site immediately to investigate the fault but were unable to identify anything at that time as the symptoms of the fault had passed. National Grid installed a data logger to record voltage levels over the following weeks.

To ensure that work could continue, Lapwing took the Oatlands site off mains electricity, installing a generator to allow Bilfinger UK to proceed with installation and commissioning. This temporary solution has enabled the pyrolysis plant to be commissioned independently of the mains supply, although the gas engine still requires grid connection for full testing.

Recognising the need for a long-term solution, Lapwing engaged Phoenix Engineering, specialists in power systems and grid stability, to investigate the root cause of the surges and implement mitigation measures to prevent further, potentially severe damage.

A number of potential issues were identified:

1. The National Grid data logger identified that the 230v supply is averaging 245v and peaking at 253v (that is the legal maximum but for more than a brief moment can be more than enough to 'fry' some capacitors).
2. Harmonics issues from generators upstream could be causing power quality issues.
3. There could be damage inside the transformer following the lightning strike. This can give the symptoms experienced, but faults like these can be very difficult to isolate.
4. There could be faults in the new electrical installations, but the nature of the symptoms experienced and them not occurring when on the generator supply makes this very unlikely.

Lapwing subsequently installed more detailed connection monitoring, which has identified a 'slow voltage variation'. This can also give rise to the symptoms experienced.

The following mitigations have been taken:

1. The over voltage problem was resolved by turning the voltage down by 6 to 8 volts at the transformer, which should prevent the capacitors from being overloaded.
2. Enhanced thermal/magnetic and electronic surge protection has been installed to every distribution board
3. A power factor correction unit has been installed, which should reduce the transmission of fluctuations in supply quality.

With all actions that can be taken on site now implemented, the site is now returning to the mains supply. Further monitoring is in place, but this challenge is not yet resolved.

2.3.3 International Supply Chains

Reverse Coal is an international project engaging the talent and knowledge of more than 300 people from over 50 different companies. Managing an international supply chain from the UK presents logistical and communication challenges, particularly when working across multiple time zones and regulatory environments.

Bilfinger UK, a subsidiary of Bilfinger SE, a multinational industrial services provider with offices across Europe, North America, and the Middle East was engaged to provide the required resources and support to ensure project progress.

Figure 2.3.2. Assembly of the char cooling conveyors in Anergy's factory

As Anergy's team is split between Singapore, India and Australia, weekly meetings were necessary to monitor project progress. Since tendering for Phase 2 of the DESNZ GGR Competition in 2022, Bilfinger have held to their price for the delivery of the pyrolysis plant. The war in Ukraine, the UK energy crisis, and broader supply chain disruptions have placed immense pressure on material costs, shipping logistics, and cashflow which have had implications on this project. Notably the piracy risks in the Red Sea were deemed too high and a force majeure extension of time was granted to cover the extra two week from shipping around the Cape of Good Hope. Additionally, cyclone events in Chennai caused further delays, impacting manufacturing timelines and component deliveries.

2.3.4 Insurance

Securing insurance for the pyrolysis plant proved challenging, as The Lapwing Estate's existing insurers were reluctant to underwrite the risk despite initial positive engagement. Whilst publicly recognising the importance of innovation in agriculture to improve farming resilience, this sentiment was not reflected in the insurers underwriting decisions, as they were unwilling to insure the pyrolysis technology at an affordable price. As a result, Lapwing had to broaden its search for insurers with a greater appetite for risk, and experience in bioenergy and industrial processes. Lapwing successfully secured insurance via brokers Cape Insurance with QBE Insurance Group.

Figure 2.3.4. Oatlands Farm is an isolated site in an agricultural setting, minimising consequential risk

The actual fire risk from the pyrolysis plant is minimal, as the design is engineered to safely contain high temperatures and operates under strict thermal controls. The primary risks stem from potential electrical faults in control cabins and the storage of large biomass quantities, rather than the pyrolysis process itself. However, large-scale biomass storage is common in agricultural projects, particularly in anaerobic digestion (AD) plants and other bioenergy facilities. The challenges in securing insurance highlights industry hesitation towards emerging technologies, even when they align with agricultural and net zero goals.

2.4 Costings

Phase 1 – During Phase 1 of the DAC and GGR Innovation Programme, Lapwing Energy were awarded £250,000 to research the design and feasibility of the Reverse Coal project.

Phase 2 – Lapwing Energy was awarded a further £3 million in Phase 2 of the DAC and GGR Innovation Programme. The project outturn costs are broken-down as below:

Work package Name	Description (inc. Key tasks)	£ Cost exc VAT
Project Management	Project and team management. Includes report writing and frequent progress meetings	£393,794.94
Permits & Licences	Permit application submission and outcome of process	£18,010.25
Plant Procurement, manufacture, installation and commissioning	Procurement of pyrolysis technology through to installation and acceptance	£2,334,135.96
Carbon Storage Solution	Design and construction of carbon storage solution + Operational monitoring	£39,742.06
Feedstock	Sourcing and processing of feedstock for pyrolysis process	£66,037.41
Pyrolysis Plant Operation	Operating of pyrolysis technology and validation and optimisation of it	£83,670.68
MRV	MRV development and monitoring of biochar produced and biochar in situ	£46,672.06
Systems Analysis and Business Development	Full system integration of Reverse Coal and commercialisation plan development	£17,759.24
		£2,999,822.60

Table 2.4. Reverse Coal DESNZ Phase 2 Costs

Lapwing Energy incurred additional cost as part of the purchaser's responsibilities under the IChemE contract between Lapwing and Bilfinger. These costs were accepted as beyond the scope of the DESNZ Phase 2 pilot plant. Furthermore, site refurbishment costs for the Oatlands site were provided in kind by The Lapwing Estate.

3.0 Results

3.1 Pyrolysis Plant Operation

There has been limited operation of the pyrolysis plant due to delays in installation and an extended commissioning period integrating the subsystems. The main process pyrolysis plant has been operated for short runs producing biochar and syngas that has been scrubbed in the GCU. The biochar produced has been successfully pumped and sequestered in Lapwing's Reverse Coal demonstrator repository (Figure 1.3). The plant has been able to demonstrate a biochar production rate capable of sequestering >100 t CO_2e per annum. Production data is limited but so far the plant has demonstrated a biochar production rate of 22kg/hr (60% design capacity). One hour of production at this rate equates to 69kg of CO_2e removal and amplified to 8000 hours of operation a year it exceeds 555t of CO_2e removal. Once ramped up to full design capacity following optimisation, we anticipate >900t of CO_2e removal.

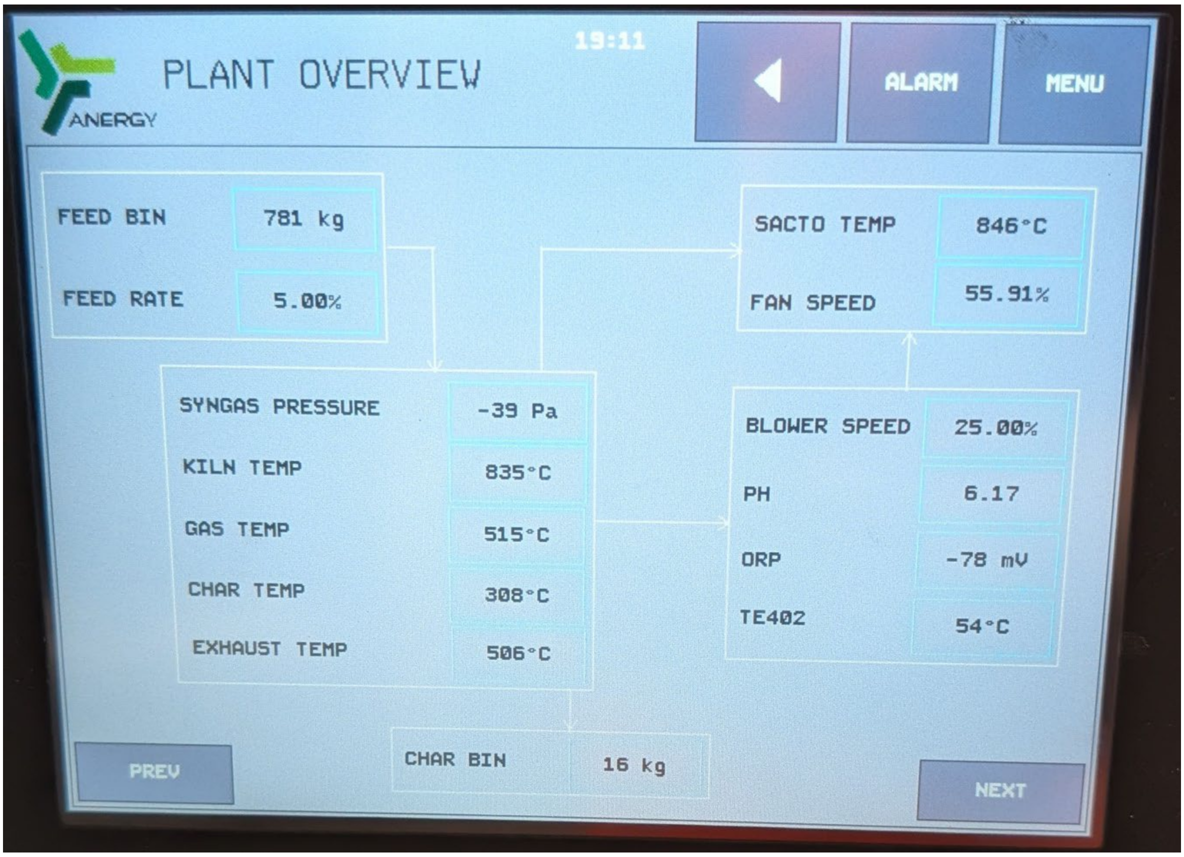

Figure 3.1.1 Snapshot of the HMI plant overview (credit: Bilfinger UK)

During operations of the pyrolysis plant, syngas has been produced and processed through the gas cleaning unit. However, due to the short production runs there has not yet been a sufficient steady supply of syngas to operate and commission the gas engine and generate electricity for export. This is expected to be achieved prior to this report's publication.

During the short operational runs, syngas has instead been safely discharged through the SACTO. Via the sight glass in the SACTO, a blue flame can be seen that typically indicates a clean, efficient combustion of hydrogen and carbon monoxide which are the two main components of good quality syngas. The absence of yellow, orange, or sooty flames suggests that there are very low levels of tars, oils, or particulates in the gas.

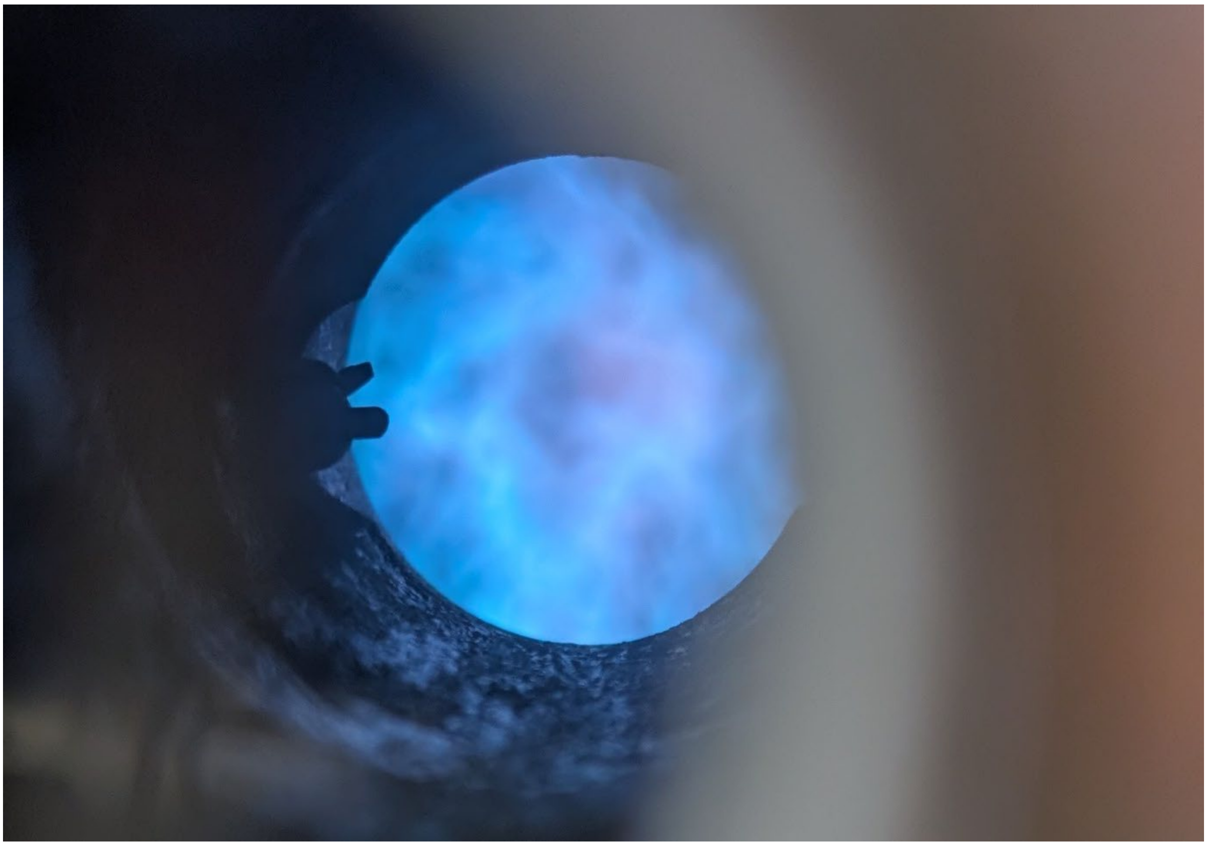

Figure 3.1.2. Sight glass into the SACTO (Syngas burning) (credit: Bilfinger UK)

Crucially, the short operational runs have validated several technical aspects: clean syngas combustion, functional gas cleaning, safe flaring through the SACTO, and biochar transfer to the Reverse Coal repository. These are all positive indicators that the plant is on track to deliver full functionality once a stable syngas supply is established and the gas engine is brought online.

3.2 Carbon Storage

A key pillar of the Reverse Coal approach is the long-term secure storage of carbon through an engineered biochar burial system designed to minimise physical loss and oxidation. Lapwing Energy has developed a robust and scalable method to ensure that following the production of biochar via pyrolysis of woody biomass, the solid carbon is retained for geological timescales.

"The Reverse Coal MRV strategy offers a practical blueprint for assessing long-term biochar stability under real-world conditions. Storing carbon by burying it in a stable form in the ground seems an obviously sensible idea, with the added advantage that the main tool you need to monitor and verify its continued presence is a shovel. This approach has the potential to be scaled up across the UK and globally."

- Professor Chris Evans, UKCEH, Climate Change Adaptation Committee

The solution includes two types of demonstration repository constructed adjacent to the pyrolysis facility at Oatlands: a fully subterranean "quarry" model and a "land raise" model with an engineered embankment. These repositories are filled using Lapwing's patented system in which biochar is suspended in water and pumped into large filter bags. The water is then drained and recirculated, while the biochar is retained. The filter bags reduce operator contact, prevent material mixing, and allow the char to settle, compact, and resist environmental exposure.

Figure 3.2.1 & 3.2.2 Reverse Coal biochar pumping system clear & active

Initial trials showed successful deployment of commercially available biochar, and commissioning of the system using Lapwing's own char has proven successful. Site conditions, including historical coal layers and porous sand strata, have informed the design. HDPE membrane liners are used in the landraise model to isolate stored material and manage hydrostatic pressure, with water levels adjusted to maintain equilibrium with fluctuating groundwater.

To confirm carbon mass, the system uses calibrated load cells under the biochar bin, with additional sampling ports to verify integrity and composition of the material post-deposition. The stored carbon will be monitored over time to validate permanence.

Lapwing's storage solution is designed not just to meet environmental permit conditions, but to exceed them—demonstrating a scalable, low-impact carbon sequestration methodology that transforms degraded lowland peat into a secure carbon sink.

Figure 3.2.3 University of Lincoln viewing the landraise storage model

The design and operation of the Reverse Coal facility have been carefully developed to ensure full compliance with the conditions set out in Lapwing's environmental permit, issued by Bassetlaw District Council. A critical factor in securing this permit was Lapwing's decision to exclusively use non-waste biomass as feedstock—principally short rotation coppice willow (SRCW) and other clean, untreated woodchips.

By operating strictly as a non-waste facility, Reverse Coal avoids the additional regulatory burdens associated with waste processing, including the need for continuous emissions monitoring under the Medium Combustion Plant Directive. This design choice significantly reduces capital and operational expenditure while aligning with environmental compliance requirements.

4.0 Lessons Learnt

4.1 Permissions

Securing a permit for the Reverse Coal activities was a crucial milestone that set the stage for compliance with regulatory frameworks and ensured a clear pathway to implement the project.

The Environment Agency and Bassetlaw District Council were extremely supportive of the project and the proactive approach taken to permitting. Both bodies were satisfied with the methodologies for feedstock handling as well as biochar burial. Lapwing is permitted by Bassetlaw District Council to undertake the processing of woody biomass and vegetable matter for pyrolysis and biochar burial.

Lapwing worked with Kathryn Jukes, of Directions Planning, to ensure that the pyrolysis plant could be installed within the constraints of agricultural permitted developments.

4.2 Feedstock Handling

The practical handling of feedstock has been a continuous learning process, developed through on-site experimentation and informed by supplier engagement. Lapwing Energy has implemented a comprehensive and adaptable strategy for sourcing, storing, and managing biomass feedstock to ensure consistent quality and efficient processing. This strategy is critical to mitigate seasonal variations in supply, maintain quality during storage, and optimise logistics for delivery into the pyrolysis plant.

Figure 4.2.1. Aerial shot of Oatlands and feedstock stored on the Eastern apron and North of the site

Initial months of feedstock handling at the Oatlands site reinforced the importance of selecting the correct storage surface. Asphalt and concrete surfaces have been confirmed as the best options for reducing contamination, while gravel is a cost-effective alternative offering drainage but less protection. Storage on fields, although low cost, has been deprioritised due to the higher risk of contamination and logistical limitations in poor weather. Outdoor feedstock is now carefully heaped and protected from water ingress, while indoor drying has become central to Lapwing's feedstock strategy.

Figure 4.2.2. Lapwing operators using a telehandler to handle and pile woodchip

Significant operational improvements have been achieved within Shed 1. Feedstock drying performance has increased through a revised approach—limiting material thickness to 150 mm, which has greatly improved airflow and drying consistency. These changes have made the system more responsive to weather variability, with the flexibility to dry feedstock outdoors during favourable conditions and revert to shed drying in wet periods. Importantly, separation between wet and dry zones is strictly maintained to preserve the quality of the dried material.

Furthermore, operational practices for fan and vent maintenance have been refined to reduce downtime and management burden. Floor vents have been improved to sustain better airflow without frequent manual intervention. Shed 2 continues to serve as the primary storage space for dry feedstock, with effective stock rotation and layout management ensuring compliance with fire safety and access requirements.

4.3 Fire Risks

A comprehensive fire prevention and mitigation strategy has been developed for the Reverse Coal facility at Oatlands Farm. As highlighted in section 2.3.3, the pyrolysis plant is designed to minimise fire risks through robust safety features, including automated shutdowns, gas-tight equipment, and controlled environments.

Figure 4.3.1. Summary of key fire prevention strategies

The Misterton Fire Crew of the Nottinghamshire Fire Service were invited to visit Reverse Coal's facility as a proactive approach to fire safety. Recognising that the novel technologies at Oatlands Farm might pose unfamiliar challenges to first responders, Lapwing Energy invited the crew to tour the site, learn about its operations, and discuss fire prevention strategies.

Figure 4.3.2. Misterton fire crew being shown around Oatlands Farm

The Misterton crew, accompanied by senior representatives, examined feedstock handling, pyrolysis processes, gas-to-electric conversion systems, and the irrigation infrastructure. The fire crew noted the facility's remote location and clear boundaries, which simplify fire containment and eliminate risks to neighbouring properties. Discussions highlighted Lapwing Energy's response priorities: 1) protecting life, followed by 2) environmental safeguards, and 3) minimising property damage.

The crew commended Lapwing on taking this proactive approach, and committed to develop a Defined Response Plan so that any crew attending an incident would be pre-briefed on what to expect and how to respond.

4.4 Dissemination Events

Dissemination and exploitation have been an essential part of the project and Lapwing's approach to sharing learnings and championing the case for Reverse Coal. The Lapwing Group hosted a dissemination event to showcase the projects ongoing at The Lapwing Estate that are working towards this shared vision of rethinking farmed peatlands.

Figure 4.4.1 Flogas discussing their plans for decarbonising LPG at the Lapwing dissemination event

Lapwing invited the funders of multiple projects (DESNZ, DEFRA, Natural England and UKRI) as well as project partners (UKCEH, UoL, British Steel, Bilfinger UK etc.) and industry. The event was held in October 2024.

Figure 4.4.2. Lapwing team explaining the carbon storage solution at the Lapwing dissemination event

The morning session included presentations from project partners, DESNZ, and the core Lapwing team highlighting the integration of projects. This led to an open forum flagging the challenges and obstacles that could inhibit R&D in the greenhouse gas removal space from rapidly commercialising.

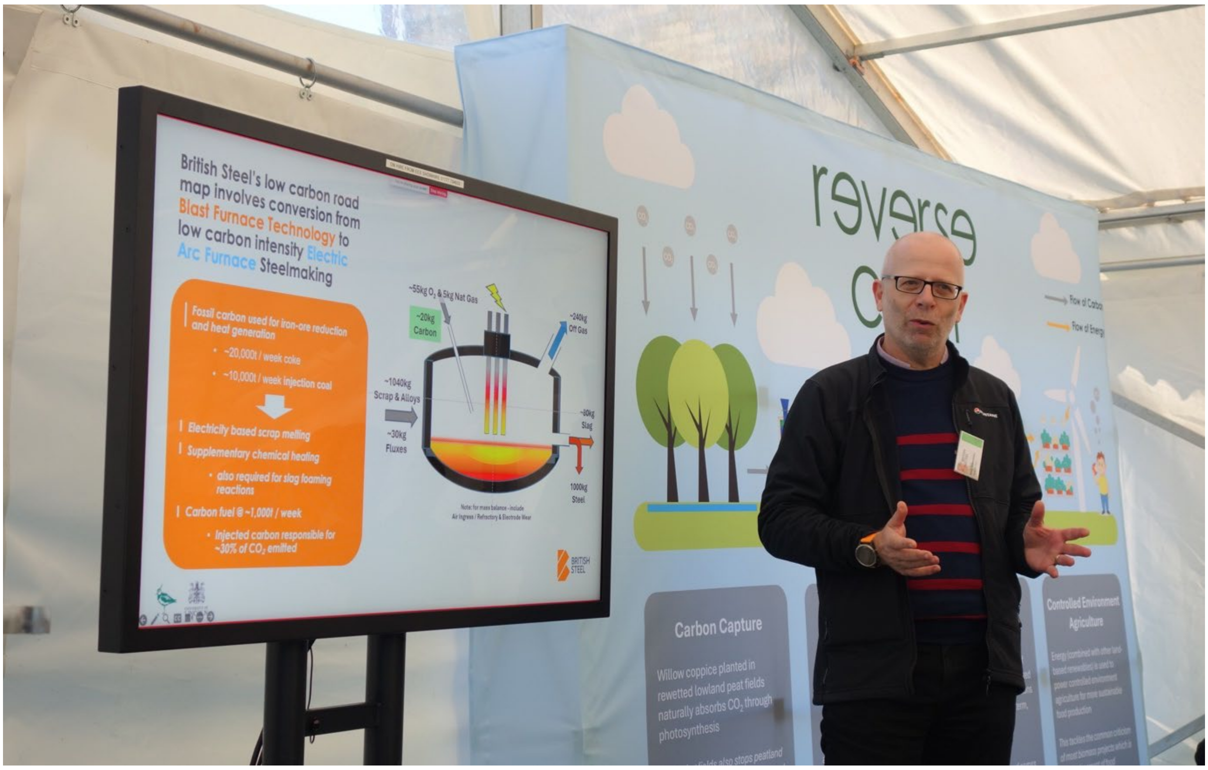

Figure 4.4.3. British Steel presenting their decarbonisation ambitions at the Lapwing dissemination event

The afternoon tour of The Lapwing Estate fostered valuable discussions as well as offering hands-on workshops giving guests the opportunity to sequester biochar in Reverse Coal's patented storage repository.

Figure 4.4.4. Charlotte Powell, DESNZ, Head of Bioenergy and Carbon Removals, sequestering carbon by pumping biochar into Lapwing's carbon storage solution at the Lapwing dissemination event.

4.5 Plant Construction & Commissioning

The construction and commissioning of the Reverse Coal plant highlighted the significant complexity involved in integrating novel carbon removal technologies into a functioning demonstration facility. A key lesson was the critical need for flexibility and proactive problem-solving in a supply chain that included over 50 companies, each contributing to different elements of the project. This emphasised the importance of assessing not just technical capability of subcontractors but also organisational resilience and resource availability when selecting contractors. The project has relied heavily on Lapwing's in-house project management capacity, which was required to take on much broader responsibilities than originally anticipated—ranging from in-depth grid connection optioneering and fault identification to fire safety design in buildings and equipment integration.

Another key learning has been the trade-off between capital expenditure (CAPEX) savings and operational expenditure (OPEX) efficiency. In several instances, Lapwing opted to reinstate or upgrade equipment—such as a larger feedstock bunker and product bin—to support smoother plant operation and minimise long-term staffing costs. While these decisions added pressure to the project's constrained capital budget, they were necessary for increasing operational resilience. Importantly, the use of existing buildings at Oatlands rather than new building construction reduced the project's footprint and enabled compliance through permitted development rights. However, this re-purposing introduced new challenges around planning, insurance, fire risk management, and equipment retrofitting. These experiences underscore the importance of aligning facility design with insurance, safety, and operational requirements from the outset and ensuring early engagement with all regulatory bodies. Together, these lessons will directly inform the design, contracting, and commissioning strategies for future scale-up of Reverse Coal technology.

4.6 Uncertainties

4.6.1 Feedstocks

Sourcing biomass feedstocks in the UK has presented several uncertainties, driven by market fluctuations, policy incentives, weather conditions, and external economic factors. These challenges impacted both the availability and cost of materials like willow, miscanthus, and other biomass feedstocks sourced for Phase 2 operations.

Extreme Price Variations

One of the biggest uncertainties has been price volatility in the biomass market. For example:

- Since the tender for Phase 2, prices for feedstocks have risen substantially compared to our initial budget estimate.
- Purchasing-in pre-dried willow chip tends to be twice the price of fresh-cut willow chip. This reflects the reduction in water content purchased as well as the cost of the drying process which requires additional time, space, and energy.
- The Oatlands site has drying facilities which has been adapted to use recovered heat from the operational plant. A week's worth of supply of pre-dried willow chip was purchased at the premium price for start-up, as the plant will need to be operational in order to dry further feedstocks.
- The cost of woodchip and biomass pellets has fluctuated significantly, driven by demand spikes, rising transportation costs, and supply shortages.

Weather-Related Delays & Alternative Harvesting Strategies

- One supplier faced a one-year delay in harvesting a plantation of willow in the Wakefield area due to sustained wet weather conditions, which prevented harvesting equipment from accessing the site.
- Prolonged wet periods make it difficult to use heavy machinery, leading to missed harvesting windows and potential reductions in feedstock quality. An additional year does however provide another growing period increasing the yield.

- The optimum period to harvest to minimise leafy growth is during winter months, but this tends to present the most challenging ground conditions.
- One supplier is developing equipment under the DESNZ Biomass Feedstocks Innovation Programme that is better suited to working on wet ground, and another has developed an attachment to strip unwanted foliage from plantations that are in leaf.

Impact of Gas Price Increases

- The surge in gas prices in recent years following the war in Ukraine has increased demand for alternative heating fuels, including biomass.
- This has led to higher competition for wood-based feedstocks, driving up costs for industries relying on biomass for biochar production and energy generation.

Domestic Renewable Heat Incentive (RHI) & Biomass Boiler Demand

- The UK Government's Domestic Renewable Heat Incentive (RHI) significantly increased the demand for wood pellets and chips as homeowners and businesses adopted biomass boilers.
- This policy has redirected a large share of the UK's biomass supply to domestic heating, reducing the availability of feedstock for industrial and carbon sequestration applications.
- In 2024, one potential supplier advised Lapwing that they can now sell chipped forest co-products (that used to be left as waste) for more per tonne than timbers suitable for roof trusses – a situation they described as "bonkers!"

These uncertainties make long-term planning and cost management difficult and for these reasons Lapwing is continuing to investigate other feedstock opportunities that are more available and financially viable.

4.6.2 Biochar Prices

Market adoption of biochar in industrial applications, such as steel and cement manufacturing, depends on proven performance, regulatory acceptance, and cost competitiveness with existing materials. Early-stage engagement with potential industrial users can help establish demand and inform product development. However, market penetration may require additional research, pilot projects, and policy support to incentivise low-carbon alternatives. Lapwing has engaged with British Steel as part of a separately funded research project to understand their demand and inform biochar development.

Biochar's role in biodiversity enhancement, water filtration, and soil remediation offers further commercial opportunities, but these markets are in their early stages. Identifying industrial or agricultural buyers willing to pay for these benefits will require clear economic justification and data-driven impact assessments. Lapwing is exploring this opportunity with local water companies to understand their appetite.

4.6.3 Carbon credit prices

The long-term commercial success of Reverse Coal and other biochar projects depends on stable and well-defined carbon markets. Carbon credits represent a potential revenue stream, but market volatility, evolving regulatory frameworks, and uncertainties in credit pricing pose risks. Ensuring that biochar qualifies for carbon sequestration credits requires adherence to lifecycle assessments (LCA) and verification standards, which are still developing. Lapwing has engaged with multiple biochar carbon credit certification bodies and found a wide range of approaches. Interestingly Reverse Coal's novel approach to carbon burial has been met with intrigue as this has fallen outside the scope of existing methodologies for biochar application.

Lapwing has registered with Puro.Earth as a crediting platform for engineered carbon removal.

4.6.4 Electricity prices

Electricity generated from pyrolysis is treated differently from solar and wind in the UK due to its classification as a bioenergy source rather than a renewable energy technology. While solar and wind are able to benefit from government subsidies, preferential grid access, and established incentives like Contracts for Difference (CfD) and Feed-in Tariffs (FiTs) (historically), pyrolysis-based electricity generation does not receive the same level of support.

One key distinction is that solar and wind are considered intermittent renewables, whereas pyrolysis can provide baseload or dispatchable power, meaning it can operate continuously or be adjusted to meet demand. However, because bioenergy with carbon capture and storage (BECCS) is still an emerging policy area, pyrolysis electricity does not currently receive the same financial incentives or grid priority dispatch as wind and solar. Lapwing has been asked to provide a year's worth of data before a longer-term power purchase agreement (PPA) will be agreed for export. Until then electricity sales will be at the highly variable spot prices (which include times of low demand which result in negative prices).

Additionally, grid connection challenges and regulatory barriers make it more difficult for pyrolysis-generated electricity to secure long-term, high-value PPAs compared to solar and wind, which are now mainstream energy sources in the UK's net-zero strategy. Addressing these disparities will require policy recognition of pyrolysis as a carbon-negative technology, potentially unlocking new support mechanisms to encourage its adoption.

4.6.5 Plant Consumables & Maintenance

A key uncertainty for Lapwing is the consumption of reagents and plant maintenance requirements, as operational data is still limited. Until the pilot plant has been running for 6 to 8 months, it remains unclear how frequently consumables such as reagents, filters, LPG and materials will need replacement, or how extensive routine wear and tear on components will be. LPG will be required for each cold start of the pilot plant.

Projected water consumption has been reduced significantly by making two of the three systems closed-loop. Further work is needed to understand if and how the third system can be converted to closed loop: potentially saving 2.4m^3 per day.

While Lapwing has planned for annual downtime and built contingencies into its operational model, the true scale of maintenance needs and associated costs will only become clear with long-term performance monitoring. Over time, this data will allow for more accurate forecasting and optimisation, reducing operational risks and improving overall efficiency.

5 Reverse Coal Assessment

5.1 CAPEX & OPEX

At the time of writing, the Reverse Coal pilot facility is in the early stages of operational deployment, and as such, it is not yet possible to comprehensively assess capital expenditure (CAPEX) and operational expenditure (OPEX) across a full operational cycle. While capital costs associated with the design, procurement, installation, and commissioning of the facility are well documented (see Section 2.4), operating cost data—such as the frequency of component replacement, consumables usage, system wear and tear, and labour requirements—remains incomplete due to the limited runtime of the plant.

Many of the key operational variables, including fuel consumption during startup, syngas engine efficiency, feedstock drying dynamics, and maintenance intervals, can only be accurately determined after sustained continuous operation. Lapwing intends to gather detailed cost data over an initial 8 to 12 month monitoring period to refine the financial model and inform scaling decisions. Until this dataset has been collected and analysed, any attempt to project lifetime CAPEX and OPEX would be speculative and may misrepresent the long-term economic profile of the system.

5.2 Life Cycle Assessment

As outlined in the *Reverse Coal Overview* (Section 1.0), the scope of the Phase 2 project is focused on carbon processing through to carbon storage. While the wider landscape transformation and CEA system are fundamental to The Lapwing Estate's long-term vision and Net Zero ambitions, they sit outside the immediate scope of this GGR process and involve a broader set of land use and economic assumptions.

Figure 1.5 highlights the proportionate impact of each step in the wider Lapwing vision as noted above. The Reverse Coal Life Cycle Assessment (LCA) for Phase 2 focuses on step 3 of this wider model.

Lapwing Energy engaged the specialist advice of Alder BioInsights—specifically the expertise of their Principal Consultant for Biofuels, David Turley—to develop a robust LCA focused on carbon processing and storage.

The LCA conducted for the Reverse Coal project based on the design specification of the plant demonstrates that for every dry tonne of biochar produced through the facility's pyrolysis process, approximately 3.29 tonnes of CO_2 equivalent (CO_2e) is captured and retained within the biochar. On an annual basis this equates to approximately to 947 tonnes of CO_2e removal (assuming a continuous 8000-hour operation). This high ratio of carbon removal is a result of optimised pyrolysis conditions that maximise the conversion of woody biomass into stable carbon, while minimising emissions and process losses. The figure incorporates all upstream emissions associated with the collection, drying, transport, and processing of feedstock, and reflects the net climate benefit of the system.

The long-term effectiveness of the system ultimately depends on the durability of the biochar once it is stored. The Reverse Coal approach—placing the biochar into geotextile bags and burying them in a managed storage repository—was designed to minimise the risk of carbon re-emission. Initial field trials, where test bags of biochar were extracted after six months, showed minimal evidence of degradation, movement, or exposure, indicating that the material remained stable and secure in the subsurface environment.

Nevertheless, longer-term monitoring is essential to build confidence in the assumed >1,000-year permanence of the storage method. Plans are in place for periodic retrieval and analysis of stored biochar, including chemical and structural testing to detect any early signs of breakdown or environmental interaction. This data will not only validate the assumptions used in the LCA but also feed into future versions of the methodology and storage protocol, allowing continuous improvement of the carbon sequestration standard.

For this demonstrator project, willow chips are being sourced from conventional plantations. Therefore, the peatland abatement component is not yet realised in practice. However, the biochar pathway already delivers meaningful negative emissions, validating Reverse Coal's foundational concept.

As the project evolves to include biomass grown on rewetted peatlands, the carbon removal potential will further improve, unlocking both deep carbon sequestration and broader landscape restoration goals that are central to The Lapwing Estate's environmental vision.

5.3 Process Risks

Within the scope of the Phase 2 Reverse Coal project, the process risks begin at buying in willow chip and end at carbon storage and energy generation.

Feedstock supply chain uncertainties pose a significant process risk that can ultimately halt operation of the pilot plant. As availability, pricing and reliability of delivery depend on external suppliers and fluctuating market conditions, it is a high risk that needs active mitigation. Lapwing's long-term approach is to grow biomass on The Lapwing Estate, but during Phase 2 this was not feasible due to the short timeframe available.

During Phase 2 Lapwing took the approach to secure a large volume of woodchip to stockpile against future market uncertainties. Similarly quality control is another challenge to manage, as natural variation in moisture content and particle size can impact the pyrolysis efficiency. The moisture content will impact the hydrogen ratio in the syngas as well as quality of biochar as more energy is needed to thermally decompose the biomass. Attempting to ensure as much consistency in deliveries as is reasonable will mitigate potential process risks.

The pyrolysis process itself carries process risks related to operational stability, safety, and energy consumption. Maintaining the correct temperature range is crucial for ensuring consistent biochar production. Temperature fluctuations can lead to incomplete pyrolysis of biomass, excessive gas emissions, or the greatest risk, equipment failure. Given that pyrolysis generates flammable gases posing fire and explosion risks, Lapwing engaged specialist advice from Orbis Environmental & Safety Consulting to conduct a DSEAR assessment, leading to strict monitoring and safety controls in place. Additionally, pyrolysis requires a significant thermal energy input, and inefficiencies in energy recovery can undermine the project's overall carbon savings.

The pyrolysis process has a demand for reagents which presents operator risks handling and connecting chemicals into the process. The Lapwing team has engaged with chemical specialists and suppliers to produce detailed method statements as well as identifying appropriate PPE as a final protection measure.

Lapwing's carbon storage solution presents its own set of challenges, particularly around long-term stability, regulatory approval, and public perception. The process risk of transporting biochar to the repository has been significantly derisked by dropping biochar into a quench tank before pumping it into the repository. This reduces human interaction with biochar and the dust risk. As biochar is a flammable product, quenching it and at the same time cooling it prevents a fire risk.

The Reverse Coal aim is to demonstrate that biochar remains stable and does not degrade over geological time in Lapwing's patented storage conditions. This is essential for securing carbon credits and demonstrating a permanence beyond the current 100-year timeframe attributed to existing biochar applications.

Regulations could impose extra costs on beneficial activities e.g. sourcing willow from trees in need of coppicing, land use change & SRCW planting at scale need an Environmental Impact Assessment (EIA). Local regulatory policy is also undergoing change, e.g., the Humber 2100+ strategy, and so there is a need to proactively engage with policy stakeholders, this is a positive as well as a challenge, as widening the stakeholders engaged requires time and expertise to engage with them.

5.4 Monitoring, Reporting and Verification

Lapwing Energy has patented the design of the carbon storage repository outlined in section 2.9.1. The MRV approach for the repository system is highlighted below (Fig 5.4.1). The main MRV components are *(i)* empirical measurement of biochar stability under the optimised conditions for biochar preservation within the repository; *(ii)* measurement of change in carbon storage in the biochar peat-clay cap; *(iii)* repository monitoring of N_2O and CH_4 emissions and *(iv, v)* repository monitoring of environmental conditions.

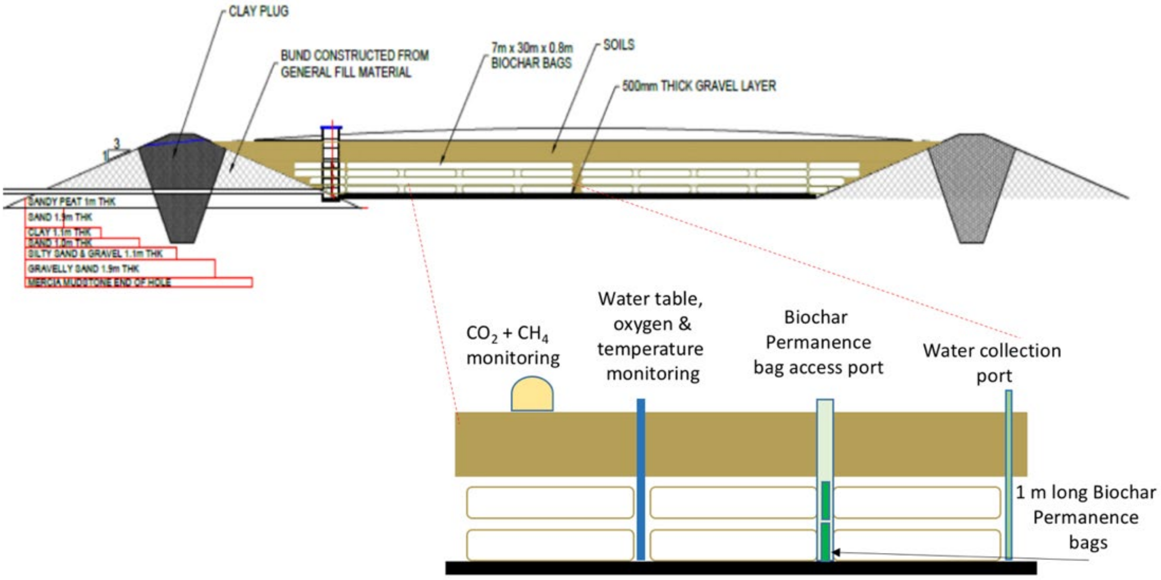

Figure 5.4.1. Cross-section of repository and overview of biochar MRV repository sampling aspects

During Phase 2, Lapwing installed a small biochar repository (SBR) to replicate the conditions of the larger demonstrator repository. This was to enable early testing of biochar in Reverse Coal conditions, prior to the plant being operational. Lapwing and UKCEH deployed biochar in the SBR in April 2024. This comprised of biochar produced at low and high temperatures by suppliers using willow sourced from Lapwing's supply chain. In addition, miscanthus biochar previously produced at low temperature was incorporated in the SBR. The biochar derived from high temperature willow was the closest product to that expected from the Lapwing plant that Lapwing was able to get made commercially.

The SBR presented an opportunity to trial MRV approaches on biochar samples recovered after 6 and 12 months, in parallel with plant installation and commissioning.

The SBR study has now progressed to include data from both six-month and twelve-month deployments, providing critical early insights into the long-term stability of biochar under field conditions. While some carbon losses were observed in specific biochar types, particularly those with finer particles, these insights are helping to refine repository design and inform monitoring strategies for long-term stability. Across both time points, the integrity of the mesh containment bags was confirmed, with no tear or physical failure observed. This suggests that the containment approach is viable for longer-term burial and mechanical resilience, a promising indicator for full-scale deployment.

Figure 5.4. Biochar samples extracted from the SBR

Although the SBR has been highly valuable as an exploratory tool, it is clear that full repository systems (DBRs) will offer more accurate assessments by enabling closed-loop water management, minimising edge effects, and providing more representative scale. Recommendations for full-scale MRV now include standardising initial biochar dry mass and particle size, using larger containment volumes to minimise environmental interface, and investigating pelletised biochar to assess dust minimisation and densification benefits.

Ultimately, while the study remains in its early phases, the results from the SBR system have provided foundational insight into both the performance of different biochar types and the operational parameters required for credible carbon storage verification. These lessons are now being integrated into Lapwing's scaled repository systems and MRV strategies. Continued monitoring of the SBR and newly established demonstration sites will deepen understanding and ensure that the Reverse Coal model is underpinned by a scientifically rigorous, scalable, and transparent verification approach.

5.5 Environmental & Social Impacts

Within the scope of Phase 2, the direct environmental and social impacts are limited, as the project operates within an existing agricultural setting with minimal disruption. However, the wider benefits of the technology are unlocked at the commercial scale where there are significant opportunities for lowland peat restoration, carbon sequestration, and enhanced food production through Controlled Environment Agriculture (CEA).

5.5.1 Environmental Considerations

A key focus of the Reverse Coal project has been ensuring that feedstock sourcing and site operations adhere to sustainable principles. The project relies on sustainable biomass feedstocks, minimising land-use competition and reducing the risk of unintended environmental consequences.

During Phase 2 Lapwing has tried to help re-establish the biomass economy in Lincolnshire after major buyers withdrew from purchase agreements, leaving local growers with large areas of biomass but no guaranteed off-taker. This has led to overgrown biomass and created distrust with growers. To try and restore confidence, Lapwing has engaged with local growers, offering a stable market for sustainable biomass. Additionally, working with wildlife trusts, forest thinnings are another sustainable supply that support responsible land management.

Similarly, Lapwing was approached by a contractor working for the local highway authority to store chipped ash dieback, harvested along roads in the area until haulage offsite could be arranged. Following discussions with the plant designers, and sample testing at the UoL, the ash dieback chip was confirmed as suitable and purchased directly, and so forms another strand for the supply chain. Minimising haulage distances costs reduces costs by approximately 30%, and also presents a social benefit to the local authority, in reduced traffic levels and pollution by ensuring the carbon in the ash is retained and stored locally.

Additionally, Reverse Coal has retrofitted existing farm sheds and agricultural equipment for use in greenhouse gas removal technology, reducing the need for new infrastructure, equipment and limiting construction-related emissions.

Lapwing has also taken a proactive approach to the visual impact of the project, particularly regarding skyline visibility. The small stack and GCU have been carefully designed to minimise their visual footprint, ensuring that the facility does not significantly alter the local landscape especially from the vantage point of the closest village. This was a key consideration during the planning permission process, reflecting Lapwing's commitment to responsible development and community engagement. Greenhouse gas removal can be a divisive topic, tending to relate to the large capital expenditure and visual impact of developments. The focus of Reverse Coal has been to demonstrate that this technology can fit into existing agricultural businesses without negatively disrupting local environments.

Water conservation is another crucial element of Reverse Coal's environmental strategy. There are three water circuits and Lapwing has been able to design two as closed-loop circuits with the third to be investigated. This significantly reduces demand for potable water, improving sustainability while preventing excess wastewater discharge into the surrounding environment. This is an important factor given the increasing stress on freshwater resources particularly in the Midlands regions.

5.5.2 Social Impact and Future Opportunities

Since conception, Reverse Coal and the Lapwing Group have expanded to build a team capable of delivering Phase 2 while developing the wider Lapwing vision. Graduate researchers have been employed to support the project and to operate the pyrolysis plant, gaining hands-on experience in biochar production, carbon sequestration, and biomass processing. New roles have also been created to drive commercialisation, ensuring the project's long-term sustainability.

While the direct social impacts of Reverse Coal at this stage are limited, the future expansion at The Lapwing Estate will unlock broader economic and community benefits. The restoration of degraded lowland peat will contribute to climate resilience, reducing greenhouse gas emissions from peat oxidation while improving soil health and biodiversity. Additionally, this is the restoration of a lost heritage asset. The integration of CEA for enhanced food production will offer new opportunities for local employment and strengthen domestic food security, reducing reliance on imports and improving access to high-quality, nutrient-rich produce. These are key targets identified in the UK Government's food strategy.

As Reverse Coal scales, it has the potential to become a model for sustainable land management and carbon sequestration, demonstrating how innovative biochar technology can be integrated into existing agricultural landscapes to deliver both climate and community benefits.

5.6 Scaling

It is clear from innumerable discussions, that there is a massive appetite from investors for green projects. There are however barriers – chief of which is confidence that involvement would be as an investor with an expectation of a return, and not just as an altruistic benefactor. Investors need proof of technology, proof of concept, proof of business; and a clear plan for staged scaling. Despite the interest, the Phase 2 demonstrator can be just too small for some of those with billon-pound investment funds. They would gain more confidence from an intermediate stage of scaling, supported by a smaller scale investor who might then sell on before the next stage.

For biochar sequestration to form a significant part of any business model, investors will want to know that the Lapwing approach to MRV instils confidence in the long term. Having a shiny, well managed facility to show potential investors around will appeal, although for the farm-scale investors it still needs to visually fit as part of a wider farm, and not an unrelated off-site industrial development.

For all investors, endorsement by influential bodies adds real value. The endorsements and showcasing already provided in successive government publications are a fantastic addition to the project' credibility.

The team's aspiration is to successfully prove the Reverse Coal concept technically and commercially during the operational research and development stage of Phase 2, and then progressively build the model in successive stages. The ambition is to scale to 12 larger pyrolysis kilns running in parallel, capable of processing 350,000 tonnes of willow (from approximately 35,000 ha of SRCW).

To determine the appropriate finance options for the rethinking of farmed peatlands transformation model (at 3 proposed stages), it is necessary to determine the initial capital expenditure needed before ongoing revenues can support the model. This will impact the attractiveness of different finance options.

6 Business Plan

6.1 Next Stages

Post Phase 2, Lapwing initially intends to operate for 8-12 months, processing the remaining feedstock stockpiled on site to validate the pilot plant against the business model developed in Phase 2 before a decision on scaling to the next phase is made.

In Phase 1 the business model for Reverse Coal focused on the utilisation of electricity within farm operations and the burial of carbon for carbon credits as revenue streams. In summary the costs associated with running the pilot plant including the purchasing-in of willow, the cost of labour and materials to run the plant have all increased in cost. The price rises are highlighted in section 7.2.

As it stands there is no additional premium for the enhanced level of verifiable carbon removal that the Reverse Coal storage solution offers. The science by UKCEH indicates that biochar stored in Reverse Coal conditions offers greater permanence and carbon stability and Lapwing will continue to verify this. But as the voluntary market for biochar does not differentiate between 100 years and 1000 years permanence it does not currently give an additional financial incentive to bury biochar.

As the operational costs are continuing to rise and the value of carbon credits remains uncertain, Lapwing is having to re-evaluate the business model, investigating alternative feedstock supplies and markets for biochar. A consistent feedstock remains key for a consistent quality biochar and syngas composition.

6.2 Momentum

Throughout Phase 2 The Lapwing Estate has become a vibrant hub of innovation with numerous research projects hatching from the core Reverse Coal project. One of the most valuable outcomes from the Reverse Coal project has been the team built, growing UK capabilities of delivering innovative projects and carbon removal technology.

The Lapwing group has been exploring all parts of the system to identify new opportunities for co-benefits and new revenue streams. By combining innovative approaches and identifying other industries to decarbonise, the total costs of carbon removal fall.

Figure 6.2.1 provides a snapshot of the projects and themes the Lapwing group is investigating: Food production; Energy; and Water.

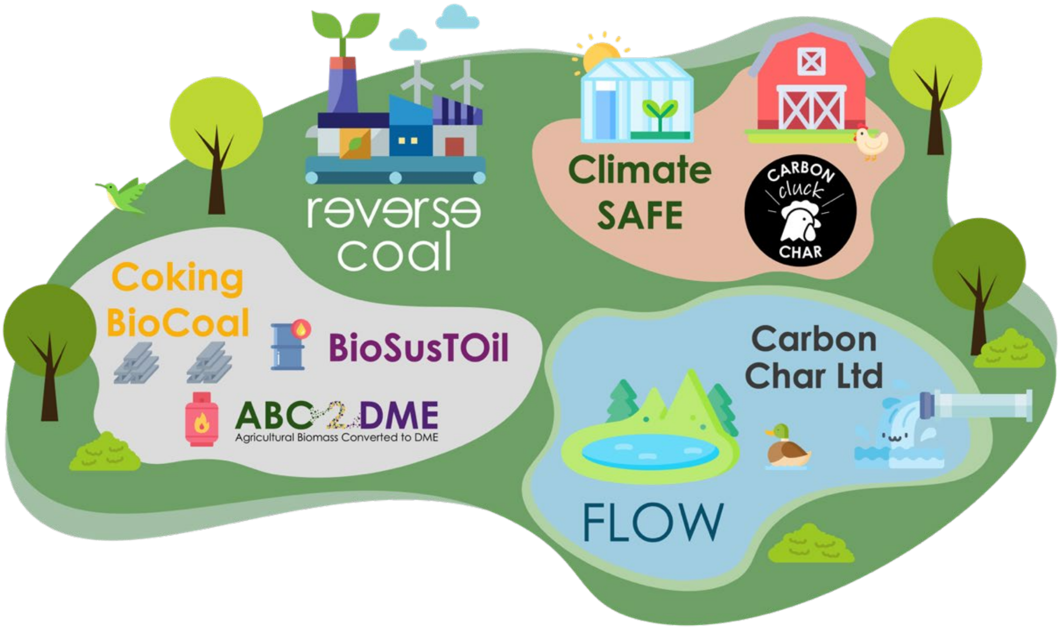

Figure 6.2.1 The Lapwing Estate hub of innovation with Reverse Coal as a central part

During Phase 2 the project team has been invited to attend and present at a broad range of events sharing the Reverse Coal vision. Some notable events include:

Figure 6.2.2. James Brown joined Tripurari Prasad (far left) & Mo Safdar (second to the left), as a panellist at the London Impact Investment Network hosted by Alex Miller (far right) (2025)

Figure 6.2.3. Jonathan White & Louis Mitchell interviewed as part of a Sky Business feature on safety in net-zero projects (2025)

Figure 6.2.4 James Brown presenting at the Lincolnshire Farming Conference (2024)

Figure 6.2.5. Jamie Smith presenting at the Bioladies Network at the Earlham Institute (2024)

Figure 6.2.6. James Brown visited 10 Downing Street to discuss improving water management and the reduction of herbicides to improve farm resilience (2024)

Figure 6.2.7. James Brown joining the panel at the Greater Lincolnshire LEP Conference (2023)

Figure 6.2.8. The Lapwing Estate hosting a CLA site visit (2023)

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Case study:
Greenhouse Gas Removal

Lapwing Reverse Coal Project:

Novel engineering of a natural solution will enable the removal of CO2 from the atmosphere to lock it back in the ground.

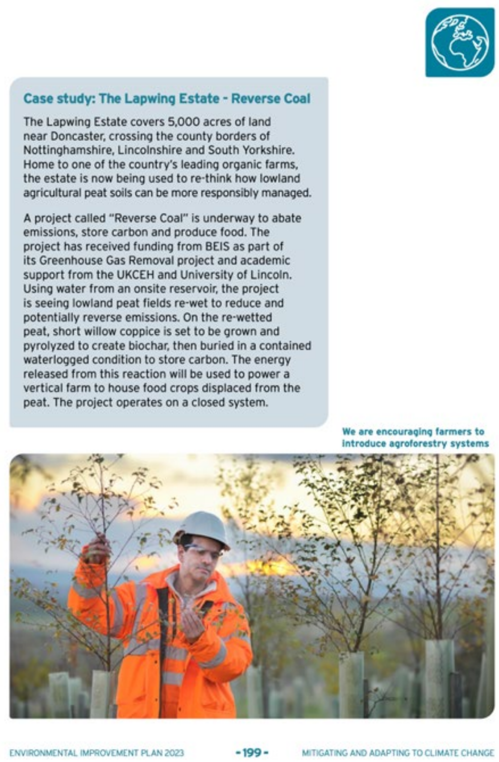
The Lapwing Estate sits on lowland peat which has been historically drained and farmed for organic food production. These practices have degraded the soil and led to greenhouse gas emissions as the peat oxidises (lowland peat is responsible for 3% of UK GHG emissions).

Reverse Coal was awarded nearly £3 million through NZIP's Greenhouse Gas Removal and Direct Air Capture innovation programme. To capture carbon dioxide and abate existing emissions, they will rewet the peat and establish fast growing willow crops which will be chipped and dried and then fed into a high temperature pyrolysis plant. This plant converts the willow (biomass) into a solid form of carbon akin to coal, called 'biochar'. The biochar is then expected to be buried for long term storage of CO2. The heat and power generated from the biochar production are directed into controlled-environment agriculture, for example heating greenhouses for more sustainable and secure food production.

"We are grateful to BEIS for backing us to develop our novel Reverse Coal approach as a pioneer in this space. This support extends beyond the pure financial investment and associated boost to credibility, to project oversight through regular reviews, extending our networks and enhancing our collective knowledge."

CEO James Brown

This project is exploring an innovative new way to sustainably intensify production of high quality, healthy food, whilst at the same time supporting the government's target for net zero by 2050.



Case study: The Lapwing Estate - Reverse Coal

The Lapwing Estate covers 5,000 acres of land near Doncaster, crossing the county borders of Nottinghamshire, Lincolnshire and South Yorkshire. Home to one of the country's leading organic farms, the estate is now being used to re-think how lowland agricultural peat soils can be more responsibly managed.

A project called "Reverse Coal" is underway to abate emissions, store carbon and produce food. The project has received funding from BEIS as part of its Greenhouse Gas Removal project and academic support from the UKCEH and University of Lincoln. Using water from an onsite reservoir, the project is seeing lowland peat fields re-wet to reduce and potentially reverse emissions. On the re-wetted peat, short willow coppice is set to be grown and pyrolyzed to create biochar, then buried in a contained waterlogged condition to store carbon. The energy released from this reaction will be used to power a vertical farm to house food crops displaced from the peat. The project operates on a closed system.

We are encouraging farmers to introduce agroforestry systems

ENVIRONMENTAL IMPROVEMENT PLAN 2023 - 199 - MITIGATING AND ADAPTING TO CLIMATE CHANGE

Figure 6.2.9. & 6.2.10 NZIP Progress Report 2021-22 & Environmental Improvement Plan 2023

The Reverse Coal project would not have been possible without the backing of the Department for Energy Security and Net Zero as well as the Department for Environment Food and Rural Affairs, Natural England, The Lapwing Estate, UK Research and Innovation, IDRIC, and the Environment Agency.

This support has vindicated The Lapwing Estate vision and noteworthy recognitions & industry validations include:

- Featured in the UK Net Zero Innovation Portfolio Progress Report (2021-22).
- Case study in the UK 2023 Environmental Improvement Plan.
- Highlighted in Powering up Britain: Net Zero Growth Plan (2023).
- A visit by the Environment Agency main board (2023)
- Included in the Midlands Engine Food White Paper (2024).

6.3 Dependencies & Uncertainties

As Reverse Coal moves beyond the Phase 2 pilot stage, there are several factors that will influence how successfully the project can scale. Some of these, like feedstock supply and carbon markets, are external and difficult to control, while others, like how biochar storage is verified for carbon credits, will require ongoing work with UKCEH to refine and prove. Sections 2.3, 4.5 and 5.3 emphasise these dependencies & uncertainties.

First and foremost, the project is dependent on the long-term reliability and performance of the pyrolysis plant and associated systems, including the gas clean-up unit and energy generation infrastructure. At the time of writing, the facility has not yet undergone extended continuous operation. As a result, Lapwing is not yet in a position to fully assess the ongoing performance of key components such as the kiln, gas engine, SACTO, and condensate treatment systems. Their durability, maintenance cycles, energy balance, and responsiveness to variable feedstock inputs remain to be tested at scale over time.

The wider investment landscape is another factor to consider. There had been growing interest in green finance and carbon removal, but large-scale institutional investors are looking for proven, revenue-generating projects before committing capital. There is a current but hopefully temporary global shift away from prioritising Net Zero which may disrupt the immediate momentum of GGR technology. However as Reverse Coal has always had a holistic focus on Net Zero, food security, energy security and water security, Lapwing is confident that the same ends can be achieved even if driven by other priorities.

While Lapwing has proactively mitigated many risks and developed a flexible, modular system, some key dependencies and uncertainties can only be addressed through the experience and data gathered during prolonged operation of the pilot plant. The coming 6–12 months of full system operation will be critical in converting these unknowns into validated learning, enabling stronger projections, de-risked expansion, and full commercial rollout.

7 Route to Market

As highlighted in figure 6.2.1, the Lapwing group is actively researching new revenue streams and routes to market that can be tapped into. Some opportunities can be directly unlocked from the Reverse Coal plant like providing biochar to the steel industry as a coking coal substitute, whereas others like developing BioDME from syngas and activated carbon for water industries will require further investigation. In summary the Lapwing group is under NDA with all customers as Lapwing develops bespoke solutions.

7.1 Commercialisation

Throughout Phase 2, a strong focus has been placed on commercialising Reverse Coal to establish it as the leading biochar burial standard for long-term carbon sequestration. The ambition is to create a "gold standard" greenhouse gas removal solution by delivering permanence of over 1,000 years—validated by a robust, patent-protected burial methodology.

Lapwing has actively pursued commercial opportunities, including the patenting of its novel carbon storage process and trademarking the 'Reverse Coal' biochar brand to protect integrity and ensure quality.

The commercialisation effort has also catalysed the development of a highly skilled team. Phase 2 has equipped Lapwing with unique expertise across pyrolysis operations, feedstock logistics, biochar production, and carbon credit certification. This positions the company to scale Reverse Coal through two key commercial deployment pathways: turnkey delivery of pyrolysis systems to third parties and a hub-and-spoke model aggregating biomass to central processing sites—mirroring the successful sugar beet industry structure.

Revenue streams under development include electricity, heat, biochar, carbon dioxide, and carbon credits. A 1.6–2.0 GWh/year generation capacity enables Lapwing to substitute costly imported electricity, offering significant savings across its wider farming operations. While heat currently has limited value due to distribution constraints, potential uses under evaluation include CEA, food-grade CO_2 production, or even converting heat into electricity via Organic Rankine Cycle (ORC) systems.

Biochar markets are evolving, and the voluntary carbon market flexibility in separating the carbon credit from the physical biochar enables participation in both high-value industrial decarbonisation applications and regenerative agriculture. Plans are underway to functionalise biochar as a carrier for bio stimulants, unlocking immediate farmer value while maintaining the sequestration benefit.

Two clear pathways for future scale-up have been defined. First, enabling third-party landowners to deploy Reverse Coal systems through licensing and consultancy. Second, expanding Lapwing's own capacity at Oatlands and a second site already secured, consolidating regional biomass through a hub-and-spoke model. Both strategies maintain focus on permanence, profitability, and replicability—ensuring Reverse Coal can become a cornerstone of the UK's carbon removal and land restoration agenda.

7.2 Barriers & Risks

The commercialisation of large-scale biochar production and carbon sequestration projects presents multiple challenges, including financial, regulatory, and market-related obstacles. While the early stages of development may benefit from government funding and pilot projects, transitioning to a fully market-driven model requires careful planning. Key barriers include securing consistent revenue streams, managing infrastructure costs, obtaining necessary permits, ensuring long-term feedstock supply, and mitigating financial risks associated with investment and land acquisition. Addressing these challenges is critical for scaling up operations while maintaining financial viability and long-term sustainability.

7.2.1 Financial Viability and Revenue Streams

A major hurdle in commercialisation is ensuring that operating revenues exceed costs once external funding support ends. Potential income sources include surplus electricity sales, biochar production, and heat generation. However, electricity markets are volatile, and securing stable purchase agreements remains a challenge. Internal energy use agreements, such as direct power supply to nearby operations at the farm, may improve financial predictability, but long-term external sales are subject to fluctuating market prices.

Biochar presents another uncertain revenue stream. While it has promising applications as a soil amendment, carbon sequestration tool, and industrial feedstock, market demand is still developing. Regulatory frameworks around biochar certification and carbon credit eligibility further complicate pricing and sales strategies. Ensuring that biochar can be effectively monetised through carbon credit schemes or industrial adoption is essential to Lapwing's financial success.

Supplementary revenue opportunities, such as biodiversity net gain (BNG) credits and water management services, could contribute additional income. However, these markets are still emerging, and pricing remains uncertain. Industrial partnerships, such as biochar supply agreements with steel, cement, or water industries, offer long-term potential but require significant engagement and validation.

7.2.2 Infrastructure and Grid Connectivity Challenges

Expanding biochar production at scale requires substantial investment in infrastructure. One of the primary challenges is power transmission. Even at moderate production scales, grid connectivity costs can be significant. Large-scale facilities, particularly those exceeding 30 MW of generation capacity, may require costly grid upgrades, additional transmission lines, and negotiations with national utilities. Without guaranteed grid access, surplus electricity generation may be wasted, reducing financial viability. Grid connectivity was a major hurdle to be overcome as part of the Reverse Coal project.

An alternative is direct internal use of generated power, such as supplying heat and electricity to controlled environment agriculture (CEA) operations. This approach reduces dependency on grid exports but requires integrated planning between energy production and agricultural demand. Transmission costs can be further mitigated by co-locating facilities near high-energy-demand operations, such as greenhouses or industrial processing sites.

Given the grid connectivity charges, Lapwing is exploring the opportunity to convert syngas to BioDME as it would offer an off-grid solution for quite literally bottling and selling energy generated by the plant.

Permitting and environmental regulations add another layer of complexity. While small-scale projects may operate under existing agricultural classifications, larger facilities often require environmental impact assessments, air quality permits, and planning approvals. These processes can introduce delays, increase costs, and require ongoing compliance monitoring. Engaging with regulators early and ensuring alignment with national climate policies can help streamline approvals.

7.2.3 Feedstock Supply and Land Use Considerations

Scaling biochar production requires a consistent and sustainable biomass supply. SRCW is a preferred feedstock due to its rapid growth and high carbon capture potential. However, demand for willow and other biomass sources may exceed local availability, necessitating partnerships with additional growers or alternative biomass sources. Lapwing has identified willow growing along the SSSI on The Lapwing Estate, but the costs of removal and permissions have proven that it could be almost twice the cost to harvest as commercially available willow.

Land-use changes required for large-scale biomass production, particularly peatland rewetting for paludiculture, must balance food security and environmental considerations. While restoring degraded peatlands contributes to carbon abatement, it can reduce arable land availability, potentially shifting food production to other areas and increasing global environmental impacts. Strategic land management planning is required to ensure sustainable biomass production without unintended consequences.

Acquiring or securing long-term land leases is another financial challenge. Large-scale expansion requires either outright land purchases or long-term lease agreements with landowners. Purchasing significant land areas involves high upfront capital costs, while leasing requires ongoing financial commitments. For example, securing 35,000 hectares for biochar production could cost over £1 billion in land purchases or £140 million in initial lease payments. Structuring land agreements to align with project revenues and long-term sustainability is crucial to commercial success.

7.2.4 Market and Policy Uncertainty

Refer to sections 4.6.2, 4.6.3 and 4.6.4.

7.2.5 Investment and Financing Strategies

Given the high capital requirements for Lapwing's commercial-scale biochar operations, securing investment while maintaining financial control is a key challenge. Traditional debt financing, green bonds, and structured investment vehicles such as Special Purpose Investment Vehicles (SPIVs) offer potential solutions.

Equity crowdfunding may be viable for smaller-scale projects but poses risks at larger scales due to ownership dilution. Institutional investors, including pension funds and infrastructure funds, may be more suitable for large-scale financing. However, attracting such investment requires well-defined revenue models, long-term agreements, and regulatory certainty.

Industrial partnerships offer another avenue for securing funding. For example, companies seeking to offset carbon emissions under the UK Emissions Trading Scheme (ETS) could invest in biochar production in exchange for long-term supply contracts. Similarly, energy-intensive industries could pre-purchase biochar to reduce their carbon footprint and regulatory obligations. These structured agreements could provide upfront capital while ensuring stable long-term demand. This is the approach being taken to develop BioDME.

7.2.6 Opportunities in the Humber Industrial Cluster

Integration with existing industrial hubs, such as the Humber Industrial Cluster, presents a strategic opportunity for large-scale biochar projects. The Humber region is the UK's largest industrial emitter of CO_2, making it a key focus for decarbonisation efforts. Biochar could be used as a coal and coke substitute in steel and cement production, helping industries reduce emissions and comply with regulatory requirements.

Additionally, biochar can be refined into activated carbon for applications in chemical and water treatment industries. Research has also shown that willow-derived biochar has potential as a feedstock for energy storage technologies, including supercapacitors. These alternative applications create additional revenue opportunities and expand market potential.

Industrial bioremediation is another area of interest. Research has demonstrated that willow plantations can effectively treat landfill leachates and improve soil quality. Integrating biochar production with industrial remediation services could generate new revenue streams while enhancing the environmental benefits of land restoration projects.

Hydrogen production and floating solar energy systems also offer synergies with large-scale biochar facilities. Co-locating renewable energy assets with biochar production can optimise land use and create diversified energy solutions for industrial users. Long-term leasing agreements for renewable energy installations, such as floating solar on reservoirs, could generate stable income while reducing project financing requirements.

Figure 7.2.6 The Lapwing Estate reservoir with floating solar

Commercialising large-scale biochar and carbon sequestration projects requires overcoming financial, regulatory, and market challenges. Ensuring stable revenue streams, securing land agreements, and managing infrastructure costs are critical to success. While uncertainties remain in carbon credit markets and industrial adoption, strategic investment, industrial partnerships, and regulatory engagement can help mitigate risks.

By integrating biochar production with industrial decarbonisation initiatives, sustainable agriculture, and biodiversity enhancement, large-scale projects like Reverse Coal can create long-term value while contributing to net-zero goals. A phased implementation strategy, supported by diverse financing mechanisms and market-driven solutions, will be essential in achieving commercial viability.

7.3 Wider Benefits

As highlighted in section 5.5, the scope of Phase 2 of Reverse Coal is from woodchip bought in to biochar burial and electricity production. At the commercial scale the landscape solution 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 fulltime jobs replacing zero hours seasonal contracts

The Lapwing vision provides a globally leading BECCS/Biochar solution creating a 1Mt contribution to net zero that yields bioenergy and carbon storage without jeopardising food security.

7.4 Job Benefits

Currently, the pilot plant requires two full-time operators working alternating shifts, but as the Oatland site scales, the economy of scale improves, allowing the same number of operators to manage multiple kilns simultaneously.

The integration of year-round Controlled Environment Agriculture (CEA) will help reduce reliance on hard-to-fill seasonal jobs, replacing them with higher-value, long-term positions that require technical and green skills. Across multiple sectors, the project is expected to create approximately 1,100 new jobs, spanning biochar production, carbon storage, agriculture, and engineering.

Additionally, the regional economic multiplier effect is estimated at 5x, meaning that over 5,500 jobs will be generated through supply chain growth, indirect employment, and supporting industries, making Reverse Coal a major driver of employment and sustainability-led economic development.

7.5 Carbon Savings

The core purpose of Reverse Coal has been biochar production for carbon burial and sequestration. While biochar burial can support carbon sequestration goals, its economic feasibility depends on viable storage or utilisation pathways. Similarly, syngas offers potential for conversion into low-carbon fuels, but market conditions, regulatory incentives, and infrastructure costs need must be carefully assessed. The financial and structural implications of these choices significantly impact the long-term bankability of such projects. We have investigated other opportunities to capture CO_2 from the process and prevent re-emissions.

Carbon capture technologies provide several pathways to reducing emissions, but each comes with cost considerations and operational challenges. Traditional post-combustion capture (PCC) using amine-based solvents is widely used but requires significant capital investment and ongoing operational costs. Newer solvent-based systems with reduced environmental impact could offer alternatives, though their commercial readiness varies.

Another option is CO_2 utilisation in CEA, where captured emissions can enhance plant growth in greenhouses. Large-scale agricultural operations could absorb a significant portion of emissions, reducing the need for costly sequestration. However, demand fluctuates seasonally, limiting year-round applicability.

Industrial partnerships for CO_2 sequestration provide another route, especially in regions with established carbon storage initiatives. Infrastructure investments such as CO_2 pipelines to nearby sequestration sites could enable long-term storage, aligning with national decarbonisation strategies. The feasibility of such projects depends on policy incentives, carbon pricing stability, and the willingness of industrial emitters to collaborate on shared infrastructure.

Emerging CO_2-to-product technologies, such as algae-based conversion systems, offer alternative monetisation strategies. These processes can convert emissions into high-value products like bio-based animal feed or specialty chemicals. While promising, these technologies require further scaling before they become commercially viable.

8 System Technology Rollout

Over 300 people from approximately 50 companies have contributed to the Phase 2 pilot project to develop an integrated project delivery team with the requisite skills to scale the pilot plant and roll out Reverse Coal hubs across the UK.

As mentioned in section 3.1, so far Phase 2 has only been able to demonstrate short runs of the pyrolysis kiln, producing biochar and validating basic operational functionality. These initial runs have provided valuable early data on feedstock flow, thermal control, and product output, but the plant has not yet undergone a fully integrated extended continuous operation. Extended runs are crucial to determining if the model is financially viable.

Lapwing plans to persevere and get the pyrolysis plant fully operational. To enable this, Lapwing has purchased approximately 8 months' worth of feedstock, which is now held in readiness on site. This initial operational period will be used to determine if the plant can run commercially. The intended plant life is 20 years. In parallel, Lapwing will continue to investigate potential feedstock opportunities and also associated revenue streams that can stack up so that the Reverse Coal financial model and business case are proven to be viable on an ongoing basis.