The Future Forest Company

"Enhanced Weathering of basalt rock as a method of atmospheric CO_2 removal"

Phase 1 Design Study Report

(Public Release)

for

The Department of Business, Energy, and Industrial Strategy

under the

Direct Air Capture and Greenhouse Gas Removal Competition

Contract THE20205

Project Start: 6th April 2021

Project End: 24th December 2021

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Contents

1. Executive Summary

Enhanced Weathering is the acceleration of the natural weathering of basalt, a process which sequesters huge volumes of carbon over geological timescales. The purpose of this project is to demonstrate the commercial viability of accelerated weathering, underpinned by peer-reviewed science and an operational model.

The Future Forest Company has advanced its Enhanced Weathering project rapidly through 2021. We have employed a growing team of researchers, project managers, scientists and analysts to further our understanding of Enhanced Weathering as a commercial operation.

Based on peer-reviewed research, we have developed and refined a proprietary model to estimate carbon dioxide sequestration by weathering over time which is explained in Section 2. In parallel, we are working with two internationally recognised agencies to generate methodologies to allow third-party verification of our carbon removal from Enhanced Weathering activities. Both approaches are market-leading and will set conditions for further Enhanced Weathering projects worldwide.

We have also undertaken extensive research into the risks of spreading basalt and its potential for sequestration and the co-benefits to agriculture and forestry. This balance is discussed briefly in Section 2.

Based on our proprietary basalt weathering model and our in-house best-practice protocols for spreading basalt, we have moved from our bench-scale Phase 1 trial on our own estate, through to a commercial trial with a third-party landowner in the space of a year. This commercial trial, referred to throughout this report as the 1k-tonne trial, will sequester 200 tonnes of CO_2 over its lifetime, 50% of which will be captured within 12 years. This proposal builds on the 1k-tonne trial, and focuses on additional comminution to increase weathering rates during Phase 2.

In this Design Study Report we show how we can increase the rate of weathering, and hence the rate of CO_2 sequestration, beyond that shown in our trial application. We propose a specific project to conduct further crushing of the basalt to accelerate weathering rates to the limits of commercial viability.

Successfully increasing the rate of weathering hinges on reducing the particle size and increasing the reactive mineral surface area of commercially available basalt. The challenge is to do so whilst ensuring crushing is both commercially viable and environmentally sustainable. In Section 3 we detail the engineering design for a facility to achieve this.

Our Phase 2 project plan is nested within the wider expansion of our Enhanced Weathering programme. The experience which the Future Forest Company gains in parallel to Phase 2, particularly around data capture, carbon modelling and verification will allow us to integrate our Phase 2 project into our commercial operations on completion of the BEIS GGR Programme. The project plan for Phase 2 is laid out in Section 4, with a breakdown of associated costs, and is deliverable in significantly less than the three-year timeline envisaged in the GGR competition.

Our modelling suggests that the project will sequester up to 260 tonnes of carbon dioxide as a result of the operations at our site. Subject to adjustments to the project scope, it could sequester up to a further 21,000 tonnes of CO_2 into early 2023. Beyond the project window, the equipment purchased will be run on a commercial basis to sequester up to 25,000 tonnes of CO_2 per annum until the end of life of the equipment (likely 2027). This run-rate would make the UK a world leader in atmospheric carbon dioxide removal and would far exceed the current market supply.

Accelerating the rate of sequestration through additional comminution as outlined in this report presents considerable commercial risk. The process which we propose sits at the limit of the capability of commercially available machinery and thus, without Government backing, it is highly unlikely that any business would raise the capital required for a large-scale trial. We propose this project because we believe that time is not on our side; we must explore every possible avenue to remove atmospheric carbon dioxide as fast as human ingenuity allows.

Our proposal offers the opportunity for the UK to lead atmospheric carbon removal at scale. The co-benefits of the programme include job and knowledge creation, with opportunities to sell services and consultancy abroad; support to sustainable agriculture and forestry; and, a platform for further world-leading research.

2. Scientific Outline

Enhanced Weathering

Enhanced weathering (EW) refers to the acceleration of the natural process of weathering (the chemical and physical breakdown of rocks) through the spreading of readily dissolvable, finely crushed silicates (such as basalt) across large areas of land. Atmospheric CO_2 dissolves in rainwater to form weak carbonic (HCO_3^-) acid, which then dissolves the finely crushed basalt, releasing solutes such as calcium (Ca^{2+}) and magnesium (Mg^{2+}). These solutes are transported via rivers to the oceans, where CO_2 is permanently locked up by the precipitation of carbonates ($CaCO_3$). When deployed at scale, this process has the potential to sequester megatonnes of atmospheric carbon dioxide.

Basalt Weathering Model

We are using a peer-reviewed, published one-dimensional geochemical reactive transport soil process basalt weathering model to estimate CO_2 removal and mineral weathering over multi-year timescales. The model inputs information on the basalt mineralogy, particle size and surface area, density of application (in tonnes per hectare), coupled with soil chemical and physical parameters and climate data relevant to local site-specific conditions.

The output of the model (shown schematically below in Figure 1) shows the change in mineral solubility over time as weathering progresses and reactive minerals dissolve (Figure 1A). The model also generates an estimation of the cumulative tonnes of CO_2 removed per hectare over time (Figure 1B). These outputs are based on experimentally derived kinetic and thermodynamic data for weathering reactions using published geochemical databases.

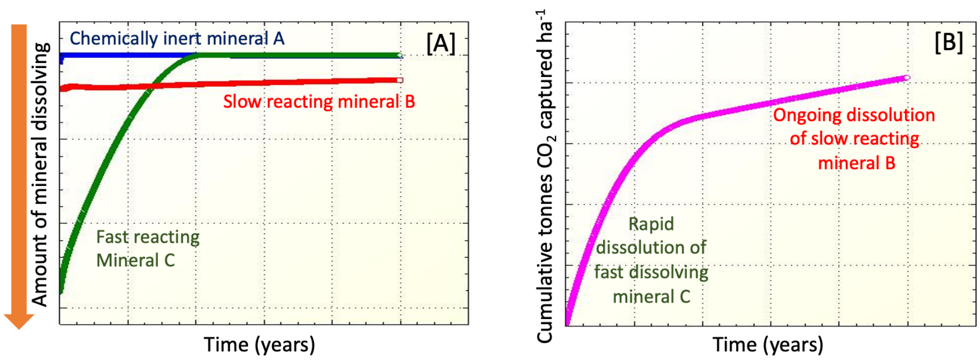

Figure 1: Schematic representation of the output of the 1D geochemical reactive transport basalt weathering soil profile model. Shown on the primary axis in [A] is the amount of mineral dissolving over time for a stable, chemically inert mineral (shown in blue) that does not dissolve under the conditions of the model, as well as dissolution of slow- (red) and fast-weathering (green) minerals. Figure [B] shows the schematic cumulative tonnes of CO_2 removed per hectare over time due to basalt weathering, with rapid weathering of the fast-weathering minerals contributing to initial CO_2 sequestration, and ongoing dissolution of slow reacting minerals as weathering progresses.

Weathering rates, and hence the timescales of CO_2 sequestration are highly dependent upon site-specific conditions. We are currently in the process of refining the model using input parameters derived from site-specific data obtained from the 1k-tonne trial. We are using the basalt geochemical and mineralogical composition of the basalt spread; local climate variables (such as precipitation, air temperature) obtained from high-resolution, long-term data from the UK Meteorological Office; soil chemical and physical properties, and land use and crop type determined from the baseline soil survey of the 1k-tonne trial site.

Soil baseline surveying

Thorough soil surveying and sampling of the site was conducted to establish the soil chemical and physical properties (e.g., pH, soil type, etc) prior to spreading for the 1k-tonne trial. This baseline will allow us to monitor and verify carbon sequestration after spreading. A lightweight all-terrain vehicle, fitted with gamma-ray detection sensors, was driven over the fields to measure the signal response, which was then confirmed by taking additional in-field soil samples to allow for the measurements to be correlated to soil chemical and physical properties. This resulted in the generation of field-scale maps (e.g., soil pH shown in Figure 2) which highlights the high degree of spatial variability of the soils. It will be critical to assess the importance of such variability on modelled CO_2 sequestration, which will be assessed by performing a sensitivity analysis.

Figure 2: Soil gamma-ray pH map for the fields spread on for the 1k-tonne trial. Black dots show location of physical soil samples taken to groundtrouth the gamma-ray signal. Field names redacted.

Particle Size and Surface Area

The importance of particle size in accelerating weathering to enhance CO_2 removal is well documented. A key challenge for upscaling Enhanced Weathering is related to the further processing of basalt quarry fines in order to decrease the particle size and increase the reactive mineral surface area to achieve desirable weathering rates in soils over meaningful timescales. Specific surface area (a function of particle size and shape) is one of the key determinants for weathering rates, shown in Figure 3. Increasing the specific surface area of the basalt through further processing of quarry fines would dramatically speed up the weathering rates and hence increase carbon dioxide removal potential over a shorter time period. Further comminution of basalt, particularly of basalts containing high proportions of slower-reacting minerals would open the range for commercially viable basalts, and thereby increase the overall potential for carbon sequestration through Enhanced Weathering. In Section 3 we detail the engineering design for a proposed facility to achieve this.

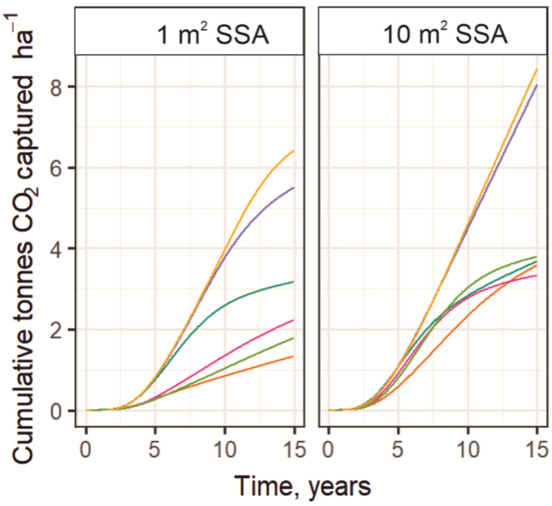

Figure 3: Modelled cumulative tonnes of CO_2 removed per hectare for six different types of basalt with specific surface areas (SSA) of 1 and 10 m^2 g^{-1} (Modified after Lewis et al., 2021). Higher SSA's (and hence smaller particle size) result in faster weathering and hence greater CO_2 removal potential over the modelled 15-year period.

Methodology for quantification and verification of CO_2 removal

We are currently developing an in-house methodology to allow for the monitoring, reporting and verification (MRV) of CO_2 removal from Enhanced Weathering activities. This will form the basis of a new, verified carbon methodology for Enhanced Weathering with internationally recognised carbon standards organisations. We are working with several of the leading carbon standards bodies and expect to have methodologies approved by the end of May 2022. The first of our commercial Enhanced Weathering projects will be certified to produce carbon credits by September 2022.

The methodology we are developing will use a 'model and measure' approach, where CO_2 removal will first be estimated using a location-specific 1D geochemical reactive transport soil profile model. CO_2 sequestration will then be measured and verified at specified time intervals in order to assess CO_2 sequestration and 'true up' the model.

Prior to spreading, thorough soil surveys will be conducted to conduct a baseline against which to compare future CO_2 sequestration. This will help determine critical input parameters to the carbon sequestration model, such as: basalt geochemical and mineralogical composition; climate variables (such as precipitation, air temperature); soil chemical and physical properties (e.g., pH, soil type, etc); land use and crop type; etc.

After spreading, the sites will be subjected to measurement and quantification of inorganic carbon concentrations in order to ensure, and verify, that CO_2 removal is occurring; this will allow us to refine our model. A secondary purpose of the monitoring is to ensure there are no adverse impacts from toxic metal release or pH changes to the environment or ecosystems from commercial scale Enhanced Weathering activities.

The methodology will be combined with a detailed life-cycle analysis (LCA) which covers all carbon emissions from grinding, transport and spreading in order to ensure the entire project is CO_2 negative.

Carbon Life Cycle Analysis

Because basalt fines are a by-product of the aggregates industry, the life-cycle analysis for Enhanced Weathering begins with the existing basalt fines. The life cycle analysis then accounts for the additional processing (crushing), haulage and spreading (including intermediate handling), all of which are Scope 1 emissions. The analysis then goes carbon negative at the point at which the volume of carbon sequestered has surpassed that expended in the process.

Measuring the emissions associated with the process is relatively straightforward with sufficiently advanced data capture. The Department for Environment, Food and Rural Affairs (DEFRA) provides emissions factors per mile for haulage. We will use established systems to capture mileage, and measure fuel use associated with spreading. The emissions from additional grinding can also be directly accounted for through fuel use. The generic Life Cycle Analysis for our Enhanced Weathering process is at Appendix 1, and the specific Life Cycle Analysis for Phase 2 is detailed in Section 4. Our 1k-tonne trial showed that it was possible to operate with emissions of approximately 5% of the total sequestration.

Environmental Impact

It is important to assess whether there are any negative impacts on ecosystem, hydrology, or humans from Enhanced Weathering activities. The primary risk from large-scale spreading of basalt is the potential contamination of soils by toxic metals (e.g., copper (Cu), cadmium (Cd), chromium (Cr), mercury (Hg), nickel (Ni), lead (Pb) and zinc (Zn)x). In order to ensure a low risk of contamination to the environment from spreading basalt, every potential basalt source will first be geochemically screened using an internationally certified and accredited ISO 17025 laboratory. We will maintain this quality assurance by continuing to sample every 10k-tonne batch of the quarry fines used in our operations. These heavy metal concentrations will be compared against UK and European soil and environmental protection agency guideline soil guideline 'trigger values' to mitigate the risk of contamination (Table 1). From the 1k-tonne trial, it can be estimated that the maximum concentration changes after spreading will be insignificant (<5%) when compared to the average soil background values at the 1k-tonne trial site.

	Copper [Cu] (mg/kg)	Cadmium [Cd] (mg/kg)	Chromium [Cr] (mg/kg)	Cobalt [Co] (mg/kg)	Mercury [Hg] (mg/kg)	Nickel [Ni] (mg/kg)	Lead [Pb] (mg/kg)	Zinc [Zn] (mg/kg)
1k-tonne basalt quarry fines concentrations	**58.0**	**0.7**	**64.0**	**43.0**	**0.02**	**56.0**	**6.0**	**130**
1k-tonne topsoil background concentrations (EU LUCAS)	12.7	0.1	34.8	9.3	0.07	37.9	25.8	61.1
UK soil guideline values	35.1	0.6	-	4.2	-	28.2	-	35.6
EU Agricultural soil guideline values	100	1	100	20	0.5	50	60	200
% change to soil background concentrations	**2.8**	**4.8**	**1.1**	**2.8**	**0.2**	**0.9**	**0.1**	**1.3**

Table 1: The concentration in the soil after spreading is estimated by assessing the upper 30 cm of the soil, assuming a basalt spreading density of 20 tonnes per hectare, assumed soil bulk density of 1100 kg/m^3, the heavy metal concentration in the basalt, as well as determining the maximum background concentration of the heavy metal in the area where the basalt will be spread from the European Land Use and Cover Area frame Statistical survey (LUCAS topsoil survey).

Ongoing monitoring of soil and soil pore water concentrations will be carried out to assess the release of toxic metals during weathering, and to ensure any long-term risks remain low from repeat applications.

A second potential environmental risk is contamination of basalt run-off into waterways causing siltation and increasing turbidity of local waterways and potentially affecting the ecosystems. In our commercial operations, we are working with competent landowners and operators to ensure adherence to the relevant quality assurance standards, codes of good practise and environmental impact guidelines (e.g., Prevention of Environmental Pollution From Agricultural Activity (PEPFAA) and woodland creation Woodland Carbon Code (WCC) code) to minimise environmental impacts (e.g., use of buffer strips and maintaining suitable distances from watercourses to reduce surface run-off).

The final environmental risk is damage to sensitive ecological systems due to spreading activities. To militate this risk, we will not spread on natural ecosystems (e.g., peatlands or acid soils). The most natural classification of land we will spread on is improved pasture land, which has a low ecological value and is highly unlikely to be compromised by the spreading process. A preliminary ecology survey was conducted at Phase 2 site in October 2021 (Appendix 2), which identified areas of grassland that are suitable for Enhanced Weathering activities, as well as some peat areas that are unsuitable. A full site ecological and environmental impact survey of Phase 2 site will be conducted in the summer 2022.

Agricultural Benefits

Basalt has been used for decades as a soil enhancer. There is strong anecdotal evidence for the use of basalt as a natural fertiliser to improve soil pH, water retention, microbial activity, in general the plant growth and the soil structure. To date, few scientific studies have investigated the nutrient release (e.g., phosphorus, potassium, nitrogen) during basalt weathering to reduce dependence on conventional chemical-based fertilisers, pesticides and herbicides and increase soil organic carbon sequestration. Whilst this is not the primary objective of the project, it has the potential to be a very important co-benefit and will be the focus of ongoing research in parallel to quantifying and verifying carbon sequestration.

3. Engineering Design

Overview

We contracted a UK-based, market-leading consultancy to undertake a review of available crushing technologies and make recommendations on equipment selection and flowsheet configuration. Through their access equipment manufacturers, they were able to generate estimates of capital expenditure, operational costs, water and power consumption for several solutions and to arrive at the recommendation below.

The design which we propose can take existing quarry products and further crush them to accelerate weathering rates. This ensures that sequestration occurs within a meaningful time period, rather than decades into the future. Our preferred engineering design can process 75 tonnes of basalt per hour and, assuming a downtime of 10% over the working year, this design is capable of producing up to 130k-tonnes of crushed basalt per year. Once applied, we would expect this volume of basalt to sequester 20,000 - 25,000 tonnes of CO_2 per annum within 5-10 years of application.

The capital and operating costs of this design are captured in Section 4.

Assumptions

A number of assumptions underpinned this design:

- The feedstock for the process can be drawn directly from existing quarry operations, thereby minimising its moisture content.
- The feedstock is a pure basalt with impurities (clays and other contaminants) forming <1% of the total.
- To minimise capital expenditure and commercial risk, the crushing process will be conducted using commercially available equipment rather than developing bespoke machinery.

In light of what we had learnt throughout Phase 1, the following comminution index values were used as the basis for equipment sizing and design:

1. Crushability Work Index = 16 kWh/t
2. Abrasion Index = 0.2 – 0.22
3. Bond Ball Work Index = 18 – 20 kWh/t

The particle size distribution of a sample from the quarry used in the 1k-tonne trial informed the engineering design, as it represented the optimum material available to us at the time.

Process Review

In its most simple form, the process required to generate our desired product from the existing available feedstocks requires two major pieces of equipment: a crusher to reduce particle size and a screen to ensure the target size is achieved. The selection of the type of crusher and screen will affect the product particle size distribution, power requirements, CAPEX and OPEX.

Four equipment suppliers were contacted. Three of the suppliers recommended crushers but one indicated that in their view milling was required. This recommendation was discounted due to the high CAPEX required, which would have set the project outside of the boundaries of Lot 1, and our analysis centred on crushing and screening.

Simulation

A set of software designed by an Original Equipment Manufacturer (OEM) was used for the simulation of the process. Although this generated a simulation based on the OEM's own equipment, it gave a good approximation for similar equipment across the industry.

The software was used to replicate the circuit configurations suggested by two of the three equipment suppliers and was used to explore the effect of modifying the product size on required energy. Power draw was determined using the simulation major equipment loading values with the installed power of individual motors.

Because of the limitations of this simulation, values were considered indicative for comparative purposes and allowed us to generate the preferred configuration.

Considerations

Three further considerations underpinned our preferred design: site variables; CAPEX and OPEX; and environmental impact.

Site Variables

As basalt is a naturally occurring material, the mineralogy will vary from quarry to quarry, potentially affecting the particle size of the final product required to achieve target rates of carbon sequestration.

In addition to its mineralogy, differences in onsite operations will cause variations in the particle size distribution of the feedstock. Some materials may have a low proportion of particles larger than the target product size, and the most economic solutions may be either to forego crushing and simply screen the oversize or to stockpile the oversize material and operate the crusher only once an appropriate mass has accumulated. At the opposite end of the spectrum, some sites may have a significant proportion of the feedstock above the target size and here it may be preferable to feed directly into a crusher, with screening following.

Our preferred design incorporates sufficient flexibility to refine the comminution process at our chosen location during Phase 2.

CAPEX and OPEX

There was a difference of over £1m between the CAPEX costs of the systems recommended by the two equipment suppliers. OPEX costs for both recommendations were estimated using the software simulation to inform power and water consumption values and allowed us to select the system with the lowest OPEX costs (assumptions which underpinned OPEX estimates are shown with that analysis at Appendix 4).

Environmental Impact

The carbon footprint of the process is critical. Whilst equipment suppliers were not forthcoming with estimated emissions from the circuits supplied, we calculated likely emissions by estimating power draw and had to balance between system efficiency and carbon emissions.

Engineering Design

Our engineering design was chosen on the balance of the comparative performance generated through simulation, the flexibility to deal with site variables, a balance of risks for supply, usage and maintenance, and the budget for Lot 1 projects.

The system creates a crushing circuit capable of processing 75 tonnes of basalt per hour. Even with a maximum downtime of 20%, this design can produce 120k-tonnes of basalt per year at our required specification. Once applied, this basalt would sequester 30k-tonnes of carbon dioxide within 5-10 years of application. The flowsheet for our preferred engineering design is shown overleaf in Figure 4.

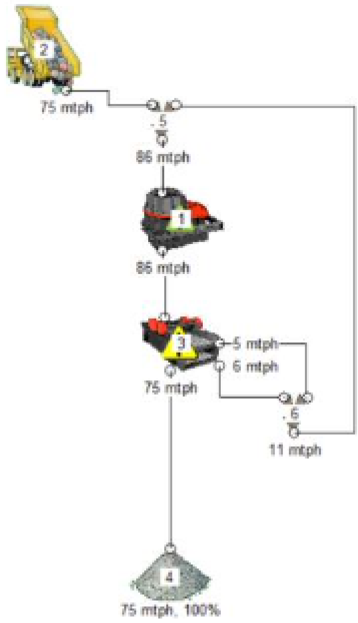

Figure 4: Flow Sheet

By employing proven technologies, already widely used across the UK aggregate industry and sourced from a UK supplier, we minimise the technical risks associated with our proposal. The project plan for installation and operation of this equipment during Phase 2 is set out in the following section of this report.

4. Phase 2 Project Plan

Overview

Our Phase 2 Project will deliver a crushing facility in an existing, third-party owned basalt quarry which has a high production rate of chemically and mineralogically suitable basalt fines, and sufficient basalt reserves to provide an enduring operational footprint. This will be integrated into the end-to-end GGR process to deliver a 1.3k-tonne trial at the Phase 2 site, sequestering approximately 260t of CO_2 from that trial (the results for the Life Cycle Analysis of Phase 2 are at Appendix 4).

Thereafter the project could either be concluded or spreading could continue at other sites if BEIS chose the option to pursue ambitious sequestration. If there is no appetite for this, the facility will be immediately transitioned to commercial employment, where we anticipate it providing sufficient crushed basalt to sequester an average of 20,000 - 25,000t CO_2 per year of production. Over the life of the equipment, this would equate to the removal of at least 100,000t of atmospheric CO_2.

The crushing facility will be delivered by the end of Q2 2022, as shown on the Gantt chart at Appendix 5. Testing will take place during Q3 and, by the Stage Gate Review in September 2022, we will be in a position to evaluate the performance of the operation. Thereafter the facility will be run to the limit of the BEIS project, as outlined above, before being transitioned across to commercial operations within the end-to-end process.

Our financial models suggest that a budget of £550,000 will allow us to operate the chosen engineering design for the duration of the Phase 2 site trial. After that point, we could either end the BEIS contract and transition the project to a commercial basis or extend the project to run on third-party owned land. In the latter case our financial model suggests that a budget of £3m would allow us to operate throughout the remainder of 2022 and the first three months of 2023. Doing so would generate sufficient basalt to sequester up to a total of 21,000t of carbon dioxide. The decision for how to run the project would be taken in conjunction with BEIS during the forthcoming approval period and is subject to BEIS ambition for carbon dioxide removal.

Team

Subject to the decision by BEIS to fund this project, we will build in Q1 2022 a bespoke team to run the crushing facility. The Future Forest Company will provide the global functions of human resources, finance, administration to support this team which will otherwise work distinct from our commercial operations.

Location

The trial is to be conducted at the Phase 2 site, a property owned by the Future Forest Company. The site and the associated quarry are located in an area of the UK which is both rich in basalt and has sufficient agricultural land that we can integrate the crushing facility seamlessly into our commercial operations on completion of the project.

The Future Forest Company will enter into an agreement with the quarry owner whereby, using project funding, the Future Forest Company will lease the necessary space for the project, will pay a fixed rate for the basalt feedstock, pay for the installation, maintenance and running of the equipment and manage the project. In return the quarry owner will provide access to life support for the facility operator, access to utilities and services (including weighbridge) and will provide overall assurance of safe operations across the entire quarry (including the day-to-day operation of the crushing facility).

Installation Plan

Following the completion of the eligibility check for this proposal and agreement from BEIS that this project will be accepted, the Future Forest Company will work with our consultancy, preferred equipment manufacturer and the quarry owner to refine the installation plan. This will include agreeing a suitable area for the crushing facility, balancing sufficient distinction between existing quarry operations and successful integration with them; agreeing access to utilities (power and/or water); and the timeline for installation and commissioning.

This will be completed within six weeks, allowing us to refine the technical specification with our supplier, to order the equipment at the point at which the BEIS GGR contract is awarded and to schedule delivery, installation and commissioning.

Installation and commissioning will be straightforward as our Engineering Design employs mobile equipment regularly used in the aggregates industry. The equipment can be dismounted from a low-loader without specialist equipment and can be positioned on a firm, flat surface without the requirement for extensive preparation. Connection to power (likely a stand-alone generator) and commissioning will be conducted by engineers from the equipment supplier, who will oversee the first production runs. This process is likely to take two weeks and will include quality control checks (particle size distribution) on the product.

Operational Plan

Once production has begun, it will take approximately one week to produce sufficient basalt for the trial. It will take a further week to haul and spread the basalt, with an additional week to capture the necessary data.

Spreading will be conducted by agricultural contractors able to provide geospatial data for the application of the basalt fines (we will use the same contractor with whom we conducted the 1k-tonne trial as they have a proven capability). The data will be used to refine the life cycle analysis and our operational model. It will also allow us to assure the application process and to verify that what has been produced has been successfully spread.

Should BEIS wish to achieve greater volumes of sequestration, the crushing facility could be continuously operated to feed an end-to-end GGR process limited only by the project budget. Should BEIS decide not to extend the project boundary, the crushing facility will be immediately transitioned to commercial use.

Monitoring and Verification

Monitoring and verification of the carbon removal will be conducted as outlined in Section 2.

Quality Assurance

As detailed at Section 2 the Future Forest Company will conduct an initial test to ensure that the basalt produced is free of impurities which might cause environmental or agricultural harm, and to determine its potential for sequestration. We maintain this quality assurance by repeatedly testing our materials, at a rate of not less than every 10k-tonnes. The same internationally accredited labs will be used as were for the initial testing and results will be shared as part of our commitment to transparency.

Costs - Phase 2 site Trial

Table 4 (below) summarises the expenditure associated with Phase 2 under the current, agreed boundaries and combines it with the capital expenditure to give overall project costs. Per tonne values have been omitted but are included in the financial model for the extended operating window.

Following the 1k-tonne conducted this year, we have high confidence in all our figures, excepting those for running the crushing equipment. Here we have medium confidence based on the analysis conducted by our contractor for the engineering design.

Phase 2 site Project Costs			**Low Estimate**	**High Estimate**
Total Cost (£)			**£ 490,189.00**	**£ 556,756.78**
Proposed Budget (£)			**£ 550,000.00**	**£ 550,000.00**
Variation			**-10.87%**	**1.23%**
Total Basalt Crushed (t)			**1,350**	**1,300**
Net Carbon Sequestered (t)			**270**	**200**
Project Duration (months)			**3**	**3**

Table 4: Summarised Phase 2 site project figures.

Costs - Ambitious Sequestration

As noted above, there is a model for the Phase 2 project whereby sequestration within the project could be maximised by extending the project boundary to include operations on third party land. The costs associated with this model are summarised in the table below and offer an opportunity to maximise carbon dioxide removal within the limits of the Lot 1 budget.

Project Extension			Low Estimate	High Estimate
Total Cost			£ 2,896,879.52	£ 3,046,906.08
Operations in 2023 (weeks)			14	16
Variation from £3M budget			-3.44%	1.56%
Total Basalt Crushed (t)			105,300	80,621
Net Carbon Sequestered (t)			21,060	12,403

Table 5: Summarised figures for maximised sequestration.

Post-Pilot Development

Once the pilot has been successfully established, the Future Forest Company will continue to work with equipment manufacturers to both replicate and scale the capability. Multiple crushing processes will be established following the operational model outlined above.

Dependencies

As noted, this project is dependent on access to a suitable quarry and a commercial relationship with its owner. It is also dependent on finding an equipment manufacturer capable of producing equipment able to operate to our specification. Our work to date suggests both are achievable.

Assumptions

This process must be commercially viable in the long term. The unit costs associated with the financial model underpinning ambitious sequestration indicate this is the case.

Risks

Aside from failing to achieve the dependencies listed above, the principal risks to the success of developing a commercially viable process lie in a collapse of the carbon price. Given the demand for carbon credits both in the near and medium term is highly likely to increase and there are no indications that developing technologies are likely to scale to meet that demand in any reasonable timeframe, the likelihood of this risk being realised is judged to be low. A full risk assessment is included in the commercially sensitive version of this report.

Appendix 1 - Generic Life Cycle Analysis

Life Cycle Carbon Tool - The (Global) Future Forest - Basalt Spreading

Instructions:
Enter inputs into the yellow cells
Grey cells are automatically calculated

Amount of Basalt and Field Area to be spread

Mass of Basalt (tonnes)	Spread area (ha)
1,000	1000

Stage 0.1 Extraction of Basalt at Quarry

Note: in most instances the basalt stones are a "waste product" from quarying larger rocks, so this will be zero fuel (as quarrying specifically for this isn't needed)

Fuel consumed (litres of diesel)	tCO2e
0.1	0.00

Stage 0.2 Transport of Basalt to the Crusher

Note: in most instances the basalt will be crushed onsite at the quarry (so transportation will be zero as it isn't required)

Fuel Consumed (litres of diesel)	tCO2e
10	0.03

Stage 0.3 Haulage of Additional Machinery & Equipment Prior to Crushing process

Machine Type	Distance to Quarry (miles)	Type of Low loaders	Number Needed	tCO2e	
Crusher Type 1	10	Articulated (>33t)	2	0.03	assumed 100% loaded
Crusher type 2	50	Rigid (>7.5 tonnes-17 tonnes)	1	0.06	
Portable cabin				-	
				-	
			Total tCO2e	0.09	

Stage 1 Crushing Process

Electricity Consumption (kWh)	Electricity tCO2e
2	0.00

Fuel Consumed (litres of diesel)	Diesel tCO2e
	-

Stage 1.1 Movement and Storage of Basalt at the Quary / Crusher site

Fuel consumed (litres of diesel)	tCO2e
0.50	0.00

Stage 2 Transport from Crusher to Farm(s)

Name of Farm	Lorry type	Amount of Basalt sent to Farm (in tonnes)	Distance to farm (miles)	tCO2e per farm	
farm a	Rigid (>3.5 - 7.5 tonnes)	200	2	0.16	assume lorries will be at 100% capacity full (laden)
farm b	Rigid (>7.5 tonnes-17 tonnes)	300	15	0.98	
farm c	Articulated (>33t)	1,000	25	2.38	
farm d	Rigid (>7.5 tonnes-17 tonnes)	50	20	0.22	
				-	
				-	
TOTAL		1,550	Total tCO2e	3.73	
Shortfall (Amount at Quarry - Amount delivered)		- 550			

Stage 2.1 Train Freight (option if trains are used)

Name of Farm	Amount of Basalt sent to Farm (in tonnes)	Distance on train (miles)	tCO2e per farm
farm a		50	0.00
farm b			0.00
farm c			0.00
farm d			0.00
			0.00
			0.00
Total	-	Total tCO2e	-
Shortfall (Amount at Quarry - Amount delivered)	1,000		

Stage 3 Transport from Farm to Field

Note: this is the "final mile" from Farm storage to the fields

Name of Farm	Fuel consumed (litres per mile)	Distance to field (miles)	tCO2e per farm
farm a	0.2	1	0.00
farm b	0.3	1	0.00
farm c			-
farm d			-
			-
			-
		Total tCO2e	0.00

Stage 4 Spreading of Basalt

Name of Farm	Fuel consumed per farm (litres)	tCO2e per farm
farm a	1000	2.51
farm b	1000	2.51
farm c		0.00
farm d		0.00
		0.00
		0.00
	Total tCO2e	5.02

Appendix 2 - Phase 2 Site Ecology Impact Assessment

Preliminary Vegetation Survey: Summary Update Report

Phase 2 Site

October 2021

Head of Ecology, The Future Forest Company Ltd.

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1. Background

Our Phase 2 site (hereafter "the site") is currently being considered for the application of Enhance Weathering (EW) material as part of ongoing work by the Future Forest Company Ltd to capture carbon from the atmosphere and store it in the land. As part of these considerations, a preliminary assessment of the vegetation present on the property was carried out by the Head of Ecology, The Future Forest Company Ltd., in order to identify the most suitable locations for this work. Our Head of Ecology has extensive vegetation survey experience (Phase 1 habitat, NVC, SCM, rare plants).

2. Survey Methods

The following method was employed at the site. Large parts of the site were carefully walked over on the 21st October 2021 as part of an initial 'recce survey' aimed at identifying the likely nature conservation importance of habitats present and to thereby identify locations most appropriate for Enhanced Weathering activities.

Vegetation surveys should normally be carried out between May and September in Scotland, when many flowering plant species are most evident, thereby permitting accurate classification of vegetation communities. This is planned in summer 2022. However, some habitats, by their nature, can be surveyed at any time of year, including the more intensively managed fields at the site, and peatland, for example.

A Phase 1 habitat survey method approach was used at the site, with habitats classified according to current Phase 1 habitat guidance. Boundaries between habitats were mapped onto a satellite image (QField/QGIS), although it should be noted that some of the boundaries on the vegetation map on *Figure 1* are indicative as different habitats often merge and grade into each other untidily.

Plant communities were surveyed by eye, and where appropriate *i.e.* semi-natural, classified to (sub) community level as per the National Vegetation Classification (NVC) survey method. However, those areas most appropriate for Enhanced Weathering activities at the the site were largely mapped to Phase 1 level only as they were intensively managed for agriculture and not, as such, 'semi-natural' and did not therefore require more detailed vegetation (NVC) survey work upon them; *See Figure A2-1 below.*

In order to assist with any peatland assessment, a peat probe (maximum depth of 1m) was used to gain a measurement of peat depth in some key areas. However, this work should not be considered a substitute for a comprehensive soil survey.

Finally, the habitats and NVC plant communities at the site have also been assessed as being ‘highly dependent on groundwater’ (denoted by **) or ‘moderately dependent on groundwater’ (denoted by a *), in order to assist with forward planning, where relevant.

3. Results & Conclusion

The recce vegetation survey results are presented in *Figure A2-1* overleaf.

Figure A2-1 highlights those areas of land at the site which are suitable for application of basalt from a biodiversity perspective *i.e.* there are no biodiversity constraints to Enhanced Weathering applications on these areas. All other 'unhighlighted land' should be viewed as being *unsuitable* for Enhanced Weathering applications at this time, including two areas of marshy grassland and semi-improved (species-poor) neutral grassland also highlighted beside one of the fields in *Figure 1*. *Unsuitable* areas at the site include significant areas of peatland to the north, areas of marshy grassland and riparian edges.

The majority of the land suitable for Enhanced Weathering activities at the site is located in the southern section of the site and has been classified as ***Improved grassland (I)***, having been subject to long-term agricultural improvement and modification. Much of it is currently grazed by cattle and sheep. Many of these fields are ***I (Je): Improved grassland with Juncus effusus (Je)*** - soft rush - frequent and abundant in places. On these fields, the soft rush has become an issue in places due to likely soil compaction and poaching by machinery and livestock, however, the land is NOT considered 'marshy grassland'.

The **Improved grassland** at the site does not sit on peat and is not considered to be either moderately or highly dependent on groundwater.

Therefore, the application of basalt on the fields highlighted in *Figure A2-1* will not affect any vegetation of nature conservation importance at the site.

Figure A2-1: Main areas suitable for Enhanced Weathering applications at the site.

Key to Figure A2-1

I	Improved grassland (often with soft rush (Je)) - suitable for EW work.
Grey polygons	Land which has significant areas of Improved grassland (Je) present but is understood to be unsuitable for EW work, due to machinery constraints arising from the terrain.
Hatched / orange polygons	Marshy or Semi-improved neutral grassland *unsuitable* for EW work

The areas highlighted in Figure A2-1 represent approximately 65 hectares where basalt spreading could take place.

Appendix 3 - Design Assumptions

Assumptions for OPEX calculations include:

- 8 hour operating day, 5 days a week. Target 90% availability. During the 10% downtime, maintenance is conducted.

- 1 operator at £15/h with PPE costs of approx. £500/y.

- Maintenance costs (i.e. spare parts) at 5% CAPEX per year.

- Electricity price approx. £0.10/kWh.

- Water cost approx. £1.50/m3 and assumes no recycle (NB: The price is likely higher than should be expected but actual price will be heavily dependent on site).

- No materials are used in the process.

- Waste removal / treatment are the purview of existing site operations.

- Installation costs 3% CAPEX

- 5% rate of inflation on costs year-on-year

- Equipment value at approx. 25% CAPEX after 5 years.

Appendix 4 - Life Cycle Analysis Results

Mass of Basalt (tonnes)	Spread area (ha)
1,350	67.5

Element of footprint	tonnes of CO2e	Percentage
Extraction of Basalt at Quarry	-	0.0%
Haulage of Additional Machinery	1.97	12.7%
Transport of Basalt to the Crusher	2.51	16.2%
Crushing Process	5.41	34.9%
Movement and Storage of Basalt at Quarry	2.51	16.2%
Transport from Crusher to Farm	0.77	5.0%
Transport from Farm to Field	0.49	3.1%
Spreading of Basalt	1.83	11.8%
Location based Total	**15.49**	**100.0%**
tCO2e / tonne of Basalt	**0.01**	
tCO2e / hectare spread	**0.23**	

Farm name	Tonnes of CO2e per Farm
Phase 2 site	15.49

Table A5-1: Breakdown of carbon footprint.

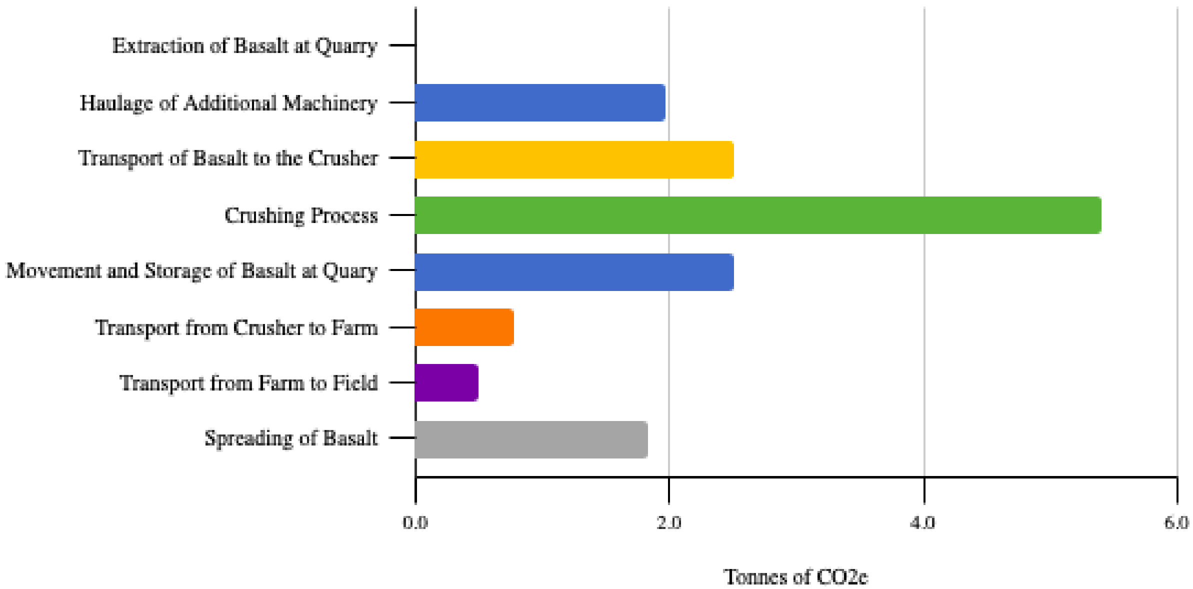

Figure A4-1: Breakdown of carbon footprint in tonnes of CO_2e.

Appendix 5 - Phase 2 Gantt Chart

BEIS Phase 2 (by Quarter)

2021: Dec | 2022: Jan, Feb, Mar, Apr, May, Jun, Jul, Aug, Sep, Oct, Nov, Dec | 2023: Jan, Feb, Mar, Apr, May, Jun, Jul

	Start	End
Tendering Process		
Application for BEIS Phase 2(Application for BEIS Phase 2)	08-Dec-2021	26-Jan-2022
BEIS Eligibility check / assessment(BEIS Eligibility check / assessment)	27-Jan-2022	03-Feb-2022
BEIS reviews, due diligence, pre-contrat development(BEIS reviews, due diligence, pre-contrat development)	03-Feb-2022	25-Mar-2022
Contract awarded(Contract awarded)	08-Apr-2022	08-Apr-2022
BEIS Phase 2 Pilot Implementation		
Monitoring, recording and verification accreditation (started Sep-21)(Monitoring, recording and verification accreditation (started Sep-21))	03-Jan-2022	30-Jun-2022
Agree T&Cs with quarry operators(Agree T&Cs with quarry operators)	07-Feb-2022	25-Feb-2022
Employee interviews(Employee interviews)	01-Mar-2022	12-Mar-2022
Equipment procurement final technical design(Equipment procurement final technical design)	07-Mar-2022	18-Mar-2022
Employee hiring(Employee hiring)	14-Mar-2022	29-Apr-2022
LOIs to contractors and suppliers(LOIs to contractors and suppliers)	04-Apr-2022	08-Apr-2022
Lead in time for crushing equipment(Lead in time for crushing equipment)	11-Apr-2022	08-Jul-2022
Quarry site prep (power, welfare etc.)(Quarry site prep (power, welfare etc.))	20-Jun-2022	01-Jul-2022
Crushing equipment delivery and commissioning(Crushing equipment delivery and commissioning)	11-Jul-2022	22-Jul-2022
First production run - 25% run rate(First production run - 25% run rate)	25-Jul-2022	29-Jul-2022
Second production run - 50% run rate(Second production run - 50% run rate)	01-Aug-2022	05-Aug-2022
Third production run - 75% run rate(Third production run - 75% run rate)	08-Aug-2022	12-Aug-2022
Full production - first week(Full production - first week)	15-Aug-2022	19-Aug-2022
Stage Gate Review	8-Sep-2022	8-Sep-2022
(Option for Ambitious Sequestration)	8-Sep-2022	31-Mar-2022

Table A5-1: Phase 2 Gantt Chart showing project timeline.