BEIS (Direct Air Capture and GGR Programme)

Integration of GGR technologies into linear infrastructure projects

Final Phase 1 Report

Issue | 21 January 2022

This report takes into account the particular instructions and requirements of our client.

It is not intended for and should not be relied upon by any third party and no responsibility is undertaken to any third party.

Job number 281727

Ove Arup & Partners Ltd
4 Pierhead Street
Capital Waterside
Cardiff CF10 4QP
United Kingdom
www.arup.com

ARUP

Contents

Tables

Figures

Appendices

B3 Biochar Standard Comparison

B4 Soil Health Methodology

B5 Ash Source

Appendix C - EMW

C1 Quarry Information

C2 Crushed Rock LCA

Appendix D - Industry Consultation

D1 Industry Survey Result

D2 Economics Review

D3 Stakeholder Register

D4 Integration Biochar and Dolerite into Linear Infrastructure Projects

D5 Options Note and Review

D6 Options Review

Appendix E - Regulatory Review

Appendix F - Social Value

Appendix G - Banwell Bypass

G1 Banwell Strategy

G2 Banwell PSSR

G3 Banwell Drawings

G4 Environmental Considerations

G5 Material requirements and Landtake

G6 PyroCore Feedstock Trial Proposal

G7 RAMS Earthworks Embankment

Appendix H - MIM Specification of Works

Appendix I - Risks and Opportunities

I1 Risk Register

Appendix J - Cost Plan Supporting Information BEIS

1 Executive Summary

This Design Study summarises the research and conclusions from Phase 1 of the project – 'Integration of Greenhouse Gas Removal (GGR) Technologies into Linear Infrastructure Projects' ("the project") – and presents the business case[1] for implementation and demonstration during Phase 2.

Phase 1 of the programme was completed following award of funding from the Direct Air Capture and Greenhouse Gas Removal (GGR) Innovation Programme ("the Programme"), as part of the Net-Zero Innovation Programme within the Department for Business, Energy and Industrial Strategy (BEIS).

The project examines the feasibility of integrating GGR technologies in the form of quarry fines (to activate 'Enhanced Mineral Weathering', EMW) and biochar into earthworks and landscaping areas of infrastructure projects ("the technologies"). Phase 1 assessed the feasibility, risks and opportunities of implementing these technologies in the context of infrastructure project delivery in the UK.

Phase 1 was led by Arup, supported by Costain, bringing extensive joint experience working on the design and delivery of major UK infrastructure schemes. Academic experts from Newcastle and Edinburgh Universities, engaged in cutting-edge research on the GGR technologies, have provided a critical, robust evidence base to inform the Phase 2 pilot project. The team has also engaged with Alun Griffiths and North Somerset Council on the Pilot site Banwell Bypass.

The team has engaged with specialists and consultees to develop the most effective design solutions in terms of economic, environmental, and social value. The ultimate ambition is to demonstrate that these technologies can be upscaled for use within the UK infrastructure sector, where there is a targeted £650 billion[2] investment pipeline over the next 10 years, estimated to support 425,000 jobs a year (HM Government, 2021).

The project has been designed to achieve the wider objectives of the GGR Innovation Programme. These objectives are:

- To demonstrate 1,000 tCO_2e removal per annum by 2025 (as part of Phase 2 – Pilot Phase – of the Programme);
- To demonstrate the potential for the technologies to upscale to 50,000 tCO_2e per annum by 2030; and
- To demonstrate the technologies could achieve carbon capture at a cost of <£200 per tonne of CO_2e removed.

---

[1] The business case follows best practice HM Treasury '*Better Business Cases'* guidance following the Five Case Model (HM Treasury, 2018)

[2] The £650 billion investment equates to £254 billion of economic infrastructure (public), £208 billion private investment (across all sectors), £97 billion regulated utilities and £89 billion social infrastructure (public)

This business case report summarises the selection of the preferred option for Phase 2 – Pilot Phase – which is the integration of GGR technologies within the earthworks of the Banwell Bypass scheme (a new highway scheme around the village of Banwell in North Somerset, funded by Homes England's Housing Infrastructure Fund, which will enable housing development, encourage active travel and boost biodiversity. The pilot design has been developed to demonstrate that the Programme objective of 1,000 tCO_2e removal can be achieved through actions completed in 2025, at a current estimated cost of £300 per tonne of net CO_2 removed.

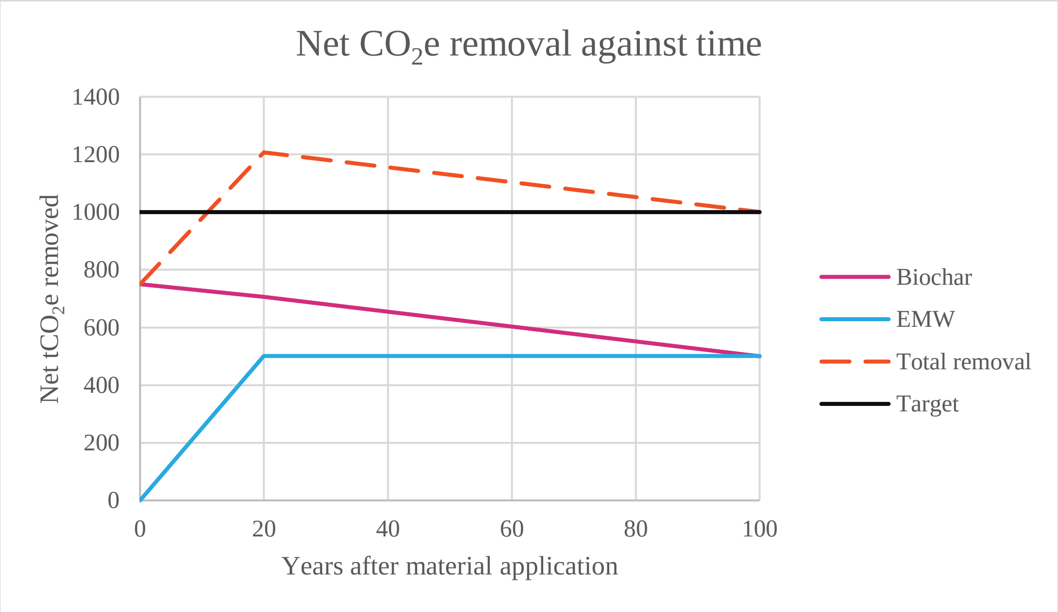


Figure 1: Contribution of each material to the net CO_2e removal of the pilot site, over a 100-year period[3].

In considering the longer-term programme objectives, the options assessment has also identified the opportunity for a reference site in Phase 2 – Moreton-in-Marsh (MiM).

MiM is a 365-acre site in Gloucestershire, owned by Capita, and home to the Fire Service College. Previously an RAF airfield, the runway is now used as a mock motorway ('M96') for simulation of major road traffic accidents in a low-risk environment.

This report represents the Outline Business Case for Phase 2, presenting cost and delivery plans for demonstration of GGR technologies at the above pilot and reference sites, alongside the research and key findings from Phase 1 which form the foundations of the case for implementation.

[3] A linear model has been assumed for biochar decomposition and weathering rates, the details of which are given in section 1.3 of Appendix B and section 1.3 of Appendix C, respectively.

2 Strategic Case

2.1 Purpose

The strategic aim of this project is to demonstrate that biochar and dolerite/basalt (or “quarry fines” via enhanced mineral weathering) Greenhouse Gas Removal (GGR) technologies can be upscaled cost-effectively for use within the UK infrastructure sector. The strategic case sets out a plan for change in the sector and the opportunity to embed these technologies at scale by demonstrating successful technical implementation within a pilot linear infrastructure project.

2.2 Background

The UK infrastructure sector (“the industry”) contributes a significant amount of annual embodied carbon. In 2017, 13% of the entire UK carbon footprint came from the construction, operation and maintenance of infrastructure assets (99 $MtCO_2e$) (Institution of Civil Engineers: The Carbon Project, 2020).[4]

Infrastructure is a vital part of the UK economy. This includes linear infrastructure, which refers to any man-made structure that is linear in nature, covering rail, road, water, digital and energy. Government investment in infrastructure is confirmed to at least 2030 (HM Treasury, 2021) (HM Government, 2021), and will likely remain a perpetual priority sector for investment for the UK.

As a result, the industry is therefore a key strategic target for the UK’s transition to net zero by 2050. The industry is featured in five of the Ten Point Plan items in the Energy White Paper: Powering our Net Zero Future (HM Government, 2020). The National Infrastructure Strategy reiterated that “*infrastructure investment is fundamental to delivering net zero by 2050*” (HM Treasury, 2020). Most recently, the Net Zero Strategy (HM Government, 2021) details an indicative pathway to the 2037 emissions requirement, with linear infrastructure featuring heavily within this pathway.

Government net-zero policies and strategies are reinforced by the major infrastructure operators, agencies, and key industry bodies (see Figure 2). Linear infrastructure therefore has strategic backing for significant UK carbon savings, including GGR to address hard-to-decarbonise emissions.

[4] This increases to 54% if infrastructure operational carbon such as vehicle emissions is included (419 $MtCO_2e$) (Institution of Civil Engineers: The Carbon Project, 2020).

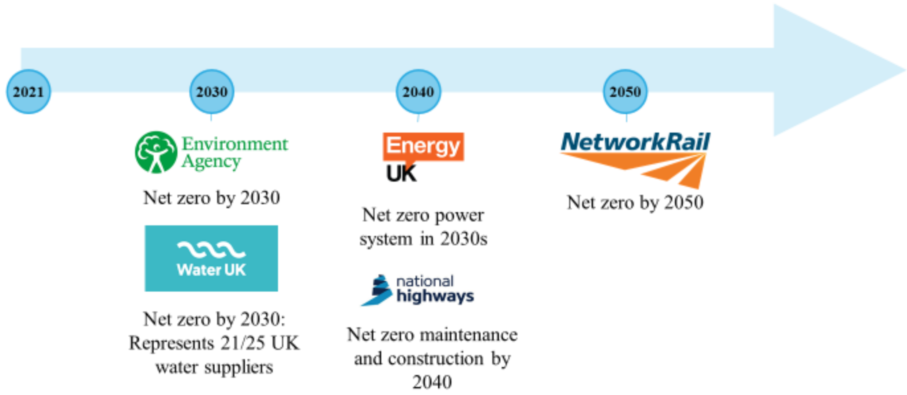


Figure 2: Net zero strategies from key industry clients (Network Rail , 2020) (National Highways, 2021) (Environment Agency, 2021) (Water UK, 2020) (Energy UK, 2021)

2.3 Case for Change

This section sets out the case for change, including an overview of the technologies and the market gaps and barriers that currently constrain widespread adoption.

2.3.1 Summary of the Technologies

A brief overview of the technologies is provided below. Comprehensive technical summaries are included in:

- **Appendix B:** Biochar; and
- **Appendix C:** EMW

2.3.1.1 Biochar GGR Technology

Biochar is the product of biomass pyrolysis[5]. Biomass is organic material formed by plants, including the carbon absorbed by plants (plants, plant products and products of biomass utilisation, including sewage sludge).

Pyrolysis stabilises the carbon, as heating in the absence of oxygen leads to molecular fragmentation with partial rearrangement into consolidated aromatic carbon rings (carbonisation). Carbon in this configuration is highly resistant to microbial attack and degradation and hence can remain stable for long periods of time, providing an effective means of long-term carbon storage.

As demonstrated in Figure 3, biochar may encompass a range of materials due to different feedstock properties and processing parameters.

This project considers a pelleted feedstock of sawmill co-products with slow pyrolysis (ca. 20 min.) at high temperature (~700°C) specified to maximise carbonisation and the stable carbon content of the biochar products.

[5] The different gasification and pyrolysis production systems available for biochar production have been reviewed in detail (see Appendix B)

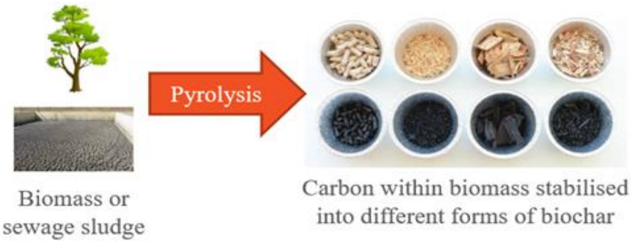


Figure 3: Overview of the biochar generation process

2.3.1.2 Carbonation and enhanced mineral weathering

Quarry fines (dolerite or basalt) remove atmospheric CO_2 via weathering, which is a natural pedogenic (soil forming) process sped up by the fine profile of the crushed rock. CO_2 in the soil reacts with the groundwater to form a weak carbonic acid that breaks down the rock, releasing bicarbonate ions and base cations. These released materials may precipitate to form calcium carbonate (mineral carbonation) or the bicarbonate ions may drain to river systems, and ultimately the oceans or to groundwater (enhanced mineral weathering).

Figure 4: Dolerite fines used in enhanced mineral weathering

2.3.2 Market Gap

Consultation with various key industry bodies (detailed further within Appendix D) has highlighted the challenge of achieving the net zero targets, with a pressing need to reduce emissions and limited existing options to address residual, hard-to-decarbonise emissions. Tree planting was cited frequently as the principal method for offsetting carbon from infrastructure, however, it was noted that this would not provide sufficient scale nor necessarily always represent the optimal ecological and social outcome.

A significant market gap therefore exists in the industry for cost effective GGR technologies. The biochar and EMW technologies offer a viable option – currently considered to be at demonstration technology readiness levels (TRL) of 7 and 6 respectively[6].

2.3.3 Market Barriers

Despite the high TRLs of the technologies, various barriers were identified throughout the Phase 1 research that hinders the widespread adoption in the industry. These are summarised in Table 1.

Table 1: Summary of market barriers to GGR technology adoption

Barrier / Market Failure	Description	How this will be addressed in Phase 2
Policy / Market Gap (UK Certification)	Currently, only woodland creation and upland peatland restoration have certification standards that enable them to be used for carbon offsetting in the UK. Additional R&D is needed to expand the number of nature-based and built environment offsetting schemes available (Environment Agency, 2021). International certification standards exist for biochar, but there is little guidance (and no recognised standard) for the application of EMW.	Link with other BEIS biochar projects looking at international certification standards and application in UK context – progress through Biochar Forum (extended to EMW).
Policy Gap / Regulatory Barrier	There is currently a policy gap to allow large scale utilisation of biochar. Biochar is currently considered a waste material, which restricts the use and means greater investment and lead times for implementation at scale (e.g., permit application).	Demonstration of the technical evidence and analysis required to attain biochar permits for large scale utilisation would contribute to designing future mechanisms that are streamlined, with supporting policy and regulation to ensure effective and robust implementation.
Information and Technical (Standards)	The technologies are not widely understood and there is currently a lack of clear guidance to inform the industry. This may preclude their use. Ideally, the method for using the materials would be in an industry code.	Successful large-scale pilot application in a live infrastructure project setting would help address concerns and uncertainties and contribute to a more practical understanding of the technologies, including methods of incorporating into schemes. This, in conjunction with design and implementation guidance, would build confidence as well as momentum around the potential scale of opportunity for the industry.

[6] TRL Level 6 is 'Prototype System Verified' and TRL 7 is 'Integrated Pilot System Demonstrated'

Barrier / Market Failure	Description	How this will be addressed in Phase 2
Information and Technical (Validation)	Validation is required to quantify the long-term GGR potential of EMW processes and refine the conservative methods by which biochar is used as a GGR technology.	The pilot site and accompanying reference site would assist with the provision of the necessary validation - including potential for longer-term monitoring and the ability to test specific elements of the GGR processes and performance.
Technical (Application)	The inherent variability of biochar means that its properties are not yet exhaustively characterised. Biochar is often considered to represent a homogeneous material by those unfamiliar with it, and this hinders the development of tailored applications. Technical standards, relating to chemical composition, are also a current gap in the application of quarry fines for GGR purposes.	From a technical and environmental review, softwoods and hardwoods have been identified as the most suitable feedstocks for biochar production at this stage. This narrows material variability considerably and allows for technical (application) standards to be developed during Phase 2 that meet the objectives of the programme as well as fulfilling the requirements of the projects.
Supply constraints	The biochar industry is in early-stage development. There are competing uses for biomass feedstock, including other potential methods of carbon sequestration e.g., BECCS[7]. The supply chain for quarry fines exists but is not fully utilised. To achieve the biochar production scale required for use across the industry, supply constraints (quantity, quality, production, distribution) need to be addressed. Quarry fines supply is assured, given the long-term existing production permits granted to the quarrying industry through the planning process (in the context of the national strategic need for supply of construction aggregates).	Other projects/businesses (some within the BEIS programme) are focussed on biochar production. This project would help demonstrate demand potential and provide confidence for others to invest (e.g., in production facilities that could in turn help to rapidly scale up and deliver economic and social value across the supply chain). Quarry fines supply is less constrained, but validation is required along with standards on material use, sourcing and transportation for optimal lifecycle outcomes.

The pilot and reference interventions detailed within this report target these barriers, aiming to prove technical feasibility and develop a roadmap to achieving cost effective (£/tCO2e removal) adoption at scale to contribute to the industry meeting net zero targets.

[7] Bioenergy with carbon capture and storage

2.4 Strategic Objectives

The objectives of the project are as follows:

Successfully integrate GGR technologies – biochar and EMW - into a strategically aligned linear infrastructure pilot project to remove at least 1,000tCO2e from the air per annum.

Deliver to an affordable (<£200 per tonne CO2e removed) and robust cost plan which achieves cost savings and Value for Money at every stage. Use lessons learned to address any remaining cost challenges to large scale adoption.

Deliver maximum Social Value, demonstrating how the project can significantly advance the development of GGR technology in the UK and directly generate new opportunities (jobs, training and skills, community engagement and participation), including at the local level within the communities served by the project.

Develop a programme detailing how the GGR solution can continue to be developed, beyond March 2025, to create a roadmap for reaching 50k tCO2e removal per annum, to include the main technical, regulatory and information barriers to implementation and key development milestones.

3 Economic Case

This section outlines the selection of the preferred option for investment and its likely impact. Options were appraised in line with HM Treasury's Green Book guidance to demonstrate Value for Money.

3.1 Analysis of Options

A long list of options was considered for the pilot site project. After initial consideration, a shortlist was assessed at a high level against the recommended six Critical Success Factors as set out in Table 2 below (which presents the scoring of shortlisted options).

Table 2: Options Assessment Summary

Critical Success Factor (CSF)	**Option 1** Moreton-in Marsh	**Option 2** Banwell Bypass	**Option 3** M62	**Option 4** A12	**Option 5** HS2 West Ruislip
CSF 1: Strategic Fit					
CSF 2: Value for Money (benefits optimisation)					
CSF3: Potential affordability / cost					

Critical Success Factor (CSF)	Option 1 Moreton-in Marsh	Option 2 Banwell Bypass	Option 3 M62	Option 4 A12	Option 5 HS2 West Ruislip
CSF 4: Supply side capacity and capability					
CSF 5: Potential achievability/risk profile					
CSF6: Alignment with regulatory agenda					

Assessment	Rating	Recommendation
Fully/ largely meets CSF		Option preferred
Partially meets CSF		Further analysis is required to take option forward
Fails to meet CSF		Discount option

'Do Nothing' and 'Do Minimum'[8] options were assessed as failing to meet the programme objectives and Critical Success Factors. The M62 programme did not align on the programme and the A12 design was too far developed to allow incorporation of the technologies. For HS2, the programme did not align and there were additional risks relating to highly sensitive stakeholder management.

Moreton-in Marsh is a test facility and cannot offer the same practical implementation and social value benefits as a 'live' infrastructure project. The preferred option was therefore identified as Banwell Bypass, with Moreton-in-Marsh proposed as a reference site to allow robust validation of impacts within a controlled environment and realise other benefits that such an environment provides (see section 3.2).

The proposed pilot scheme has been developed during Phase 1, working in conjunction with the Banwell team. During Phase 2 the pilot scheme design will be finalised, as directed by the Banwell Bypass planning process and detailed design programme.

3.2 Rationale for Reference Site Inclusion (Value for Money)

Although the reference site (Moreton-in-Marsh, MiM) would incur additional cost (£1.2 million additional cost – see section 4.2), this would still be within the overall budget available, with significant benefits to its inclusion as follows:

- It would offer a controlled site for testing construction and monitoring methods. Some elements, such as mixing, could be tested before application at Banwell;

[8] Do Minimum would involve further research (similar to Phase 1) with only limited practical application (small scale testing in a controlled environment – not a live infrastructure project)

- It would offer the chance to test speculative uses which may not be feasible at the live pilot site. It would also allow greater flexibility for amendments to be made, with greater confidence, to pilot site proposals;
- It would help demonstrate potential impacts (e.g., plant growth impacts and slope stability) to contribute to obtaining agreement and understanding of wider benefits;
- It would provide opportunities for showcasing the use of the technologies in a safe and readily accessible environment. It would promote increased awareness of the material applications and technologies, potentially accelerating their use in future linear infrastructure projects, delivering greater social value; and
- The reference site would also have the added advantage of potentially allowing longer-term testing and monitoring beyond the Phase 2 programme of works should this be desirable.

In summary, a safely accessible reference site would be an invaluable tool in the long-term for disseminating the project to future stakeholders. It is therefore seen as a critical, value for money investment in developing confidence and growing the market to 2030 and beyond.

3.3 Benefits appraisal

This section sets out the appraisal (largely qualitative) of benefits, from the short-term pilot project benefits, that will set the path to meeting the 2030 target of 50k tCO2e per annum, to the longer-term benefits from scale-up and widespread adoption.

3.3.1 Environmental Value

A regulatory and environmental review (see Appendix E) of the risks associated with biochar and quarry fines material has been undertaken, covering the following analysis: civil engineering, geo-environmental, ecology and landscape, and carbon assessment.

The primary environmental value is GGR (1,000tCO_2e removal by 2025) but there are wider environmental benefits (and risks) identified as follows.

Table 3: Environmental Impacts

Environmental Impact	Biochar	Dolerite / Basalt quarry fines (via Enhanced Mineral Weathering process)
Climate Change Mitigation	1.64 – 2.13 tCO2e per tonne of biochar (see section 1.4, **Appendix B**) Most of the carbon in biochar (~96%wt) mineralises to CO2 or decomposes into organic substances	0.131 – 0.205tCO2e per tonne of rock fines, over approximately 27 years (see section 1.3 and 1.5, **Appendix C**) The residence time of dissolved inorganic carbon in the ocean via

Environmental Impact	Biochar	Dolerite / Basalt quarry fines (via Enhanced Mineral Weathering process)
(net GGR potential - tCO2e, after transport)	very slowly, with a mean residence time of approximately 556 ± 483 years in soil (Wang, Xiong, & Kuzyakov, 2015). The lower end of this scale corresponds to non-virgin feedstock derived biochar (for example chicken litter) that is not considered in this report.	enhanced weathering is approximately 100,000 years; via mineral carbonation in soil indicates residence times upwards of 30,000 years (Renforth & Henderson, 2017) (Renforth, Manning, & Lopez-Capel, 2009).
Soil health	Biochar properties can improve soil health through increased nutrient availability, improved soil-water properties, plant-microbe relations, and soil remediation (see section 1.2.6 of Appendix B and Appendix B).	Dolerite is used as a soil amender for the cultivation of crops (e.g., REMIN[9] product) and can be used to improve soil health as well as sequester carbon (see section 1.2.5 of Appendix C).
Plant growth/nutrient lean soils	Biochar (soft/hardwood derived biochar especially) is suitable for application to soft estates where nutrient lean soils are required. See section 2.1.1, Appendix I for review of use on National Highways nutrient lean soils)	Dolerite fines are highly compatible with a low nutrient policy initiative. Dolerite fines have been used to establish a species-rich grassland upon a low-nutrient green roof (SILL, 2021). See section 2.1.1 of Appendix I for review of use on National Highways nutrient lean soils.
Ecology	Biochar may provide favourable habitats for soil biota due to abundant macropores, and the labile fraction of biochar carbon can provide energy sources for microbe growth.	Remineralisation can improve plant-microbe relations. Users of REMIN report improvements in soil fauna such as earthworms – an indication of improved soil health (REMIN, 2018).
Water pollution	Biochar's high surface area to volume ratio means it acts as an absorbent to remove aqueous contaminants such as heavy metals, organic contaminants, and nitrogen and phosphorous (Xiang, et al., 2020). See section 1.2.5 of Appendix B, and Appendix I.	An increased dissolved silica flux to rivers and oceans can mitigate the effects of nitrogen and phosphorous runoff from agriculture, by stimulating the growth of diatoms over algae that produce toxins. With sustained, intensive application there is a risk of increased turbidity and sedimentation, however (Beerling, et al., 2018).
	Potential contamination risks will be mitigated through quantitative risk assessment and ensuring quality feedstock sources (virgin feedstocks)	Potential contamination risks will be mitigated through quantitative risk assessment and ensuring appropriate specification/chemical composition of quarry fines

[9] REMIN rock dust is sold with organic certification: One tonne of REMIN applied to soil removes an additional 70kg to 230kg atmospheric CO2 (19kg – 60kg inorganic C) over time

For Banwell Bypass, the analysis supporting this report will feed into the Environmental Impact Assessment, currently being prepared and due to be submitted as part of the planning application in May 2022. In 2020, Natural England (NE) advised all Somerset Councils on unacceptable levels of phosphates in the Levels and Moors[10]. NE has advised that a Habitat Regulations Assessment must be undertaken before determining planning applications that may give rise to additional phosphates. As a result, a significant number of applications are on hold and future strategic housing and brownfield sites have also been delayed. If the Banwell scheme can demonstrate the additional benefits of phosphate and nitrate capture, incorporating GGR material application, this could have wider environmental and social benefits in other areas facing similar challenges.

3.3.2 Economic Value

Between £16 billion and £25 billion of economic (transport, energy and digital) infrastructure contracts will be brought to market over the next year, with a projected £250 billion over the next 10 years (within a total £650 billion of economic and social infrastructure investment) (IPA, 2021). Encouraging and driving innovation in a sustainable manner that aligns with the path to net zero by 2050 is central to the Government's infrastructure ambitions.

Significant analysis has been undertaken exploring current market barriers to widespread adoption and the measures required to accelerate innovation and drive down costs. The following roadmap section sets out high level actions to reach a target of at least 50,000 tCO2e removal per annum by 2030 and reach a cost of <£200/tCO2e removal.

3.3.2.1 Roadmap to 2030

Soft Market Testing

The UK biochar market is at an early stage of development with small-scale horticultural products[11] being the main option for purchasing biochar. An assessment of pyrolysis plant options for biochar production was undertaken (Section 1.5 of Appendix B) with PyroCore emerging as the preferred option. Reasons for discounting alternative options included (i) capital costs of new UK-based pyrolysis plant not feasible within project budget (ii) inability to currently meet the biochar quantities required, and (iii) pyrolysis technology not aligned with scale-up plans.

For the purposes of the proposed Phase 2 pilot scheme and developed cost plan, the current estimated cost of biochar is between £350-500 per tonne of biochar. If the feedstock costs are assumed at £100/tonne, this results in an estimated net removal cost in excess of £500/tCO2e. Further details are presented in Section 1.4 of Appendix B. These costs are well above the BEIS target. However, by 2030, it is anticipated that the capital cost per tonne is likely to decrease significantly.

[10] Governed by the RAMSAR designation
[11] The two main suppliers are Carbon Gold (Carbon Gold, 2021) and Oxford Biochar (Oxford Biochar, n.d)

Operational expenditure figures are also expected to reduce as operational hours increase, maintenance costs reduce with scale, and automation improves efficiency. For further details, see Appendix B.

Unlike biochar, quarry fines are sourced from well-established extractive industry, with aggregate minerals recognised as a national strategic resource (GOV UK, 2012). Next to chemical composition, the greatest sensitivity affecting the net carbon removal potential of quarry fines is the transport distance from quarry to application on site. Nine quarries were contacted to understand their material chemical composition and carbon sequestration potential when factoring in distance from quarry to site. An assessment was undertaken (Section 1.5 of Appendix C). Builth Wells Quarry was identified as the most efficient and cost-effective source of fines and recommended as the EMW material source for the Phase 2 project. The net cost is estimated at £217.39/tCO2e removed through carbonation and £97.56/tCO2e removed through EMW.

Supply

Publications such as the Royal Society Report (The Royal Society, 2018) have made the sequestration potential of biochar public; 7 of the 24 projects publicly announced by BEIS are using biochar (GOV, 2021).

Contact with producers, such as PyroCore, also suggests a growing interest in established UK biochar production systems. The growth of pyrolysis application across other sectors e.g., waste management (PyroCore units are currently used onboard Queen Elizabeth Aircraft Carriers), will also benefit biochar production through economies of scale as larger production units are developed with greater throughput and efficiency.

A flowchart of the expected scaling stages is given below in Figure 5.

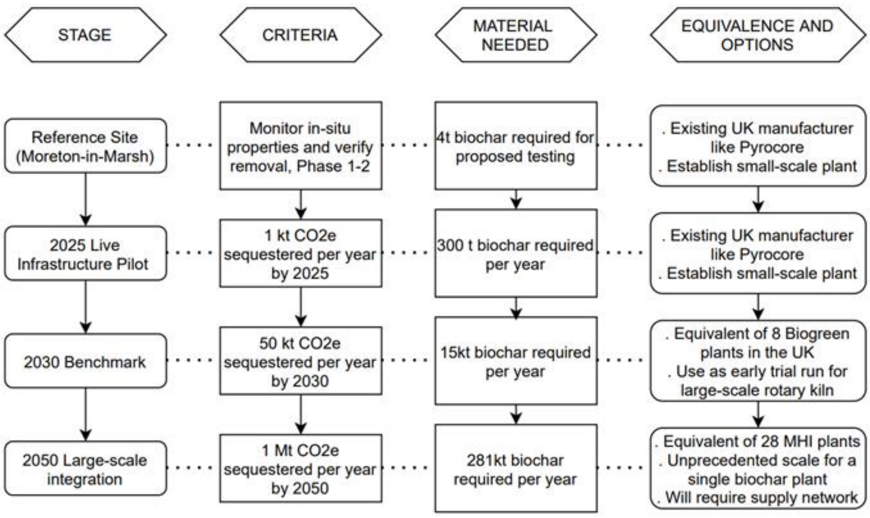


Figure 5: Flowchart to show likely progression of biochar production

A supply of 281kt of biochar in 2050 outstrips any consideration of small-scale units and even of a single plant, considering current rotary-kiln pyrolysis technology (See Section 1.5 of Appendix B, Appendix B1, and Appendix B2 for a review of commercially available pyrolysis systems). Instead, multiple large-scale rotary kiln plants will be required, and the use of biochar in infrastructure will require a growing domestic biochar industry.

Regulation

Biochar is currently considered a waste which is a significant challenge to adoption at scale, given that the use of wastes is highly regulated in the UK. Further information is given in Appendix E. There are several regulatory mechanisms that may typically be applied to enable the use, disposal or recovery of waste or to change the status to a non-waste:

- Waste exemptions;
- End of waste protocol;
- Regulatory position statement;
- Standard rules environmental permit; usually with an associated volume limit, defined controls, and limitations, and specific to the use and type of waste for a particular purpose;
- Bespoke environmental permit which can cover a wider array of situations than a standard rule permit but is more complex with applicable supporting risk assessments and controls etc.

There are currently no exemptions, end of waste protocols or relevant regulatory position statements that would apply to the scale and application rate proposed. It is not expected that this policy gap can be resolved in the consenting programme for the current proposals, so for the purpose of the pilot project it is assumed that biochar is classed as waste material and would therefore require a permit. However, there will be challenges in obtaining a permit for recovery. For instance, although biochar is currently regarded as a waste, there is no direct List of Waste Code for it. This would need to be explored with the Environment Agency, as the use of a recovery permit is usually limited to specific waste codes and activities in the first instance.

As part of the programme, several project teams have collaborated to set up the Biochar Forum – a forum to examine the issues associated with the potential use of biochar (with plans to extend to EMW) for applied GGR. The Forum is currently being managed by Severn Wye[12] with the intention to work with BEIS, Defra and the Environment Agency to develop the regulatory framework for the use of biochar for the purpose of carbon sequestration. Engagement with some members of the Environment Agency, through the Biochar Forum has indicated that a Regulatory Position Statement might be a longer-term and achievable goal. Next steps for progressing the environmental permit comprise:

[12] Severn Wye Energy Agency

- Undertaking a pre-application consultation with the local Environment Agency team and request that they log a National Help Desk enquiry relating to the pre-application.
- Subsequently, facilitating a discussion at national level within the Environment Agency to drive the decision-making process.

Unlike biochar, quarry fines are sourced from a well-established extractive industry, with aggregate minerals are recognised as a national strategic resource (GOV UK, 2012). However, a major factor (along with chemical composition) affecting the net carbon removal potential of quarry fines is the transport distance from quarry to application on site.

Correspondence with quarries such as Clee Hill Quarry and Leaton Quarry reveal that incorporation into asphalt production on-site is a common use for quarry fines. Other suppliers such as Moons Hill Quarry appreciate the growing market for quarry fines use in agricultural amendment and as a means of removing carbon. The recommended source, Builth Wells Quarry, is itself involved in supplying basalt fines to a local carbon capture project (Agg-Net, 2021).

Demand

Considering road schemes alone, National Highways has allocated £347 million of funding to the development of potential future projects over the next five years. This includes 32 schemes, identified with DfT, to be developed for the third Road Investment Strategy (RIS3) from 2025-2030 (National Highways, 2021). These projects will provide the opportunity to rapidly scale up the implementation of the GGR technologies.

If all the potential topsoil volume for the Banwell Bypass – a £38 million[13] scheme with approximately 48,000m^2 of cuttings and embankments – utilised the assumed blend[14], the approximate removal potential would be 1,700tCO2e (very conservative estimate). If the 32 schemes represented, on average, a similar scale to Banwell, they could deliver over the 50ktCO2e removal target.

This is just the highway pipeline to 2030. There are wider opportunities across linear infrastructure. For example, HS2 Ltd is currently procuring a Phase 2a Design and Delivery Partner (DDP) for the section connecting the West Midlands and Crewe. The £500m contract is expected to be awarded in summer 2022 and would offer an opportunity for early integration of the technologies within the design of the 36-mile Phase 2a route (HS2 Ltd, 2021).

Additionally, Network Rail published a safety-led review (Network Rail, 2021) into the management of earthworks. Network Rail manages 190,000 earthworks assets. Failures of railway cuttings and embankments are a major safety concern and regular inspection, and upgrade of earthworks are required to ensure resilience to climate change. The technologies' potential to improve the stability

[13] North Somerset Council awarded Alun Griffiths the £38m Banwell Bypass design and build contract.

[14] A blend of 25.9% biochar, 24.1% dolerite, and 50% locally derived topsoil (by volume) will be used within the upper surface of the earthworks (see Appendix G and Appendix G5)

of top-soiled slopes has been explored in section 1 of Appendix I– also a consideration for the maintenance and resilience of the existing road network.

These are just some of the potential economic opportunities that can be explored to scale up. However, the roadmap also addresses the identified market failures to cost effective implementation, particularly technical obstacles, policy gaps, regulatory barriers and information failures[15].

Evidence of such barriers was highlighted in the findings of the consultee and industry engagement (see Appendix D) which suggested that market awareness needs to be created.

Work to address these barriers would be developed further during the Phase 2 pilot project; work beyond March 2025 would aim to build on the momentum established by the Biochar Forum and leverage in the research and project budgets of infrastructure operators in the UK (such as National Highways, Network Rail, and the Environment Agency).

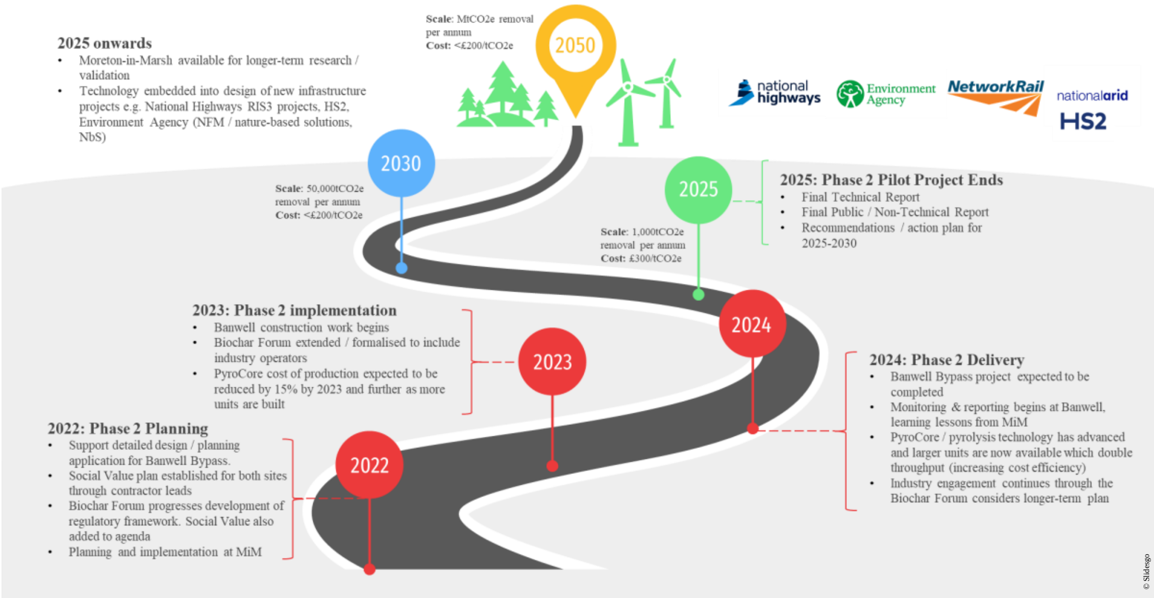


Figure 6: GGR Roadmap

Social Value

Infrastructure's purpose is to meet fundamental societal needs. There is currently a significant focus on improving infrastructure provision in the UK, and the recent and emerging value-based infrastructure delivery models seek to improve efficiency and productivity and drive innovation to achieve better outcomes for society resulting in greater social value.

The essence of social value is to identify the wider benefits of public decisions and business activities for people, the economy, and the environment. If infrastructure is to play a key role in the levelling-up agenda, social value creation

[15] Information failure as a 'market failure' refers to a situation when economic agents – producers and consumers – do not possess complete information regarding either the cost or the benefit resulting from a market transaction.

must be integral to all stages of the project, including funding, planning decisions and delivery. Appendix F sets outs out the key drivers of social value in the context of infrastructure delivery.

Good practice is that any social value opportunities agreed upon in a project's planning and design phase are set out within contractual requirements to ensure clarity and delivery. A best practice is to set out a social value delivery plan, articulating the approach to social value outputs and outcomes expected at all project stages. As such (and as outlined in Figure 6), social value 'thinking' will be embedded across the project supply chain, championed by the project delivery team, and drawing on best practice approaches. A Social Value Plan will be drafted as part of Phase 2 inception. This plan will be a working document that is monitored and updated throughout the period to project completion in 2025, to include social value outputs and outcomes delivered within the Phase 2 timeframes and recommendations on maximising social value outcomes on the roadmap to 2030 and beyond.

With the value of planned infrastructure investment in the national pipeline running into the hundreds of billions of pounds – see section 3.3.2 – it is imperative that the demand for social value outcomes is fully embedded into early-stage project design (ideally through the business case); without this, and effective engagement and consultation, it will always be considered an "add-on" and opportunities will be lost.

For Banwell, a Needs Analysis and Social Value Action Plan has been completed by the Social Value Portal (The Social Value Portal, November 2020), with an estimated additional social and local economic value between £2.9 million - £5.9 million, representing 7.5% - 15% of the contract value.

Priority needs to be addressed include: (i) high employment deprivation in Banwell village centre (ii) high level transport CO_2e emissions per capita in North Somerset, and (iii) high percentage of physically inactive adults. The Social Value Action Plan recommendations include providing employment opportunities for local people (particularly those further from the job market; including NEETs and long-term unemployed), subsidised sustainable transport opportunities and volunteer support to community events. The Social Value Action Plan developed during Phase 2 inception would build on this plan further and consider potential to link into community events. The risk assessment is covered for each project in Sections 7.4 and 8.4.

3.4 Appraisal Summary

The preferred option is identified as:

- **Pilot site: Banwell Bypass + Reference Site: Moreton-in-Marsh**

At the inception of Phase 2, a benefits realisation plan would be developed to provide a more detailed plan towards maximising the economic, environmental, and social value of the technologies at national scale – the initial programme / plan is set out in the Management Case (see Section 6). The Phase 2 Pilot locations are indicated in Figure 7, along with the PyroCore facility in Wells and two nearby quarries.

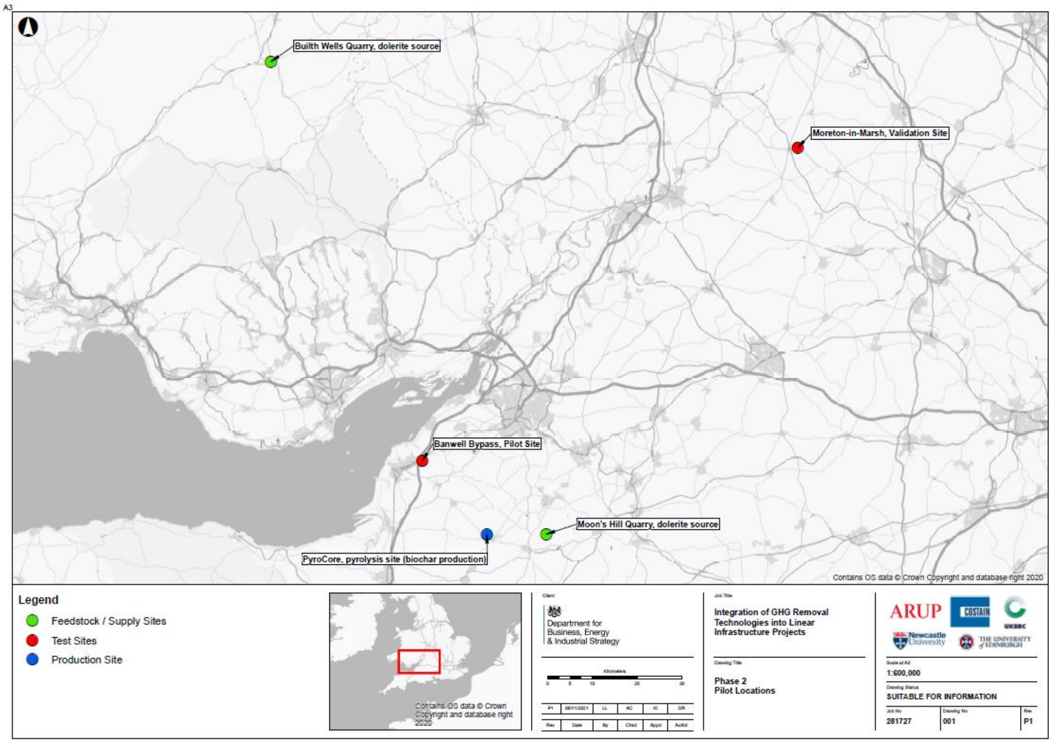


Figure 7: Phase 2 Pilot locations

4 Financial Case

The financial case sets out the potential funding requirement, including summaries of the full cost plans, underlying cost assumptions and main financial risks identified.

4.1 Financial resources & budgets

The project is part of Lot 2 – “Mid Stage” – and is therefore eligible for up to £5 million of funding[16]. The project cost is estimated at **£4.75 million** (excluding VAT) for Phase 2 based on the following cost estimate:

Table 4: Summary of Phase 2 Project Cost

Item	**Total Cost**
A, Project Management	£1,061,000
B. Pre-construction activities	£1,780,000
C. Construction Activities	£1,123,000
D. Post Construction Activities	£449,000
E. Risk	£337,000
Total (Excluding VAT)	**£4,750,000**

[16] SBRI Phase 2 – Pilot phase: contacts of between £1m and £5m per pilot project

VAT @20%	*£888,000*
Total Cost (including VAT)	*£5,638,000*

A higher rate of optimism bias (46%) is applied to the base cost for pre-construction activities, with 23% applied to other items, consistent with transport (road) optimism bias estimates[17] (DfT, 2021). Optimism bias equates to £1,054,000, equivalent to 22% of project cost.

Table 5: Profile of Base Cost Estimates (excluding Optimism Bias)

Year	2021/22	2022/23	2023/24	2024/25	**Total**
Banwell Bypass – Pilot Site					
A. Project Management	-	£249,000	£166,000	£138,000	£553,000
B. Pre-Construction Activities	-	£512,000	£341,000	-	£853,000
C. Construction Activities	-	-	£509,000	£340,000	£849,000
D. Post Construction	-	-	-	£259,000	£259,000
Total	-	**£761,000**	**1,016,000**	**£737,000**	**£2,514,000**
Moreton-in-Marsh – Reference Site					
A. Project Management	-	£177,000	£118,000	£99,000	£394,000
B. Pre-Construction Activities	-	£301,000	£200,000	-	£501,000
C. Construction Activities	-	-	£88,000	£58,000	£146,000
D. Post Construction	-	-	-	£141,000	£141,000
Total	-	**£478,000**	**£406,000**	**£298,000**	**£1,182,000**

4.2 Cost Plans

Detailed cost plans have been prepared for the pilot and reference sites – Banwell Bypass and Moreton-in-Marsh (see Appendix J). All costs exclude VAT and do not exceed the maximum allowable budget (where VAT applies, this has been specified).

Only eligible costs – those directly associated with the development, implementation, operation, and monitoring of the GGR pilot project – have been included in cost estimates. All project activities, including reporting and payments, would be completed by 31 March 2025. No profit is included in project costs. Contract cost savings are outlined in section 5.1.

4.2.1 Banwell Bypass Cost Plan Summary

A summary of the estimated base cost is provided in Table 6 below. A detailed cost plan for the Banwell Bypass Pilot is included at Appendix J.

Table 6: Banwell Bypass Base Cost Estimate

Item	Cost Estimate
Project Management (incl. stakeholder engagement)	£553,000
Pre-construction activities (incl. planning statement and permits)	£853,000
Construction Activities	£849,000
Post Construction Activities	£259,000

[17] Optimism bias uplifts taken from Table 8 of DfT TAG Unit A1.2 for category 'roads'. Higher uplift (46%) applied to pre-construction activities given uncertainty (e.g. obtaining permits) and 23% uplift (for Stage 2 schemes) applied to other base costs.

Total	**£2,514,000**

4.2.2 Moreton-in-Marsh Cost Plan Summary

A summary of the estimated base cost is provided in Table 7 below. A detailed cost plan for the Banwell Bypass Pilot is included in Appendix J**.**

Table 7: Moreton-in-Marsh Base Cost Estimate

Item	Cost Estimate
Project Management (incl. stakeholder engagement)	£394,000
Pre-construction activities (incl. planning statement and permits)	£501,000
Construction Activities	£146,000
Post Construction Activities	£141,000
Total	**£1,182,000**

4.3 Budget arrangements and reporting

The cost plan would be refined and agreed upon with BEIS prior to the issue of the contract (if successful). During biannual stage gate reviews, a detailed budget report would be prepared to demonstrate spend against the cost plan, including financial risk assessment and any proposed mitigation measures should these be necessary.

4.4 Financial Risk

The main financial risks identified are as follows:

- Cost inflation: where market costs for the GGR materials turn out higher than forecast. This is considered a significant risk given recent construction price inflation (ONS, 2021). However, market testing has informed the cost plan, with conservative assumptions applied to biochar source material. Risk of cost inflation in materials has been built into the cost plan (assumption of 25%)[18].

- Cost uncertainty: some aspects of the project (e.g., sampling, testing and analysis) will involve learning, innovating and refining processes. Unit costs are expected to reduce over time but there may be several iterations before the most cost-effective methods and processes are established. Optimism bias has therefore been applied to take account of potential underestimation of costs on account of the 'first of a kind' nature of the project.

- Regulatory risk: potential underestimation of the costs associated with achieving the necessary permissions, planning and permits. This would be mitigated through early and effective stakeholder management, particularly utilising the Biochar Forum, and pre-application discussions

[18] The price of wood material has increased since April 2020, peaking in September 2021, an increase of 25.1% from September 2020 (ONS, 2021)

with the local permitting officer then the Environment Agency's national help desk[19].

- Technical/environmental risk: potential additional costs associated with removal of the topsoil material in the case of failure or unforeseen environmental impact that requires mitigation at cost. Technical risk will be mitigated through trials of the topsoil 'blend' at MiM prior to application at the pilot site.

5 Commercial Case

5.1 Commercial Strategy

The commercial strategy is aligned with the SBRI approach to risk and would deliver cost savings compared to exclusive development contracts. The investment would fast-track the deployment of the technologies into a live infrastructure project. This would provide a more cost-effective approach, with pilot project designs already well-developed. Professional fees on infrastructure projects typically represent 10% of total cost; in the case of Banwell Bypass that represents approximately £3.8 million.

The proposed commercial strategy would see Alun Griffiths as the delivery agent for the Banwell Bypass pilot project and Costain as the delivery agent for the MiM reference project. The commercial strategy would foster a culture of openness, sharing and learning, with close links between the two projects, contributing to maximising social value. A social value framework would be embedded into the commercial/procurement strategy from the outset of Phase 2 (see section 3.3 and Appendix F).

5.2 Contract Management

The Phase 2 contract would be managed by North Somerset Council. High-level delivery milestones would be agreed upon with BEIS before contract award (if successful). Key contract dates are understood as follows:

- Project milestone discussion (March 2022).
- Contract award & projects start (April 2022).
- Projects complete no later than March 2025.

The Commercial Case will be developed further once the ITT for Phase 2 is issued (expected December 2021).

Further detail on proposed Phase 2 programme management and reporting is provided within the Management case.

[19] See section 3.3.2.1: the Biochar Forum is a collaboration to examine the issues associated with the potential use of biochar (with plans to extend to EMW) for applied GGR.

6 Management Case

An overview of the pilot project (Banwell Bypass) is provided in Section 7. An overview of the reference project (Moreton-in-Marsh) is provided in Section 8. This section provides a combined overview of how both projects would be managed.

6.1 High Level Programme

As summarised in Sections 3.1 and 3.2 , Phase 2 proposals would principally involve the delivery of two pilot projects:

- Banwell Bypass (scaled, live pilot project to achieve 1,000tCO_2 removal); and
- Moreton-in-Marsh (reference site for verification – see section 3.2 for benefits).

A high-level overview of the programme for delivery is provided below in Figure 8.

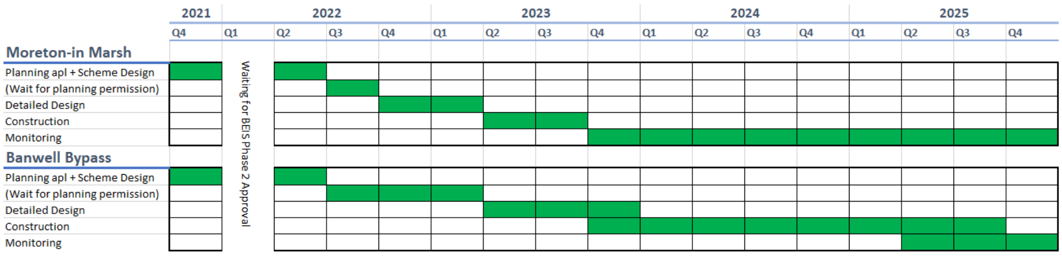


Figure 8: High level Phase 2 overview

Key milestones include:

- Planning submission for Banwell Bypass in May 2022;
- Construction of Moreton-in-Marsh in Q2 of 2023;
- Construction of Banwell Bypass pilot project complete prior to Q3 2025.

Stage gate reviews would be held every six months after project inception (as stated in the competition guidance) to assess progress against agreed milestones, deliverables, cost plan and to update the assessment of risk (see section 6.5).

6.2 Governance & Project Management

A summary organogram of the governance is provided in Figure 9. North Somerset Council would manage the contract and a Project Steering Group would be established to ensure co-ordination and sharing between the projects.

The Phase 1 team would continue into Phase 2. However, the governance and project management arrangements will be different from Phase 1. It is proposed that there will be a single point of contact for both sites (in respect of the contract management) through North Somerset Council.

For the MiM site, the team would be unchanged from Phase 1, although Costain would lead the delivery of the project instead of Arup due to their experience in construction. For the Banwell Bypass Pilot Project, an addition to the current consortium is required, with Alun Griffiths joining as delivery lead given their status as the appointed contractor on the scheme.

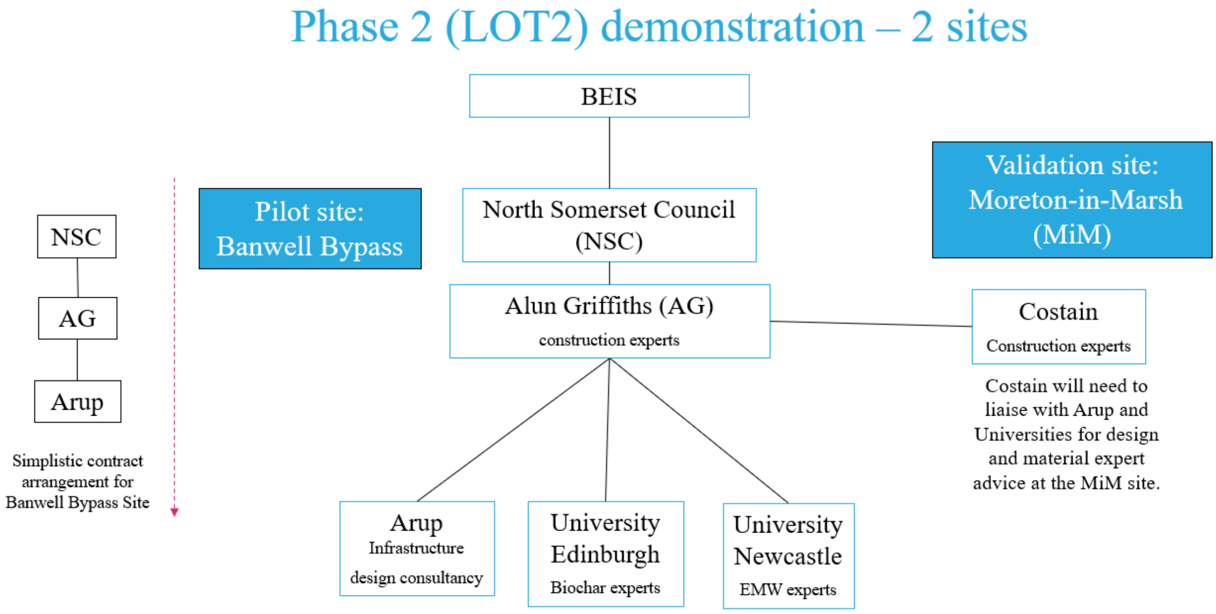


Figure 9: Governance overview for Phase 2

6.3 Key Stakeholders

In addition to the project team outlined in Figure 9, there are the following key stakeholders:

- The Environment Agency (EA) who will be key for providing the required environmental permits for the completion of both projects;
- The Department for the Environment, Food and Rural Affairs (DEFRA) who will need to support the EA with policy to achieve the permits;
- Capita, who own and operate the Moreton-in-Marsh site; and
- A variety of local stakeholders who may impact the schemes, particularly in relation to achieving planning permission.

Managing these stakeholders will be key for the successful completion of both projects.

6.4 Monitoring and evaluation

Detailed monitoring and evaluation plans have been prepared (and costed) for both schemes and are included in Appendix G and Appendix H.

6.5 Risk Management

An extensive risk register has been produced, supported by a geotechnical opportunities and risks review – see Appendix I. For the majority of risks, mitigating actions have been identified to reduce residual risk level to ‘low’. Risk would be continually managed through Phase 2.

7 Pilot Site: Banwell Bypass

7.1 Overview of the Site

Banwell is a village in North Somerset, located approximately 6km east of Weston-Super-Mare and 28km southwest of Bristol. The immediate surrounding land use is agricultural, with the Mendip Hills Area of Outstanding Natural Beauty (AONB) is to the south of the village.

The proposed Banwell Bypass will alleviate congestion around Banwell village and create the potential for future housing delivery, supporting the emerging North Somerset Local Development Plan, and providing sustainable transport opportunities. Alun Griffiths (Contractors) Ltd, with Arup and TACP as technical and environmental designers/advisors, are submitting a planning application and general scheme design in May 2022. For full details of the site, refer to Appendix G.

7.1.1 Overview of Reasons for Selection

Arup and Alun Griffiths are the incumbent designer and contractor on the project, meaning an existing relationship between the key parties that will provide for efficient integration of the proposed pilot. The client – North Somerset Council - (NSC) – is keen to be as innovative and sustainable as possible, with Alun Griffiths also having positive feedback for the project. These stakeholders are therefore excellent champions for the project.

The extensive use of embankments throughout the scheme generates a large volume of earthworks, ideal for incorporating biochar and quarry fines at scale into the topsoil. Proximity to both proposed pyrolysis supplier, feedstock, and potential dolerite quarry locations also effectively limits the required material haulage and cultivates a valuable sense of local ownership and involvement in the project. The site therefore suits the aims of the pilot technically as well.

Following planning permission and detailed design, construction is due to start in September 2023 and be open for use in September 2025. This Banwell delivery plan fits well with the BEIS programme for Phase 2. This was a critical success factor for project selection, given the challenges of identifying a live infrastructure project with a delivery plan that would allow the aims and objectives of the Phase 2 programme and scope to be achieved.

The Banwell Bypass scheme was therefore found to be an excellent fit for the purpose of the pilot project, as demonstrated in Section 3.1.

7.2 Proposed Development

The proposed new development principally consists of a new single carriageway road bypassing the village of Banwell. The route has been confirmed as ‘Route 2’ provided in the overview plan below in Figure 10, along with the Southern Link road.

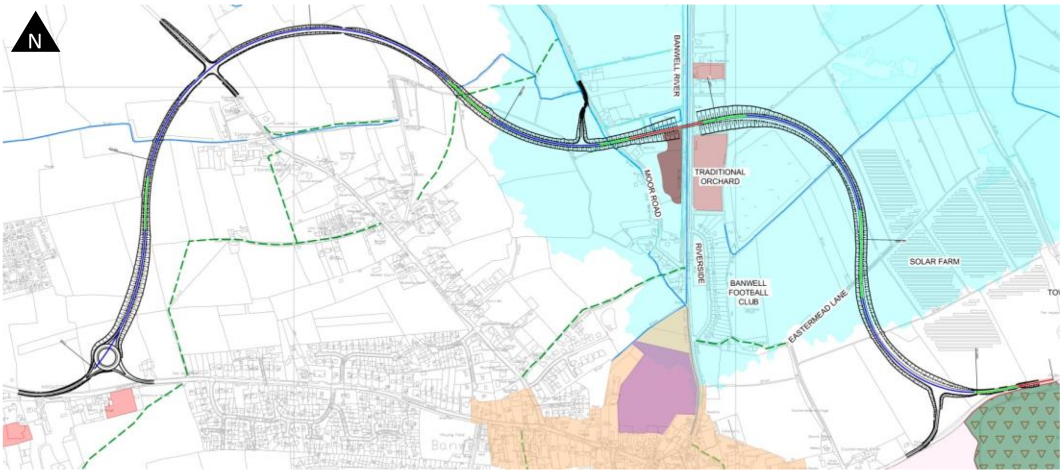


Figure 10: Plan overview of Route 2 location (selected as route for new road) (See Appendix G3 for complete site drawings, including the Southern Link Road)

Approximately 48,000 m^2 of cuttings and embankments will be required for the scheme. This area will be confirmed during the detailed design planned for Q2 2022. A blend of 25.9% biochar, 24.1% dolerite, and 50% locally derived topsoil (by volume) will be used within the upper surface of the earthworks. A breakdown of the proposed application is given below in Table 8.

Table 8: Estimated blend placement breakdown for Banwell Bypass (design is ongoing)

Placement	Blend thickness (m)	Area used (m^2)	Volume of blend (m^3)
1:2 Embankment	0.15	19,208	2899
1:3 Embankment	0.25	6,375	1594

See Appendix G for full details, Appendix G3 for more detailed drawings, and Appendix G5 for proposed blend calculations.

7.3 Consents and Licences

7.3.1 Planning Permission

For planning permission to be granted, there must be full details submitted about the pilot proposal. Planning conditions may need to be attached to any permission subject to negotiation with the Local Planning Authority. The Local Planning Authority in this instance is the client for the main scheme: North Somerset Council (NSC) and who will be leading Phase 2. Efficiencies will therefore be achieved by working closely with NSC prior to planning submission (refer to Appendix G4 for the potential environmental impacts.

7.3.2 Permit for use of the Materials

Whilst the use of dolerite does not require a permit, there is currently a policy gap regarding the large-scale utilisation of biochar. Under current regulatory definitions, the biochar component would likely be a ‘waste’, requiring greater investment and lead times for implementation via permitting. A pre-application meeting with the local Environment Agency team, then escalation to the national advisory help desk, will kick start a process for defining the permitting process (with the most relevant currently considered to be a recovery permit). A position statement would be a preferred option but the lead time to this being developed and agreed is unlikely to align with the project consenting timeframes. A more detailed explanation and details on the engagement completed to date are provided in Appendix E.

7.4 Key Risks and Opportunities

A risk and opportunities (R&O) register for this submission is presented in Appendix I1 of the report. A summary of the key risks and opportunities for the Banwell Bypass scheme is presented in Table 9, please see section 5.2 of Appendix G for more risks and opportunities. Geotechnical risks and opportunities are discussed at length in Appendix I.

Table 9: Key risk and opportunities assessment for Banwell Bypass

Risk & opportunity	Description	Mitigation and further action
Risk: Programme alignment	Like any project, the programme for Banwell is subject to change. For example, delays in the planning process may slow completion and jeopardise the carbon removal target of the project. However, based on the current programme for the Banwell Scheme and proposed Phase 2 timeline, the construction of the Phase 2 Pilot is considered to be compatible with the Phase 2 requirements.	Moreton-in-Marsh provides mitigation of this risk as works will be able to commence earlier at the reference site. This allows for construction methodologies and monitoring methods to be refined before their full-scale deployment at the Banwell Bypass.
Risk: Permit Achievement	There is currently a policy gap for the permitting of biochar and dolerite for the purpose of carbon removal. It is not possible to determine how long a central-led position statement will take to achieve. This may impact the	Engagement with the Environment Agency and the Department for Environment, Food and Rural Affairs has been undertaken in a biochar forum set up during Phase 1 to understand the most efficient way to achieve the required permit (please see section 3.4 of

Risk & opportunity	Description	Mitigation and further action
	programme for the Banwell Bypass project.	Appendix D, and Appendix D4 for further information on the biochar forum). The permit application will begin as soon as possible on the project to ensure that a permit is in place prior to breaking ground. There are several challenges to be addressed in obtaining a recovery permit. Initial consultations with some members of the Environment Agency indicated that there should be broad support considering the wider environment and societal benefits of the proposals, but specific details of the permit, and demonstration of recovery will need to be explored at a local and national level to enable a consensus among different departments. A more detailed explanation and programme for the permitting process is provided in Appendix E.
Opportunity: Deployment of technologies within a live infrastructure site	Use of both technologies on this scale is unprecedented and novel within an infrastructure scheme. Lessons learned from this scheme will likely inform all future applications of the materials in infrastructure.	Thorough reporting and dissemination during Phase 2 will be important, for informing existing Phase 1 stakeholders and engaging new potential interest in the materials.
Opportunity: Proximity to Ash (Fraxinus Excelsior) source	A local feedstock source has been identified 2km south of the scheme. Engaging with local landowners to tackle an Ash Dieback problem whilst reusing the wood to remove carbon is a strong way to create community engagement with the works, and with biochar itself (please see Appendix B5).	Contact has been established between Alun Griffiths and the Ash (Fraxinus excelsior) owners to determine the suitability of the site for feedstock sourcing as well as storage and chipping also. Other local landowners should be consulted, and engagement activities arranged to maximise awareness of biochar's utility.

8 Reference site: Moreton-in Marsh

8.1 Overview of the Site

As part of the Phase 1 feasibility study, it has been concluded by the Project Team that a reference site would be of benefit to the overall study. The reference site identified is located immediately east of Moreton-in-Marsh (MiM), a small market town located in the Evenlode Valley in Gloucestershire. The site itself is currently a testing facility associated with the Fire Service College and highways services testing (owned by Capita), with the site typically used for fire-related training. Pertinent information relating to the physical characteristics of the site (e.g., topography, geology, and environmental sensitivity) are detailed in Appendix H.

One of the main benefits of this particular site to the study is that it offers a controlled environment to allow for processes associated with the use of these materials to be more fully understood. This includes optimising construction methods and monitoring and verification testing approaches, the findings of which could also help inform the use of these materials and specific monitoring requirements for the Banwell Bypass scheme and future linear infrastructure projects.

The reference site also provides additional risk mitigation in the event of potential delays to the planning process for the main Banwell site discussed in Table 5.

A summary of the proposals for the reference site is provided in Appendix H of this report.

8.2 Proposed Development

The proposed development at MiM comprises six development plots, referred to in Appendix H as Plot(s) 1 to 6. The total land take required at MiM to facilitate the construction of the six plots is 1,230m^2. Detailed justification for the purpose of each development plot is provided in Appendix H of this report. A summary of this information is provided in Table 10.

Table 10: Justification for the proposed trials at Moreton-in-Marsh

Plot	Description and rationale
Plot(s) 1 to 4	Plots 1 to 4 would comprise four separate embankments, which would be constructed to the dimensions and specification outlined in Appendix H**.** The main embankment batters (1 in 3 slope) and battered end slopes (1 in 1.5 slope) would be covered with 300mm and 150mm of topsoil respectively. Pozidrain should be used for water containment, either directly beneath topsoil or at the base of the proposed embankments (see section 4.4 of Appendix H). The topsoil composition placed on each embankment plot would consist of different compositions of biochar: quarry fines: topsoil; with Plot 2 comprising just topsoil to serve as a control area. All plots would be planted with the equivalent seed mix proposed for the Banwell Bypass earthworks. The purpose of these plots would be to explore the sensitivity of carbon removal to topsoil volume ratio and compare the efficacy of carbon removal between the different topsoil compositions. This would be validated through monitoring and testing. Embankment slope stability, changes in the chemical properties of the soil (soil dry weight and soil leachate), material parameters, vegetation growth, microbial communities, and water quality would be monitored and tested (see Appendix H).
Plot 5	Plot 5 would comprise a mixing area, located adjacent to Plots 1 to 4. The primary purpose of this plot would be to trial the mixing process of the three material types (biochar, quarry fines, and topsoil). This is to ensure that an effective and economical mixing methodology could be defined – e.g., ensuring that the blend is homogenous, and any fragmentation of the biochar is minimised. Note that the mixing of these material types into a homogenous blend has not previously been trialled and defining

Plot	Description and rationale
	optimum methods would be useful for both the proposed Banwell Bypass pilot and future schemes. Further detail is provided in Appendix H.
Plot 6	Plot 6 would comprise a 30m^2 plot (6m x 5m). The primary purpose of this plot would be to understand the CO_2 sequestering potential of dolerite quarry fines when used as a bulk fill. This plot would also provide an in-situ source of weathered fines. Changes in the chemical properties of the soil (soil dry weight and soil leachate), material parameters, vegetation growth, and water quality would be monitored and tested. Further detail is provided in Appendix H.

8.3 Consents and Licences

Arup have been notified by the site owner (Capita) that there are no exemptions from planning for any developments that are to take place on the site. As such, particular conditions may be required to be addressed as part of any future planning applications to approve development at the site. The likely requirements associated with obtaining planning permission for the development is detailed in Appendix H. For the regulatory position of the use of biochar at the reference site, see Appendix E. At this stage, it is assumed that a waste recovery permit will be required (see Appendix E).

8.4 Key Risks and Opportunities

A risk and opportunities (R&O) register for this submission is presented in Appendix I1 of the report. A summary of the key risks and opportunities for the Moreton-in-Marsh scheme is presented in Table 11. Further detail of specific risks and opportunities are presented in section 4.3 of Appendix H.

Table 11: Key risk and opportunities assessment for Moreton-in-Marsh

Risk & opportunity	Description	Mitigation/further action
Risk: Programme alignment	It is possible that the alignment of programme for Moreton-in-Marsh (MiM) and the identified live pilot project's (Banwell Bypass) completion may not be aligned, and completion may be delayed beyond the 2025 date required for demonstration of the 1,000tCO_2e/annum target.	The trials at MiM will aim to demonstrate the value of these technologies as a whole, benefitting future applications. The trials at MiM will align with the Banwell Bypass programme with respect to mixing trials and overlap with the monitoring intervals, and therefore providing an overall benefit.
Risk: Validation and monitoring	The carbon benefits and behavioural characteristics of these materials have been postulated in the literature, however, monitoring of these behaviours is in some cases a novel concept (e.g., monitoring structural/geotechnical changes associated with quarry fines as a result of weathering). There is a potential risk that monitoring these behaviours may be difficult to validate, and unexpected problems may arise that	The primary purpose of these trials at MiM is to validate the material behaviours and monitoring, to streamline this process during the pilot site and future applications.

Risk & opportunity	Description	Mitigation/further action
	have not previously been accounted for (e.g., sampling and testing issues).	
Opportunity: Longer term monitoring	Moreton-in-Marsh offers the potential for longer term monitoring of carbon removal, and environmental/engineering/ ecological impacts associated with the materials. Significantly benefit validating the carbon performance of the materials, and to refine any monitoring needs should this be required. Refinements could be implemented/assist Pilot Site studies (Banwell Bypass).	The potential for longer term monitoring could be a key opportunity for using Moreton-in-Marsh as the reference site.
Opportunity: Onboarding National Highways early on	Having Moreton-in-Marsh is important to get National Highways on board with the use of these materials for carbon removal. National Highways will be aware of the development of these technologies and the results of monitoring as and when it happens, as National Highways currently operate within Moreton-in-Marsh (e.g. through smart motorway development).	National Highways would be in a better position to appreciate the next steps that would need to be taken to integrate the materials into standard highways design.

9 Conclusions and Recommendations

This report has demonstrated a viable and cost-effective route for the integration of biochar for carbon storage and dolerite or basalt quarry fines for direct GHG capture via EMW into the UK infrastructure sector.

The current understanding of the science underpinning the potential for carbon capture using biochar and EMW processes has been presented. The potential application of these technologies, and their suitability for GGR within infrastructure developments has been summarised.

Plans for pilot schemes to demonstrate and quantify the effectiveness of the technologies have been presented, including the Banwell Bypass scheme and the Moreton-in-Marsh test facility. The plans include detailed proposals for construction and a regime of controlled monitoring and testing, which would provide essential supporting data to facilitate the refinement of the current deployment strategies for these technologies and expansion of these towards 2030 and beyond.

Growing from this immediate application, key material and supply-chain opportunities have been identified and an upscaling roadmap presented, including the incorporation of a Social Value Plan to embed best practice across the GGR supply chain of both projects. This demonstrates that the planned pipeline of infrastructure investment represents a huge opportunity (building off a £650 billion pipeline of investment) to deliver carbon removal at scale (>50ktCO2e) as well as wider social value outcomes to support levelling up through a 'just transition'[20] to a net zero economy.

[20] A fairer, greener future for all

A full review of market opportunities, barriers and risks has been completed through extensive discussion with key industry stakeholders. This review has guided the research undertaken. A key aim of this stakeholder engagement process has been to maximise the relevance of the research and ensure that the Phase 2 pilot proposals address key stakeholder concerns as far as possible.

Identified scientific and economic challenges have been presented, together with risks associated with industry perceptions of the use of the two technologies, key issues around regulation and permitting, and further steps that will be needed to facilitate potential upscaling of the use of these technologies.

In terms of the next steps and recommendations:

- Develop the commercial case and management to confirm delivery aspects;
- Set out a high-level plan for the Biochar Forum in developing the regulatory framework, to include indicative timeframes;
- Support Banwell Bypass detailed design for planning application;
- Review the risk register and update any risk levels / mitigating actions as appropriate;
- Draft Social Value Plan – including key stakeholders, engagement, and draft value framework for the projects;
- Confirm governance and project management arrangements;
- Refine costs (if appropriate) through engagement with suppliers e.g., PyroCore / supplier quarries.

The above will help to ensure that Phase 2 (if the project is taken forward) is successful in achieving the desired outcomes of the BEIS programme.

Appendix A - Glossary

Appendix 1 Glossary

Abbreviation	Full term
AG	Alun Griffiths
BAU	Business As Usual
BQM	Biochar Quality Mandate
BSL	Biomass Suppliers List
C pot	Carbonation potential
CASPER	Carbonate Accumulation in Soils through the Prediction of Elemental Release
CEC	Cation exchange capacity
CH	Chainage
CV	Calorific Value
E pot	Enhanced mineral weathering potential
EA	Environment Agency
EBC	European Biochar Certificate
EMW	Enhanced mineral weathering
HE (NH)	Highways England (now National Highways)
HHV	Higher Heating Value
HyPy	Hydrogen Pyrolysis
IBI	International Biochar Initiative
ICE	Institution of Civil Engineers
IRMS	Isotopic Ratio Mass Spectrometry
LCA	Life cycle assessment
LOI	Loss on Ignition
MIM	Moreton-in-Marsh
MIST	Mineral Solutions Ltd
MRT	Mean Residence Time
NIC	National Infrastructure Commission
NR	Network Rail
NSC	North Somerset Council
ODT	Oven dry tonnes
ORC	Organic Rankine Cycle
PPT	Peak pyrolysis temperature
PSD	Particle size distribution
PyC	Pyrogenic Carbon Content
RHI	Renewable Heat Incentive
RIA	Railway Industry Association
SIC	Soil Inorganic Carbon
SOC	Soil Organic Carbon
TDS	Tonnes of dry solids
TRL	Technology Readiness Level
UK BRC	United Kingdom Biochar Research Centre
WASC	Water and Sewage Company
XRF	X-Ray Fluorescence Analysis

Appendix B - Biochar

1 Biochar

1.1 Overview

Biochar is a carbonaceous solid produced by the thermochemical treatment of organic materials (biomass) in an oxygen-limited environment (Pardo, Sarmah, & Orense, 2019). This process is called pyrolysis. By restructuring plant-based carbon into a more stable form, an intervention is made upon biomass that would otherwise decompose and release its carbon back into the carbon cycle. Biochar therefore represents an immediately quantified removal of carbon upon its integration into infrastructure.

1.2 Materials and Processes

This section is organised in a linear narrative as below in Figure 1. CO_2e removal and carbon persistence is discussed in section 1.3.

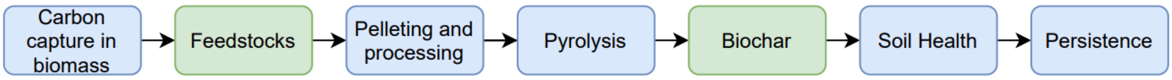


Figure 1: Flowchart to show materials (green) and processes (blue) for biochar

1.2.1 Carbon Capture in Biomass

Turnover of carbon in soils is the dominant flux in the terrestrial carbon cycle and is responsible for transporting twenty times the quantity of anthropogenic emissions each year (Renforth, Manning, & Lopez-Capel, 2009). The carbon cycle is maintained by the carbon-fixing properties of plants, phytoplankton, and bacteria. Oxidised forms of carbon are reduced to organic carbon compounds through photosynthesis and are stored in living biomass. This may be released into the atmosphere through respiration, forest fires, or the burning of fuel, or the decomposition of organic matter, specifically cellulose, hemicellulose, and lignin (Neemisha, 2020). The pyrolysis of biomass disrupts this decomposition and immobilises a fraction of the organic carbon in a stable form.

1.2.2 Feedstocks

Biomass is typically classed as either a virgin or non-virgin biomass. Virgin biomass is derived immediately from an organic source that does not involve chemical or biological transformation, amendment, or treatment. Virgin biomass encompasses materials like straw, soft/hardwood, manure, agricultural residue (e.g husks), or forest residues (e.g clippings). Non-virgin biomass encompasses materials such as construction and demolition waste, municipal solid waste, refuse-derived fuels, slurries, bedding matter, manures, sewage, and paper sludge (Shackley & Sohi, 2010).

Two feedstocks were initially considered for this project, anaerobically digested sewage sludge and softwood sawmill co-products (chips, sawdust, clippings).

Over England and Wales, 10 companies produce 1.2M tonnes of dry solids (tds) (the total, dry solid content of sludge) per year spread out over 1516 wastewater treatment works (Ofwat, 2021). The same companies produce a further 1M tds per year from 275 sludge treatment centres (Ofwat, 2021). Since 2018, water and sewage companies (WASCs) in England and Wales are required to publish annual information to encourage market speculation. Third parties (outside of WASCs) provided 48% of the industry's total sludge disposal from 2020-2021, up 3% from the period between 2019-2020 (Ofwat, 2021). The trading of sludge for treatment is low, and companies report several barriers for competition (Ofwat, 2021). The most common barrier identified was the government guidance "Rules for farmers and land managers to prevent water pollution" followed by regulations surrounding the co-digestion of multiple organic wastes in the same digester (Ofwat, 2021). Both issues are potentially circumvented by the pyrolysis process, meaning that WASCs represent a promising feedstock source if regulatory and permitting hurdles regarding waste derived biochar can be overcome.

A total of 150 sawmills processed UK roundwood in 2019, with 83% of mills producing less than 25,000 m^3 of sawnwood (softwood and hardwood) a year (Forestry Comission, 2020). Total production in 2019 was 3,410,000 m^3 of softwood and 47,000 m^3 of hardwood (Forestry Comission, 2020). From 2009 to 2019 the number of active sawmills has reduced by 20% with most of this decrease being borne by smaller operations, though softwood consumption is still higher in 2019 than 2009 so processing operations are centralising (Forestry Comission, 2020). Of the mills producing more than 25,000 m^3 of product, a total of 2,476,000 tonnes of other coproducts such as chips, bark, and sawdust were produced in 2019 (Forestry Comission, 2020). The exact figure of generated coproduct that is available for biochar production is not known. For instance, from industry consultation it was found that BSW Timber sell their coproduct to A.W. Jenkinson Forest Products, who sell them on for uses such as livestock bedding or equestrian walkway lining (A.W. Jenkinson Forest Products, 2021).

Beyond existing supply sources, it is important to place feedstock within the context of developing trends. The UK Committee on Climate Change aimed in 2019 to develop 30,000 hectares of new woodland in the UK every year, totalling an additional 930,000 ha by 2050 (Gambles, 2019). This is parallel to the emerging trend of structural timber use in construction. Given that 80% of UK timber was imported as of 2019, the turnover of managed woodland is likely to increase with the emerging domestic supply, opening significant opportunities for forestry residue as a biochar feedstock (Gambles, 2019).

Furthermore, The Department for Business, Energy and Industrial Strategy (BEIS) has awarded £4 million of funding for the project development stage of the Biomass Feedstocks Innovation Programme, comprised of 25 projects with up to £200,000 of funding per project (GOV UK, 2021). The research upon mobile pelletisation and the development of on-site pre-processing for trees offers the potential for highly flexible biochar production, greatly reducing biomass transport and enabling more site-specific feedstock options.

After consideration of environmental and regulatory positions, sewage sludge derived biochar was considered unfeasible within the scope of this work due to planning constraints associated with the anticipated waste status of non-virgin feedstock derived biochar. The proposed feedstock which has informed the life cycle analysis and the expected material properties is soft and hardwood sawmill coproducts.

1.2.3 Pelleting and Processing

Pelleting may be conducted either before or after pyrolysis. However, a pelleted feedstock adds consistency to the pyrolysis process by making the biomass uniform in shape. It also generates a uniform biochar with more consistent properties across batches, and greatly reduces the risks of material loss through dust generation whilst handling, potential run-off, and wind erosion (Shackley & Sohi, 2010). Given that the physical macrostructure constrains the rate of oxidation within the soil by reducing the surface area per weight of the biochar, pelleting may also benefit the long-term stability of biochar's carbon removal function (Cross & Sohi, 2013).

The basic steps of pelleting are as given (European Biomass Industry Association, 2021);

1. Comminution – maximum particle size is brought below the thickness of the desired pellet.
2. Drying – raw material is typically dried in a rotary drum.
3. Conditioning – the material can be conditioned with dry steam and water to the required temperature and moisture content to activate the biomass lignin as a pellet binding agent.
4. Milling – pellets are extruded by the action of rolling on a perforated matrix and cut at the desired length. The two main types are flat die and ring die.

It is therefore proposed that feedstock be pelleted before pyrolysis for ease of biochar handling and to maximise the long-term stability of biochar in the soil. This is recommended for the reference site at Moreton-in-Marsh and the live pilot site at Banwell Bypass.

1.2.4 Pyrolysis

There are several carbonization processes that can be used to produce biochar, including but not limited to; pyrolysis, gasification, hydrothermal carbonization, flash carbonization, and torrefaction (Cha, et al., 2016) For the purposes of this project only pyrolysis is considered.

Pyrolysis is a thermal process whereby biomass is decomposed in the absence of oxygen within an approximate temperature range of 300-900 °C (Cha, et al., 2016). It is essentially incomplete combustion, and air may be removed by purging the feedstock with N_2. The biomass is transformed by pyrolysis into three products; bio-oil (a high-energy-dense liquid), syngas (a low-energy-dense gas), and biochar (a carbon-rich high-energy-dense solid) (Woolley & Hallowell, 2018). The distribution of these products as a proportion of original feedstock weight also depends upon the pyrolysis conditions. For instance, at lower peak pyrolysis temperatures (PPT) and slower rates of heating, the biochar yield tends to increase (Woolley & Hallowell, 2018). Conversely during pyrolysis with higher PPT, more of the total chemical energy of products is contained in pyrolysis gases and liquids, rather than solids (Mašek, Brownsort, Cross, & Sohi, Influence of production conditions on the yield and environmental stability of biochar, 2011) The suggested pyrolysis supplier (PyroCore) typically do not produce a liquid yield, and further detail regarding the use of their by-products is given in section 4.1.1 of Appendix G. The different types of pyrolysis by temperature are given below in Table 1.

Table 1: Range of pyrolysis processes and outputs (Shackley & Sohi, 2010)

Pyrolysis	**Temperature and duration (range)**	**Solid (Biochar) (% o.d)**	**Liquid (Bio oil) (% o.d)**	**Gas (Syngas) (% o.d)**
Slow	250-750, mins-days	2 - 60	0 - 60	0 - 60
Intermediate	320-400, mins	19 - 73	18 - 60	9 - 32
Fast	400-750, ms-s	0 - 50	10 - 80	5 - 60

The boundaries between slow and fast pyrolysis are blurred. A key point to consider is whether vapours and aerosols components are rapidly removed to optimise liquid formation (fast pyrolysis) or whether they remain in contact with the solid, undergoing secondary reactions which produce added carbonaceous solids (slow pyrlysis) (Mohan, Sarswat, Ok, & Pittman, 2014). Fast pyrolysis is typically focused upon maximising the extraction of energy rich liquid and gas products, whereas high temperature slow pyrolysis (650°C) maintains high energy value of the pyrolysis gas and liquid fractions without compromising the stable carbon content of biochar (Crombie & Mašek, 2015). High temperature slow pyrolysis has been pursued as the most desirable process to retain the maximum amount of feedstock carbon within the produced biochar (Shackley & Sohi, 2010).

Further information regarding the industrial processes used to produce biochar is given in section 1.5.2.

1.2.5 Biochar Material Properties

Figure 2: Biochar from four different feedstocks, left to right; mixed softwood pellets, rice husk, woodchip, fine woodchip (UK BRC, 2019)

Shown in Figure 2 above, biochar is not a single homogeneous material. During pyrolysis the mass of the feedstock reduces but the basic structure of the original material remains, so biochar and its properties are determined by the choice of feedstock, pyrolysis conditions, and any other alterations made depending on its intended use, such as pelleting (Morgan, Sohi, & Shackley, 2020). The reader is referred to (Ippolito, et al., 2020) for an exhaustive review of feedstock and pyrolysis conditions upon biochar properties. Numerous bodies seek to standardise biochar properties for wider integration into agricultural and infrastructural practices, and some key organisations are given in Table 2 below. Readers are also directed towards (Tomczyk, Sokolowska, & Boguta, 2020).

Table 2: Key sources for biochar standards and classification, adapted from (Ralebitso-Senior & Orr, 2016)

Source	**Document**	**Description**
(International Biochar Initiative, 2015)	Standardized Product Definition and Product Testing Guidelines for Biochar That Is Used in Soil	Sets out a common definition for biochar with testing requirements for key properties
(Shackley, Ibarrola, Hopkins, & Hammond, 2014) (British Biochar Foundation)	Biochar Quality Mandate (BQM) version 1.0	Methodology for evaluating the environmental and health risks of using biochar as a soil amendment
(European Biochar Certificate, 2021)	Guidelines for a sustainable production of biochar	Establishing the biochar properties that are necessary to ensure safety and sustainability

Source	Document	Description
(UK Biochar Research Centre, 2019)	UKBRC Standard Biochar – Standard Biochar Specification Sheet	Ten biochars produced from five feedstock, using a pilot scale rotary-kiln pyrolysis plant at 550 °C and 700 °C
(UK Environment Agency, 2015)	Product comparators for materials applied to land: non-waste biochar	Sets out criteria to characterise non-waste biochar

Historic Use

Biochar's modern renown owes a debt to methods of cultivation practiced by the Amazonian peoples, resulting in the dark earths known as Terra Preta (Soentgen, et al., 2017). Radiocarbon generated chronologies of sites in the central Amazon confirm their anthropogenic origin by showing a rate of Terra Preta formation that is much faster and less homogeneous than natural pedogenesis, with deposits varying between 350-2300 years old (Neves, Petersen, Bartone, & Heckenberger, 2004). High acidity and extremely low nutrient contents are the dominant features of Amazon lowland soils, however the areas covered by terra preta (approximately 0.1 – 0.3% of the wooded Amazonian lowlands) demonstrate enduring fertility and an almost neutral pH value of 6.7 (Soentgen, et al., 2017).

Awareness of this method ultimately reached Europe and subsequently western scientific practice through colonial interactions dating back to the 16th century. Whilst written descriptions of the agricultural use of charcoal have been found dating back to 17th century China, much of the current interest in biochar stems from the work of Wim Sombroek made upon Amazonian soils, specifically (Woods, et al., 2009). Consideration and restraint must therefore be exercised in the description of this material; commoditisation of biochar as the revival of a "forgotten" practice is ahistorical and constitutes an act of erasure in the context of the significant population collapse that was caused by the European persecution and displacement of indigenous populations (Soentgen, et al., 2017).

Current Uses

Biochar production and use typically fulfils five broad and overlapping groups of objectives: waste management, soil improvement, energy production, climate change mitigation, and water pollution mitigation (Lehmann & Stephen, Biochar for environmental management: an introduction, 2015).

Waste Management - numerous companies such as Splainex Ecosystems in the Netherlands and PyroCore in the UK are orientated towards reducing material waste volume and the pollutant impact of sewage and non-recyclable waste through pyrolysis (PyroCore, 2021) (Splainex Ecosystems, 2018).

Soil Additive - biochar properties can be tailored to specific soils and may target crop productivity through increased nutrient availability, improved soil-water properties, plant-microbe relations, and soil remediation (Lehmann & Stephen, Biochar for environmental management: an introduction, 2015). Integration into pavement subsurface in Stockholm, Sweden, has also improved the growth of urban trees (Embrén, 2016). Companies like Carbon Gold sell biochar for horticulture within the UK (Carbon Gold, 2021).Energy Production - a well-established use of pyrolysis, biochar can be tailored to give high calorific contents for use in energy production. Before shutting down due to consequences of the Fukushima disaster, the Tokyo Sludge Pyrolysis Plant was producing 9.86 kt of biochar per year to be used as fuel in a nearby power station (Mašek, Sohi, Kiso, & Boag, 2010). Splainex Ecosystems and PyroCore also generate energy from combusting the gas and liquid that is produced, and pyrolysis can be orientated to energy production as with the BIOMACON boiler systems (BIOMACON, 2021). The biochar from these processes is therefore currently a by-product, as biochar production is not the primary motivation for pyrolysis.

Climate Change Mitigation - the stable carbon in biochar (approximately 97 ± 0.6 %wt from a meta-analysis of 24 studies) decomposes very slowly and is therefore suitable for sequestering carbon, with a mean residence time of approximately 556 ± 483 years (Wang, Xiong, & Kuzyakov, Biochar stability in soil: meta-analysis of decomposition and priming effects, 2015). The lower end of 73 years given by this figure is the result of crop and grass-derived biochar being included in the meta-analysis, as well as biochar produced at low PPT (Wang, Xiong, & Kuzyakov, 2015). These uncertainties have been managed within this project through the proposed use of woody feedstocks and high PPT. Carbonfuture is a marketplace that allows biochar producers to sell carbon removal credits to this end (Carbonfuture, 2021).

Water Pollution Mitigation - biochar’s high surface area to volume ratio means it acts as an adsorbent to remove contaminant such as heavy metals, organic contaminants, and nitrogen and phosphorous from industrial and municipal waters (Xiang, et al., 2020). Its potential for integration into infrastructure projects as a filtration medium is discussed in more detail in section 1.6 of Appendix I.

Physical Characteristics

The reflexivity of biochar to its feedstock is demonstrated in Figure 3, and one study gives a range of 200 – 1000 kgm^{-3} for the typical bulk density of biochar, with 500 kgm^{-3} as an average (Adekiya, Olayanju, Ejue, Alori, & Adegbite, 2020).

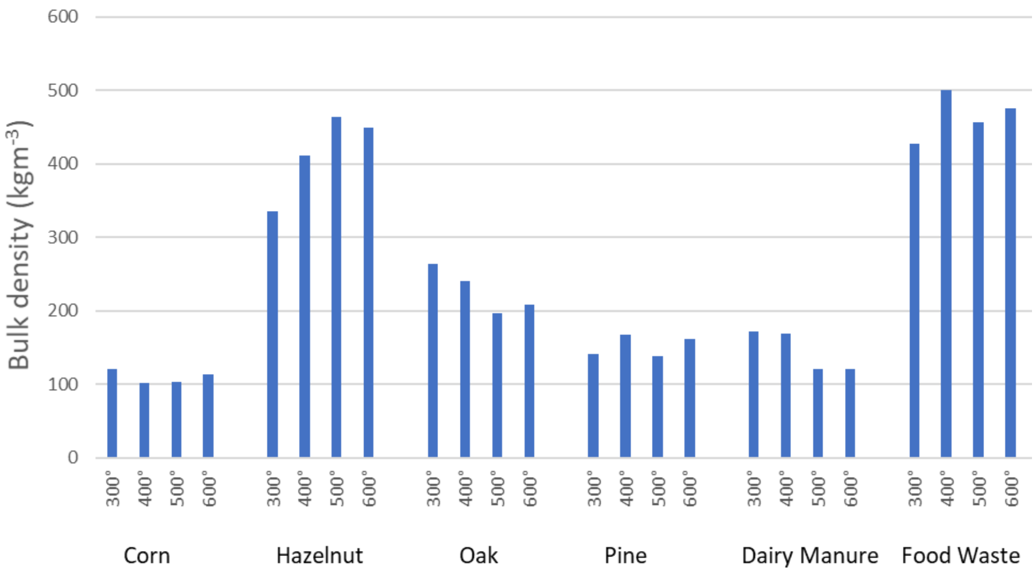


Figure 3: Graph to show bulk density of biochar (kgm^{-3}) against feedstocks pyrolysed at different PPT (°C) (Rajkovich, et al., 2012)

The bulk density of Oak derived biochar varies between 250 – 200 kgm^{-3} for 300 – 600 °C respectively, and Pine varies from 130 – 170 kgm^{-3} over the same temperature range (Rajkovich, et al., 2012). The higher end of Oak bulk density (250 kgm^{-3}) has been used as a provisional figure throughout this report, to take into account the fact that pelletisation increases biochar bulk density compared to powdered biochar.

Porosity similarly depends upon feedstock type and peak pyrolysis temperature, as biochar retains the basic structure of its feedstock material. It is typically a highly porous material however, and the porosity of a soft wood derived biochar varies over 0.59 to 0.72 for pyrolysis temperatures of 300 – 700 °C respectively (Brewer, et al., 2014).

Chemical Characteristics

Most biochar is alkaline, with pH typically increasing as peak pyrolysis temperature increases (Khanmohammadi, Afyuni, & Mosaddeghi, 2015). The UK Biochar Research Centre finds 7.91 and 8.44 as the pH for mixed softwood pellets pyrolysed at peak temperature 550°C and 700°C respectively (UK BRC, 2019).

1.2.6 Biochar and Soil Health

Via pyrolysis, biochar is essentially a constructed material dependent upon feedstock and pyrolysis conditions. Combined with its novelty to quantified investigation, systematic evaluations of its effect upon the soil are still developing (Shackley & Sohi, 2010). Despite this, there is a broad acknowledgement that the benefits of biochar upon soil health, crop production, and the environment are most pronounced when biochar is applied to soils with low fertility and of high acidity (Adekiya, Olayanju, Ejue, Alori, & Adegbite, 2020). For further detail and context readers are directed toward Adekiya, et al., (2020), Shackley & Sohi (2010), and towards Mohan, et al., (2014) and Beesley, et al., (2011) for extensive reviews of the contaminant removal properties of various biochar. The relationship between biochar and soil health has been reviewed using the methodology outlined in Appendix B4.

Nutrients and Acidity

Nitrogen is typically present on the surface of biochar as C-N heterocyclic structure and has a low bioavailability (Adekiya, Olayanju, Ejue, Alori, & Adegbite, 2020). The availability of potassium ranges from 0.4 to 34% of total P in biochar. Between 55-65% of the available K, Ca, and Mg from biochar can be related to their total concentration (Ippolito, Spokas, Novak, Lentz, & Cantrell, 2015). Average pH and cation exchange capacity are given below in Table 3 below for hardwood and softwood.

Table 3: Average pH, cation exchange capacity (CEC), and nutrient concentrations (dry weight basis) of biochar from different feedstocks (Adekiya, et al., 2020; Ippolito, et al., 2015)

Source	pH	CEC ($cmol_c/kg$)	C	N	P	K	Ca	Mg
Hardwoods	7.94	13.8	74.4	0.72	0.11	0.95	1.01	0.95
Softwoods	7.48	14.5	74.6	0.79	0.07	1.69	2.07	1.80

Increasing pyrolysis temperature decomposes acidic functional groups such as carboxylic COOH, phenolic OH, and lactonic O, forming alkali bases and making biochar more basic (Adekiya, Olayanju, Ejue, Alori, & Adegbite, 2020). As biochar ages and is exposed to water and oxygen, more functional groups are generated on the surface and the CEC can increase (Adekiya, Olayanju, Ejue, Alori, & Adegbite, 2020). Pelleted biochar has less surface area per unit volume than biochar fines and therefore generate less functional groups upon its surface after the same amount of time in soil. Since the C/N ratio of much biochar is higher than the 25-30 range deemed optimal for N mineralisation, N immobilisation in biochar can occur and cause N deficiency in crops, at least in the short term (Adekiya, Olayanju, Ejue, Alori, & Adegbite, 2020). Indeed, whilst the total N content of biochar can vary, the amount of available N as nitrate (NO_3) is typically negligible, and the low extractable N concentrations as NO_3, NH_4, and NO_2 can be attributed to gaseous N loss during pyrolysis (Ippolito, Spokas, Novak, Lentz, & Cantrell, 2015). One pathway for making minerals available to surrounding soil is the solubilisation of biochar ash, which occurs much faster than the progressive release of nutrients from the biochar itself (Shackley & Sohi, 2010).

High PPT and pelleted woody feedstock therefore reduce the mineral and nutrient content that is available from biochar when compared to other feedstocks, such as sewage sludge, which typically generates biochar with high ash content (UK BRC, 2019).

Inorganic and Organic Carbon Content

Total organic carbon is a key measure of the soil organic matter. It reflects the soil capacity to affect nutrient supply and retention for the needs of plants and microbiota, and through these, the physical properties like aggregate stability, water holding capacity, and infiltration (Adekiya, Olayanju, Ejue, Alori, & Adegbite, 2020). The easily decomposed fraction of carbon in biochar can generate constraints to crop growth if substrate nitrogen is low, because N and C are both required to build new biomass, and microbes out-compete roots for nitrogen (Shackley & Sohi, 2010). The nitrogen in biomass is progressively volatilised during pyrolysis, so the C:N ratio is typically higher in the biochar than the feedstock. If a sufficient amount of the carbon is stable however, it will not create the microbial demand for external N. Nitrogen immobilisation therefore depends upon the amount of biochar integrated, the labile fraction, and the C:N ratio (Shackley & Sohi, 2010). The benefit of biochar for plant production may also directly stimulate more carbon input into soils via plant residue return and rhizodeposition, or the material lost from plant roots into soil (Wang, Xiong, & Kuzyakov, Biochar stability in soil: meta-analysis of decomposition and priming effects, 2015).

A long-term five-year study by Dong, et al., 2019 showed that biochar can also increase soil inorganic carbon content in the shallow (0-40cm) soil layers. Application rates in clayey, sandy, silt were positively related to soil inorganic carbon content, as biochar increased the pedogenic inorganic carbonate formation (Dong, Singh, Li, Lin, & Zhao, 2019). This process is explored in the testing proposed at the Moreton-in-Marsh reference site (see Appendix H), as the provenance of measured inorganic carbon is to be determined by Isotopic Ratio Mass Spectrometry (IRMS) methods.

Structure and Water Capacity

This factor determines the soils vulnerability to erosion and root penetration. Mean weight diameter is a measurement of the average size of soil aggregates. A higher value means larger aggregates are present and implies greater stability. Biochar has been found to increase the mean weight diameter of silty loam soils at low amendment rates, improving aggregation by 126 to 217% over 60 weeks (Adekiya, Olayanju, Ejue, Alori, & Adegbite, 2020). Due to the low bulk density of biochar, (heavily dependent upon feedstock but 250 kgm^{-3} is assumed in this report) compared to typical soil (≈2000kgm^{-3}) amendment will typically result in a reduction of bulk density (Adekiya, Olayanju, Ejue, Alori, & Adegbite, 2020). Biochar has high porosity due to the pyrolytic emission of structural water. It can therefore promote larger pores in fine textured soils like loam and clay, but for soils with an already high permeability such as coarse sand it can narrow the available pore space (Adekiya, Olayanju, Ejue, Alori, & Adegbite, 2020). The potential benefits of this pore space provision are discussed further in sections 1.6 to 1.8 in Appendix I.

Biological Activities

The microbial population, diversity, and activity affect all the factors of soil health, along with plants and enzyme activity, and are in turn affected by them (Adekiya, Olayanju, Ejue, Alori, & Adegbite, 2020). The porous structure, large internal surface area, and high-water retention capacity provide favourable habitats for soil biota, which can inhabit the macropores (2mm-2μm) and avoid predators like mites and nematodes (Adekiya, Olayanju, Ejue, Alori, & Adegbite, 2020). Condensed volatile compounds and the labile fraction of C in biochar can serve as substrates (energy sources) for microbe growth and metabolism and can even be toxic to certain microbial pathogens (Adekiya, Olayanju, Ejue, Alori, & Adegbite, 2020). As a result of its general potential to neutralise soil pH however, significant biochar amendment may alter the bacteria to fungi ratio in favour of bacteria because bacteria thrive at near neutral pH levels. This may also affect microbial feeders, and their predators in turn (Adekiya, Olayanju, Ejue, Alori, & Adegbite, 2020). However, the modification of plant pH may also increase plant productivity and therefore increase the amount of C-substrate available through roots and residues (Shackley & Sohi, 2010). The potential to encourage microbial growth is promising for biochar applications where the biodiversity of the soil is a key issue, and this effect is being monitored against biochar application rates at Moreton-in-Marsh.

Chemical Pollution

Aluminium and to a lesser extent manganese in acidic soils can be complexed and detoxified by reactive functional groups on the biochar surface. As before with the functional groups improving CEC over time, the prevalence of these functional groups increases with peak pyrolysis temperature, and biochar can sorb and detoxify lead and cadmium in the same way (Adekiya, Olayanju, Ejue, Alori, & Adegbite, 2020). Biochar contains two potential contaminants, namely the persistence of heavy metals, dioxins, polycyclic (PAHs) in the feedstock itself, and the generation of PAH in the pyrolysis process (Shackley & Sohi, 2010). Most heavy metals will therefore be present as ash within biochar, so it may be possible to manipulate contaminant loadings through the selective removal of ash (Shackley & Sohi, 2010).

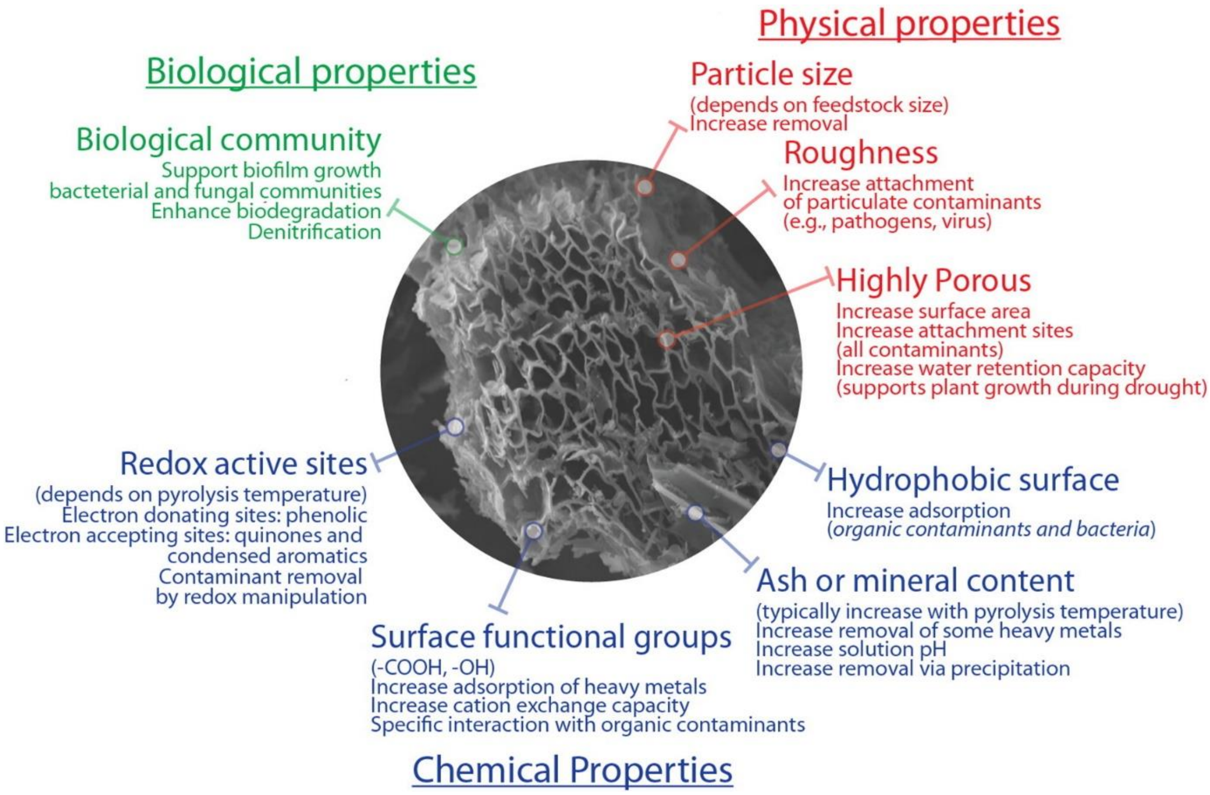


Figure 4: Physical, chemical, and biological properties of biochar for removal of contaminants from stormwater (Mohanty, et al., 2018)

As biochar can achieve surface areas similar to activated carbon, some feedstocks produce biochar that is suitable for filtration purposes. Inclusion in storm-water runoff experiments gave significant performance for metalloid/metal-ion adsorption and removal, organic contaminant removal, nutrient removal, and biological contaminant deactivation and removal (Woolley & Hallowell, 2018). Biochar produced from sea mango has also been shown to achieve a leachate remediation performance of 95.1% colour reduction, 84.94% COD leachate, and 95.77% NH3-N removal through adsorption (Woolley & Hallowell, 2018). However, inorganic contaminants that cannot be degraded by microbial action like heavy metals are not removed by biochar but are immobilised within the soil matrix (Beesley, et al., 2011). Pollution risk is therefore mitigated via the pathway by suppressing pollutant mobility, but this is dependent upon the physical persistence of the biochar in the soil (Beesley, et al., 2011). This is a key opportunity for biochar use within infrastructural environments, identified and elaborated upon in section 1.6 of Appendix I.

All these processes within the soil are deeply interrelated and interact differently as time in the soil increases, as illustrated in Figure 5 below.

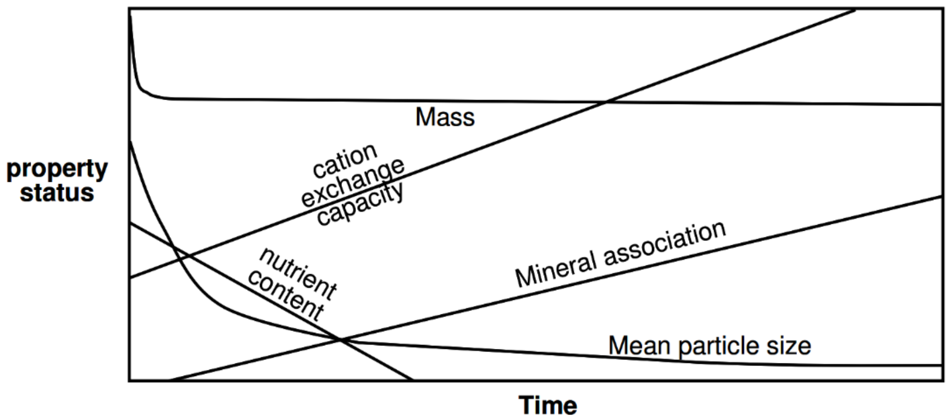


Figure 5: Schematic to illustrate possible trajectories of biochar processes within soils, over an approximate decadal timescale (Shackley & Sohi, 2010)

1.3 CO_2e Removal from Biochar

In this section, the assumptions and models that determine the total potential CO_2e removal offered by biochar are described and explained.

1.3.1 Total Removal Potential

At the point of production, the total CO_2e removed in a tonne of biochar is the product of the carbon content by weight (% wt) and the conversion factor between the molecular mass of carbon, to carbon dioxide. Using the UK Standard Biochar specification sheet, a value for softwood derived biochar pyrolyzed at PPT 700°C can be calculated (UK BRC, 2019):

$$\frac{90.21\ (C_{tot}\ \%wt) \times 1\ (tonne) \times \frac{44}{12}(molecular\ conversion}{100}) = 3.38\ tCO_2e/t \qquad \text{Eq. 1}$$

The figure given by Eq. 1 is a snapshot however and does not account for the emissions associated with biochar production or its possible long-term oxidation.

1.3.2 Persistence Models

Chemically, the carbon stored in biochar may be lost through mineralization, whereby the carbon oxidises to form CO_2 that is readily available to plants. This is primarily driven by microbial activity but may also occur as a result of oxygen in the soil making contact with reactive elements of the biochar (Lehmann, et al., 2015). Carbon may also be lost through chemical decomposition, that is, transformation to other organic substances that are typically microbial metabolites or debris (Lehmann, et al., 2015). Carbon “loss” through biochar transport is not dealt with here but is covered as a risk to monitoring in section 2.1.3 of Appendix I.

Persistence is used hereafter to signify the property that determines the resistance of biochar to decomposition or mineralisation. The symbol BC_{+100} is used to denote the amount of carbon by percentage weight of original biochar that is predicted to remain present in the soil after 100 years, and BC_{-100} is conversely the biochar that can be expected to mineralise and decompose by this time (Budai, et al., 2013). The global warming potentials of greenhouse gases are commonly assessed over a 100-year time horizon, so it is used to characterise biochar also (IPCC, 2014). The 100-year time interval is also the most commonly used measurement of longevity used by carbon credit.

In 2013 the International Biochar Initiative conducted a review of 27 assessment methods available for determining biochar persistence, and identified three broad categories (Budai, et al., 2013):

1. Alpha methods – methods which allow routine estimation of the BC_{+100} at minimal costs.
2. Beta methods – methods which quantify BC_{+100} using a model based off parameters derived from Alpha methods.
3. Gamma methods – methods which provide physiochemical underpinning for Alpha and Beta methods.

For further information on biochar persistence methods the reader is directed to (Leng, Huang, Li, & Li, 2019). Alpha, Beta, and Gamma methods are summarised below before the proposed persistence model for this project is elaborated upon.

Alpha Methods

H:C_{org} Ratio

H:C_{org} ratio has been adopted by the IBI as a threshold to separate biochar from raw feedstocks by ensuring the abundant formation of fused aromatic ring structures (Leng, Huang, Li, & Li, 2019). Organic carbon is used because high-ash biochar contains inorganic carbon in the form of inorganic carbonates; these do not form aromatic groups and behave differently to organic carbon (Leng, Huang, Li, & Li, 2019). The IBI’s H:C_{org} upper limit of 0.7 is a conservative value derived from several incubation experiments and their modelling results to ensure that 50% (95% confidence) of biochar C should persist in soil for 100 years (Leng, Huang, Li, & Li, 2019) (Budai, et al., 2013).

O:C_{org} Ratio

The O:C_{org} ratio is required in addition to the H:C_{org} ratio for EBC certification (EBC, 2012). However H:C_{org} is preferred because oxygen is typically calculated by difference (O = 100 - C - H - N - S - ash) which may lead to overestimation of oxygen content (Leng, Huang, Li, & Li, 2019). This method does not typically distinguish well between poultry derived high-ash biochars and wood derived low-ash biochars (Enders, Hanley, Whitman, Joseph, & Lehmann, 2012). Biochars of different O:C_{org} ratio allegedly have different persistence qualities

(Leng, Huang, Li, & Li, 2019). The typical calculation by difference introduces uncertainty however so it has not been used here.

Fixed Carbon and Volatile Matter Content

Fixed carbon and volatile matter have a close relationship to stable (persistent) C content and labile (non-persistent) C content, respectively (Leng, Huang, Li, & Li, 2019). High volatile matter is positively correlated to mineralizable C content and therefore dominates the responses of incubation studies, due to the short-term nature of nutrient release and microbial activity it promotes (Leng, Huang, Li, & Li, 2019). However, there is only a weak correlation between volatile matter content and half-life data, and this method was discarded as an indicator of stability by the IBI (Budai, et al., 2013). It has therefore not been used here.

Beta Methods

Mean Residence Time

Assuming an exponential decay rate, persistence can be expressed in terms of mean residence time (MRT), which is the inverse of the decay rate (1/k) (Lehmann, et al., 2015). The half-life is the time that elapses before half of the biochar mineralizes and can be obtained by multiplying the MRT by the natural logarithm of 2 (Lehmann, et al., 2015). These models require biochar incubation data, which can be expensive and time-consuming to produce.

Key sources regarding biochar persistence are given below in Table 4.

Table 4: Key sources of data for biochar mean residence time

Source	**Description**
(Lehmann, et al., 2015)	Meta-analysis of biochar data 111 different biochars produced under varying pyrolysis conditions compared in terms of MRT
(Wang, Xiong, & Kuzyakov, Biochar stability in soil: meta-analysis of decomposition and priming effects, 2015)	Meta-analysis of biochar data 128 observations of biochar from 24 studies compared in terms of MRT

Biochar is not a homogeneous substance however and more nuanced analysis can be made by conceptualising its composition in terms of “pools” with different rates of mineralisation (Lehmann, et al., 2015). Biochar is typically split into two pools; the “recalcitrant” pool represents the fraction of the biochar that is persistent in the soil and performs the sequestration function over centennial scales, and the “labile” pool is the fraction of the biochar that has low persistence because it is degradable by microbial activity and mineralises into CO2 and CH4 over weekly to decadal scales (Mašek, Brownsort, Cross, & Sohi, 2013). Models also exist that use three pools, though two are more commonly used (Leng, Huang, Li, & Li, 2019).

Wang, Xiong, & Kuzyakov, 2015, found that the MRT of labile and recalcitrant biochar pools were estimated to be approximately 108 days and 556 years, with pool sizes 3% and 97% of biochar carbon, respectively. A double first-order exponential decay model was used to fit the experimental data, given below:

$$y = a.e^{-k1.t} + b.e^{-k2.t} \qquad \text{Eq. 2}$$

Where y: amount of biochar remaining in the soil at time t; t: time; a and b: the size of labile and recalcitrant C pools of biochar respectively (by dry weight); k1 and k2: exponential coefficients for labile and recalcitrant pools, respectively (Wang, Xiong, & Kuzyakov, 2015). The values for this approximate model are given below in Table 5.

Table 5: Kinetic parameters of the double first-order exponential decay model describing biochar decomposition in soils. Values represent means ± standard errors (Wang, Xiong, & Kuzyakov, Biochar stability in soil: meta-analysis of decomposition and priming effects, 2015).

	Size (%wt)	**Decomposition rate (k1 and k2)**	**Mean residence time**
Labile C pool	3 ± 0.6%	0.0093% day -1	108 ± 196 days
Recalcitrant C pool	97 ± 0.6%	0.0018% year-1	556 ± 483 years

Within the labile fraction, it was found that it was predominantly made up of a semi-labile C, that has stability in the range of years to decades, and the purely labile fraction that is lost to microbial activity within weeks or months is a minor fraction (Mašek, Brownsort, Cross, & Sohi, 2013). For this reason, Alpha methods such as $H:C_{org}$ typically represent an underestimate of the carbon stability because they are based off of short-term incubation studies that observe the decomposition of ‘purely labile’ fractions. A method for determining the weight of these fractions is given in (Bakshi & Laird, 2018).

This method has not been used, as long-term incubation studies are not a practical means of assessing the biochar longevity before application to the soil.

Gamma Methods

Gamma methods are impractical for the purposes of biochar production due to the high level of technical expertise required, high expense, and low availability (Budai, et al., 2013). Instead, they are specialised tools that can be used to calibrate alpha or beta methods. They are therefore only briefly summarised here for the reader’s reference, see (Leng, Huang, Li, & Li, 2019) for further detail.

Nuclear Magnetic Resonance (NMR) Spectroscopy

Quantifies the aromatic fraction of total carbon (aromaticity) using direct polarization ^{13}C nuclear magnetic resonance spectroscopy (Rittl, 2015) (Budai, et al., 2013). Aromaticity is strongly correlated with MRT (Leng, Huang, Li, & Li, 2019).

Benzene Polycarboxylic Acid (BPCA) Determination

The polycondensed aromatic structures in pyrogenic carbon are converted to single benzene rings containing different carboxylic acid groups, the number of which present in each BPCA is related to the condensation degree of the carbon. The individual contributions of BPCA can be used to determine the aromaticity (Rittl, 2015). This however involves several steps prior to quantification by gas chromatography, resulting in disparate results which may vary from 0 to 43% depending on material analysed (Rittl, 2015).

Pyrolysis Gas Chromatography Mass Spectrometry

Pyrolysis products are quantified using gas chromatography and mass spectroscopy. The sum of the most abundant fingerprints of charred material in pyrograms (i.e., monoaromatic hydrocarbons, polyaromatic hydrocarbons, benzonitriles/total quantified peak area) is related to the proportion of condensed aromatic carbon present in biochar (Budai, et al., 2013).

Chosen Persistence Model

$H:C_{org}$ has been chosen as the primary indicator of biochar stability for multiple reasons; H and C_{org} determination is cheap and widely available, the dataset resulting from this pilot project is expected to raise the confidence intervals of stability models associated with $H:C_{org}$, and demonstration of biochar stability that is independent of its location reduces the need for future schemes to plan expensive soil monitoring programmes.

Table 6: H:Corg and BC+100 equivalences at 95% confidence, adapted from (Budai, et al., 2013)

	BC_{+100} (%)			
$H:C_{org}$	Mean	Lower Limit	Upper Limit	Chosen Value
0.4	80.5	72.6	88.2	70
0.5	73.1	67.1	78.9	50
0.6	65.6	60.5	70.6	50
0.7	58.2	52.5	63.8	50

Organic carbon is used here explicitly as opposed to total carbon to ensure the atmospheric origin of the removed carbon, and because inorganic carbon does not form aromatic groups and behaves differently to organic carbon (Leng, Huang, Li, & Li, 2019). However, this distinction only becomes meaningful for non-virgin feedstocks such as waste or poultry manure, as woody feedstock typically has low inorganic carbon content such that for the sake of this project $C_{total} \approx C_{org}$ when considering wood-derived biochar.

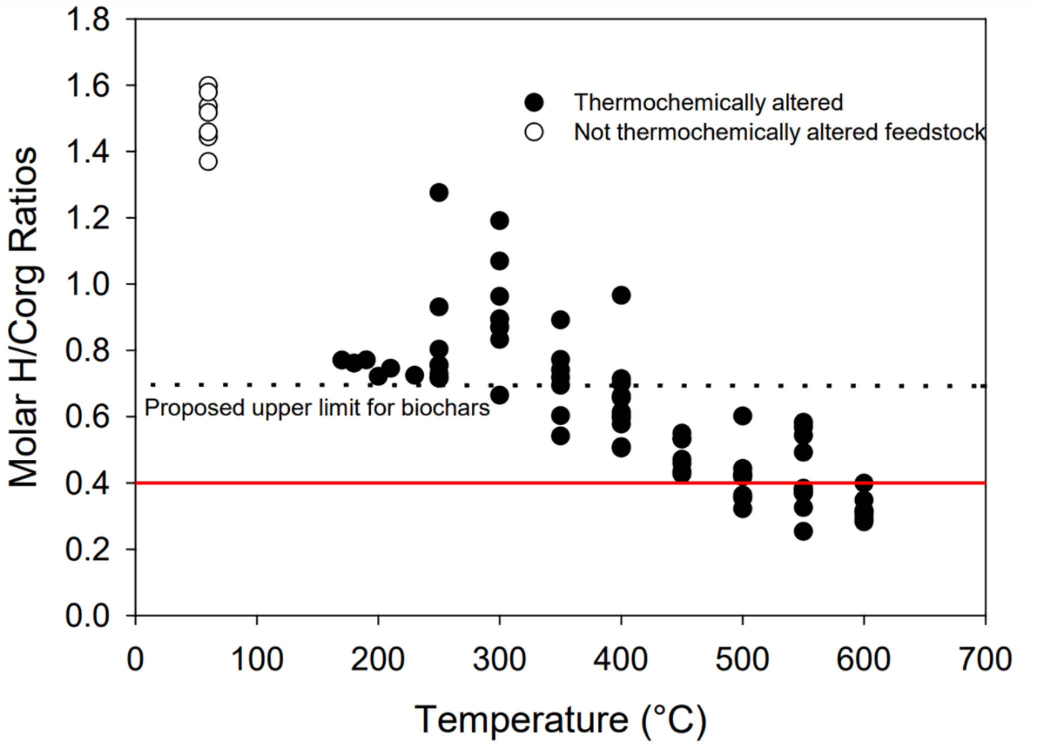


Figure 6: Table to show the relationship between H:Corg ratios and the PPT of biochar in comparison to untreated biomass. The dashed line is the upper limit of 0.7, below which, material is considered to be thermochemically "altered" (IBI, 2015). Red line added to show upper limit of 0.4 used in this project.

The most conservative meta-analytical estimate for biochar longevity is based on linear extrapolation of initial short-term loss. This provides an average annual degradation rate of 0.3% for a $H{:}C_{org}$ below 0.4, readily achieved by high temperature processing (EBC, 2020). This assures that at least 74% of the original carbon should remain unmineralized or decomposed after 100 years with a confidence interval of 95% (EBC, 2020) (Leng, Huang, Li, & Li, 2019). This figure does not account for potential material movement through migration, filtration, or runoff, but the implications of these mechanisms for carbon removal are trivial as deposition of biochar in watercourses and subsoils (anoxic environments) actually slows their decomposition, as outlined in section 2.1.3 of Appendix I. Long term reference site monitoring is likely to confirm that degradation rate gradually diminishes as less completely carbonised fractions are eliminated and validating this should permit claims of additional removal. Biochar can also be produced exhibiting enhanced longevity associated with $H{:}C_{org} \sim 0.1$. Given the proposed PPT of 700°C within this project, from Figure 6 it is likely that the generated biochar will have a $H{:}C_{org} \leq 0.2$, and should therefore have a BC_{+100} even higher than the $BC_{+100} = 74\%$ used in this report.

1.3.3 Passive and Indirect Carbon Benefits of Biochar

For biochar to perform as a certified carbon removal at the point of sale, conservative assumptions are made about its persistence which allow high confidence intervals. The necessary focus upon the quantifiable carbon within the biochar should not detract from the passive sequestration potential that it provides once in the soil however, so these are listed here;

- Biochar has been shown to increase the formation of pedogenic carbonates to a depth of 40cm within soils (Dong, Singh, Li, Lin, & Zhao, 2019). Long-term application of rice husk (70%) and cotton seed hull (30%) derived biochar to a live agricultural site at rates of 30, 60, and 90 t ha^{-1} increased the soil total inorganic carbon by 18.8, 42.4, and 62.3% respectively (Dong, Singh, Li, Lin, & Zhao, 2019). Potential reasons for this are that the high ash content of the biochar may have increased the Ca^{2+} soil concentration; the higher pH may have accelerated SIC formation; the porosity of biochar encourages microbial activity which forms SIC by generating CO_2 upon the degradation of SOC (Dong, Singh, Li, Lin, & Zhao, 2019). Whilst the biochar proposed within this project is of low ash content through wood feedstock, it should still provide porosity that encourages microbial activity.
- Minimising stormwater surface runoff reduces the volume of water that needs to be processed in wastewater treatment works limiting a wastewater source that is heavy with contaminants such as petroleum, pesticides, and fertilizers (EA, 2009). Over large-scale applications of biochar, this should reduce the volume of water that requires treatment and reduce the associated energy costs of treating stormwater surface runoff.
- Increase in plant resilience fosters increased CO_2 turnover in the form of biomass.
- Slows the rate of SOC decay in a process called negative priming, Where biochar alters the organic carbon storage capacity of the soil it applied to (Sohi, Krull, Lopez-Capal, & Bol, 2010). Biochar amendment can suppress SOC mineralisation by reducing microbial accessibility of SOC through soil aggregation (Wang, et al., 2019). It also does this by improving the soil moisture capacity, that is, the amount of soil moisture retained by the soil after excess water has drained away after a rainfall/irrigation/flood event (Wang, et al., 2019).

1.4 Biochar Carbon Life Cycle Analysis

1.4.1 Literature Review

The scope of examined sources shown in Table 7 is not exhaustive, and more recent publications have been prioritised to keep abreast with the surge of academic and industry interest in the technology. The recent reviews conducted by Matuštík, et al., (2020) and Terlouw, et al., (2021) are excellent references for further life cycle assessments of biochar use.

Table 7: Summarised literature review of biochar life cycle assessments

Source	**Country**	**Feedstock**	**Pyrolysis Parameters**	**Remaining C in biochar over 100 years (%)**	**Net tCO_2e sequestered per tonne of biochar**	
					Low	High
(Lefebvre, et al., 2021)	Brazil	Sugarcane	Slow, 550°C	-	1.64	
(Puettmann & Sahoo, 2020)	US	Forest residue	Mobile 20kW Gasifier, Oregon Kiln, Air-Curtain Burner	-	1.92	2.83
(Hamedani, et al., 2019)	Belgium	Willow (w) and pig manure (p)	60min, 500°C	75 and 33.7	0.466 (p)	2.09 (w)
(Barry, Barbiero, Briens, & Berruti, 2019)	Canada	Municipal sewage sludge	Slow, 500°C	-	0.2*	
(Azzi, Karltun, & Sundberg, 2019)	Sweden	Woodchips	700°C	64	3.32	
(Robb & Dargusch, 2018)	Indonesia and Australia	Oil palm waste	280°C	14-70	0.49 (mean)	

Source	**Country**	**Feedstock**	**Pyrolysis Parameters**	**Remaining C in biochar over 100 years (%)**	**Net tCO_2e sequestered per tonne of biochar**	
					Low	High
(Brassard, Godbout, Pelletier, Raghavan, & Palacios, 2018)	Canada	Switchgrass	78-104s, 459-591°C	50-70	2.11	2.56
(Roy & Dias, 2017)	-	Cardboard and poplar	Large range	-	-0.16	1.5
(Muñoz, Curaqueo, Cea, Vera, & Navia, 2017)	Chile	Forest residue	Electric pyrolyser, 300,400, 500°C	80**	2.59	2.74
(Hammond, Shackley, Sohi, & Brownsort, 2011)	UK	Straw and wood chips	Slow, fast, gasification, and combustion	68	2.1	3.9
(Roberts, Brent, Stephen, Scott, & Lehmann, 2010)	US	Stover and yard waste	450°C	80	1.32	1.4

* From Figure 12 of source, assuming agricultural production
** Muñoz, et al., 2017 use the stability value given by Roberts, et al., 2010

Lefebvre, et al., (2021) create a life cycle assessment from scenarios in Sao Paulo State, Brazil. They find that the emissions from the pyrolysis process are the main source of carbon throughout the process, however, biochar spreading is considered local to the farm that produced the feedstock, so transportation considerations are diminished. The context is agricultural also, where spreading machinery is on hand.

Puettmann & Sahoo, (2020) consider the use of mobile pyrolysis units to replace slash-burning in forests. Minimising feedstock preparation was found to increase the sequestration potential. Due to the mobility of the pyrolysis options, the transportation effect of the feedstock was diminished.

Hamedani, et al., (2019) conduct an LCA based off two feedstocks in Belgium, pig manure and willow, to be used as a soil amendment in drought sensitive agricultural soils. They use locally available feedstock and thus omit CO_2 emissions from transport. High energy cost of pre-treatment step of pig manure meant willow was the most beneficial. Avoiding the use of agricultural product such as fertiliser made great contributions to the net carbon sequestration.

Barry, et al., (2019) create LCA’s from the use of biochar as coal substitute in cement kilns and agricultural spreading. The use of sludge required dewatering, drying, and milling, so 9918kg of dewatered sewage sludge with 72% wt water content was required to produce 1t of biochar. Transportation distances of 50km for use in a cement kiln as coal substitute, with 100km for application of biochar to agricultural land. Fixed carbon contents in varied from 9.5 (500C fast) to 23.7% wt (500C°, slow pyrolysis).

Azzi, et al., (2019) consider the life cycle assessment of pyrolysis in Stockholm for providing biooil and syngas in heating and power, and biochar as manure additive. Net removal potential was dominated by the stability of carbon in biochar, and the remaining third was derived from agricultural emissions reductions and increased soil organic carbon content in the field.

Robb and Dargusch, (2018) make a cost benefit and carbon footprint analysis of using oil-palm waste feedstock for biochar use in Australian broad-acre farming systems. The study finds that when land-use change for the growing of feedstock is considered, the process creates a net carbon emission. The balance otherwise remains one of net removal for all scenarios, as biomass is pyrolyzed in Indonesia, transported to ports in Australia, and then transported by road to farms.

Brassard, et al., (2018) use a life cycle approach to assess switchgrass pyrolysis for biochar production, from switchgrass cultivation to soil amendment and bio-oil and syngas consumption. The scenario which considered a pyrolysis temperature of 591 C° and 104 s residence time gave higher sequestration potential than the 459C° and 78s residence time due to higher stable carbon content, though this option had energy emissions. As with other agricultural scenarios the biochar is applied using a tractor during other spreading activities, so the effect of application is minimised here in contrast to a civil engineering context.

Roy & Dias, (2017) examine the prospects of pyrolysis technologies and present the life cycle CO_2e sequestered for 12 different feedstocks produced for either combustion or soil amendment with slow pyrolysis. Woody feedstock is shown to be best for net greenhouse offset. The risk of basing the feasibility of field studies upon highly controlled laboratory or pilot scale facilities is highlighted.

Muñoz, et al., (2017) conduct an LCA based upon six different scenarios, including the production of biochar from agricultural (oat hulls) and forestry residue (pine bark), at different pyrolysis temperatures, for use as a soil amendment in an agricultural setting over one season. Pine bark pyrolyzed at 500 C° offered the greatest net removal potential, and transport was the primary cause of negative environmental effects. Considers the avoided use of urea and the generated syngas as offsets, and forestry waste creates more calorific syngas.

Hammond, et al., (2011) consider slow pyrolysis biochar systems in the UK for a range of different sized process chains, small (2000 oven dry tones of feedstock per year), medium, (20,000 odt/yr), and large (100,000 odt/yr). The largest abatements were the carbon stabilisation (41-62% as range across all scales) and then the indirect effects of biochar upon soil such as changes in soil organic carbon levels. This study extrapolated from the work of (Sohi, Krull, Lopez-Capal, & Bol, 2010) to model an increase in soil organic carbon (SOC) stocks resulting from biochar addition, assuming a reduction in the rate of SOC decay of 10%.. Spreading was assumed to be a 115kW tractor towing a 30 m^3 lime spreader, and losses were assumed to minimal due to biochar wetting at application. Agricultural context meant there were no extra soil operations considered for incorporation, a key difference with infrastructure. Transport and spreading were low carbon additions. Woody feedstock was best for net greenhouse offset, similar to Muñoz, et al., (2017) and Hamedani, et al., (2019).

Roberts, et al., (2010) find that land-use change impacts are a sensitive parameter, changing the sequestration potential of switchgrass to a net emitter. Viability of the pyrolysis-biochar system was strongest for biomass sources linked to waste management, and the transport was found to be a significant hurdle to profitability. The transportation of feedstock to pyrolysis for drying was also considered in the carbon assessment. A common conservative assumption was used, that slow pyrolysis has been optimised to give 80% of biochar Carbon as stable. Transportation was found to have significant effect upon costs, but low for greenhouse considerations.

1.4.2 Goal and Scope

Functional Unit

To facilitate comparison with other LCA systems, the functional unit is defined as the tCO2e sequestered per tonne of biochar. The global warming potentials of greenhouse gases are commonly assessed over a 100-year time horizon, so it has been used here also (IPCC, 2014). Activities which emit carbon dioxide are given numerically positive values, and activities which remove carbon dioxide are assigned numerically negative values.

System Boundaries

Sawmill residue has been considered as an existing product stream. The impact of its production has therefore not been considered in line with common practice (Matuštík, Hnátková, & Kočí, 2020). As a baseline it has been assumed that these products would have otherwise decomposed and returned their carbon content to the atmosphere. The degradation has therefore been considered in so far as only 74% of the original biochar content is assumed to remain after 100 years, but the lost 26% has not been modelled as returning to the atmosphere as CO_2e. The LCA is therefore built upon the assumption of non-intervention, where only the effects that differ from this baseline of complete biomass decay have been considered. In other words, had the process recommended in this project not been implemented, all the organic carbon in the feedstock would have decomposed and returned to carbon cycle. In this way the carbon removal is an intervention in the decomposition of the feedstock. The passive and indirect carbon benefits of biochar application to soil discussed in section 1.3.3 have not been considered here, and therefore make the generated net removal figure more conservative than typical literature analysis.

Life Cycle Inventory (LCI)

The emissions factors used to construct each scenario are given below in Table 8. These have been calculated using a range of sources and assumptions - the full detail of which is omitted here for brevity but covered extensively in the accompanying spreadsheet in Appendix B1.

Table 8: Emissions factors used

Description	**Unit**	**Value**	
		550 °C	700 °C
Sawmill biochar carbon content	% (by dry weight)	85.52	90.21
Sawmill pyrolysis biochar output	% (by dry weight)	21.80	17.34
Sawmill residue required for 1t biochar	Tonnes	4.59	5.77
Pelleting	kWh/t feedstock	72	
UK electricity grid	gCO_2e/kWh	140	
Annual sawmill biochar production	t biochar/ yr	560	
Pyrolysis energy efficiency	%	81	
Pyrolysis upkeep (construction)	tCO_2e/t biochar	0.15	
Pyrolysis running energy (softwood)	tCO_2e/t biochar	0.220	
Pyrolysis water and energy cost	tCO_2e/t biochar	0.000041	
Pyrolysis generated energy	tCO_2e/t biochar	-0.4	
Transport distance to application	Km	1.5	
Transport distance to pyrolysis site	Km	20	
Transport distance from pyrolysis to application	km	21.5	
Transport emission	$kgCO_2e/t$ km	0.955	
Spreading emission by mass	tCO_2e/t biochar	0.000343	
81 kW Tractor 12 t trailer	$kgCO_2e/km$	1.03	
Factory gate carbon sink sawmill biochar	tCO_2e/t biochar	-2.32	-2.45

Feedstock

The feedstock considered for use in the project is wood residue such as chips, sawdust, and shavings from sawmills/wood processing. The sawmill residue is assumed to be softwood, as this is the wood analysed by the UK Standard Biochar information (UK Biochar Research Centre, 2019). Whilst a potential Ash (Fraxinus excelsior, hardwood) source has been used to populate the model, this assumption is fine because the carbon contents of softwood and hardwood derived biochar are typically consistent (Ippolito, Spokas, Novak, Lentz, & Cantrell, 2015).

Drying

It has been assumed that drying takes place at the pyrolysis site, either at the wood source or at the PyroCore facility in Wells. The relocation to Avonmouth does not affect this calculation as Wells and Avonmouth are approximately equidistant to Banwell Bypass. The final moisture content for the wood stock is 10 wt%, an approximate optimum moisture content for the pelletisation of woody biomass (Reza, Lynam, Vasquez, & Coronella, 2012). The starting moisture content of the sawmill residue has been assumed to be 40 wt%, based on the average of the range given for freshly felled Ash (Kent, Kofman, Owens, Coates, & Cooley, 2009). The most common type of dryer for biomass is the rotary dryer, and this has been used here (Amos, 1998). The drying process has been simply modelled using the specific heat capacity of feedstock and water to calculate the energy required to reduce the feedstock moisture content, adapted from (Krokida, Marinos-Kouris, & Mujumdar, 2015). The overall energy required for the process has then been found using average rotary dryer efficiency ratings η, where η represents the ratio between energy used for evaporation of moisture in product, and the energy in drying supplied air and other work such as turning the kiln and loading (Coskun, Bayraktar, Oktay, & Dincer, 2009). This can then be converted into CO_2e by standard national grid conversions. η for wood product has been taken as 0.37, and 0.85 for sewage sludge (Del Giudice, et al., 2019) (Chun, Lim, & Yoshikawa, 2012).

Pyrolysis

The figures as given in the supplementary information of (Hammond, Shackley, Sohi, & Brownsort, 2011) have been used to model the pyrolysis stage. A plant outputting 500 t biochar/yr is estimated to have a nested 7.35 tCO_2e/yr from the construction of the plant, which is equivalent to 0.015 tCO_2e/t biochar. The emissions arising from heating the pyrolysis unit itself are calculated using the 110 kW rating, assuming that the plant is running for 8000 hours/ annum. The emissions arising from the water needed to cool the produced biochar have also been included through the emissions embedded in a litre of water, and the volume of water used per kg of biochar is as given by Biogreen (Biogreen, n.d.). Slow pyrolysis has been used in this model.

The energy efficiency of slow pyrolysis for corn-stover feedstock is typically given as 81%, and this figure has been used to model energy recovery of the pyrolysis system assuming that the bio-oil and syn-gas by-products are combusted for energy generation (Cong, Mašek, & Zhao, 2018) (Soka & Oyekola, 2020). However, a pyrolysis efficiency of 100% has been used here, as for feedstock with calorific values (CV) above 12 MJ/kg, PyroCore technology generates a fully autothermal process (see section 1.1.2 of Appendix G). The calorific value of freshly felled Ash (Fraxinus excelsior) is approximately 17.71 MJ/kg so an autothermal process can be safely assumed, with start-up energy assumed as included within the construction of the plant (Owens & Cooley, 2013). Up to 600 kWe of generated energy can be expected from the PyroCore system for high CV feedstocks, so a conservative third of this output has been assumed and calculated as an offset against national grid emissions (see section 4.1.1 of Appendix G). It is likely that when a feedstock is settled upon and reliable CVs are available, this energy generation will be greater than the conservative value used here and should increase the net carbon removal capacity of biochar. Pyrolysis has been modelled for PPT 550 and 700 °C, to allow the use of the information given by the UK Standard Biochar information sheets (UK BRC, 2019).

Handling, Transport, and Application

Transport has been modelled as being undertaken by an articulated lorry with a maximum capacity of 48.5 t, with a load factor of 50% (Hammond, Shackley, Sohi, & Brownsort, 2011). The selected transport distance has been doubled in the calculation to simulate the lorry returning to site upon delivery of material.

The proposed material mixing method (see Appendix E) is the same for quarry fines and biochar, so to avoid double counting of the carbon emissions it has been modelled for both materials within this LCA. The application of the materials over the mixing area is not yet confirmed, so it has been assumed that a lime spreader will be used to place the materials before mixing begins. To ensure mixture with the topsoil and the quarry fines an 81kW tractor with a 3m rotavator has been used. The emission factor of 1.03 $kgCO_2e/km$ is derived from (Hammond, Shackley, Sohi, & Brownsort, 2011) and (Lindgren & Hansson, 2002).

Stability

As laid out in section 0, a conservative average degradation rate of 0.3% has been assumed for high temperature biochar with a $H:C_{org}$ below 0.4, based on the most conservative metanalytical estimate for biochar carbon degradation published to date (EBC, 2020). This gives 74% of the original carbon as existing after 100 years with a confidence interval of 95%. Indirect effects arising from biochar application to soil as laid out in section 1.3.3 have not been included to produce a conservative removal estimate.

1.4.3 Method and Results

Method

No third-party software has been used. The life cycle assessment has been made in Excel where all values have been commented upon and sourced (see Appendix B1). Two overarching scenarios have been considered, and for each of these scenarios, the PPT has also been varied between 550 and 700 °C, giving a total of four results as summarised below in Table 9.

Table 9: Scenarios considered in biochar LCA

Scenario	PPT °C	Description
1a	550	Softwood residue is the sole feedstock. It is dried, pelleted, and pyrolysed at source site at 550°C, then transported to application site for mixing with quarry fines and topsoil.

1b	700	Softwood residue is the sole feedstock. It is dried, pelleted, and pyrolysed at source site at 700°C, then transported to application site for mixing with quarry fines and topsoil.
2a	550	Softwood residue is the sole feedstock. It is transported to the pyrolysis site for pelleting, and pyrolysis at 550°C, then transported to application site for mixing with quarry fines and topsoil
2b	700	Softwood residue is the sole feedstock. It is transported to the pyrolysis site for pelleting, and pyrolysis at 700°C, then transported to application site for mixing with quarry fines and topsoil

To test the sensitivity of the results, the transport distance between pyrolysis site and application site was increased until the net removal of each deployment scenario was zero.

Results

The results are summarised below in Table 10.

Table 10: Summary of LCA findings

Scenario	PPT °C	Net tCO_2e/t biochar	Principal emission	Maximum transport distance (km)
1a	550	-2.00	Drying	1050
1b	700	-2.13	Drying	1115
2a	550	-1.64	Drying	208
2b	700	-1.67	Drying	173

Scenarios that dry and pyrolyse feedstock at source significantly increase the maximum transport distance that can be made before net removal is zero. This is to be expected, as the required haulage falls significantly due to the water weight lost in drying, and the mass lost in pyrolysis. The net removal potential of sawmill residue derived biochar is lower than other softwood biochar as summarised in Table 7, however this is likely due to the drying of freshly felled wood. If the wood was cut in early spring (~35% moisture content by weight) and left to dry over summer (assuming a reduction of 10% wt), the net carbon removal of scenarios 2a and 2b increases to 1.91 and 1.93 tCO_2e/t biochar, respectively (Kent, Kofman, Owens, Coates, & Cooley, 2009).

Whilst other feedstock options will be pursued, this figure represents a conservative minimum for net biochar removal that has been used to define material requirements. Due to the assumption that the emissions associated with drying are the responsibility of the project, sourcing feedstock in the form of chippings and residue from sawmills should reduce the starting moisture content and eliminate the principal emission of this model. Furthermore, all secondary effects of biochar addition to soil have not been considered, and neither has the potential energy saving this project creates by reducing the need for imported topsoil.

1.5 Pyrolysis Options Review

This section briefly describes the process of pyrolysis to assess the technologies available for biochar production. The current industry of biochar production is then reviewed to generate options for the Phase 2 supply, and these options are appraised by how well they scale for larger, future applications of biochar.

1.5.1 Key Considerations

Pilot and Operational Scales

Phase 2 of the pilot phase should result in the implementation and demonstration of a GGR supply solution in a real-world environment. The ultimate objective is to develop technologies that remove greenhouse gases at the Mt CO2 yr-1 scale or greater at a cost of <£200 per tonne of CO2 removed, by 2050 (GOV, 2020). Dual consideration must therefore be given to the short-term requirements of a pilot-scale project, and the eventual need to scale up the technology.

Feedstock Scales

Virgin feedstocks like wood chip have higher calorific value than non-virgin options like sewage sludge, and therefore typically have higher carbon contents (Shackley & Sohi, An assessment of the benefits and uses associated with the application of biochar to soil, 2010). Comparing the UK Biochar Research Centre's (UKBRC) standard biochar produced from soft wood against sludge feedstock, the mean total carbon by weight was 90.21% and 29.55% for nominal peak temperature of 700°C, respectively. For a fixed removal goal then, approximately three times as much sewage derived biochar (by mass) would have to be created to generate the equivalent amount of stable carbon than from a soft wood feedstock. In this way there is a disparity in the scale of pyrolysis operation required between alternate feedstocks.

Social Implications

Due to a widespread opposition to incineration plants in the UK, the pyrolysis process may face scrutiny and public optics will be important for marketing (UKWIN, 2021). This introduces a visual aspect of the project that must be considered carefully when choosing a pyrolysis supplier. The chosen pyrolysis option should therefore be as self-sustaining as possible with minimal emissions of any sort. It is also important that the supplier has successful case studies that demonstrate their ability to deliver low emission pyrolysis, as these will be important when engaging with the community in Banwell.

Legal Requirements

Under a 2010 EU directive pyrolysis processes fall under the classification of waste incineration plant, because "substances resulting from the treatment are subsequently incinerated" i.e the syn-gas and bio-oil (EU, 2010). The Clean Air Act 1993 states that no dark smoke shall be emitted, defined as shade 2 or greater on the Ringelmann chart (HMSO, 1993). Pyrolysis systems must burn partially oxidised combustible gases that contain high concentrations of Carbon Monoxide and volatile organic compounds before release (Environment Agency, 2009). As biochar is not being combusted, and it is not considered a residue, it does not have to contain less than 3% organic carbon (Environment Agency, 2009). Leasing a self-contained pyrolysis unit would preferably mean that these certifications and emissions requirements were met by the plant supplier.

Biochar Quality

Multiple emerging trends have the capacity to produce char products in large quantities in the UK, such as waste incineration (Elliot-Smith, 2020), sewage sludge pyrolysis (Firth & Jones, 2019), and possibly even graphite/graphene production (ABUNDIA, 2021). Biochar production is not the primary aim of any of these processes however, and there is a significant risk that the popularity of biochar is being used to "greenwash" an otherwise unmonitored product. Pyrolysis plants that already comply to biochar standards such as those set out by the European Biochar Certificate or the International Biochar Initiative are therefore favourable (European Biochar Certificate, 2021) (International Biochar Initiative, 2015).

1.5.2 Pyrolysis Technology

There are several carbonization processes that can be used to produce biochar, including but not limited to; pyrolysis, gasification, hydrothermal carbonization, flash carbonization, and torrefaction (Cha, et al., 2016). See section 1.2.4 and Table 1 for more information on the process of pyrolysis in terms of material processes.

Slow pyrolysis is commonly achieved using drums, rotary kilns, and screws/augers. Fast pyrolysis uses fluidized beds, rotating cones, entrained flow, vacuum pyrolysis and ablative reactors. The suitability of the technique is dependent upon the feedstock, for instance a feed system with greater torque may be required for biomass with higher moisture content (Roy & Dias, 2017). High temperature slow pyrolysis is therefore ideal for maximising the net carbon removal potential of biochar. A summary of the technologies used to achieve slow pyrolysis is given below in Table 11.

Table 11: Summary of slow-pyrolysis technologies (Cruz, 2012). Output ranges have been gathered from commercially available pyrolysis plants.

Technology	Description	Scale
Drum Pyrolyzer	Raw material is carried through a cylinder by paddles Reactor is heated internally Long solid and vapour residence time Gases normally used to provide energy for pyrolysis	Continuous Lab to mid-scale Uncommon in industry
Rotary Kilns	Inclined cylindrical reactor heated externally Only one moving part as biomass moves by gravity through the kiln	Largest of all options, used in lime production 1,000 – 11,680 t/yr Continuous production
Screw/Auger Pyrolyzer	Tubular reactor where biomass is moved via an auger or screw	Lab to mid-scale 161 – 2,100 t/yr Continuous production
Flash Carbonizer	Ignition of flash fire in a packed bed under air flow and high pressure	Lab scale Uncommon in industry

Of the four technologies displayed above in Table 11: Summary of slow-pyrolysis technologies . Output ranges have screw pyrolysers have been found to be the most common in containerised pyrolysis units, and rotary kilns have been found to represent the largest scale production scale option. Screw pyrolysers and rotary kiln options are discussed in more detail below.

Screw/Auger Pyrolyser

Screw pyrolysers move biomass through a tube via a rotating screw/auger and can be externally heated or use a heat carrier such as sand or iron spheres. External heating methods and their compactness make them suitable for small-scale applications. Mechanically driving the biomass through the system also increases the flexibility of the deployment; in comparison to a rotary kiln which requires fixed conditions to facilitate gravity-driven flow, a screw system can simply adjust the internal rotation rate.

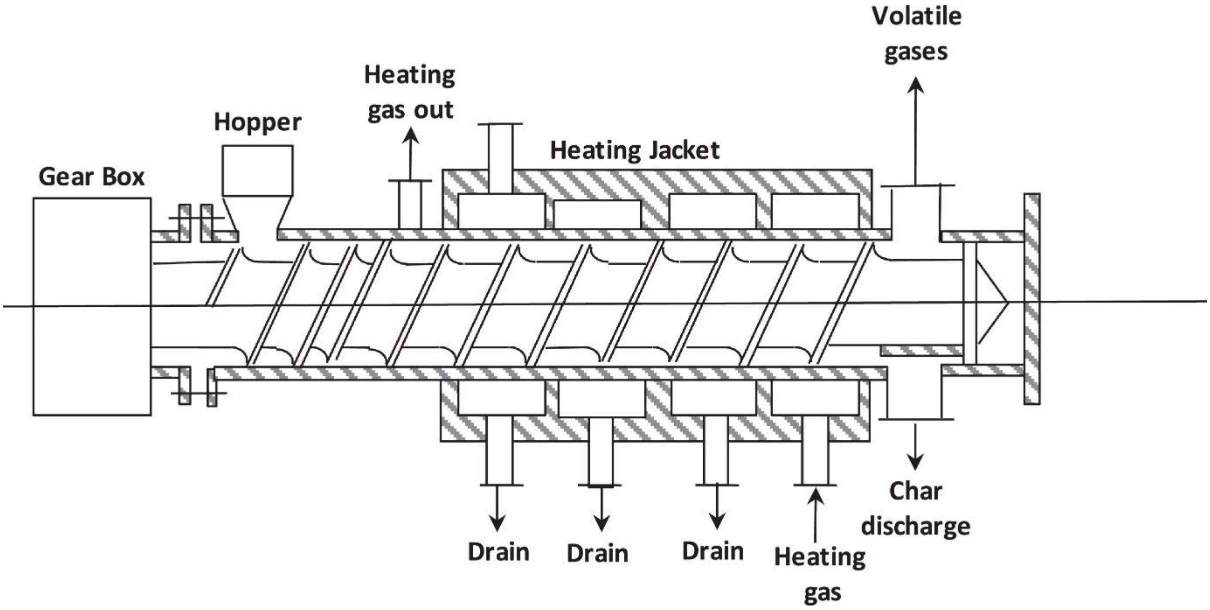


Figure 7: Example of a screw pyrolysis reactor (Sharifzadeh, et al., 2019)

The benefit of a screw in small to mid-scale applications becomes limiting at industrial scales however, as the mechanical stability of such a large moving part becomes complex and difficult to guarantee under high loads. It therefore becomes more efficient to rotate the entire chamber itself, as is done with rotary kilns.

Rotary Kiln Pyrolyser

Rotary kilns are a form of continuous pyrolyser that use an externally heated cylindrical shell, inclined at an angle for gravity led movement through the system (Boateng, Garcia-Perez, Mašek, Brown, & del Campo, 2015). The absence of moving parts in the cylinder interior minimises the risk of jamming and makes rotary kilns far more suitable for large-scale deployment than screw pyrolysers. Depending on throughput rate, the large volume of a rotary kiln interior can mean that secondary biochar as a result of biochar/vapour interaction is not formed (Boateng, Garcia-Perez, Mašek, Brown, & del Campo, 2015). Pyrolysis in a high-grade steel reactor can lead to the increased heavy metal content in biochar, due to abrasion of the reactor tube (Boateng, 2016). With increasingly large-scale operations maintaining a tight air seal for anoxic conditions becomes more difficult.

The lab-scale rotary kiln as shown below in Figure 8 (left) is a typical example of rotary kiln used for pyrolysis. After purging the system with nitrogen, biomass is introduced at a rate determined by the screw feeder, moving into the kiln where it dries, devolatilizes, and chars. The biochar is then transported into a collection drum via a screw conveyor, which acts as a heat exchanger due to its water jacket (Boateng, 2016). Gases and vapours that are separated in the discharge chamber are used in the afterburner chamber, and circular processes use these products to heat the kiln, thus perpetuating the process.

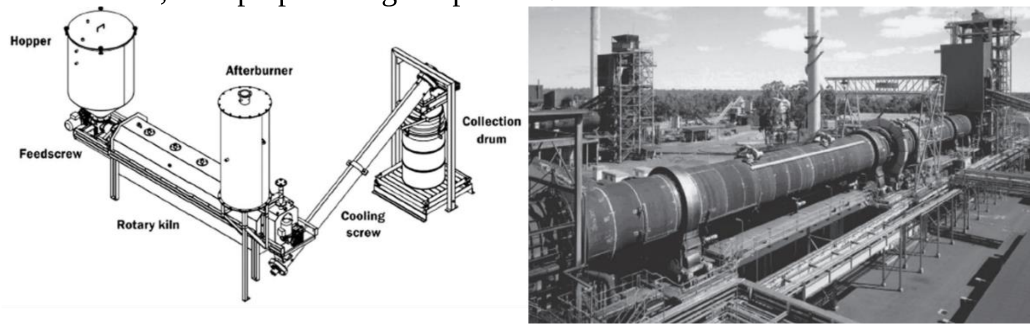


Figure 8: Left; rotary kiln pilot-scale pyrolysis unit (Stage III) at UKBRC, University of Edinburgh (UKBRC, 2021)- Right; 4.6 by 68m rotary kiln for coal treatment at Iluka Resources I, Australia, of 900,000 tons throughput per year capacity (Boateng, 2016)

Rotary kilns are the most suitable option for large-scale pyrolysis. As shown by Figure 8 they are used for industrial processes and have been used for the mass manufacture of cement since the mid 1880’s (Boateng, 2016).

Issues with scaling

As equipment capacity increases, the question of plant construction is introduced, and the mechanical stability of the pyrolysis units becomes a concern. The control and monitoring of the process also becomes harder as heat transfer and material flow operate over larger volumes, and this makes it more difficult to effectively monitor the particle temperature history as it moves through the unit. At larger scales more rigorous sampling methods are also required, as variability between runs can be potentially larger than within a single batch (Mašek, et al., 2018). Due to the industrial amounts of material, product quality and consistency become harder to assure as samples become smaller and smaller with respect to the batch volume.

Benefits of scaling

Carbon abatement has been found to increase for agricultural use of biochar if produced at larger scale, from 0.7 to 1.1 t CO_2e/odt feedstock for small biochar systems (defined as 500 t biochar/yr) to 0.9-1.3 t CO_2e/odt feedstock for large scale industry (25000 t biochar/yr) (Hammond, Shackley, Sohi, & Brownsort, 2011). Larger scales also minimise char handling losses as a percentage of overall handled char. Whilst unprecedented for biochar production, the UK and the ROI have a long history of using rotary kiln technology in cement and clinker production. In 2008 the dry process cement manufacturing capacity of Platin works, Drogheda, was increased by 1.4 million tonnes annually by the construction of Kiln 3, costing €200 million (Irish Cement, n.d.). Operations of this size reduce the cost per tonne of biochar by reducing the amount of staff required to monitor the process also.

1.5.3 Pyrolysis Options

The UK biochar market is in its infancy, as small-scale horticultural products are the only well-advertised commercial option for purchasing biochar. The two main suppliers of this are Carbon Gold and Oxford Biochar (Carbon Gold, 2021) (Oxford Biochar, n.d). In most countries except for those in North Asia, the quantities being produced and sold are below 20,000 tonnes a year (Joseph & Taylor, 2014). Due to the secondary position of most biochar production to biogas extraction or energy production worldwide, there are very few centralised resources that can be used as a reference point for pyrolysis and biochar companies. Contact networks for biochar production are typically informal or suffer from irregular updating, however, by developing the Biochar Forum during Phase 1 of this project it is anticipated that engagement between large-scale demand and pyrolysis suppliers should improve in the near future. The small scale of many of the referenced operations also often means the websites have little information that can be used for comparison. Some key references are given below in Table 12.

Table 12: Key reference points for biochar and pyrolysis technology suppliers

Source	**Source Type**	**Description**
(Rasmussen, 2012)	Web page	List of names and links for large scale pyrolizers including: Combined Heat and Char Systems Combined Power and Char Systems Pyrolysis Systems
(Joseph & Taylor, 2014)	Book chapter	Summarises some small to mid-scale technologies
(International Biochar Initiative, 2015)	Report	List of names and links for 326 for-profit biochar enterprises active in 2015

The discussed pyrolysis options are summarised below in Table 13, ordered largest to smallest by maximum annual biochar output. Tonnes of biochar produced per year has been chosen as the functional unit to enable comparison and assumptions have been stated in the table. These assumptions have been made for the sake of quantitative comparison, so the figures in this table should be used with caution and for estimative purposes only. Where multiple units exist the unit with the greatest yearly output has been displayed, and where multiple rotary kilns are used within one plant the output of a single rotary kiln has been displayed.

Table 13: Summary of considered pyrolysis plant options, organised by maximum yearly biochar output

Company	**Biochar Certification**	**Technology**	**Max yearly biochar (tonnes)**
(Splainex Ecosystems, 2018)	None	Large scale rotary kiln Industrial plant	**11680** (assuming a 20% biochar yield, 292 working days a year, 200 tpd)
Mitsubishi Heavy Industries (MHI)*	None stated	Tokyo Sludge Pyrolysis Plant Externally heated rotary kiln	**3285**
(Biogreen, n.d.) France	None	Spirajoule™ (Hollow shaft screw conveyor) BGR750L8 Plant	**2100** (assuming 20% biochar yield and 7000 h/yr)
(PYREG, 2021) Germany	EBC	Screw conveyor PX1500 Containerised	**1440** (sludge) **560** (woodchip)
(Pyrum Innovations, 2021) Germany	Ecoloop Certificate for oil	Rotary valve Industrial plant	**1000** (assuming 20% biochar yield)
(PyroCore, 2021) UK	None	Screw Containerised	**700** (assuming 7000 h/yr)
(Tigercat, 2021)	None	Open-top flame curtain Mobile container 6050-Carbonator	**700** (assuming 20% biochar yield, 7000 h/yr, 0.5 t/hour throughput)
(BIOMACON, 2021) Germany	EBC	Screw C500-I Boiler	**453**
(BlackCarbon, n.d.) Denmark	Partnered with IBI	Screw BC300 Housed unit	**161** (assuming 7000 h/yr)

* (Mašek, Sohi, Kiso, & Boag, 2010) (Koga, et al., 2007)

Splainex Ecosystems Ltd

Splainex Ecosystems Ltd were founded in 1994 in the Netherlands to drive the commercialisation of pyrolysis technology for waste treatment and recycling purposes. They give support for each stage of the plant development and offer turn-key projects with after-sale assistance also. They have pyrolysis units located in Germany, USA, China, Japan, Spain, Czechia, Cyprus, and the Philippines.

Figure 9: Splainex sewage sludge facility, throughput capacity 200 t/day (Splainex Ecosystems, 2016)

Whilst primarily orientated towards waste material reduction and energy recovery, feasible variants upon the scope of work are welcome and biochar is discussed as a common primary product. Equipment is supplied in four units that covers feedstock pre-treatment, rotary-kiln with ancillary equipment, energy recovery and electricity generation, and flue gas treatment and disposal. If required, single lines can be combined to reach greater throughput capacity. Given the land and capital required to permanently establish this option it was not pursued.

Mitsubishi Heavy Industries – Tokyo Sludge Pyrolysis Plant

Constructed in 2007, the MHI sludge pyrolysis plant outside of Tokyo processed 300 t/day of oven dried sludge. This was split over three rotary kilns, each handling 100 t/day dewatered sludge at 25% moisture content. The final product was used for fuel and met a minimum energy content of 20,000 Kcal kg^{-1}. The plant reportedly ran 24/7 every year since commissioning in 2008. The plant was commissioned by public tendering, designed by Abeyo company, and built by MHI under license from a German technology provider. There is little information regarding its current operation or more recent outputs, and the plant is now reportedly closed due to the after-effects of the Fukushima incident (Mašek, Sohi, Kiso, & Boag, 2010)). Given the land and capital required to permanently establish this option it was not pursued.

Biogreen

Biogreen is a patented pyrolysis process in use since 2003. Equipment is delivered in containerised modules, but the largest capacity as referenced in Table 13 is an assembled plant. It uses a screw feed operation which is fully continuous and automatic, with full control of pyrolysis conditions.

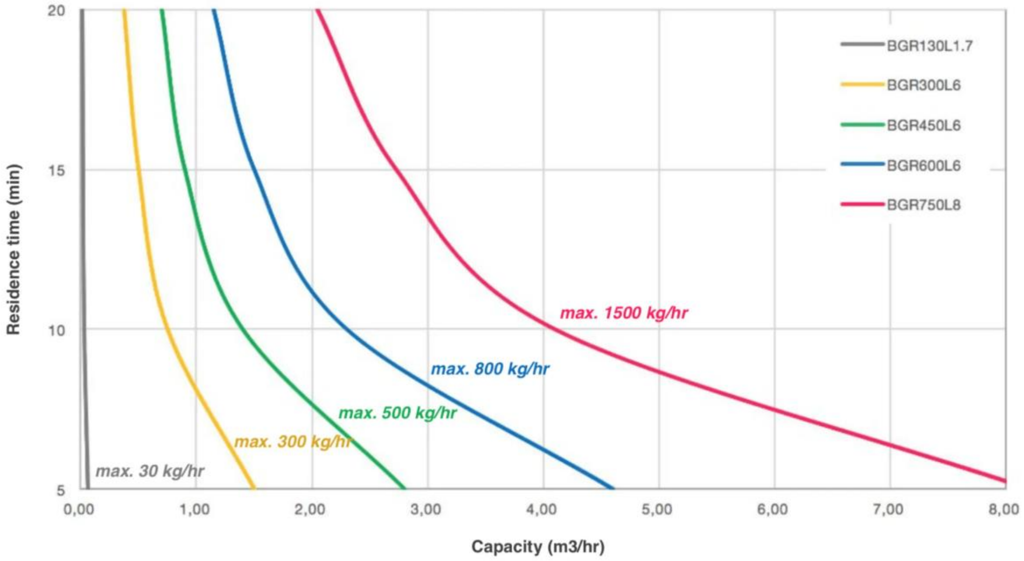


Figure 10: Graph to show residence time against maximum throughput by volume for five different Biogreen pyrolysis units (Biogreen, n.d.)

Capacities vary on feedstock density so the output of sewage sludge derived biochar would be higher than wood derived biochar, which is denser. Biogreen systems are designed for modularity so equipment can be installed in parallel to achieve different outputs.

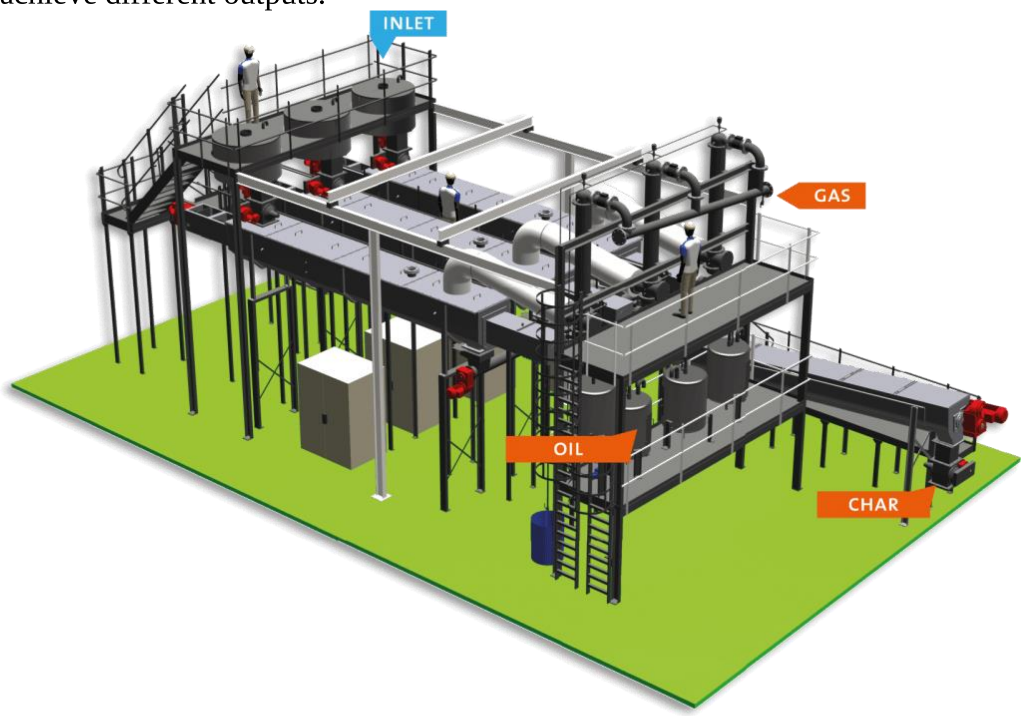


Figure 11: Concept view of Biogreen industrial installation. Yearly biochar production of 2100 tonnes (Biogreen, n.d.)

Biogreen is completely powered by electricity and over 45 units have been supplied worldwide. The biomass must be a free-flowing material of moisture content below 10%, and particle size less than 30mm. Biogreen has been used for wood residue, sewage sludge, and industrial sludge. From correspondence, biomass to biochar projects for 1 tonne per hour (inlet) capacity are typically an order of magnitude of £2.72m. This includes feeding hopper, pyrolysis unit, solid residue cooling, control cabinet, steam boiler (12 bars). It does not include feedstock preparation, pyrolysis oil recovery or auxiliary equipment that are custom to the demand (Biogreen, n.d.). Given the land and capital required to permanently establish this option it was not pursued, and after discussion with Biogreen representatives, leasing options were not available.

PYREG

PYREG was founded in 2009. It specialises in manufacturing modular pyrolysis units for biochar production and has plants in five different countries. The process is autothermal so only energy generated is used to perpetuate the pyrolysis, and plants in Sweden and Switzerland feed excess energy back into local heating networks. Plants are certified with European Biochar Certification and they meet the Waste Incineration Ordinance. Customers have already been found by PYREG for $CO_{2\ removal}$ certificate purchasing. PYREG make analyses of the proposed feedstock and provides support during permit applications. The units may be bought, or an operator model can be used whereby a PYREG partner company would buy and operate the system for the client, however this is only available for larger companies and municipalities.

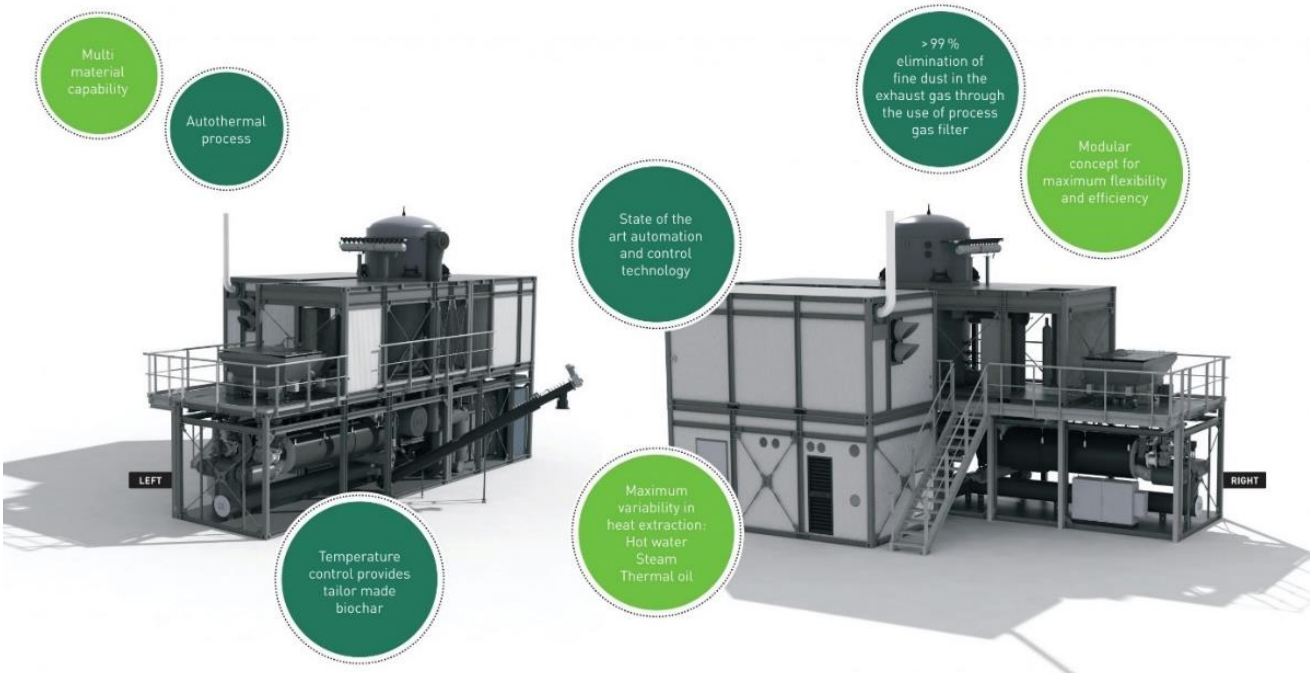


Figure 12: Schema of the PYREG PX 1500 (PYREG, 2021)

Biomass must be < 30mm in size, pourable and free flowing, minimum 75% dry substance content, and 10 Mj/kg minimum calorific value. The plants are capable of processing sewage sludge, biomass, and industrial waste. Additions can be made to the units for flue gas cleaning. There are three-unit sizes, P500, PX500, and PX1500. They are approximately 21-75 m^2. (PYREG, 2021)A screw feeder is used for continuous operation. Following consultation PYREG was not available for lease and so this option was not pursued due to the short-term nature of the project.

Pyrum Innovations

Pyrum Innovations is a French based pyrolysis company founded in 2007. Their major plant in Dillingen pyrolyses 5000 tonnes of rubber tyres a year and has been refined through experience since 2008. After the plant is started with external energy, energy is generated by the recovered gas to enable a self-sufficient operation and depending upon pyrolysis conditions surplus energy may be won for reselling.

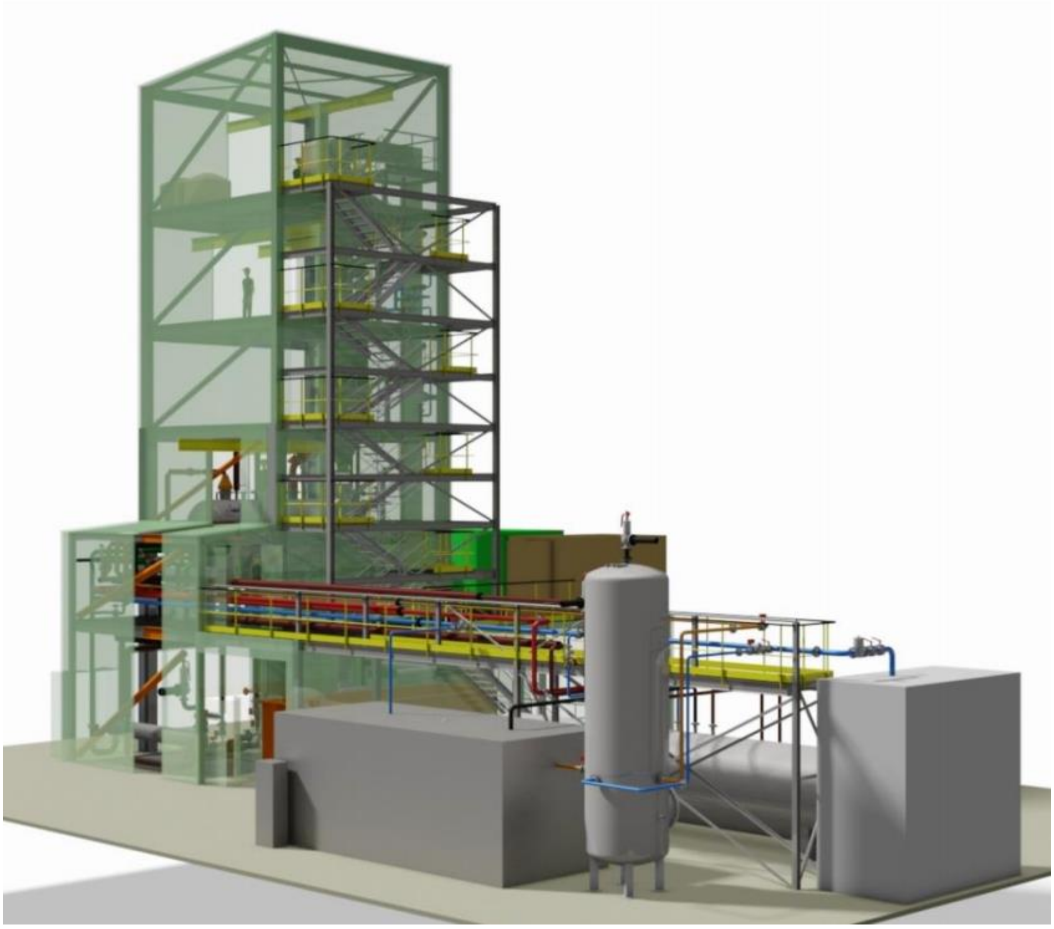


Figure 13: Plan of the Pyrum Thermolysis 5000 tonnes/yr unit (Pyrum Innovations, 2021)

The input materials are currently limited to used tires, bitumen mats and isolations, elastomer rubber waste, and plastics. The plant handles a granulate size spectrum from 3 to 15mm. From Figure 13 the industrial plant is a fixed option, with little potential for easy re-siting once erected. Other reference sites have established similar plants so the technology is presumably for sale (Pyrum Innovations, 2021). Due to the capital and land take requirements to establish a plant this supplier was not pursued, and enquiries regarding leasing options were not answered.

PyroCore

PyroCore was established in the UK in 2018. It focuses on converting waste into a resource and reducing landfill waste, and there is a demonstration plant in Wells, Somerset. Typical feedstocks are end of life vehicle non-recyclable parts, clinical waste, municipal, and electrical waste, though all feedstock types can be used, and energy generation is expected from high calorific value feedstock. Units are available to buy for permanent on-site placement or in a mobile skid-mounted containerised form.

Figure 14: PyroCore demonstration facility in Wells, Somerset (PyroCore, 2021)

PyroCore is the chosen option for this project, and further details are given in section 4.1.1 of Appendix G.

Tigercat

Tigercat is a Canadian company founded in 1992 that specialises in the design and manufacture of forest harvesting systems. The Tigercat 6050 Carbonator is an open topped wood debris conversion system for reducing the volume of biomass. Whilst air is not deliberately expelled, the biomass is burnt from above. The layer of biomass beneath outgasses and rises through to the flame above where it is burned, creating anoxic (total depletion of oxygen) conditions approximate to pyrolysis where biochar forms. This is called flame curtain pyrolysis (Schmidt & Taylor, 2014).

Figure 15: Annotated picture to show dimensions of Tigercat 6050 Carbonator (Tigercat, 2021)

The Tigercat 6050 is highly portable and truck mountable and does not require any kind of pre-processing (assuming reasonable moisture content < 30%). Remote monitoring options and temperature controls are included with the unit but the consistency of the produced biochar may be compromised by the open air batch process (Tigercat, 2021). However, similar flame curtain pyrolysis processes have been found to produce biochar that generally fulfils all the requirements for the premium quality of the European biochar certificate (Schmidt & Taylor, 2014). This option has not been pursued due to the lack of control over the produced gases, and for not aligning with the project's potential to stimulate the pyrolysis industry, specifically.

BIOMACON

BIOMACON was founded in 2003 in Germany. They have three reference plants and provide six different biomass-biochar compact converters for farm and industrial use. The feedstock options are not specified but must have at least 15% lignin content and 35% cellulose content to meet the warranty. One machine in Switzerland has a biochar certificate. Outputs range between 7 and 68kg/h, generating 25-40kW and 300-500 kW respectively.

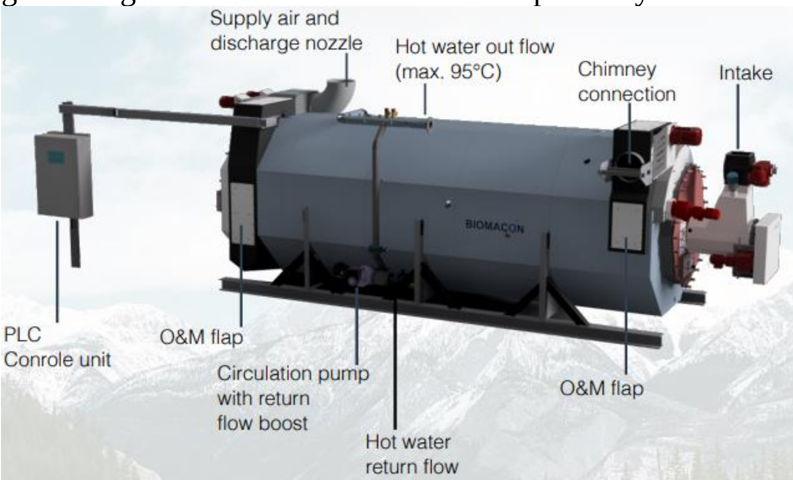


Figure 16: Rendition of BIOMACON boiler unit (BIOMACON, 2021)

The systems are boilers, so are geared towards energy provision over biochar production. Following consultation with BIOMACON representatives, this option was not pursued due to the inability to meet the biochar quantities required.

BlackCarbon

Started in 2005, the BlackCarbon BC300 unit in Barritskov, Denmark, is a continuous flow pyrolysis plant of approximately 23kg/h output. It uses a Stirling Engine and a combined heat and power (CHP) burner to produce heat and electricity. The gases are combusted externally in the Stirling Engine to run a generator.

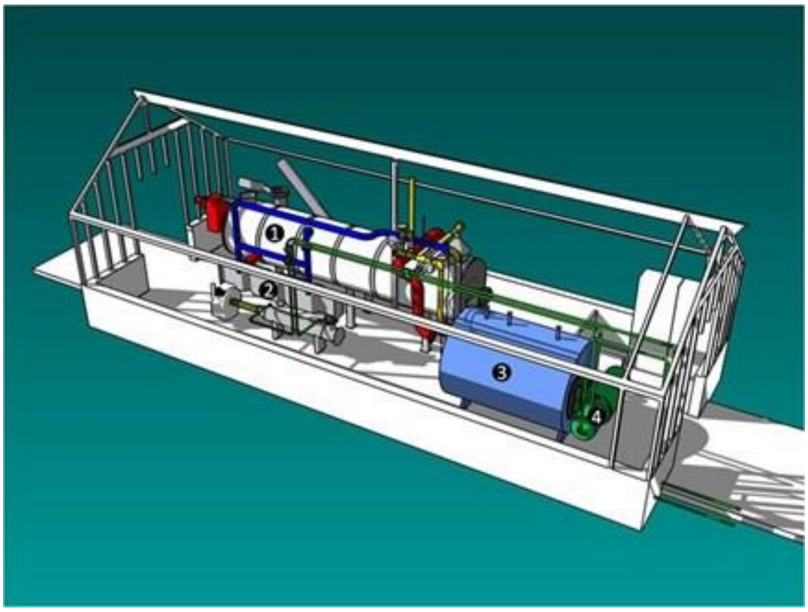


Figure 17: Schema to show the BlackCarbon BC300 unit (BlackCarbon, n.d.)

As with BIOMACON, the primary function of BlackCarbon is as a boiler, so this option was not pursued due to the inability to meet the biochar quantities required.

Scaling Pathway

The demand for biochar is increasing rapidly. Publications like the Royal Society Report (The Royal Society, 2018) have made its sequestration potential public, and 7 of the 24 projects publicly announced by BEIS are using biochar (GOV, 2021). Contact with PyroCore also suggests a groundswell in interest for established UK biochar production systems, evidenced further by the establishment of the Biochar Forum. A flowchart of the expected scaling stages is given below in Figure 18.

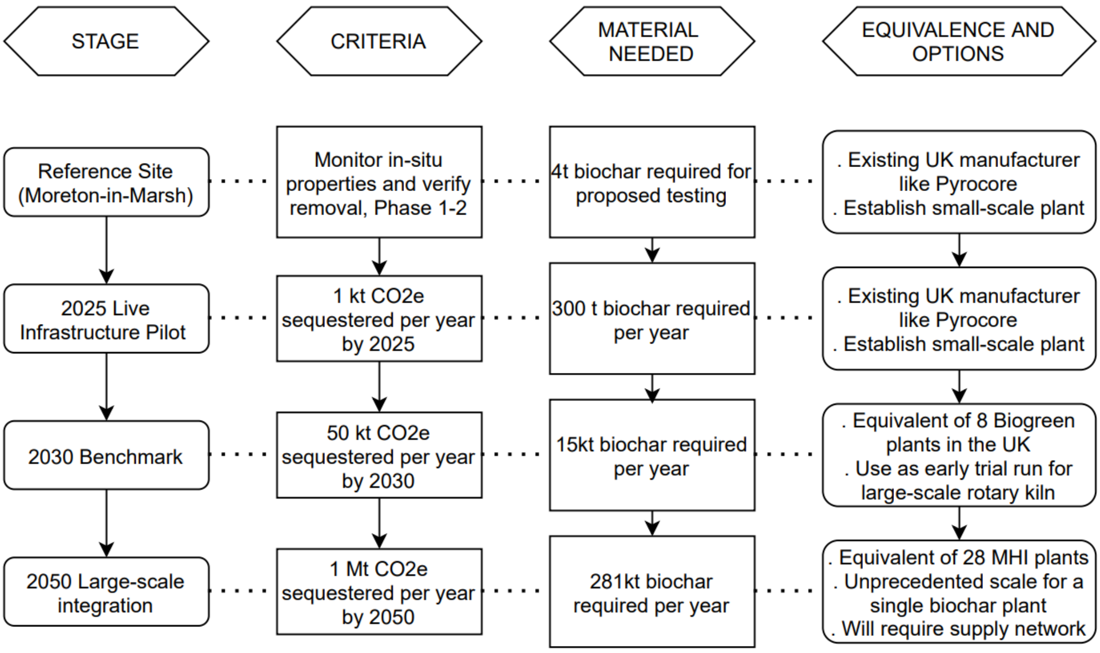


Figure 18: Flowchart to show likely progression of biochar production. Material needed has been calculated assuming biochar will be used to meet half of the removal goals, using the LCA review (see section 1.4.1) net carbon sequestration average of 1.64 tCO_2e per tonne of biochar, assuming softwood feedstock

Given the project's requirement to demonstrate value to the UK economy, it is recommended that a domestic company be used where possible. Due to the small size of the UK pyrolysis industry this is also favourable in terms of establishing a longer-term demand and creating strong industry networks. Upon the completion of Phase 2 in 2025, the pilot project must demonstrate a removal of 1kt $CO_2e\ yr^{-1}$, requiring approximately 300 tonnes of biochar. As with the reference site material requirements, this demand could be met by agreement with an existing UK company such as PyroCore. Alternatively, this could be used as an opportunity to begin very early trial runs of large-scale rotary kilns, though the cost of this outstrips the resources of the project and is therefore not be feasible. PyroCore is recommended for meeting the biochar requirements for both the reference site and the pilot site.

The target of 50 kt CO_2e per year by 2030 requires approximately 15kt of high-quality biochar. Even large-scale screw pyrolysis options like Biogreen are inadequate here, and whilst modularity is helpful in expanding production this demand represents an 8-fold increase in their current capacity. Whilst more expensive in up-front costs, it is prudent to consider establishing a single large-scale rotary kiln unit in partnership with a wastewater treatment body or sawmill company. Splainex Ecosystems Ltd are recommended here. Combined with the establishment of demand for biochar as a construction material resulting from this project, Splainex Ecosystems Ltd also ensure standalone commercial viability through energy generation. The trial of a single rotary-kiln would provide approximately 11,680 t biochar/yr once operational and retain the possibility for site expansion through additional rotary-kilns.

The annual demand for 281kt of biochar in 2050 outstrips any consideration of small-scale units and even of a single plant, considering current rotary-kiln pyrolysis technology. Instead, multiple large-scale rotary kiln plants would be required, and the use of biochar in infrastructure would require a growing domestic biochar industry.

1.6 Feedstock Review

Our search yielded no companies that can supply the required quality of biochar, the required quantity of biochar and the feedstock, together in one package. PyroCore is able to provide the pyrolysis process sufficient to produce the required quantity and quality of biochar, but do not typically source their own feedstock (see section 4.1 of Appendix G).

Through stakeholder engagement a landowner local to Banwell has been identified as requiring a large quantity of Ash (Fraxinus excelsior) trees felled, due to Ash Dieback disease. Discussion is ongoing regarding the number of trees required to fulfil the material requirements of the Banwell Bypass and Moreton in Marsh reference site, please see Appendix B5 for full details. The agreement between the Phase 2 contractors and the site owner is not yet fully developed, so it is necessary to make a review of the commercially available feedstock options.

From sections 1.2.2 and 1.2.3, wood pellets have been identified as a potential feedstock. Factors of source sustainability, transparency, and pellet production are considered below.

1.6.1 Pellet Regulations

Energy generated from biomass is Britain’s second biggest source of renewable electricity. In Q1 of 2021, it supplied 7.5% of Britain’s electricity, second only to wind that generated 25.6% (Biomass UK, 2021). Just like biochar however, the benefits of biomass energy are strongly dependent upon the sustainability of the wood source and emissions accruing from land-use production, harvesting, and production into usable feedstock (Land Energy, n.d). Transparency and a well quantified production process is therefore critical when selecting a feedstock provider.

To promote the wider use of biomass for heating, the Renewable Heat Incentive (RHI) was introduced by the government in 2014 to ensure that all biomass comes from a verifiable supplier (GOV UK, 2015). Suppliers must demonstrate that greenhouse gases resulting from the life cycle of their biomass are at least 60% lower than the EU fossil fuel average for heat when used in a boiler with 70% efficiency (GOV UK, n.d). Land criteria requirements must also be met by the supplier, such as confirmation of legal felling and sustainable woodland management (GOV UK, n.d). Compliance can be demonstrated by using a government approved Biomass Suppliers List (BSL) (GOV UK, n.d). Whilst the requirements pertaining to boiler efficiency are secondary to the production of biochar for this project, the assurance of responsible felling practices are paramount.

Independent of the BSL approval process but included as an additional search option within the list, is the EN plus certification scheme for wood pellets. It is an internationally recognised quality certification scheme covering the entire wood pellet supply chain, meeting and in some cases exceeding the requirements of the ISO 17225-2 standard for biofuel pellets (GOV UK, n.d). Certificate holders are required to document the CO_2eq per tonne of pellets produced (ENplus, 2015). This facilitates accurate carbon accounting over the entire life cycle of the biochar, so is of high value to the project.

1.6.2 Pellet Suppliers

Ten biomass pellet companies were contacted to find a suitable material supplier, and information from the seven that responded is summarised below in Table 14.

Table 14: Table to summarise information obtained from responsive biomass suppliers (for contact details please see Appendix D3)

Supplier	**Postcode**	**Distance as crow flies to Avonmouth (km)**	**Diameter (mm)**	**Price £/tonne**		**Notes**
				Material	**Haulage**	
The Wood Pellet Delivery Co	NR13 6BA	317	-	238	inc	Furthest delivery west is Milton Keynes
Woodlets	KA26	430	6	299	-	Subsidiary distributor of Land Energy
White Horse Energy	GL7 1YG	56	-	275	-	Bulk tonne bag
Midland Bioenergy	CV10 0QP	139	6	261	-	Enquiry left with information for bulk order
Balcas Energy	BT94 2ES	462	6	209	-	Quote from website
Nuergy	EH53 0LQ	430	6	234	inc	Subsidiary distributor of Land Energy

Land Energy	KA26 9PF	430	6	215 - 230	inc	

Typically, the biomass can be delivered in four main ways:

1. 10kg plastic bags.
2. 1t pallets of 100 plastic bags.
3. 1 – 1.35t bulk industrial bags.
4. Tipped or “blown” deliveries from trucks.

From consultation with Land Energy, numerous options have been identified for the delivery of pellets to Avonmouth from their production plant in Girvan, Scotland. They are summarised below in Table 15.

Table 15: Pellet delivery options as identified by Land Energy

Delivery Method	**Details**	**Indicative Price (£/t ex VAT)**
Direct	27 tonne deliveries by articulated lorry, pellets pneumatically blown into large silo at Avonmouth	215
Direct	28 tonnes tipped deliveries by articulated lorry, into large silo at Avonmouth that has equipment for bulk material handling	210
Local Storage Hub	Store the required feedstock locally to Avonmouth, and provide just-in-time deliveries to match requirements	230

The carbon embodied within the pellets as given by Land Energy is 0.117 $kgCO_2e$/t pellet at the factory gate in Girvan, and 0.223 $kgCO_2e$/t pellet if delivered directly to Avonmouth.

Should commercial feedstock become necessary due to unforeseen difficulties in processing the proposed Ash (Fraxinus excelsior) source, Land Energy is recommended as the pellet supplier due to the transparency of their supply chain and their interest in the project.

B1 Biochar LCA

Appendix B1 Biochar LCA
Scenario Flows

LIFE CYCLE INVENTORY			
Description	**Unit**	**Value**	**Notes**
Functional unit	tCO_2e/t biochar	1	A numerically positive value means a carbon emission, and a negative number means that carbon has been sequestered
Pyrolysis temperature	C°	700	USER INPUT
Sawmill residue required for 1t biochar 550C	tonnes	4.59	
Sawmill residue required for 1t biochar 700C	tonnes	5.77	
Production emissions for 1t sawmill residue	tCO_2e/t feedstock	0.01	
Drying sawmill residue 550C	tCO_2e/t biochar	0.490242995	
Drying sawmill residue 700C	tCO_2e/t biochar	0.479373838	
Pelleting	kWh/t	72	
UK electricity grid	gCO_2e/kWh	140	
Pyrolysis upkeep (construction)	tCO_2e/t biochar	0.14696	
Pyrolysis running	tCO_2e/t biochar	0	Softwood
Pyrolysis water and associated energy	tCO_2e/t biochar	0.0000408	
Pyrolysis generated energy	tCO_2e/t biochar	0.4	
General loading and transport biochar loss (handling)	%	1	Biochar lost per tonne handled, assumed CO_2 conversion
Handling emission sawmill biochar 550C	tCO_2e/t biochar	0.031357333	Dependent upon pyrolysis temp
Handling emission sawmill biochar 700C	tCO_2e/t biochar	0.033077	Dependent upon pyrolysis temp
Loading emissions through diesel use	tCO_2e/t biochar	0.016842105	
Transport distance to application	km	1.5	USER INPUT (One leg)
Transport distance to pyrolysis	km	20	USER INPUT (One leg)
Transport distance from pyrolysis to application	km	21.5	USER INPUT (One leg)
Transport emission	$kgCO_2e$/t km	0.955	Load 50%
Rate of spreading (sawmill biochar)	t biochar/ ha	100	USER INPUT
Length of strip	km	10	USER INPUT
Sawmill biochar per km	t/km	28.1	
Spreading emission by area	$kgCO_2e$/ ha	32.06	
Spreading emission by mass	tCO_2e/t biochar	0.0003206	
Biochar loss in spreading	%	3	Biochar lost per tonne handled, assumed CO_2 conversion
Spreading loss emission sawmill biochar 550C	tCO_2e/t biochar	0.094072	Dependent upon pyrolysis temp
Spreading loss sewage sludge biochar 700C	tCO_2e/t biochar	0.099231	Dependent upon pyrolysis temp
Rotavator tractor emissions	$kgCO_2e$/km	1.03	
Factory gate carbon sink sawmill biochar 550C	tCO_2e/t biochar	2.32	After 100 years
Factory gate carbon sink sawmill biochar 700C	tCO_2e/t biochar	2.45	After 100 years

Appendix B1 Biochar LCA
Scenario Flows

Updates Automatically				Requires Manual Goalseek
Scenario	**Net carbon sequestration tCO_2e/t biochar**	**Net carbon sequestration tCO_2e/m^3 biochar**	**Principal emission**	**Distance till no net removal (km)**
1a	-2.00	-0.340	Drying	1049
1b	-2.14	-0.364	Drying	1121
2a	-1.64	-0.279	Drying	209
2b	-1.72	-0.279	Drying	218

Appendix B1 Biochar LCA
Scenario Flows

Appendix B1 Biochar LCA
Scenario Flows

SCENARIO 1a				
Description:				
Softwood residue is the sole feedstock. It is dried, pelleted, and pyrolysed at source site at 550°C, then transported to application site for mixing with quarry fines and topsoil.				
Stage	**Description**	**Unit**	**Value**	**Notes**
Feedstock	Feedstock production emissions 1t biochar	tCO_2e/t biochar	0.03	
Drying	Drying	tCO_2e/t biochar	0.49	
Pelleting	Pelleting	tCO_2e/t biochar	0.046238532	
Pyrolysis	Embodied pyrolysis construction	tCO_2e/t biochar	0.14696	
Pyrolysis	Pyrolysis energy cost	tCO_2e/t biochar	0	
Pyrolysis	Energy generated from pyrolysis	tCO_2e/t biochar	-0.4	
Pyrolysis	Biochar cooling	tCO_2e/t biochar	0.0000408	
Loading	Biochar handling diesel use	tCO_2e/t biochar	0.016842105	
Transport	Transport emission (to application)	tCO_2e/t biochar	0.002865	Return trip
Unloading	Biochar handling diesel use	tCO_2e/t biochar	0.016842105	
Application	Spreading emissions	tCO_2e/t biochar	0.0003206	
Application	Tractor	tCO_2e/t biochar	3.66548E-05	
Carbon sink	Carbon sink	tCO_2e/t biochar	-2.32	After 100 years

Net carbon sequestration (with production)	tCO_2e/t biochar	-1.97
Net carbon sequestration (pure waste-stream)	tCO_2e/t biochar	-2.00
Principal Carbon emission	-	Drying
Carbon removal per bulk volume	tCO_2e/m^3 biochar	-0.340267305

SCENARIO 1b				
Description:				
Softwood residue is the sole feedstock. It is dried, pelleted, and pyrolysed at source site at 700°C, then transported to application site for mixing with quarry fines and topsoil.				
Stage	**Description**	**Unit**	**Value**	**Notes**
Feedstock	Feedstock production emissions 1t biochar	tCO_2e/t biochar	0.04	
Drying	Drying	tCO_2e/t biochar	0.48	
Pelleting	Pelleting	tCO_2e/t biochar	0.046238532	
Pyrolysis	Embodied pyrolysis construction	tCO_2e/t biochar	0.14696	
Pyrolysis	Pyrolysis energy cost	tCO_2e/t biochar	0	
Pyrolysis	Energy generated from pyrolysis	tCO_2e/t biochar	-0.4	
Pyrolysis	Biochar cooling	tCO_2e/t biochar	0.0000408	
Loading	Biochar handling diesel use	tCO_2e/t biochar	0.016842105	
Transport	Transport emission (to application)	tCO_2e/t biochar	0.002865	Return trip
Unloading	Biochar handling diesel use	tCO_2e/t biochar	0.016842105	
Application	Spreading emissions	tCO_2e/t biochar	0.0003206	
Application	Tractor	tCO_2e/t biochar	3.66548E-05	
Carbon sink	Carbon sink	tCO_2e/t biochar	-2.45	After 100 years

Net carbon sequestration (with production)	tCO_2e/t biochar	-2.10
Net carbon sequestration (pure waste-stream)	tCO_2e/t biochar	-2.14
Principal Carbon emission	-	Drying
Carbon sequestration per bulk volume	tCO_2e/m^3 biochar	-0.363762626

SCENARIO 2a				
Description:				
Softwood residue is the sole feedstock. It is transported to the pyrolysis site for pelleting, and pyrolysis at 550°C, then transported to application site for mixing with quarry fines and topsoil				
Stage	**Description**	**Unit**	**Value**	**Notes**
Feedstock	Feedstock production emissions 1t biochar	tCO_2e/t biochar	0.03	
Loading	Biochar handling diesel use	tCO_2e/t biochar	0.016842105	
Transport	Transport emission (to pyrolysis)	tCO_2e/t biochar	0.175229358	Return trip
Transport	Transport emission (to pyrolysis)	tCO_2e/t biochar	0.18837156	Return trip
Drying	Drying	tCO_2e/t biochar	0.490242995	
Pelleting	Pelleting	tCO_2e/t biochar	0.046238532	
Pyrolysis	Embodied pyrolysis construction	tCO_2e/t biochar	0.14696	
Pyrolysis	Pyrolysis energy cost	tCO_2e/t biochar	0	
Pyrolysis	Energy generated from pyrolysis	tCO_2e/t biochar	-0.4	
Pyrolysis	Biochar cooling	tCO_2e/t biochar	0.0000408	
Unloading	Biochar handling diesel use	tCO_2e/t biochar	0.016842105	
Application	Spreading emissions	tCO_2e/t biochar	0.0003206	
Application	Tractor	tCO_2e/t biochar	3.66548E-05	
Carbon sink	Carbon sink	tCO_2e/t biochar	-2.32	After 100 years

Net carbon sequestration (with production)	tCO_2e/t biochar	-1.61
Net carbon sequestration (pure waste-stream)	tCO_2e/t biochar	-1.64
Principal Carbon emission	-	Drying
Carbon sequestration per bulk volume	tCO_2e/m^3 biochar	-0.278942199

SCENARIO 2b				
Description:				
Softwood residue is the sole feedstock. It is transported to the pyrolysis site for pelleting, and pyrolysis at 700°C, then transported to				
Stage	**Description**	**Unit**	**Value**	**Notes**
Feedstock	Feedstock production emissions 1t biochar	tCO_2e/t biochar	0.04	
Loading	Biochar handling diesel use	tCO_2e/t biochar	0.016842105	
Transport	Transport emission (to pyrolysis)	tCO_2e/t biochar	0.220299885	Return trip
Transport	Transport emission (to pyrolysis)	tCO_2e/t biochar	0.18837156	Return trip
Drying	Drying	tCO_2e/t biochar	0.479373838	
Pelleting	Pelleting	tCO_2e/t biochar	0.058131488	
Pyrolysis	Embodied pyrolysis construction	tCO_2e/t biochar	0.14696	
Pyrolysis	Pyrolysis energy cost	tCO_2e/t biochar	0	
Pyrolysis	Energy generated from pyrolysis	tCO_2e/t biochar	-0.4	
Pyrolysis	Biochar cooling	tCO_2e/t biochar	0.0000408	
Unloading	Biochar handling diesel use	tCO_2e/t biochar	0.016842105	
Application	Spreading emissions	tCO_2e/t biochar	0.0003206	
Application	Tractor	tCO_2e/t biochar	3.66548E-05	
Carbon sink	Carbon sink	tCO_2e/t biochar	-2.45	After 100 years

Net carbon sequestration (with production)	tCO_2e/t biochar	-1.68
Net carbon sequestration (pure waste-stream)	tCO_2e/t biochar	-1.72
Principal Carbon emission	-	Drying
Carbon sequestration per bulk volume	tCO_2e/m^3 biochar	-0.292753728

Appendix B1 Biochar LCA
Overarching Variables

OVERARCHING VARIABLES						
Stage	**LCI**	**Unit**	**Value**	**Note**	**Source**	**Source URL**
	UK electricity grid	gCO_2e/kWh	140		(ICAX, 2020)	https://www.icax.co.uk/Grid_Carbon_Factors.html
	Water treatment	$kgCO_2e/m^3$	0.272		(GOV, 2021)	https://www.gov.uk/government/publications/greenhouse-gas-reporting-conversion-factors-2021

Appendix B1 Biochar LCA

Feedstock production

SAWMILL RESIDUE						
Stage	**LCI**	**Unit**	**Value**	**Note**	**Source**	**Source URL**
Feedstock provision	Sawmill residue	kgCO_2e/t	7.13		(Hammond et al., 2011)	http://dx.doi.org/10.1016/j.enpol.2011.02.033
Feedstock provision	Sawmill residue moisture content	%	10	Sourcing from sawmill residues, assumed to be pre-dried for processing and selling		

Appendix B1 Biochar LCA

Loading, Transport, Spreading

Stage	LCI	Unit	Value	Note	Source	Source URL
Handling	Loading	l diesel/ t Biochar	0.19	Supplementary information	(Lefebvre et al., 2021)	https://doi.org/10.1016/j.jclepro.2021.127764
Handling	Loading	kgCO_2e/ l of diesel	3.2	Supplementary information	(Lefebvre et al., 2021)	https://doi.org/10.1016/j.jclepro.2021.127764
Handling	Handling losses at each transport stage	%	1	Assumed as being lost as CO_2	(Hammond et al., 2011)	http://dx.doi.org/10.1016/j.enpol.2011.02.033
Transport	Articulated lorry (>33 tonnes)	kgCO_2e/t km	0.955	Load factor 50%	(Hammond et al., 2011)	http://dx.doi.org/10.1016/j.enpol.2011.02.033
Application	Losses at application	%	3	Assumed as being lost as CO_2	(Hammond et al., 2011)	http://dx.doi.org/10.1016/j.enpol.2011.02.033
Application	Lime spreader	kgCO_2e/ ha	32.06		(Hammond et al., 2011)	http://dx.doi.org/10.1016/j.enpol.2011.02.033
Application	81 kW Tractor 12 t trailer	kgCO_2e/ km	1.03	Master spreadsheet	(Hammond et al., 2011)	http://dx.doi.org/10.1016/j.enpol.2011.02.033

Appendix B1 Biochar LCA

Pyrolysis and Pelleting

LCI	Unit	Value	Note	Source	Source URL
Pelleting	kWh/tonne	72.000		(Lefebvre, 2019)	https://doi.org/10.1038/s41598-020-76470-y
Pyrolysis efficiency	%	100.000	For corn stover	(Cong et al, 2018)	http://dx.doi.org/10.1021/acs.energyfuels.7b03175
Annual pyrolysis ouput	t biochar/yr	560.000	Softwood	(Pyreg, 2021)	https://pyreg.com/our-technology/
Annual pyrolysis ouput	t biochar/yr	1440.000	Sludge	(Pyreg, 2021)	https://pyreg.com/our-technology/
Pyrolysis construction	tCO_2e/yr	734.800	For small scale plant (5000 t/a	(Hammond et al., 2011)	http://dx.doi.org/10.1016/j.enpol.2011.02.032
Pyrolysis construction	tCO_2e/yr	82.298	For small scale sawmill residue plant (5000 t/a scaled to 500 t/a)	(Hammond et al., 2011)	http://dx.doi.org/10.1016/j.enpol.2011.02.033
Pyrolysis construction	tCO_2e/t biochar	0.147	For small scale sawmill residue plant (5000 t/a scaled to 500 t/a)		
Pyrolysis construction	tCO_2e/yr	211.622	For small scale sludge plant (5000 t/a scaled to 1440 t/a)	(Hammond et al., 2011)	http://dx.doi.org/10.1016/j.enpol.2011.02.033
Pyrolysis construction	tCO_2e/t biochar	0.147	For small scale sawmill residue plant (5000 t/a scaled to 500 t/a)		
Pyrolysis plant rating	kW	110.000	For small-scale plant	(Hammond et al., 2011)	http://dx.doi.org/10.1016/j.enpol.2011.02.033
Pyrolysis plant annual hours	hours	8000.000	USER ASSUMPTION		
PyroCore energy generated	kWe	200.000	Third of 600 kWe from PyroCore	PyroCore	Obtained information sheet
Pyrolysis process	tCO_2e/ t biochar	0.000	Softwood		
Pyrolysis process	tCO_2e/ t biochar	0.000	Sludge		
Pyrolysis water required	L/kg biochar	0.150	From Biogreen leaflet, assume indirect water cooling	(Biogreen, 2021)	Appendix 2b
Pyrolysis temperature	°C	550.000		(UK BRC, 2019)	https://www.biochar.ac.uk/standard_materials.php
Pyrolysis temperature	°C	700.000		(UK BRC, 2019)	https://www.biochar.ac.uk/standard_materials.php
Wood to biochar yield (dry weight conversion)	t biochar / t feedstock	0.218	For sewage sludge at 550C	(UK BRC, 2019)	https://www.biochar.ac.uk/standard_materials.php
Wood to biochar yield (dry weight conversion)	t biochar / t feedstock	0.173	For sewage sludge at 700C	(UK BRC, 2019)	https://www.biochar.ac.uk/standard_materials.php

Appendix B1 Biochar LCA

Drying

Stage	LCI	Unit	Value	Note	Source	Source URL
	Sawmill starting moisture content	wt %	40	Based on freshly felled Ash	(Kent, Kofman, Owens, Coates, & Cooley, 2009)	http://www.coford.ie/research/thematicareaharvestingandproducts/woodenergy/forestenergy/
	Sawmill final moisture content	wt %	10	Optimum for wood pelleting	(Reza et al, 2012)	https://doi.org/10.1002/ep.11615
	Sawmill moisture reduction	wt %	30			
	Dryer efficiency sawmill	-	0.37	For poplar drying	(Del Giudice, 2019)	http://dx.doi.org/10.3390/en12091590
	Specific heat of water	kJ/kg °C	4.18		(Krokida et al, 2015)	https://doi.org/10.1201/b17208
	Latent water heat of vaporisation	kJ/kg	2260	Energy for vaporisation at 100C	(Krokida et al, 2015)	https://doi.org/10.1201/b17208
	Ambient temperature	°C	10	Average of daily UK range (6 - 14)	Website	https://www.currentresults.com/Weather/United-Kingdom/average-annual-temperatures.php#:~:text=Across%20the%20UK%2C%20annual%20temperatures,C%20(43%20%C2%B0F).
	Water boiling point	°C	100			
	Temperature rise require	°C	90			
	Sawmill required 550	t	4.587155963	For one tonne biochar (10% wt moisture)		
	Dry solid content Sawmill 550	t	4.128440367			
	Lost water Sawmill 550	t	1.769331586			
	Energy to heat and vapourise Sawmill 700	kJ / t biochar	4664311.927			
	Energy with other operations	kJ / t biochar	12606248.45			
	Energy to CO_2 S550	tCO_2e/ t biochar	0.490242995			
	Sawmill required 700	t	5.767012687	For one tonne biochar (10% wt moisture)		
	Dry solid content Sawmill 700	t	4.036908881			
	Lost water Sawmill 700	t	1.730103806			
	Energy to heat and vapourise Sawmill 700	kJ / t biochar	4560899.654			
	Energy with other operations	kJ / t biochar	12326755.82			
	Energy to CO_2 S700	tCO_2e/ t biochar	0.479373838			

Appendix B1 Biochar LCA

Biochar Persistence

BIOCHAR PERSISTENCE					
Variable	**Unit**	**Value**	**Comment**	**Source**	**Source URL**
Annual degradation rate	%	0.30	Very conservative	(EBC, 2020)	https://www.european-biochar.org/en/ct/139-C-sink-guidelines-documents
Years considered	years	100.00	Typical timeline considered	(EBC, 2020)	https://www.european-biochar.org/en/ct/139-C-sink-guidelines-documents
550 Softwood biochar bulk density	t/m^3	0.15	(500) pine slow pyrolysis	(Askeland et al., 2019)	https://dx.doi.org/10.7717%2Fpeerj.6784
700 Softwood biochar bulk density	t/m^3	0.17	(750) pine slow pyrolysis	(Askeland et al., 2019)	https://dx.doi.org/10.7717%2Fpeerj.6784
C to CO_2e factor	-	3.67			-

Feedstock	Pyrolysis temperature	Carbon content by mass	Carbon mass	CO_2 factory gate	C after x years	CO_2 sequestered after x years	CO_2 lost after x years
	C°	%	t C/ t original biochar	t CO_2e / t original biochar	t C/ t original biochar	t CO_2e / t original biochar	t CO_2e / t original biochar
Softwood chip	550.00	85.52	0.86	3.14	0.63	2.32	0.81
	700.00	90.21	0.90	3.31	0.67	2.45	0.86

B2 Pyrolysis plant comparison

Appendix B2 Pyrolysis Plant Comparison

Company	Country	Founded	Service	Certification	Reference plants	Technology type	Size (m^2)	Fuel source	Feedstocks	Max pyrolysis temperature	Biochar ouput (kg/h)	Feedstock throughput (kg/h)	Annual operating hours	Max yearly biochar output (tonnes)	URL
Splainex Ecosystems	Netherlands	1994	Turnkey purchase	None stated	8	Single Line Rotary kiln	To design	Varied	All	Not stated	Not stated	Not stated	Not stated	11,680 (assuming 20% biochar yield, 292 days working	https://www.energy-xprt.com/companies/splainex-ecosystems-ltd-23558
Biogreen	France	2003	Purchase or rent (based off of request form)	None	45	Spirajoule (hollow shaft screw conveyor) BGR750L8	To request	Electric	All	850	To request	1500	To request	2100 (assuming 20% biochar yield and 7000 h/yr)	https://www.biogreen-energy.com/
PYREG	Germany	2009	Purchasing or operating model	EBC	7	Screw conveyor P500	27	Autothermal	All (with size requirements)	750	24 (woodchip) 72 (sewage sludge)	95 (wood chip) 143 (sewage sludge)	7500	180 (wood chip) 540 (sludge)	https://pyreg.com/our-technology/
						Screw conveyor PX1500	39	Autothermal	All (with size requirements)	750	75 (woodchip) 192 (sewage sludge)	293 (biomass) 383 (sewage sludge)	7500	560 (wood chip) 1440 (sludge)	
PyroCore	UK	2018	Sell	None	Not stated	Likely screw	Containerised	Not stated	All	850	100	500	Not stated	700 (assuming 7000 h/yr)	https://pyrocore.com/
BlackCarbon	Denmark	2005	Not stated	Partnered with IBI	Standalone	Screw BC300	Approx 30	CHP and engine	All	800	23	90	Not stated	161 (assume 7000 hours operation)	http://www.blackcarbon.dk/Unit
Biomacon	Germany	2003	Purchase or rent	EBC	Various uses as CO2 negative boilers	Screw C500-I	29.25	No gas pipes	Organic material lignin above 15% and cellulose	850	57	295	8000	453	https://www.biomacon.com/technologie?lang=en
Pyrum Innovations	Germany	2007	Purchase	Ecoloop certificate for oil	Not stated	Industrial plant, rotary kiln	2500 (with storage)	Electric	All	750	Not stated	650-1000	7800	1000 (assuming 20% biochar yield)	Pyrum Innovations AG: For a cleaner world - start
Tigercat	Canada (UK suppliers)	1992	Purchase or rent	None	Not stated	Open top flame cap Mobile tiger track 6050-Carbonator	43.92	Petrol engine	All	Not stated	100	500	7000	700	https://www.tigercat.com/product/6050-carbonator/
Mitsubishi Heavy Industries	Japan	1884	Contract	Not stated	Unknown	Tokyo Sludge Pyrolysis Plant 3 rotary kilns		Energy neutral Syngas	Sewage	600			8760	3285	See Appendix 2b

B3 Biochar Standard Comparison

Property	Unit	BQM (v1)			EBC (v9.3)			IBI (v2.1)		
		Criteria	Category	Tests	Criteria	Category	Tests	Criteria (Range of maximum allowed thresholds)	Category	Tests
Arsenic	mg/kg	< 10 (high grade) < 100 (standard grade)	Necessary basic property	DIN EN ISO17294-2 (E29); BS EN 13650 (soluble in aqua regia)	< 2 (EBC-Feed) < 13 (EBC-AgroOrganic) < 13 (EBC-Agro) < 15 (EBC-Material)	Recommended	DIN 22022-2 DIN 22022-7 DIN EN ISO 17294-2 / DIN EN 1483	13 - 100	Toxicant Assessment (Required for all biochars)	TMECC (2001)
Cadmium	mg/kg	< 3 (high grade) < 39 (standard grade)	Necessary basic property	DIN EN ISO17294-2 (E29); BS EN 13650 (soluble in aqua regia)	< 0.8 (EBC-Feed) < 0.7 (EBC-AgroOrganic) < 1.5 (EBC-Agro) < 5 (EBC-Material)	Recommended	DIN 22022-2 DIN 22022-7 DIN EN ISO 17294-2 / DIN EN 1483	1.4 - 39	Toxicant Assessment (Required for all biochars)	TMECC (2001)
Chromium	mg/kg	< 15 (high grade) < 100 (standard grade)	Necessary basic property	DIN EN ISO17294-2 (E29); BS EN 13650 (soluble in aqua regia)	< 70 (EBC-Feed) < 70 (EBC-AgroOrganic) < 90 (EBC-Agro) < 250 (EBC-Material)	Recommended	DIN 22022-2 DIN 22022-7 DIN EN ISO 17294-2 / DIN EN 1483	93 - 1200	Toxicant Assessment (Required for all biochars)	TMECC (2001)
Cobalt	mg/kg	n/a	n/a	n/a	n/a	n/a	n/a	34 - 100	Toxicant Assessment (Required for all biochars)	TMECC (2001)
Copper	mg/kg	< 40 (high grade) < 1500 (standard grade)	Necessary basic property	DIN EN ISO17294-2 (E29); BS EN 13650 (soluble in aqua regia)	< 70 (EBC-Feed) < 70 (EBC-AgroOrganic) < 100 (EBC-Agro) < 250 (EBC-Material)	Recommended	DIN 22022-2 DIN 22022-7 DIN EN ISO 17294-2 / DIN EN 1483	143 - 6000	Toxicant Assessment (Required for all biochars)	TMECC (2001)
Lead	mg/kg	< 60 (high grade) < 500 (standard grade)	Necessary basic property	DIN EN ISO17294-2 (E29); BS EN 13650 (soluble in aqua regia)	< 10 (EBC-Feed) < 45 (EBC-AgroOrganic) < 150 (EBC-Agro) < 250 (EBC-Material)	Recommended	DIN 22022-2 DIN 22022-7 DIN EN ISO 17294-2 / DIN EN 1483	121 - 300	Toxicant Assessment (Required for all biochars)	TMECC (2001)
Manganese	mg/kg	n/a	n/a	DIN EN ISO17294-2 (E29); BS EN 13650 (soluble in aqua regia)	n/a	n/a	DIN 22022-2 DIN 22022-7 DIN EN ISO 17294-2 / DIN EN 1483	n/a	n/a	n/a
Molybdenum	mg/kg	< 10 (high grade) < 75 (standard grade)	Necessary basic property	DIN EN ISO17294-2 (E29); BS EN 13650 (soluble in aqua regia)	n/a	n/a	DIN 22022-2 DIN 22022-7 DIN EN ISO 17294-2 / DIN EN 1483	5 - 75	Toxicant Assessment (Required for all biochars)	TMECC (2001)
Nickel	mg/kg	< 10 (high grade) < 600 (standard grade)	Necessary basic property	DIN EN ISO17294-2 (E29); BS EN 13650 (soluble in aqua regia)	< 25 (EBC-Feed) < 25 (EBC-AgroOrganic) < 50 (EBC-Agro) < 250 (EBC-Material)	Recommended	DIN 22022-2 DIN 22022-7 DIN EN ISO 17294-2 / DIN EN 1483	47 - 420	Toxicant Assessment (Required for all biochars)	TMECC (2001)
Selenium	mg/kg	< 5 (high grade) < 100 (standard grade)	Necessary basic property	DIN EN ISO17294-2 (E29); BS EN 13650 (soluble in aqua regia)	n/a	n/a	DIN 22022-2 DIN 22022-7 DIN EN ISO 17294-2 / DIN EN 1483	2 - 200	Toxicant Assessment (Required for all biochars)	TMECC (2001)
Zinc	mg/kg	< 150 (high grade) < 2800 (standard grade)	Necessary basic property	DIN EN ISO17294-2 (E29); BS EN 13650 (soluble in aqua regia)	< 200 (EBC-Feed) < 200 (EBC-AgroOrganic) < 400 (EBC-Agro) < 750 (EBC-Material)	Recommended	DIN 22022-2 DIN 22022-7 DIN EN ISO 17294-2 / DIN EN 1483	416 - 7400	Toxicant Assessment (Required for all biochars)	TMECC (2001)
Boron	mg/kg	n/a	n/a	n/a	n/a	n/a	n/a	Declaration	Toxicant Assessment (Required for all biochars)	TMECC (2001)
Chlorine	mg/kg	n/a	n/a	n/a	n/a	n/a	n/a	Declaration	Toxicant Assessment (Required for all biochars)	TMECC (2001)
Sodium	mg/kg	n/a	n/a	n/a	Declaration	Recommended	n DIN 51729, DIN EN ISO 11885 / DIN EN ISO 17294-2	Declaration	Toxicant Assessment (Required for all biochars)	TMECC (2001)
Mercury	mg/kg	< 1 (high grade) < 17 (standard grade)	Necessary basic property	DIN EN1483 (E12); BS ISO 16772	< 0.1 (EBC-Feed) < 0.4 (EBC-AgroOrganic) < 1 (EBC-Agro) < 1 (EBC-Material)	Recommended	DIN EN 15763:2010-04	1 -17	Toxicant Assessment (Required for all biochars)	US EPA 7471 (2007)
PAH (sum of USEPA 16)	mg/kg	< 20	Necessary basic property	DIN EN 15527 2008-09; DIN ISO 13877: 1995-06 – Principle B with GCMS (toluene extraction with ASE); BS EN 15527:2008	< 4 ± 2 (EBC-Feed and EBC-AgroOrganic) < 6 ± 2.2 (EBC-Agro)	Recommended	PAH analogue to DIN EN 15527: 2008-9 (extraction with Toluol); DIN EN 16181: 2019-08 with extraction method 2	6-300	Toxicant Assessment (Required for all biochars)	US EPA 8270 (2007) using Soxhlet extraction (US EPA 3540) and 100% toluene as the extracting solvent
BETX	n/a	TBC	TBC	TBC	n/a	n/a	n/a	n/a	n/a	n/a
PCB	mg/kg	< 0.5	Necessary basic property	AIR DF 100,HRMS; BS EN 1948 series	< 0.2	Recommended	DIN EN 16167 DIN EN 16215	0.2 - 1	Toxicant Assessment (Required for all biochars)	US EPA 8082 (2007) or US EPA 8275 (1996)
Dioxins/Furans	ng/kg	< 20	Necessary basic property	AIR DF 100,HRMS; BS EN 1948 series	< 20	Recommended	DIN EN 16190:2019-10 DIN EN 16215 Nr. 152/2009 (modified by Nr. 2017/771) HRGC/HRMS method	17	Toxicant Assessment (Required for all biochars)	US EPA 8290 (2007)
pH	pH	Declaration	Necessary basic property	Rajkovich et al. (2011) DIN 10390 BS EN 13037	Declaration	Recommended	DIN ISO 10390 (CaCl2)	Declaration	Basic Utility Properties (Required for all biochars)	pH analysis procedures as outlined in section 04.11 of TMECC (2001) using modified dilution of 1:20 biochar:deionized H2O (w:v) and equilibration at 90 minutes on the shaker, according to Rajkovich et al. (2011). See Appendix E for further information.
Moisture content	% total dry mass	Declaration	Necessary basic property	ASTM D1762-84 BS EN 13040	Declaration	Recommended	DIN 51718	Declaration	Basic Utility Properties (Required for all biochars)	ASTM D1762-84 Standard Test Method for Chemical Analysis of Wood Charcoal (specify measurement date with respect to time from production)
Organic Carbon	% total dry mass	≥10%, irrespective of the quality of biochar grade	Necessary basic property	ASTM D4373-02 BS EN 13039	Declared	Recommended	TruSpec CHN according to DIN 51732	10% Minimum Class 1: ≥60% Class 2: ≥30% and <60% Class 3: ≥10% and <30%	Basic Utility Properties (Required for all biochars)	Total C and H analysis by dry combustion-elemental analyzer. Inorganic C analysis by determination of CO2-C content with 1N HCl, as outlined in ASTM D4373 Standard Test Method for Rapid Determination of Carbonate Content of Soils. Organic C calculated as Total C – Inorganic C
Total Carbon (C)	% total dry mass	Declaration	Necessary basic property	BS EN 15104	n/a	n/a	TruSpec CHN according to DIN 51733	n/a	n/a	Total C and H analysis by dry combustion-elemental analyzer. Inorganic C analysis by determination of CO2-C content with 1N HCl, as outlined in ASTM D4373 Standard Test Method for Rapid Determination of Carbonate Content of Soils. Organic C calculated as Total C – Inorganic C
Hydrogen (H)	% total dry mass	Declaration	Necessary basic property	BS EN 15104	n/a	n/a	TruSpec CHN according to DIN 51733	n/a	n/a	Total C and H analysis by dry combustion-elemental analyzer. Inorganic C analysis by determination of CO2-C content with 1N HCl, as outlined in ASTM D4373 Standard Test Method for Rapid Determination of Carbonate Content of Soils. Organic C calculated as Total C – Inorganic C
Long-term carbon stability	% total dry mass	Declaration (optional method)	Necessary basic property	Accelerated ageing (oxidative) method	n/a	n/a	n/a	n/a	n/a	n/a

Molar H/C Organic ratio	Molar ratio	< 0.7 (maximum) irrespective of the quality biochar grade	Optional	ASTM D4373-02 (Corg) BS EN 13039 (Corg) BS EN 15104 (H)	< 0.7	Recommended	From already determined data TruSpec CHN according to DIN 51733	0.7 Maximum	Basic Utility Properties (Required for all biochars)	Total C and H analysis by dry combustion-elemental analyzer. Inorganic C analysis by determination of CO2-C content with 1N HCl, as outlined in ASTM D4373 Standard Test Method for Rapid Determination of Carbonate Content of Soils. Organic C calculated as Total C – Inorganic C
Molar O/Corg ratio	Molar ratio	n/a	n/a	n/a	< 0.4	Recommended	DIN 51733 (Oxygen) Truspec CHN according to DIN 51732 (Corg)	n/a	n/a	n/a
Total Nitrogen (N)	% total dry mass	Declaration	Optional	BS EN 15104	Declaration	Recommended	CHN according to DIN 51732	n/a	n/a	n/a
C:N	Molar ratio	Declaration	Optional	Ratio of C and N	Declaration	Recommended	CHN according to DIN 51732	n/a	n/a	n/a
Total Ash	% total dry mass	Declaration	Optional	BS EN 13039 ASTM D1762-84	Declaration	Recommended	Ash content (550 °C) analogue DIN 51719	n/a	n/a	n/a
Total Phosphorus (P)	% total dry mass	Declaration	Optional	Modified dry ashing followed by ICP (Enders and Lehmann 2012) BS EN 13650	Declaration	Recommended	n/a	Declaration	Advanced Analysis and Soil Enhancement Properties (Optional for all Biochars)	Modified dry ashing (Enders and Lehmann 2012). Elements in the digest determined by common analytical techniques
Total Potassium (K)	% total dry mass	Declaration	Optional	Modified dry ashing followed by ICP (Enders and Lehmann 2012) BS EN 13650	Declaration	Recommended	Main elements after melting digestion DIN 51729, DIN EN ISO 11885 / DIN EN ISO 17294-2: (P, Mg, Ca, K, Na, Fe, Si, S)	Declaration	Advanced Analysis and Soil Enhancement Properties (Optional for all Biochars)	Modified dry ashing (Enders and Lehmann 2012). Elements in the digest determined by common analytical techniques
Water holding capacity	ml/g	Declaration	Optional	Funnel and filter paper method Hilgard cup method (simple) DIN 51718 TGA 701 D4C	Declaration	Recommended	DIN EN ISO 14238, annex A	n/a	n/a	n/a
Bulk density	kg/m^3	Declaration	Optional	Mass and volume determination.	Declaration	Recommended	Bulk density (analogue VDLUFA-Method A 13.2.1):	n/a	n/a	n/a
Particle size distribution	mm	Declaration	Optional	ASTM D2862-10	n/a	n/a	n/a	Declaration	Basic Utility Properties (Required for all biochars)	Progressive dry sieving with 50 mm, 25 mm, 16 mm, 8mm, 4mm, 2 mm, 1 mm, and 0.5 mm sieves.
Neutralising Capacity	% $CaCO_3$	Optional	Optional	Rayment & Higginson (1992)	n/a	n/a	n/a	Declaration if pH is above 7	Basic Utility Properties (Required for all biochars)	AOAC 955.01 potentiometric titration on “as received” (i.e., wet) samples. Use dry weight to calculate % CaCO3 and report “per dry sample weight”.
Electrical Conductivity	dS/m	Optional	Optional	Rajkovich et al. (2011) BS EN 13038	n/a	n/a	n/a	Declaration	Basic Utility Properties (Required for all biochars)	EC analysis procedures as outlined in section 04.10 of TMECC (2001) using modified dilution of 1:20 biochar:deionized H2O (w:v) and equilibration at 90 minutes on the shaker, according to Rajkovich et al. (2011)
Cation Exchange Capacity (K, Ca, Mg, Na)	cmol + /kg	Optional	Optional	Ammonium-acetate (or BaCl2 extraction) then ICP-OES	n/a	n/a	n/a	n/a	n/a	n/a
Porosity	Ratio of pore volume / bulk Volume	Optional	Optional	e.g. mercury intrusion porosimetry	n/a	n/a	n/a	n/a	n/a	n/a
Specific surface area / total surface area	m^2 /g	Optional	Optional	Adsorption method (e.g. BET); ASTM D 6556-10; ISO 9277	Declaration	Recommended	DIN ISO 9277 (BET) and DIN 66137 (density)	Declaration	Advanced Analysis and Soil Enhancement Properties (Optional for all Biochars)	ASTM D6556 Standard Test Method for Carbon Black – Total and External Surface Area by Nitrogen Adsorption. See Appendix E for further information.
Labile carbon content	% of dry mass	Optional	Optional	Incubation studies; ASTM D1762-84	n/a	n/a	n/a	n/a	n/a	n/a
Volatile matter	% of dry mass	Optional	Optional	Incubation studies; ASTM D1762-85	Declaration	Recommended	DIN 51720	Declaration	Advanced Analysis and Soil Enhancement Properties (Optional for all Biochars)	ASTM D1762-84 Standard Test Method for Chemical Analysis of Wood Charcoal
Available Phosphorus	mg/kg	Optional	Optional	2% formic acid followed by spectrophotometry as described by Wang et al (2012)	Declaration	Recommended	n/a	Declaration	Advanced Analysis and Soil Enhancement Properties (Optional for all Biochars)	2% formic acid followed by spectrophotometry (Wang et al. 2012)
Mineral Nitrogen	mg/kg	Optional	Optional	KCl or CaCl2 extraction followed by spectrophotometry (Rayment and Higginson 1992)	Declaration	Recommended	n/a	Declaration	Advanced Analysis and Soil Enhancement Properties (Optional for all Biochars)	2M KCl extraction followed by spectrophotometry (Rayment and Higginson 1992)
Release dynamics of nutrients (P, K, N)	mg/kg	Optional	Optional	Soil column leaching experiments	n/a	n/a	n/a	n/a	n/a	n/a
Impact on soil aggregation	Size declaration	Optional	Optional	TBC	n/a	n/a	n/a	n/a	n/a	n/a
Soil water potential (available water content)	g/g or g/cm^3	Optional	Optional	Tension table and pressure plate	n/a	n/a	n/a	n/a	n/a	n/a
Priming potential impacts (impacts on SOC)	%	Optional	Optional	Incubation studies	n/a	n/a	n/a	n/a	n/a	n/a
Thermal analysis	uV / mg	Optional	Optional	Thermogravimetry-differential scanning calorimetry (TGDSC)	n/a	n/a	n/a	n/a	n/a	n/a
Volatile Organic Compounds (VOC)	% total dry mass	n/a	n/a	n/a	Declaration	Recommended	Thermogravimetric analysis	n/a	n/a	n/a
Gross calorific value	kJ/m^3	n/a	n/a	n/a	Declaration	Recommended	DIN 51900	n/a	n/a	n/a
Germination Inhibition Assay	n/a	n/a	n/a	n/a	n/a	n/a	n/a	Pass/Fail	Toxicant Assessment (Required for all biochars)	OECD methodology (1984) using three test species, as described by Van Zwieten et al. (2010)
Total Calcium, Magnesium, and Sulfur	mg/kg	n/a	n/a	n/a	n/a	n/a	n/a	Declaration	Advanced Analysis and Soil Enhancement Properties (Optional for all Biochars)	Modified dry ashing (Enders and Lehmann 2012). Elements in the digest determined by common analytical techniques.
Available Calcium, Magnesium, and Sulfur	mg/kg	n/a	n/a	n/a	n/a	n/a	n/a	Declaration	Advanced Analysis and Soil Enhancement Properties (Optional for all Biochars)	1M HCl extraction (Camps Arbestain et al. 2015). Elements in the digest determined by common analytical techniques.

B4 Soil Health Methodology

1 Soil Health Review Methodology

To focus the review of in-soil processes, the following key components of soil health as described by the UK government's Environmental Audit Committee 2016 report have been used (Environmental Audit Committee, 2016). They are:

- Nutrients and acidity;
- Organic carbon content;
- Structure and water capacity;
- Biological activities; and,
- Chemical pollution.

These categories have been used for each technology to facilitate comparison, and they are summarised below in detail to prevent repetition in the subsequent technical sections. Rigidly defining soil-health across different land-uses requires some generalisation, so these factors overlap and are strongly inter-connected. Many of the effects considered here are also potential impacts specific to agricultural systems, which have soil health issues distinct to those of an infrastructural setting. Where possible the information most relevant to an infrastructural setting has been presented.

1.1 Nutrients and Acidity

Available nutrients are the portion of an element or compound that can be assimilated by growing plants (Ippolito, Spokas, Novak, Lentz, & Cantrell, 2015) (Mukhopadhyay, Masto, Tripathi, & Srivastava, 2019). Several key chemical nutrients are required for overall soil health:

- Carbon;
- Nitrogen;
- Cation exchange capacity (CEC); and
- Appropriate pH (this naturally varies from soil to soil, although is impacted by human activity).

These are explained further below.

Along with carbon, nitrogen is essential for the growth and function of plants and microbes, so organic nitrogen and bioavailable nitrogen are key indicators of agricultural soil health (Adekiya, Olayanju, Ejue, Alori, & Adegbite, 2020).

An indicator of each technology's effect on soil health is its capacity to improve the nutrient content of soil through the provision of cation exchange capacity (CEC). Certain soil minerals, especially in combination with organic matter, possess electrically charged sites which attract and hold onto ions. For instance, negatively charged sites make up the CEC because they attract H^+, Ca^{2+}, Mg^{2+}, Na^+, and NH^{4+} ions, and positively charged sites which hold OH^-, SO_4^-, NO_3^-, and PO_4^- make up the anion exchange capacity (Mukhopadhyay, Masto, Tripathi, & Srivastava, 2019). CEC is a key index of nutrient status because exchangeable cations are the most important source of immediately available plant nutrients (Mukhopadhyay, Masto, Tripathi, & Srivastava, 2019).

1.2 Organic and Inorganic Carbon Content

Soil organic carbon (SOC) is a key measure of the soil organic matter. SOC is taken to be the measurable fraction of soil organic matter that is a result of photosynthesis, respiration, and decomposition. It reflects the soil capacity to affect nutrient supply and retention for the needs of plants and microbiota, and through these, the physical properties like aggregate stability, water holding capacity, and infiltration (Adekiya, Olayanju, Ejue, Alori, & Adegbite, 2020). Soil inorganic carbon (SIC) is a smaller portion of the total carbon content that is bound up in minerals and slower to change.

1.3 Structure and Water Capacity

This factor determines soil vulnerability to erosion and root penetration. As well as physical parameters like bulk density, permeability and porosity determine the surface run-off and groundwater flow characteristics of the amended soils.

1.4 Biological Activities

The microbial population, diversity, and activity affect all the factors of soil health, along with plants and enzyme activity (Adekiya, Olayanju, Ejue, Alori, & Adegbite, 2020).

1.5 Chemical Pollution

This refers to assorted man-made contamination that damages the soil health, through chemicals, heavy metals, tar, gases, asbestos, and radioactive substances. This has been addressed through the Environmental Impact Assessment and so has not been elaborated upon in the materials and processes sections.

References

Adekiya, A., Olayanju, T., Ejue, S., Alori, E., & Adegbite. (2020). Contribution of Biochar in Improving Soil Health. In B. Giri, & A. Varma (Eds.), *Soil Health* (pp. 99-113). Springer International Publishing. Retrieved from https://doi.org/10.1007/978-3-030-44364-1_6

Environmental Audit Committee. (2016). *Soil Health.* House of Commons. Retrieved from https://publications.parliament.uk/pa/cm201617/cmselect/cmenvaud/180/180.pdf

Ippolito, J., Spokas, K., Novak, J., Lentz, R., & Cantrell, K. (2015). Biochar elemental composition. In J. Lehmann, & S. Joseph (Eds.), *Biochar for Environmental Management* (pp. 137-161). Retrieved from https://eprints.nwisrl.ars.usda.gov/id/eprint/1590/

Mukhopadhyay, S., Masto, R., Tripathi, R., & Srivastava. (2019). Chapter 14 - Application of Soil Quality Indicators for the Phytorestoration of Mine Spoil Dumps. In V. Pandey, & K. Bauddh (Eds.), *Phytomanagement of Polluted Sites* (pp. 361-388). Retrieved from https://www.sciencedirect.com/science/article/pii/B9780128139127000144

B5 Ash Source

1 Ash Source (Fraxinus excelsior)

Through stakeholder engagement a landowner local to Banwell has been identified as requiring a large quantity of Ash (Fraxinus excelsior) trees felled, due to Ash Dieback symptoms.

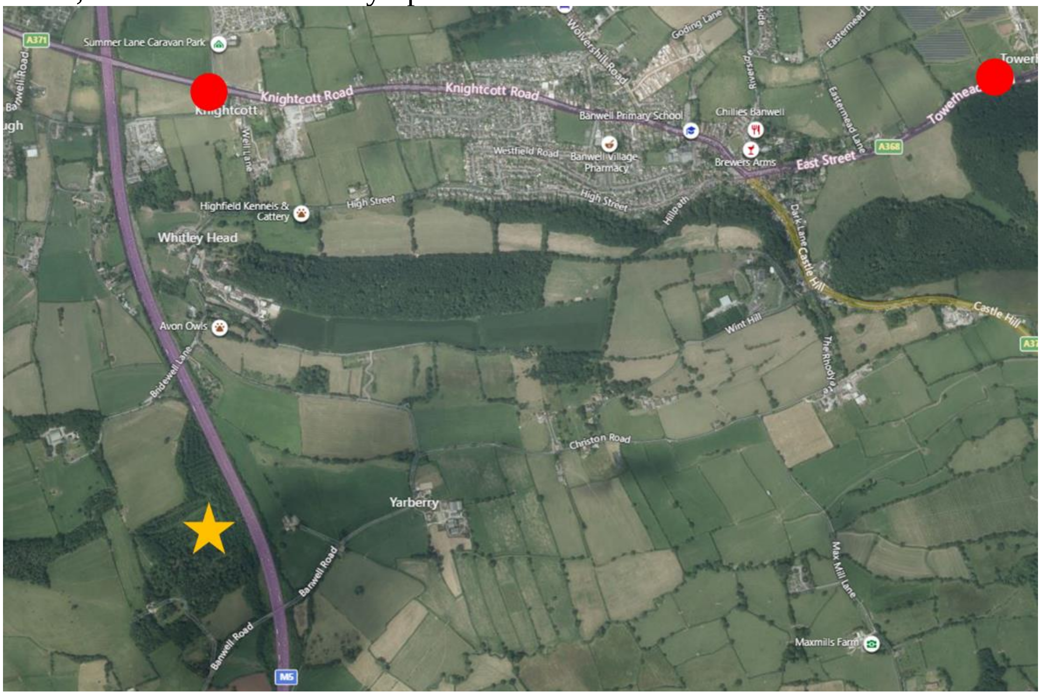


Figure 1: Aerial photograph to show position of feedstock source (yellow star) relative to the proposed start and end points of Banwell Bypass (red circles) (Bing Maps, n.d)

Located at BS29 6NA, the land is approximately 1.5 km south of where Banwell Bypass is proposed to branch north away from the A371, to the west of Banwell town, as shown in Figure 1. The land is approximately 20km north west of the PyroCore facility in Wells. Approximately 25,000 Ash trees were planted in 1996 along the west side of the M5 to provide screening from the traffic. The Ash trees are planted in discrete blocks, and the site also has Poplar and Beech trees in three other wooded areas on the 250-acre property. Due to the size of the property, area is also available for on-site pyrolysis and the placement of other required plant such as chippers and pelleters, as well as the potential need for stockpiling.

Due to the short timeframe of Phase 1 it was not feasible to fully cost and evaluate the felling licences and ecological assessments that accompany the use of the site. The life cycle analysis has been conducted using this as a base case study, as future projects will also have to engage with local landowners and feedstock sources. The growing relevance of Ash (Fraxinus excelsior) as a feedstock source for biochar is demonstrated by Phoenix Biochar, a community interest company that seeks to limit the social and environmental impact of Ash Dieback through biochar production (Phoenix Biochar , n.d)

The Ash population there has been identified as being affected by Ash Dieback (Hymenoscyphus fraxineus), a highly destructive fungus that only affects Ash, leading to leaf loss and canopy decline (The Tree Council, 2020). There has been loss of the crown canopy in the some of the trees, and the trees are still in Class 1 to 2 (100% -76% to 75% - 51% of the crown remaining) (The Tree Council, 2020). The stem wood is currently unaffected by the disease, as the landowner still uses the felled trees to power their log-burner. The decision to fell has been taken before contact was made with the landowner, so the project's involvement is not the cause of the felling. The trees and general area are pictured below in Figure 2.

Figure 2: Picture to show Ash, Poplar, and Beech trees on site (photo courtesy of Stuart Simons)

The legal responsibility of managing trees affected with Ash Dieback falls to the landowner, however, there are some factors which strengthen their pre-existing decision to pursue felling.

- The Ash trees are not locally notable, veteran, or ancient trees (Lonsdale, 2013). There is no history or special cultural/ecological attribute that is conserved within these trees (The Tree Council, 2020).
- The trees are not large, and therefore have less habitat value than older, wider trees, so chipping for biochar is acceptable (The Tree Council, 2020).
- The affected trees are directly neighbouring the M5, so allowing the Ash Dieback to progress in any way increases the risk that the motorway

becomes a major pathway for further spreading to different receptors, through fallen leaves and spores (The Tree Council, 2020).

- Loss of trees and resulting cover from the motorway will be remedied by planting new trees in their place.

Ash dieback is spread via airborne spores and the movement of infected trees through trade (The Tree Council, 2020). It may therefore be preferable to perform pyrolysis on-site for contamination reasons as well as for reducing mass haulage.

Green (freshly felled) Ash firewood has a net calorific content of approximately 17.71 MJ/kg and a mean moisture content of approximately 40% by total weight (Owens & Cooley, 2013) (Kent, Kofman, Owens, Coates, & Cooley, 2009). The PyroCore pyrolysis unit can therefore be expected to self-perpetuate once it has started, with extra energy generated for the required drying. Monitoring of Ash trees in Ireland has shown that moisture content can increase by up to 10% by total weight over the course of spring-summer (35% -45% from April to July) so felling could be conducted early in the year to minimise the amount of drying that is required (Kent, Kofman, Owens, Coates, & Cooley, 2009).

For approximately 306 t of biochar required at Banwell, and 8 t required at Moreton in Marsh, 314 t of biochar is required, rounded up to the nearest tonne. Assuming a biochar conversion rate of 17% by dry weight, 1,815 t of dry ash timber will be required (UK BRC, 2019). Assuming the wood has an initial moisture content of 40% by weight, 3,025 t of green ash timber will be required (Kent, Kofman, Owens, Coates, & Cooley, 2009). For a 25 year old ash tree with a base girth of 0.6m and a crown girth of 0.25m, a height of 10m, and a green density of 0.86 t/m^3, and a branch to stem biomass ratio of approximately 0.489, approximately 15,556 ash trees require felling, rounded up to the nearest number (Geyer & Lynch, 1990) (TRADA, n.d) (Le Goff, Granier, Ottorini, & Peiffer, 2004). Please see sheet “Ash” of Appendix G5 for full calculations.

The site owner has suggested that large areas of open space are available for siting plant such as chippers. This space could be used for constructing temporary drying/storage areas if this is permissible for Ash-dieback affected wood, and if the felling precedes the period of pyrolysis, which is expected to start in late 2022. Provided that the stem wood and large branches have not been pelleted and are kept dry and elevated from the floor (as firewood might), decomposition is not expected to be problem. Storage in this way may provide a benefit by reducing the moisture content of the wood and the subsequent need for drying.

Further information is expected in Q1 of 2022, relating to the average volume of the tree stem and branches, as well as a survey of the approximate stage of the disease in the trees. Further to this, an ecological survey has not yet been undertaken.

References

Bing Maps. (n.d).

Geotechnical Engineering Ltd. (2020). *Banwell Bypass Advanced Works: Ground Investigation.* North Somerset Council.

Geyer, W., & Lynch, K. (1990). Green Ash Growth Curves. *Transactions of the Kansas Academy of Science*, 12-16. Retrieved from https://www.jstor.org/stable/3628123

Kent, T., Kofman, P., Owens, E., Coates, E., & Cooley, S. (2009). *Harvesting and processing forest biomass for energy production in Ireland.* Coford. Retrieved from http://www.coford.ie/research/thematicareaharvestingandproducts/woodenergy/forestenergy/

Le Goff, N., Granier, A., Ottorini, J.-M., & Peiffer, M. (2004). Biomass increment and carbon balance of ash (Fraxinus excelsior) trees in an experimental stand in northeastern France). *Annals of Forest Science*, 577-588. Retrieved from http://dx.doi.org/10.1051/forest:2004053

Lonsdale, D. (2013). *Ancient and other veteran trees: further guidance on management.* The Tree Council. Retrieved from https://ancienttreeforum.co.uk/wp-content/uploads/2015/02/ATF_book.pdf

Manning, D., Renforth, P., Lopez-Capal, E., Robertson, S., & Ghazireh, N. (2013). Carbonate precipitation in artificial soils produced from basaltic quarry fines and composts: An opportunity for passive carbon sequestration. *International Journal of Greenhouse Control, 17*(1), 309-317. Retrieved from https://doi.org/10.1016/j.ijggc.2013.05.012

Owens, E., & Cooley, S. (2013). *Calorific value of Irish woodfuels.* Coford Connects. Retrieved from http://www.woodenergy.ie/media/woodenergy/content/woodfuelsstovesandboilers/PP32.pdf

Phoenix Biochar . (n.d). *Who are Phoenix Biochar CIC*. Retrieved from Phoenix Biochar: https://phoenixbiocharcic.co.uk/about

Son, Y., Stott, K., Manning, D., & Cooper, J. (2020). Carbon sequestration in artificial silicate soils facilitated by arbuscular mycorrhizal fungi and glomalin-related soil protein. *European Journal of Soil Science*, 1-8. Retrieved from https://doi.org/10.1111/ejss.13058

The Tree Council. (2020). *Ash Dieback disease: A Guide for Tree Owners.* The Tree Council; Defra; Forestry Commission. Retrieved from https://treecouncil.org.uk/science-and-research/ash-dieback/public-guidance/

TRADA. (n.d). *Ash, European*. Retrieved from TRADA: https://www.trada.co.uk/wood-species/ash-european/

UK BRC. (2019). *Standard Biochars*. Retrieved June 22, 2021, from UK Biochar Research Centre: https://www.biochar.ac.uk/standard_materials.php

WSP. (2021). *Banwell Bypass: Statement of Intent & Preliminary Sources Study Report.* North Somerset Council.

Appendix C - EMW

1 Enhanced Mineral Weathering

1.1 Overview

Dolerite and basalt are medium and fine-grained igneous rocks respectively that are quarried to provide aggregates for construction. A by-product of the rock crushing is quarry fines. For the purpose of this work and throughout this report, the terms dolerite and basalt are treated equally, given that by definition they have similar chemical and mineralogical compositions, only differing in the grain size of the minerals that they contain. “Quarry fines” are henceforth used to denote the crushed fine fractions of either dolerite and/or basalt that remain after quarry operations.

When such fines are integrated into the CO_2 rich environment of soil the dissolution of silicate minerals in dolerite and basalt forms bicarbonate ions. With sufficient drainage these bicarbonate ions are transported through ground and surface waters, ultimately resulting in the storage of carbon in the form of stable bicarbonate ions in the oceans and groundwater. This is enhanced weathering, so called because the natural process of weathering is “enhanced” by the use of fine material fractions. The bicarbonate ions may also remain in the soil and precipitate to form carbonate minerals, and this process is called carbonation (Lefebvre, et al., 2019). Quarry fines therefore remove atmospheric CO_2 from the soil over time as they weather.

1.2 Materials and Processes

This section is organised in a linear narrative as below in Figure 1. CO_2e removal and carbon persistence is discussed in section 1.3.

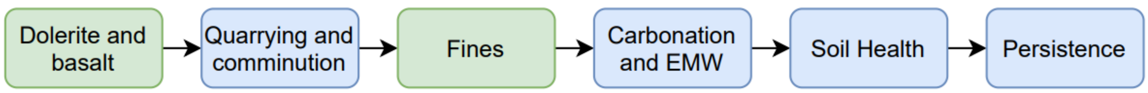


Figure 1: Flowchart to show materials (green) and processes (blue) for quarry fines

1.2.1 Dolerite and Basalt

Dolerite is a medium-grained igneous rock of basaltic[1] composition, usually found in shallow intrusions such as dykes or sills. Basalt is a fine-grained igneous rock that typically forms from volcanic activity but can similarly be found in small intrusive structures like dykes or sills. Both rocks are quarried widely in the Midland Valley of Scotland, Northumberland, and Durham, and in the Welsh Borders.

[1] ‘Basaltic’ is a term used by geologists to describe a primary magma composition

Figure 2: Dolerite from a Northumberland quarry (source David Manning, Newcastle University)

1.2.2 Processing into Fines: Quarrying and Crushing

Quarrying occurs in discrete steps; blasting and drilling; primary, secondary, and tertiary crushing; and milling if rock flour is desired (Renforth, 2012). Rock is won from the quarry-face by blasting and drilling. It is then fed through crushers that sequentially reduce the product size. Construction aggregates with specified size distributions are then screened, and this is where the bulk of quarry fines is generated, representing 20-35% of input rock weight (Renforth, 2012) (Mitchell, Mitchell, & Pascoe, 2008).

Blasting, drilling, and short-range haulage within the extraction site, along with crushing, are relatively low energy operations as shown below in Figure 3. In many quarries, the fixed plant (including crushing and screening) is powered by electricity.

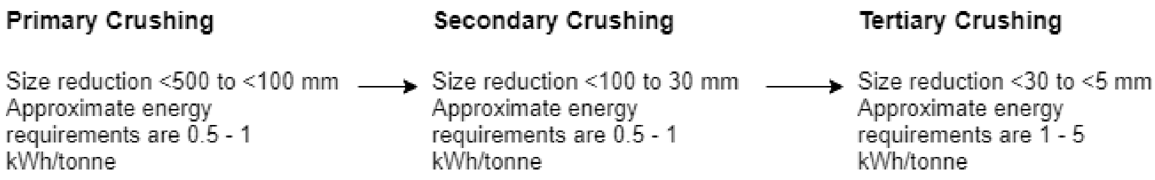


Figure 3: Quarry material flow path, adapted from (Renforth, 2012)

The fines generated from screening are the proposed materials within this project. Additional milling of these fines into rock flour significantly reduces the net carbon removal because the energy required for milling increases exponentially (as does the cost) as the product maximum particle size gets smaller (Lefebvre, et al., 2019). Energy requirements for reducing the size from the standard to between <5mm and <0.01mm range from 15 – 100kWh/tonne (Renforth, 2012).

1.2.3 Quarry Fines Characteristics

Historical Use

Rock fines have a well-established use as soil remineralisers. A systematic and pioneering review of “stone meal” for agricultural use was made at the turn of the 20th century, but its wider adoption was likely side-lined by the burgeoning popularity of manufactured fertilisers (Hensel, 1894). Similar work was later conducted in Germany in the 1930’s, which specifically utilised basalt fines from crushed rock aggregate quarries. The materials were described, and trials were made to examine the effect on tree growth, the reports of which clearly showed the benefits of applying basalt rock dust for forestry (Albert, 1938) (Hilf, 1938). The benefits of basalt for sugar cane production in Mauritius were also defined in papers published in the early 1960s (De Villiers, Soil rejuvenation with crushed basalt in Mauritius. Part I - Consistent results of worldwide interest, 1962) (De Villiers, 1962).

Current Uses

Soil improvement – dolerite and basalt fines are a commonly used soil remineraliser. Crushed volcanic rock for soil remineralisation is available to purchase in small quantities (1 kg packs to bulk lorry loads) in the UK from REMIN (Scotland) Ltd (REMIN, 2018). In October 2013, rock dust remineralisers became a category of agriculture input in Brazil by Law 12.890 (Brazil, 2013). Regulations were later established for defining, classifying, specifying and guaranteeing, tolerances, registering, packaging, labelling and marketing the remineralisers for agriculture (Manning & Theodoro, 2020). Dolerite also has 0% nitrogen content, and can be used for land reclamation and biodiversity establishment in poor-fertility conditions (as defined by N), evidenced by the healthy establishment of nitrogen-fixing plants in low nitrogen soils (Manning, Renforth, Lopez-Capel, Robertson, & Ghazireh, 2013) (Guillou & Davies, 2004). Dolerite fines have been used to establish a species-rich grassland upon a low-nutrient green roof, the Whin Sill Grassland Roof (SILL, 2021) at the Sill Visitor Centre in Hexham, Northumberland.

Climate change mitigation – enhanced terrestrial weathering and mineral carbonation were recently acknowledged by the 2018 Royal Society GGR report as feasible, large-scale greenhouse gas removal options (The Royal Society, 2018). Extensive field trials have validated the CO_2 capture potential of weathering and carbonation processes of silicate rich materials (Manning, Renforth, Lopez-Capel, Robertson, & Ghazireh, 2013) (Washbourne, Renforth, & Manning, 2012) (Renforth, Manning, & Lopez-Capel, 2009) (Kelland, et al., 2020). The residence time of dissolved inorganic carbon in the ocean as a result of enhanced weathering is approximately 100,000 years, and the carbon dating of carbonate minerals formed in soils as a result of mineral carbonation indicates residence times upwards of 30,000 years (Renforth & Henderson, 2017) (Renforth, Manning, & Lopez-Capel, 2009).

Asphalt binding – both Clee Hill and Leaton Quarry, local to Banwell, use their fines to produce asphalt coating on-site. This means that supply capacity may be irregular and in small quantities only, due to competition between uses. Scaling up and applying to other infrastructure projects therefore requires research into local availability. However, existing dolerite and basalt quarries have permits to produce in excess of 3 million tonnes of crusher fines annually, with a CO_2e removal potential of 230,000 (carbonation) – 800,000 (ERW) tonnes per year (Manning, 2021).

Physical Characteristics

The terms ‘quarry fines’ and ‘quarry dust’ are used in the mining sector to describe a wide range of materials, reflecting the wide range of rock types and crushing techniques that are available. BS EN 13242:2002 + A1:2007 describes “fines” as having an upper limiting sieve size of 4mm. Interviews conducted in 2004 showed that whilst most quarry operators define their finest aggregate as material less than 5mm in size, others go further and use 3mm, whilst some use 6mm as a limit (Manning, 2004). The crushed rock aggregate industry maintains that the broader material category of ‘fines’ is not waste but a product waiting for market, and fines are generally inert and non-hazardous (Manning, 2004) (Casas, Schaschke, Akunna, & Jorat, 2019).

The standard presentation of quarry fines is as a screened product, and in the PSD of Figure 4 below, a Type 1 subbase (widely used in construction) is given for comparison.

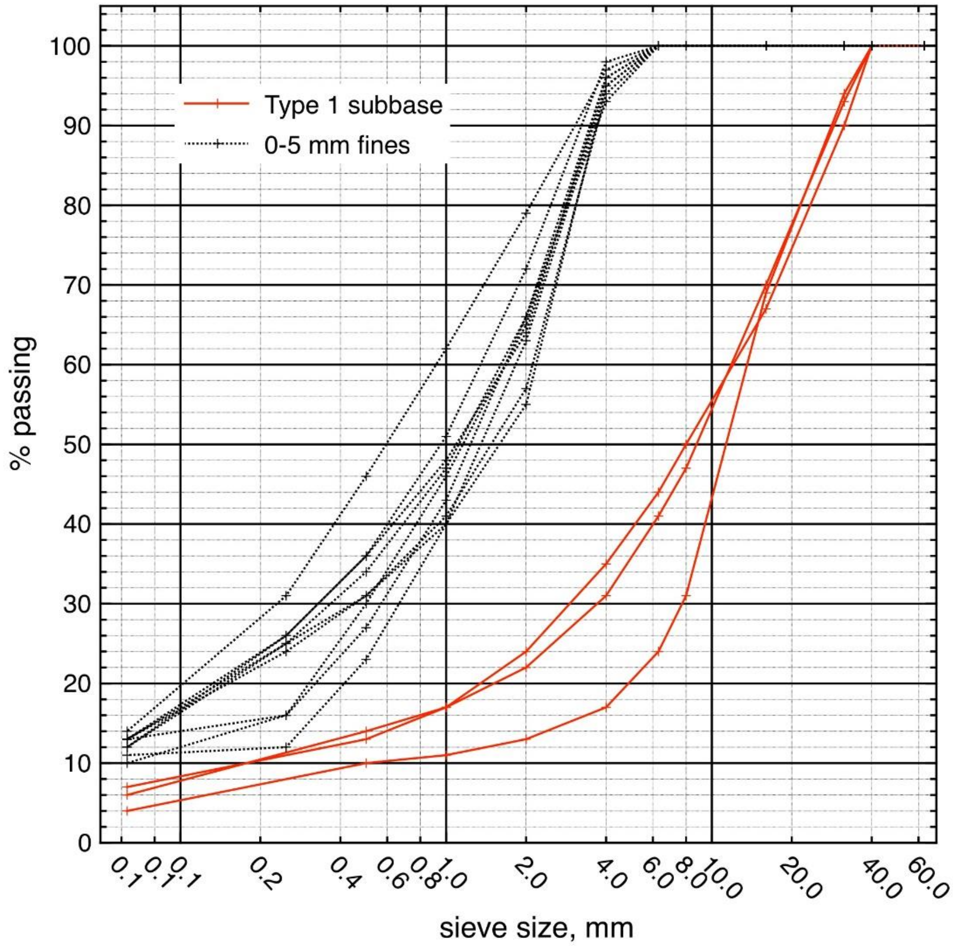


Figure 4: Representative particle size distribution of eight quarry fines (0-6mm) and Type 1 subbase for comparison, Northumberland (source David Manning, Newcastle University)

Figure 4 shows that quarry fines are typically a silty, gravelly sand. For existing run-of-mine products, typically 50% of the <5mm fraction passes a 1mm sieve; the proportion varies from one quarry to another, depending on the crushing plant's operational characteristics.

Density can vary from quarry to quarry due to the different formations that are quarried and the PSD of the generated quarry fines. Typical values are given below in Table 1.

Table 1: Table to show quarry fines density

Source	**Size (mm)**	**Particle density (t/m^3)**	**Bulk density (t/m^3)**	**Note**	**Reference**
Dolerite fines, Barrasford Quarry, UK	< 0.063	2.84	-	Gas-jar method (BSI, 1990a)	(Casas, Schaschke, Akunna, & Jorat, 2019)

Source	Size (mm)	Particle density (t/m^3)	Bulk density (t/m^3)	Note	Reference
Dolerite fines, Middleton Quarry, UK	6.3/14	2.94-2.98	1.5	BS EN 1097-6 BS EN 1097 -3	(See section 2 of Appendix C1)
Dolerite fines, Middleton Quarry, UK	< 4	3.03-3.04	1.42	BS EN 1097-6 BS EN 1097 -3	(See section 2 of Appendix C1)
Dolerite screenings, Lindisfarne, Tasmania	< 20	-	2.83 – 2.85	Saturated surface dry and oven dry	(Sloane, 1991)
Dolerite rock, Hobart, Tasmania	Solid	-	2.75 – 3.15	Not given	(Leaman, 1975)

A bulk density of 2.7t/m3 has been used in this project to generate required material quantities and plan placement scenarios.

Chemical Characteristics

Mineralogically and chemically the composition of the fines is the same as the bulk rock, although in some quarry operations minor amounts of rock adjacent to the quarried dolerite may be present if they enter the crushing chain. Chemically, dolerite and basalt vary little in composition from quarry to quarry. Representative analyses are given in Table 2.

Table 2: Table to show typical elemental compositions of UK dolerite and basalt

Wt %	**Source**			
	Dolerite, Barrasford Quarry, Whin Sill, England	**Dolerite, Barrasford Quarry, Whin Sill, England**	**Basalt, Craighouse Quarry, Scotland**	**Dolerite, Ardnamurchan, Scotland**
SiO_2	49.85	49.50	44.88	49.28
TiO_2	2.28	2.36	3.30	2.31
Al_2O_3	14.02	14.43	13.05	13.88
Fe_2O_3	12.56	12.33	14.97	14.42
Mn_3O_4	0.18	0.19	0.15	0.22
MgO	6.01	6.12	4.54	4.84
CaO	9.33	9.36	7.70	8.17
Na_2O	2.42	2.42	3.34	2.51
K_2O	0.93	0.95	1.42	1.33
P_2O_5	0.28	0.29	1.10	0.52
LOI	1.31	1.38	2.54	-
Total	99.34	99.40	99.61	97.48
Reference	(Casas, Schaschke, Akunna, & Jorat, 2019)	(Randall, 1989)	(Manning, Renforth, Lopez-Capel, Robertson, & Ghazireh, 2013)	(Gribble, 1974)

Mineralogically, dolerite is composed of pyroxene, plagioclase, and iron-titanium oxides as the dominant mineral constituents. Some parts of the Northumberland dolerite bodies contain quartz in minor amounts (<1%).

Basaltic rock typically has an unweathered pH of 7 to 8, and slightly weathered basaltic rock may have a pH between 8 to 10 (de Oliveira & Zuquette, 2014).

1.2.4 Carbonation and Enhanced Mineral Weathering

Carbonation and enhanced mineral weathering are natural pedogenic (soil forming) processes that remove carbon. Both processes involve silicate rocks in the soil breaking down and removing CO_2 via the formation of stable metal ions, carbonates, and bicarbonates. The carbonation process precipitates calcium derived from the rocks into carbonate minerals. Enhanced mineral weathering converts CO_2 into dissolved inorganic carbon that is removed via soil drainage into the water system, and eventually, the oceans and groundwater (Beerling, et al., 2020). These same processes occur upon the addition of quarry fines to soils but are accelerated by their fine particle size and thus high surface area.

The processes can be well understood as two possible pathways that diverge from a common beginning, as shown below in Figure 5.

Hydration

The hydration of CO_2, generated by respiration of roots and other soil organisms in the soil, creates a weak carbonic acid

$CO_2 + H_2O \rightleftharpoons H_2CO_3$

Rock breakdown

Using wollastonite CaSiO3 as an example, the weak carbonic acid breaks down the rock and releases bicarbonate ions and base cations

$CaSiO_3 + 2H_2CO_3 \rightarrow Ca^{2+} + 2HCO^-_3 + SiO_2 + H_2O$

Enhanced mineral weathering

With sufficient drainage, the dissolved bicarbonate ions are transferred to the oceans

$2HCO^-_3$ (to ocean)

Carbonation

Bicarbonate and calcium remain in the soil and precipitate to form carbonate minerals

$Ca^{2+} + 2HCO^-_3 \rightleftharpoons CaCO_3 + CO_2 + H_2O$

Figure 5: Flowchart to show carbonation and enhanced mineral weathering, adapted from (Lefebvre, et al., 2019).

Quantities of CO_2e removed and the rate of removal is covered in further detail in section 1.3.

1.2.5 Soil Health

The relationship between quarry fines and soil health has been reviewed using the same methodology as applied for biochar, outlined in Appendix B4.

Nutrients and Acidity

Application of crushed silicate rock such as basalt or dolerite has the potential to restore acidified nutrient-depleted agricultural soils (Kelland, et al., 2020). Rock fines are widely recognised as aiding productive soils because they weather faster than solid rock deposits and release plant-essential nutrients like Mg, Fe, and Mn and low concentrations of Cr and Ni (Beerling, et al., 2018) (Kelland, et al., 2020). The cation exchange capacity and nutrient availability of soil is also possibly increased with the addition of rock fines, due to the release of cations (Beerling, et al., 2018).

The dissolution of calcium-silicate minerals consumes hydrogen ions and generates alkaline leachate, so the application of basaltic rock dust is comparable to the effect of liming acidic soils (Kelland, et al., 2020). A one-off application of 3.5 t/ha calcium silicate powder to the 11.8 ha watershed of the Hubbard Brook Experimental Forest in New Hampshire, USA, confirmed a rapid (12-24 months) 50% increase in the delivery of weathered calcium and silica dissolved in the stream water, alleviation of ecosystem acidification, and the decreased release of soil aluminium (Beerling, et al., 2018). Ammonium acetate extractable Si and the exchangeable pool of Mg within a slightly acidic clay-loam soil were found to increase significantly in response to the addition of coarse-grained basaltic rock dust (Kelland, et al., 2020). This is a key benefit of addition to agricultural soils, as seven out of the top ten crops ranked according to global production data are classified as Si accumulators, so the addition of silicate rich rock fines ameliorates this resource depletion (Beerling, et al., 2018).

Adding quarry fines to soil therefore affects soil health in a different way than the bulk provision of N, P, and K through agricultural fertiliser, and this distinction is clarified further in section 2.1.1 of Appendix I.

Organic and Inorganic Carbon Content

Enhanced weathering may help to reverse diminishing soil organic carbon (SOC) due to the higher inputs of organic carbon from roots and mycorrhizal fungi (Beerling, et al., 2018). The increased formation of clay minerals from the weathering of silicates may also increase SOC retention through a range of organo-mineral interactions, including adsorption reactions and the physical protection of organic matter produced by decomposing organisms, which help to build soil while improving quality (Beerling, et al., 2018).

The formation of carbonate minerals within quarry fine amended soils also accumulates soil inorganic carbon (SIC). The rates and mechanics of this process are explored fully in section 1.3. The effect upon both SOC and SIC, and their dependence upon quarry fines application rates are proposed to be investigated through the reference site at Moreton-in-Marsh, detailed explicitly in Appendix I.

Structure and Water Capacity

Through increased mycorrhizal fungi and root activity, the application of silicate rich fines may improve soil structure by promoting soil aggregate formation and thus durability against erosion (Beerling, et al., 2018).

A key consideration is how carbonation and enhanced mineral weathering affect properties like porosity and permeability over time. Explicit reviews of the effects of dolerite upon soil in this respect are lacking, however tentative comparisons may be made with studies that discuss the stabilisation of soils via carbonation. If groundwater conditions are insufficient to transport the bicarbonate ions to the ocean, the ensuing calcium carbonate precipitation can fill in pores between the soil particles and provide adherence for the particles to stick together (Li, et al., 2021). When the calcium carbonate solidifies, a relatively high-strength crystal is formed, and this is the generally accepted process by which lime mortar generates mechanical strength (Deneele, Dony, Colin, Herrier, & Lesueur, 2021). Li, et al., 2021 find that for calcium carbonate precipitation induced by microorganisms, the resulting filling of pore space resulted in a decrease in soil porosity and an increase in soil compactness. Calcium carbonate colloid precipitation on the surface of soil particles also cemented particles together, improving soil strength and the ability to resist external deformation (Li, et al., 2021). The change in porosity accompanying carbonation is not well agreed in literature, but porosity can broadly be expected to drop as carbonation increases (Glasser, 2011). However, these effects are entirely dependent upon the application rate of dolerite, and to date there is little evidence to show weathering and carbonation will affect the soil structure bar an improvement in strength due to increased root growth (Jorat et al, in prep). Moreover, it is unknown how potential reductions in soil porosity may be ameliorated by the inclusion of biochar in the same soil. Further exploration of this question is expected from the testing proposed at Moreton-in-Marsh, through the extraction of samples for bulk density and dry density testing over time (see Appendix I).

Biological Activity

The ready supply of Si has benefits for crop resilience, as shown in Figure 6. The production of soluble silicic acid from silicate weathering is taken up by plants which improves stem strength and increases resistance to biotic and abiotic stresses like pests and diseases (Beerling, et al., 2018) (Kelland, et al., 2020).

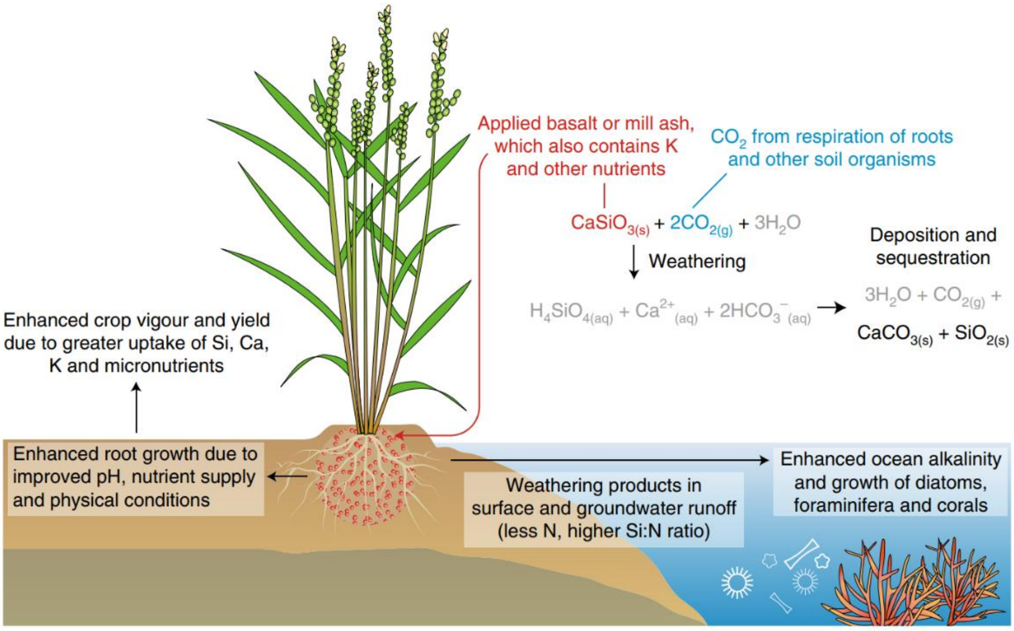


Figure 6: Diagram to show the potential effects of basalt weathering upon croplands, from (Beerling, et al., 2018)

Kelland, et al., (2020) left mesh bags of basalt particles in a slightly acidic clay-loam soil, and after 120 days extensive colonisation by fungal hyphae had taken place. They were found to closely resemble arbuscular mycorrhiza fungi, which supply plant roots with nutrients and contribute to bioweathering (Kelland, et al., 2020). This was also accompanied by a 21±9.4% increase of cereal yield under controlled environmental conditions (Kelland, et al., 2020). A number of studies point to the fact that annual crops also accelerate basalt weathering (Beerling, et al., 2018).

Dolerite fines have also been found suitable for the purposes of land reclamation and biodiversity establishment in poor-fertility conditions (Guillou & Davies, 2004). Grass pot trials were conducted using a 50:50 (by volume) blend of four rock dust types and five composts, using a seed mixture that was composed of: 20% Tivoli perennial ryegrass late tetraploid, 25% Merlin/Jupiter slender creeping red fescue, 10% Quatro's sheep fescue, 10% Trianna hard fed rescue, 20% Canon flattened meadow grass, 10% Highland browntop bent, 2.5% Kent wild white clover (N fixer), and 2.5% Birdsfoot trefoil (N fixer) (Guillou & Davies, 2004). Basalt fines were found to promote plant growth in low nitrogen compost (Kerbside Collection compost), evidenced by the establishment of nitrogen-fixing plants (Guillou & Davies, 2004). The addition of quarry fines therefore provided support to a diverse habitat in the absence of excess nutrients.

Chemical Pollution

The generation of alkaline leachate and subsequent reduction of soil acidity reduces metal toxicity like aluminium and manganese. In highly weathered acidic soils metal oxides bind strongly to potassium reserves, and the increased pH serves to reverse this process and liberate P (Beerling, et al., 2018). The increase in plant-available Si in soils reduces the uptake of heavy metals in the edible parts of crops, and it is a competitive inhibitor of arsenic in rice and cadmium in wheat, for example (Beerling, et al., 2018).

Enhanced mineral weathering can be expected to increase the dissolved silica flux to rivers and oceans, which may help to mitigate the effects of N and P runoff from agricultural regions by increasing the Si:N and Si:P ratios, favouring the growth of diatoms over non-siliceous algae that produce toxins (Beerling, et al., 2018). However, if unweathered silicates were to be washed into rivers during storm events (as happens currently with soil loss), increased inorganic turbidity and sedimentation may follow, reducing reproduction and recruitment in river fish populations.

As quarries are industrial sites, applying the quarry fines to topsoil risks creating a contaminant pathway between any pollution at the quarry site and the amended area. This is a minor risk however. Consultation with quarry fines has revealed that stockpiling upon well drained surfaces is a common practice, reducing the risk of any waterborne contaminants. Management of stockpiled fines needs to ensure that no contaminants (such as bag house fines from asphalt coating plants) are added to the stockpiles, and fines should be sourced from locations that do not use crushing plant to crush concrete from demolition. Chemical analysis of quarry fines samples should also be conducted before placement upon site, to include XRF for determining carbon removal potential of the material. XRF can also be used to identify any metals present.

1.3 CO_2e Removal from Quarry Fines

In this section, the assumptions and models that determine the total potential CO_2 removal and rates of CO_2 removal offered by quarry fines are summarised and explained.

1.3.1 Total Potential CO_2 Removal

The range of CO_2 removed from the atmosphere by carbonation and enhanced rock weathering is given by the Steinour formula, expressed in a simplified below (Renforth, 2019).

$$Cpot = \frac{M_{CO_2}}{100}.\left(\frac{CaO}{M_{CaO}} + \frac{MgO}{M_{MgO}} - \frac{SO_3}{M_{SO_3}} - \frac{P_2O_5}{M_{P_2O_5}}\right).10^3 \qquad \text{Eq. 1}$$

$$Epot = \frac{M_{CO_2}}{100}.\left(\frac{CaO}{M_{CaO}} + \frac{MgO}{M_{MgO}} + \frac{Na_2O}{M_{Na_2O}} + \frac{K_2O}{M_{K_2O}} - \frac{SO_3}{M_{SO_3}} - \frac{P_2O_5}{M_{P_2O_5}}\right).10^3.\eta \qquad \text{Eq. 2}$$

CaO, MgO, SO_3, P_2O_5, Na_2O and K_2O are the elemental concentrations of Ca, Mg, S, P, Na and K, expressed as oxides, M_x is the molecular mass of those oxides, and η is the molar ratio of CO_2 to divalent cation sequestered during enhanced weathering (η = 1.5 is a conservative global average) (Renforth, 2019). C pot and E pot are given in terms of kg CO_2 t^{-1} of material. The elemental concentrations are calculated from the oxide composition of the rock determined using X-ray fluorescence (XRF), a rapid and commercially available test.

For dolerite and basalt this approach gives a range typically between 70 (calcium carbonate formation) and 230 (EMW) kg CO_2 t^{-1} of material. This range has been used in the carbon LCA published by (Lefebvre, et al., Assessing the potential of soil carbonation and enhanced weathering through Life Cycle Assessment: A case study for Sao Paulo State, Brazil, 2019). The amount of crushed rock used in a project is measured currently through the reporting of sales from quarries to HMRC in connection with the Aggregates Levy. This provides robust verification of the amount of quarry fines used within the project, along with a maximum auditable CO_2 removal.

1.3.2 Modelled Rates of CO_2 Removal

CASPER (Carbonate Accumulation in Soils through the Prediction of Elemental Release) is a model that that predicts CO_2 removal through carbonate precipitation caused by weathering of crushed rock (Kolosz, Sohi, & Manning, 2019). It generates CO_2 within the soil using the well-established model RothC, then feeds that into a module which calculates calcite saturation indices based on a well-established model used to predict lime scale formation in water treatment plants (Kolosz, Sohi, & Manning, 2019). Respiration in soil by plants and microbes leads to high partial pressure of CO_2 in soil, so ready calcium supply in soil solution means carbon removal in the form of $CaCO_3$ can occur rapidly (Kolosz, Sohi, & Manning, 2019). In this way CASPER simulates the irreversible one-way accumulation of inorganic C from CO_2 into $CaCO_3$.

The generation of HCO_3^- that weathers the rock is driven by CO_2, simulated by the organic carbon and plant root respiration model. CO_2 flux from root activity therefore varies greatly depending upon the quarry fine placement, and this is a key factor for considering the suitability of different applications of quarry fines for CO_2 removal (Kolosz, Sohi, & Manning, 2019).

CASPER was used to model an artificial soil composed of dolerite fines and green compost over an area of 1 ha. The soil layer was 100cm thick, composed of a 50 cm layer of 0.2 mm diameter dolerite grains and a 50cm layer of green compost. This represents an application of approximately 13500 t ha^{-1}. According to the model the grains were completely consumed within 5 years, and the total carbon accumulated as calcium carbonate was 50.0 t C (Kolosz, Sohi, & Manning, 2019). Through carbonate formation alone, this gives the rate of CO_2 accumulation per tonne of rock as 0.0027 $tCO_2\ t^{-1}\ yr^{-1}$.

CASPER only addresses calcium carbonate formation. However, if rock dissolution is releasing calcium (as demonstrated by calcium carbonate formation) then we can also expect it to be releasing all the other minerals associated with the enhanced mineral weathering process. The formation of the calcium carbonate depends on the release of Ca from minerals that also contain Mg, Na and K, which all contribute to EMW. The rates for mineral dissolution used by CASPER relate to EMW, in which case the values given above need to be scaled up by a factor of 230/70 (the ratio of Epot/Cpot as given by Eq. 1 and Eq. 2).

The rate of CO_2 removal predicted by CASPER through EMW then becomes: 0.0089 $tCO_2\ t^{-1}\ yr^{-1}$.

1.3.3 Measured Rates of CO_2 Capture

In 2003 Mineral Solutions Ltd prepared trial plots at Barrasford Quarry (Tarmac, Northumberland) using funding from the Aggregates Levy Sustainability Fund, reporting the results for carbon capture in (Manning, Renforth, Lopez-Capel, Robertson, & Ghazireh, 2013). The plots were made by mixing equal volumes of quarry fines with composted green waste. In detail, four 10 m × 3 m plots on a freely draining bare rock quarry floor were spread with quarry fines to a depth of 0.25m, a 0.25m layer of compost was added, and the two materials were blended using a rotovator. Two of the plots were created using Craighouse fines and two were created using Barrasford fines, the PSD for which are given below in Table 3.

Table 3: Table to show particle size data for Craighouse Quarry and Barrasford Quarry fines (Manning, Renforth, Lopez-Capel, Robertson, & Ghazireh, 2013)

	Craighouse fines, basalt (wt%)	**Barrasford fines, dolerite (wt%)**
3.4 - 2.0 mm	10	0

	Craighouse fines, basalt (wt%)	Barrasford fines, dolerite (wt%)
2.0 - 0.063 mm	81	8
0.063 - 0.002 mm	7	82
< 0.002 mm	12	10

Over 7 years it was found that inorganic C accumulated as calcium carbonate at a rate of 4.8 t C ha^{-1} yr^{-1}, corresponding to an annual CO_2 removal per tonne of material of 0.0026 tCO_2 t^{-1} yr^{-1} (Manning, Renforth, Lopez-Capel, Robertson, & Ghazireh, 2013). As the figures reported concern only calcium carbonate, they can be extrapolated to give amounts of CO_2 removal via ERW, multiplying by a factor of 230/70 as before (the ratio of Epot/Cpot as given by Eq. 1 and Eq. 2).

The rate of CO_2 removal through EMW at the Barrasford plots therefore scales up to 0.0086 tCO_2 t^{-1} yr^{-1}. For any given tonne of crushed rock then, the time taken to remove its maximum CO_2 potential is approximately 26.74 years.

This is the assumed rate of CO_2 removal as used in this project. It is an under-estimate. Given that no attempt was made to seal or isolate the plots that were made upon coarse aggregate, further carbonation would have occurred and been unreported because sampling was only conducted to a depth of 0.3 m (Manning, Renforth, Lopez-Capel, Robertson, & Ghazireh, 2013). The presence of newly formed calcium carbonate was verified in this study using C and O isotope data, determined by a commercial laboratory, confirming that the material was formed by modern pedogenic processes.

Furthermore, there was no significant difference found between the carbonate accumulation rates for plots amended with the Craighouse fines or the Barrasford fines (Manning, Renforth, Lopez-Capel, Robertson, & Ghazireh, 2013). This suggests that quarry fines of higher PSD may be able to be used to the same effect. It was also found that the control plot, prepared solely with dolerite fines and no integrated compost, reported consistently low calcium carbonate contents. This plot also only succeeded in establishing 6 of the 21 grass species that were found across the other four plots (Manning, Renforth, Lopez-Capel, Robertson, & Ghazireh, 2013). The partial pressure of CO_2 below the ground generated by microbial and plant root respiration therefore appears to be a more decisive factor for influencing weathering rates than the PSD of the quarry fines.

Modelling undertaken by Kelland, et al., (2020) showed higher rates of CO_2e removal when both carbonation and enhanced mineral weathering were considered. A 1 D reactive transport soil profile geochemical model was calibrated to a 120 day incubation study to assess the long term carbon removal potential.

The incubation study was made using 12 columns (6 amended, 6 unamended) of mildly acidic soil with a clay-loam texture (31.8%, 35.4% and 32.8% by mass of clay [<2 µm], silt [2–60 µm] and sand [60–2,000 µm], respectively). The columns were 152mm internal diameter by 500mm length PVC pipes, with bottom sections for leachate collection. The basalt fines had a p80 value of 1.25 mm and were amended at approximately 100 t/ha.

The model was run for 5 years, and a cumulative total of 4.2 tCO_2e/ha was simulated through bicarbonate transport and calcite precipitation (Kelland, et al., 2020). Using the application rate of 100 t/ha, this corresponds to an annual CO_2e removal per tonne of material of 0.0084 $tCO_2e\ t^{-1}\ yr^{-1}$ for both EMW and carbonation (Kelland, et al., 2020).

It was found that a fraction of basalt 10-fold finer (p80 = 0.125 mm) resulted in a faster initial carbon removal rate, but ultimately gave a similar cumulative carbon removal over the course of 5 years, as shown below in Figure 7.

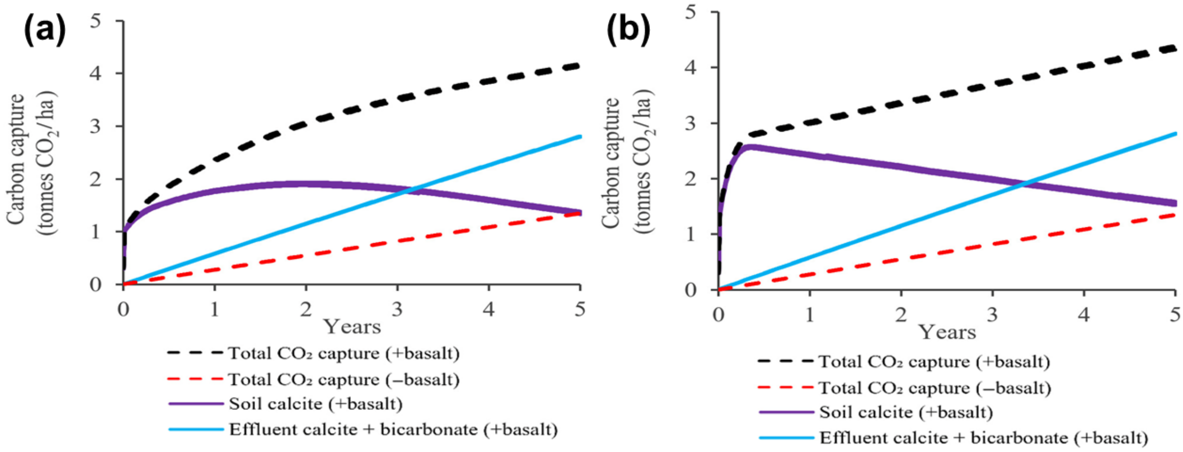


Figure 7: Reactive transport modelling of basalt mineral dissolution and carbon capture. Simulated changes in (a) cumulative CO_2 sequestration with coarse - grained basalt (p80 = 1.25 mm, i.e. 80% of particles ≤ this diameter) and (b) cumulative CO_2 sequestration with a 10 - fold finer - grained basalt (p80 = 0.125 mm). Adapted from (Kelland, et al., 2020)

Similar to the findings set out by Manning, Renforth, Lopez-Capel, Robertson, & Ghazireh, (2013), utilising a finer rock dust had little effect on the cumulative carbon removal capacity, even over a time period as short as 5 years. The value of 0.0084 $tCO_2e\ t^{-1}\ yr^{-1}$ for both EMW and carbonation is also in close agreement with the 0.0086 $tCO_2\ t^{-1}\ yr^{-1}$ determined from the data of Manning, Renforth, Lopez-Capel, Robertson, & Ghazireh, (2013), a relative difference of 2.35% (Kelland, et al., 2020).

1.3.4 Carbon Persistence

For enhanced weathering, the residence time of dissolved inorganic carbon in the whole ocean is approximately 100,000 years (Renforth & Henderson, 2017).

The carbonation route is similarly stable, as carbonate minerals like calcite (calcium carbonate), aragonite, dolomite and dolomitic limestone constitute the Earth's largest CO_2 reservoir (Liu, Bond, Abel, McPherson, & Stringer, 2005). These materials are thermodynamically stable, environmentally benign, and only weakly soluble in water (Liu, Bond, Abel, McPherson, & Stringer, 2005). The carbon dating of soil formed carbonates indicates residence times upwards of

30,000 years, and field studies of carbonates in ancient soils give 2.6 billion years as an upper limit (Renforth, Manning, & Lopez-Capel, 2009).

1.4 Quarry Fines Carbon Life Cycle Assessment

In this section, a review is first made of published life cycle assessments (LCA) for the deployment of quarry fines, and compared against the summary of a new LCA that has been generated specifically for this project (see Appendix C2).

1.4.1 Literature Review

Table 4: Table to summarise reviewed LCA for the deployment of quarry fines

Source	**Country**	**Rock**	**Net tCO_2e sequestered per tonne of rock fine**	
			Carbonation	Enhanced Mineral Weathering
(Lefebvre, et al., Assessing the potential of soil carbonation and enhanced weathering through Life Cycle Assessment: A case study for Sao Paulo State, Brazil, 2019)	Brazil	Basalt	0.108*	0.208*
(Moosdorf, Renforth, & Hartmann, 2014)	Global	Ultramafic	0.5 - 1	
(Renforth, The potential of enhanced weathering in the UK, 2012)	UK	Basic	0.294**	

* From carbonation and EMW removal potentials of 0.125 $tCO_2e\ kg^{-1}$ and 0.225 $tCO_2e\ kg^{-1}$ respectively, rescaling and subtracting the 135kg and 75kg CO_2e per tonne of CO_2e sequestered.
** Expected 0.300 $tCO_2e\ kg^{-1}$ considering 100 km of HGV travel at 0.062 $tCO_2e\ t^{-1}\ km^{-1}$.

Lefebvre, et al., (2019) conduct a life cycle assessment from extraction to the spreading of basalt fines (<5mm) onto agricultural fields in Sao Paulo State, Brazil. Transportation is underlined as the principal source of CO_2 emission within the process. The benefit from fertiliser replacement and crop response is not considered, and the application procedure is taken to be an agricultural lime spreader.

Moosdorf, Renforth, & Hartmann, (2014) budget the potential sequestration of enhanced mineral weathering over a global scale. This study uses ultramafic rocks such as olivine however, which have much higher sequestration potential due to higher CaO and MgO contents. The fines are also considered to be ground to less than 100 μm, the approximate particle diameter required to achieve complete weathering within one year.

Renforth, (2012) created an energy/carbon balance for enhanced weathering and carbonation within the UK, considering both basic and ultrabasic rock. The principal emission source is found to be comminution and material transport, and the land application is taken as agricultural spreading.

1.4.2 Methodology

The use of crushed rock for Greenhouse Gas Removal (GGR) generates a set of carbon impacts; relating to the energy needed to create the rock dust, transport it to a destination and then apply to soil. Understanding these impacts in relation to the GGR potential of the technology is critical in developing an appreciation for the net carbon benefits over the lifetime of the scheme.

Our appraisal draws together a preliminary carbon Life Cycle Analysis (LCA) to estimate the carbon cost (a) at the quarry gate and (b) per kilometre of transport. This information allows sources at different locations to be compared, and the potential carbon capture value of rocks of different compositions to be compared.

Overall, a simplified flow diagram for the system is summarised in Figure 8.

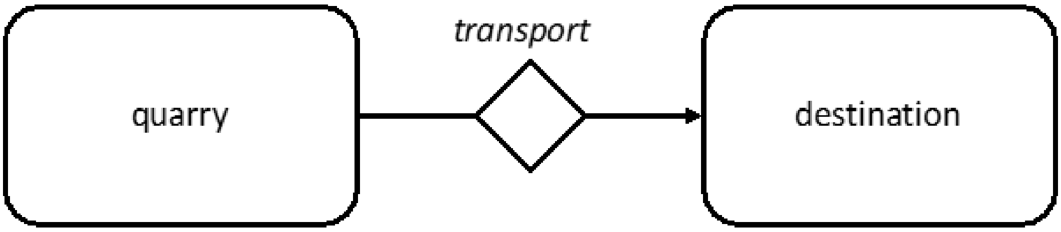


Figure 8: Flowchart to show simplified flow of rock dust from source (quarry) to eventual destination

In Figure 8, the source of the rock dust can be regarded as similar irrespective of the origin, as quarrying plant and equipment, globally, is broadly similar from one operation to another, and from one hard rock to another. A carbon cost at the quarry gate reflects all the carbon costs associated with mining, crushing, screening, handling, and loading into a vehicle for transport off site. The transport is included here to compare the suitability of different quarries.

For this life cycle assessment, the Life cycle inventory (LCI) is given in Table 5: LCI used in this study (per 1 tonne quarry fines) Table 5, and the system defined in Figure 1.

Table 5: LCI used in this study (per 1 tonne quarry fines) (Rosado, Vitale, Penteado, & Arena, 2017) (Lefebvre, et al., 2019)

LCI	Unit	Value	Comment
Basalt	tonne	1.05	Basalt production -Drilling
Water	litre	0.07	Basalt production -Drilling
Loader operation	h	0.006	Basalt production -Drilling
Explosive	g	145	Basalt production -Blasting
Loader operation*	h	0.006	Basalt production -Loading
Freight transport, lorry 16-32 metric ton, EURO6	t.km	1	Transportation from quarry to crushing unit
Lubricating oil	kg	0.004	Crushing
Electrcity	kWh	5.45	Crushing

LCI	Unit	Value	Comment
Loader operation*	h	0.006	Basalt crushing -Loading crushed basalt
Freight transport, lorry 16-32 metric ton, EURO6	t.km	Different values see results section	Transportation from crushing unit to the fields (sites)
Loader operation*	h	0.006	Basalt application
Diesel	kg	1.73	Basalt application

*Loader operation includes diesel and lubricating oil consumption, i.e., 1 hour loader operation consumes 18.9 l diesel and 0.3 kg lubricating oil.

In this study global warming contribution or so called ‘global warming potential (GWP)’ was considered as the main impact category to assess the carbon emissions of aggregate application. To this end, IPCC 2013 including was selected considering a 100 year time horizon (ifu Hamburg, 1998-2019). The following results aimed at showing the carbon cost of different activities within the life cycle of basalt/dolerite application as a carbon removal technology in the UK.

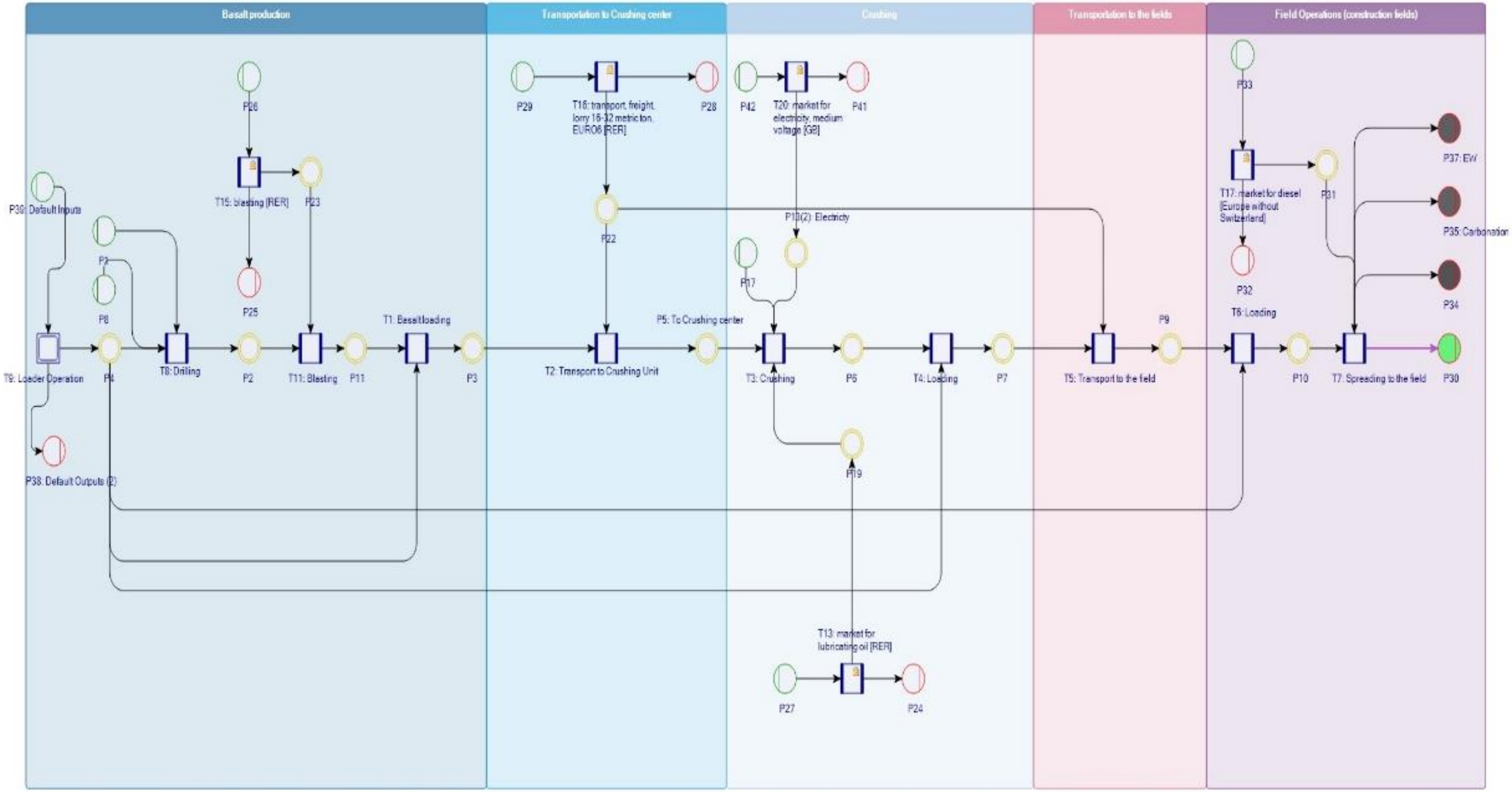


Figure 9: Scope of the quarry fines LCA and the modelled life cycle in Umberto LCA+ software

The global warming contribution of each tonne of rock mining (from cradle to the end of the crushing stage) is as low as 3.78 kgCO_2e. Accordingly, the contribution analysis show that 'crushing and loading stage' contributed to 48.6% of the GWP, followed by 'basalt production (including Drilling, blasting and loading)' by 47.1%.

Table 6: Results for cradle to gate contribution analysis of 1 tonne rock mining

Stage	**Emission value**	**Unit**	**Contribution (%)**
Basalt production	1.78	kg CO_2e	47.1
Transportation to Crushing centre	0.16	kg CO_2e	4.3
Crushing	1.84	kg CO_2e	48.6

The LCI used for the mining operation in this study were compared to (Pradhan, Tiwari, Kumar, & Barai, 2019) and the results were similar.

Transportation in LCA is usually considered as t.km (metric ton transferred per km). Here, the per kilometre carbon cost of 1 tonne crushed basalt/dolerite delivered from the gate of mining facility to the fields is analysed (Table 7).

Table 7: Results for gate-to-gate analysis of 1 tonne crushed quarry fines transportation per kilometre

Stage	**Emission value**	**Unit**	**Contribution (%)**
Basalt/dolerite Transportation (transport, freight, lorry 16-32 metric ton, EURO6)	0.16	kg CO_2e	100

It should be noted that the return of the vehicles to the crushing centres was not considered (but obviously its carbon cost is less than the departure). Transportation in this study is considered as a background LCI. The values are average compared to typical market consumption. Overall results are presented below in Table 8.

Table 8: Table to show summary of carbon Life Cycle Analyses for creation and transport of quarry fines for carbon removal

Source	**Quarry gate kg CO_2/tonne**	**Per km transport kg CO_2/tonne**
This study	3.78	0.16
Lefebvre et al (2019)	5.4	1.71
Onnela & Danielsen (2019)	2.2	0.124
WRAP (2009) overall	1.48-2.52	n/a
WRAP Type A (includes fines)	0.51-1.35	n/a
WRAP Type B (screened aggregates)	2.43-4.14	n/a
Kittipongvises et al (2016)	2.92	n/a
Renforth (2012)	n/a	0.062

Source	Quarry gate kg CO_2/tonne	Per km transport kg CO_2/tonne
Moosdorf et al (2014)	77-227	0.059-0.109

1.5 Material Sourcing

1.5.1 Aggregate Industry

Unlike biochar, quarry fines are sourced from a well-established extractive industry, and aggregate minerals are recognised as a national strategic resource (GOV UK, 2012).

Mineral Planning Authorities have set up Aggregate Working Parties, which are regional coordination groups in England and Wales that inform the authorities about the strategic availability of aggregates. Mineral Planning Authorities are expected to report on their landbank in annual monitoring reports. The landbank is the sum in tonnes of all permitted reserves for which valid planning permissions are extant. This includes current non-working sites but excludes dormant sites and “inactive sites” (GOV UK, 2012).

The Aggregates Levy is a tax on sand, gravel, and rock that has been dug from the ground, dredged from the sea in UK waters, or imported, and sales are required to be reported from businesses every quarter (GOV UK, n.d). It is a £2 per tonne tax applicable to sand, gravel, and rock, though relief is available for use in any processes that reduce pollutant emissions (GOV UK, 2020). This provides a means for monitoring the sales of material from quarries which can be used as an indication of market health and expected yearly supply of quarry fines.

1.5.2 Quarries

Next to chemical composition, the greatest sensitivity affecting the net carbon removal potential of quarry fines is the transport distance from quarry to application to site. For a given quarry then, the net carbon removal of a tonne of their quarry fines can be calculated using the figures from the LCA, the distance of quarry to site, and the supplied chemical composition of the fines.

Nine quarries were contacted to find a suitable material supplier, and information from the six that responded is summarised below in Table 9.

Table 9: Table to summarise information obtained from responsive quarries (for contact details please see Appendix D3)

Site Name	Postcode	Distance as crow flies (km)		Price £/tonne		Notes
		Banwell	MiM	Material	Haulage	
Builth Quarry	LD2 3UB	102	119	13	3-7	Basalt (0-4mm) Composition given

Site Name	**Postcode**	**Distance as crow flies (km)**		**Price £/tonne**		**Notes**
		Banwell	**MiM**	**Material**	**Haulage**	
Moons Hill Quarry	BA3 5JU	30	100	15	-	Basalt (0-4mm) Composition given Expected to rise by £2.50/t by 2022
West of England Quarry	TR12 6QW	210	319	12	-	Diorite Composition pending (0-4mm)
Barrasford Quarry	NE48 4AP	418	342	25.44		Basalt (0-4mm) Composition available (Manning, Renforth, Lopez-Capel, Robertson, & Ghazireh, 2013) Haulage expected to be expensive given distance
Clee Hill Quarry	SY8 3QA	119	75	n.a		Dolerite (0-4mm) All fines incorporated into asphalt production on site, supply irregular and in small quantities
Leaton Quarry	TF6 5HB	154	99	n.a		All fines incorporated into asphalt production on site

From the quarries given in Table 9, chemical composition data required for estimating the carbon removal potential (see Eq. 1 and Eq. 2) was available for Builth Quarry, Moons Hill Quarry, and Barrasford Quarry. These three options are compared below in Table 10.

Table 10: A table to show the estimate of carbon removal potential at three sites.

Site Name	**Content by weight (%)**						**tCO_2eq per tonne rock**	
	CaO	**MgO**	**Na_2O**	**K_2O**	**SO_3**	**P_2O_5**	**Carbonation**	**ERW**
Barrasford	9.36	6.12	2.42	0.95	0	0.29	0.140	0.242

Site Name	Content by weight (%)						tCO_2eq per tonne rock	
	CaO	MgO	Na_2O	K_2O	SO_3	P_2O_5	Carbonation	ERW
Builth	5.46	6.43	5.17	0.62	0.03	0.3	0.113	0.228
Moons Hill	3.4	2.79	4.85	2.07	0	0.26	0.057	0.151

The figures given above show the varying suitability of quarries for carbon removal. Barrasford Quarry has the largest potential CO_2e removal, but when raw material cost and the CO_2e generated by haulage is considered it has the lowest net removal and the highest £/tCO_2e rate as shown below in Table 11.

Table 11: Table to show net removal potential and £/tCO_2e considering fines production and transport emissions

Site Name	Net Removal (tCO2e/t rock)				Net £/tCO2e before haulage	
	Quarry Gate		After Transport			
	Carbonation	EMW	Carbonation	EMW	Carbonation	EMW
Builth Wells Quarry	0.109	0.224	0.092	0.205	140.64	57.93
Moons Hill Quarry	0.053	0.147	0.048	0.131	312.38	101.85
Barrasford Quarry	0.136	0.239	0.069	0.184	367.08	106.62

When the upper estimate for material haulage (£7/t to site) is incorporated into the Builth Wells figure, the net cost is £217.39/tCO_2e removed through carbonation and £97.56/tCO_2e removed through enhanced mineral weathering. Builth Wells Quarry remains the cheapest and most efficient source of fines and is therefore recommended as the material source for this project.

C1 Quarry Information

1. Breedon Quarry Natural Aggregate MSDS

2. Middleton Aggregate Properties

AGGREGATE PROPERTY SUMMARY AND DECLARED VALUES

Summary Ref: MIDDLETON QUARRY
Source Address: Forcegarth Quarry, Middleton-in-Teesdale, Barnard Castle DL12 0EP
Date of Issue: 16 December 2020
Rock Type Crushed Rock

Size	6.3/14		10/20		4/10		0/4		
Test	**Result**	Report No.	**Result**	Report No.	**Result**	Report No.	**Result**	Report No.	Test Method
LA	**9**	24811							BS EN 1097-2
Micro Deval	**6**	24811							BS EN 1097-1
Total Sulfur*									BS EN 1744-1
Particle Density APP	**2.98**	24811					**3.04**	24815	BS EN 1097-6
Particle Density OD	**2.94**	24811					**3.03**	24815	BS EN 1097-6
Particle Density SSD	**2.95**	24811					**3.03**	24815	BS EN 1097-6
Water Absorption	**0.5%**	24811					**0.1**	24815	BS EN 1097-6
Acid Soluble Sulfate*	**<0.1**	TR 677960							BS EN 1744-1
Water Soluble Chloride*	**<0.001**	TR 603331							BS EN 1744-1
Magnesium Sulphate	**1**	24925							BS EN 1367-2
Bulk Density	**1.50**	24811					**1.42**	24815	BS EN 1097-3
Petrographic*	**Low**	39909							BS 812-104
Drying Shrinkage*	**0.043**	STR 529272							BS EN 1367-4
Poilshed Stone Value	**55**	TR 703867							BS EN 1097-8
Shell Content*									BS EN 933-7
pH Value*									BS 1377-3
Aggregate Impact Value - Dry									BS 812 Pt 112
Aggregate Abrasion Value**	**3**	24811							BS EN 1097-8
Ten Percent Fines - Oven Dry									BS 812 Pt 111

**Indicates Non UKAS Accredited Test

Authorised Signatories:
Sheet Prepared By:
G. Gibson - Area Technical Manager

SAFETY DATA SHEET

Product: NATURAL AGGREGATE

Issue Date: June 2021 Issue no: 2.0

1. Identification of Substance / Preparation and Company / Undertaking:

Substance name: NATURAL AGGREGATE
Appearance is variable, but usually in the form of fine and/or coarse aggregate, dust, powder or block stone. Coarse aggregate may be rounded or angular.

Company Details:
Breedon Trading Limited (Breedon GB Materials)
Breedon Quarry,
Breedon on the Hill,
Derby,
DE73 8AP

Telephone: 01332 694 010

Email: enquiries.breedon@breedongroup.com

Web: www.breedongroup.com

2. Hazard Identification

NOT classified as hazardous in accordance with the Chemicals (Hazard Information and Packaging for Supply) Regulations.

Respirable dust may be released during processing, handling and use of natural aggregates, particularly through crushing, drilling, cutting, loading and unloading of bulk aggregates, or if the aggregate is supplied as a fine powder. If inhaled in excessive quantities over a prolonged period or extended period, respirable dust can constitute a long-term health hazard.
Dusts containing Respirable Crystalline Silica (quartz) present a greater hazard.
Long-term exposure to respirable dust can lead to respiratory system damage and disease. Respirable crystalline silica has been associated with the lung disease silicosis.
Some sand aggregates are unsuitable for sand blasting operations as they may break down, producing respirable dust containing quartz.
The quartz content of the product will vary and is related to the type of mineral deposit from which the aggregate is produced. Advice on the quartz content and other chemical information is available from the supplying unit.

3. Composition / Information on Ingredients

Produced from naturally occurring rock or sand and gravel mineral deposits.
The mineral composition and characteristics of the aggregate will depend on the type of mineral deposit from which the aggregate is produced. Further information on the composition, including free silica (quartz) content is available from the supplying unit. In general, quartzite, sandstone, sand & gravel will have the highest levels of quartz.

4. First Aid Measures

Inhalation:
Immediately remove to fresh air. If breathing difficulties are experienced, seek medical attention.

Skin contact:
Wash with water. Prolonged contact may cause irritation. If symptoms develop or persist, seek medical attention.

Eye Contact:
Do not rub eyes, as the material is abrasive and may scratch the surface of the eye. Immediately and thoroughly irrigate with eye wash solution or clean water. If symptoms develop or persist, seek medical attention.

Ingestion:
Remove to fresh air. If person is conscious, rinse out mouth and give water to drink. Seek medical advice if symptoms develop.

5. Fire Fighting Measures

Natural aggregates are non-flammable and are not combustible.

Suitable Extinguishing Media:
Not applicable.

Unsuitable Extinguishing Media:
Not applicable.

Special Exposure Hazards in Fire:
None.

Special Protective Equipment for Fire Fighters:
None.

6. Accidental Release Measures

Personal Precautions:
Avoid breathing in dust. Keep dust out of eyes. See Section 8 for guidance on personal protective equipment. See Section 7 for guidance on handling the product.

Environmental Precautions:
Natural aggregates are inert, but dust and fine particles should be prevented from entering watercourses and drains. Deposition of dust on vegetation and surrounding property should be avoided controlling the release of dust at source.

Methods for Cleaning:
Avoid dry sweeping which creates dust. Use vacuum cleaning where practicable, or suppress dust using water sprays before cleaning up.

7. Handling and Storage

Handling
The product should be handled to minimise the creation of airborne dust. Conveyor systems should be fitted with covers to minimise wind whipping. Very fine, dry material should be conveyed in an enclosed system. Water sprays and/or local exhaust ventilation and filtration should be used as required to minimise generation of dust.

Manual handling of the product should be avoided where possible. If manual handling is necessary, full account should be taken of the Manual Handling Regulations.

Storage
The product should be stored to minimise the creation of airborne dust. Very fine, dry product in bulk should be stored in enclosed silos.
Bulk aggregate containing fine material (<3mm) should not be stored in the open unless it is conditioned with water. Stockpiles should be sited to avoid wind-whipping where possible. Storage bays should be fitted with 3 sides and the aggregate stored below the level of the sides to avoid wind whipping.

8. Exposure Controls / Personal Protection

Exposure Control Limits / Source

Total Dust -	W.E.L.	10mg/m^3	8 Hrs	T.W.A.
Respirable Dust -	W.E.L.	4mg/m^3	8 Hrs	T.W.A.
Respirable Quartz - Crystalline Silica SiO_2	W.E.L.	0.1mg/m^3	8 Hrs	T.W.A.

W.E.L. = Workplace Exposure Limit
T.W.A. = Time Weighted Average

Control Measures:
Dust should be controlled by containment, suppression and extraction/ filtration where possible.
Regular monitoring should be undertaken to identify where people may be exposed to respirable dust so that further measures can be implemented to reduce exposure.

Respiratory Protection:
Suitable respiratory protection should be used to protect against inhalation of dust, and to ensure exposure is below the Workplace Exposure Levels given at the start of this section.

Hand Protection:
Gloves should be worn.

Eye Protection:
Goggles should be worn to prevent dust entering the eyes if required.

Skin Protection:
Overalls to protect skin and clothes. The use of skin barrier cream is also recommended.

9. Physical and Chemical Properties

Appearance:	Granular solid.
Odour:	None
pH:	Various
Boiling Point / Range:	Not determined
Melting Point / Range:	Not determined
Flash Point:	Not applicable
Auto Flammability:	Not applicable
Flammability:	Not applicable
Explosive Properties:	Not applicable
Oxidising Properties:	Not determined
Vapour Pressure:	Not applicable
Relative Density:	Above 2.0
Water Solubility:	Dependant on rock type
Fat Solubility:	Not determined

10. Stability and Reactivity

Conditions to Avoid
None.

Materials to Avoid
Acids (for aggregates containing $CaCO_3$ & $MgCO_3$)

Hazardous Decomposition Products
Limestone aggregates may react with acid groundwater to release carbon dioxide gas, which may build up in confined spaces to hazardous concentrations.

11. Toxicological Information

Inhalation:
If inhaled over a prolonged or extended period, respirable dust from natural aggregate can lead to respiratory system damage and disease. Respirable crystalline silica has been associated with the lung disease silicosis.

Skin Contact:
Prolonged contact with skin may cause irritation and dryness, which may lead to dermatitis.

Eye Contact:
Particles of grit or dust from natural aggregates may irritate and scratch eyes.

Ingestion:
Unlikely to cause any problems.

12. Ecological Information

Environmental Assessment:
When used and disposed of as intended, no adverse environmental effects are foreseen. Aggregates are naturally occurring, inert minerals and do not pose a significant ecological hazard.

Mobility:
Aggregates are non-volatile, inert materials that will sink in water and form a layer on the surface of the ground. Dust may become airborne, leading to deposition on vegetation.

Persistence and Degradability:
Aggregates are resistant to degradation and will persist in the environment.

Ecotoxicity:
Not expected to be toxic to aquatic organisms.

13. Disposal Consideration

Safe Handling of Residues / Waste Product:
Natural aggregates are classed as 'inert' but should be disposed of in accordance with local and national legal requirements. Natural aggregates can be readily reused or recycled.

14. Transport Information

Special Carriage Requirements:
None – not classified as dangerous for transport.
Open vehicles should be sheeted or loads conditioned with water to avoid dust nuisance.

15. Regulatory Information

Classification: **Not classified as dangerous.**

However, consideration of the following risk & safety phrases is recommended:

Risk Phrases:
R36/37 - Irritating to eyes and respiratory system.

Safety Phrases:
S36/ 37/ 39 - Wear suitable protective clothing, gloves and eye / face protection.

16. Other Information

Training Advice:
Wear and use of PPE.

Recommended Uses and Applications:
Industrial and construction applications.

Further Information:
Contact: enquiries.breedon@breedongroup.com

Key Data Used to Compile Data Sheet:
HSE Guidance Note EH40
PPE Regulations 1992
COSHH Regulations 2002
Environmental Protection Act 1990
HSE Crystalline Silica EH59

Further copies of this Safety Data Sheet may be obtained on request.

Prepared in accordance with Annex II of the REACH Regulation (EC) 1907/2006

Legal Notice

The information in this Safety Data Sheet was believed to be correct at the time of issue. However, no warranty is made or implied as to the accuracy or completeness of this information.

If you have purchased this product for supply to a third party for use at work, it is your duty to take all necessary steps to ensure that any person handling or using the product is provided with the information in this sheet.

If you are an employer, it is your duty to tell your employees and others who may be affected of any hazards described in this sheet and any of the precautions which should be taken.

This Safety Data Sheet does not constitute the user's own assessment of workplace risk, and it is the user's sole responsibility to take all necessary precautions when using this product.

C2 Crushed Rock LCA

C2 Carbon Life Cycle Analysis of crushed rock production

C2.1 Summary

A simplified analysis, because at this stage there are no details of a specific application or design, of the carbon cost of using crushed rock for CO_2 removal gives an estimate for a typical quarry gate carbon cost of 3.78 kg CO_2/tonne of rock, and a per kilometre transport cost (8 wheel rigid vehicle) of 0.16 kg CO_2/tonne.

These figures lie within the range from other studies of 0.51 - 5.4 kg CO_2/tonne for the quarry gate cost of crushed rock aggregates typically coproduced with a <5mm fraction. The equivalent carbon cost for material milled to 50% <0.05mm is 77-227 kg CO_2/tonne, reflecting the high energy consumption associated with milling.

Transport costs per tonne from published sources vary from 0.059-1.71 kg CO_2/km.

The wide range of values demonstrates the importance of clearly defining the system to be modelled by carbon Life Cycle Analysis. Despite the uncertainties that arise from the assumptions that have been raised, it is clear that the carbon cost of using existing crushed rock aggregate production to generate fines is low compared with the CO_2 removal benefits (70-230 kgCO_2/tonne of rock). The added carbon (and financial) cost of milling is significant.

C2.2 Scope

The use of crushed rock for Greenhouse Gas Removal incurs a carbon cost, given the energy needed to create a rock dust, transport it to a destination, and then apply the material to a soil.

A key question concerns the carbon cost of producing the rock dust. If this is high compared with the GGR benefits, then there is no point in using rock dust. To be able to provide an initial assessment, a simplified carbon Life Cycle Analysis is needed.

Overall, a simplified flow diagram for the system is summarised in Figure 1. In the absence of specific details relating to the location and design of a destination, this simple basis is justified at this stage.

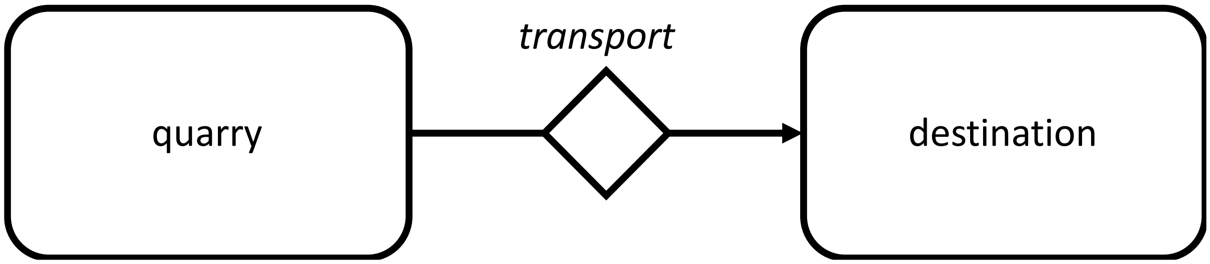


Figure 1. Simplified flow of rock dust from source (quarry) to eventual destination

In Figure 1 the source of the rock dust can be regarded as similar irrespective of the origin, as quarrying plant, and equipment, globally, is broadly similar from one operation to another, and from one hard rock to another. A carbon cost at the quarry gate reflects all the carbon costs associated with mining, crushing, screening, handling, and loading into a vehicle for transport off site.

The transport distance is unknown, and so highly variable. However, the per kilometre carbon cost of transport can be estimated. On arrival at site, depending on the scheme design the options for deployment of the rock dust vary greatly – from a top dressing at a nominal 20 tonnes/hectare (as in an agricultural application) to creation of a topsoil in which 2-3000 tonnes/hectare might be used.

The purpose of this note is to draw together a preliminary carbon Life Cycle Analysis to estimate the carbon cost (a) at the quarry gate and (b) per kilometer of transport. This information allows sources at different locations to be compared, and the potential carbon capture value of rocks of different compositions to be compared.

What is presented here is subject to the caveat that the system is poorly defined and so should be regarded as an incomplete carbon Life Cycle Analysis.

C2.3 Methodology

To provide an independent estimate, a preliminary Life Cycle Analysis has been carried out (Appendix A). This used data from Ecoinvent 3.7 (Ecoinvent, 2020), modelling the system using Umberto LCA+ (IFU Hamburg, 2019).

Published outputs addressing carbon life cycle analysis have been identified and are reviewed to collect existing estimates of carbon cost at the quarry gate and for transport.

C2.4 Results

The results of the analysis carried out here are summarised in Table 1.

Table 1. *Summary of carbon Life Cycle Analyses for creation and transport of quarry fines for carbon capture.*

Source	Quarry gate kg CO_2/tonne	Per km transport kg CO_2/tonne
This study	3.78	0.16
Lefebvre et al (2019)	5.4	1.71
Onnela & Danielsen (2019)	2.2	0.124
WRAP (2009) overall	1.48-2.52	n/a
WRAP Type A (includes fines)	0.51-1.35	n/a
WRAP Type B (screened aggregates)	2.43-4.14	n/a
Kittipongvises et al (2016)	2.92	n/a
Renforth (2012)	n/a	0.062
Moosdorf et al (2014)	77-227	0.059-0.109

Lefebvre et al 2019 considered dolerite quarries dispersed through São Paulo State (Brazil), the rationale being that this represents a major igneous province identified in Hartmann and Moosdorf (2012) as of global significance as a possible source of material for enhanced rock weathering. Reflected in the contribution analysis, the system was defined as: the extraction of the material, its transport to the grinding facility, its comminution into particles of <5mm, its transport from quarries to the fields, and its spreading on the field using agricultural spreaders.

Onnela & Danielsen (2019) present basic information concerning the carbon cost of producing a crushed rock aggregate as part of an industry-focused overview of options for crushing technologies. The report is intended to make better use of rock materials from local quarries in infrastructure projects, including unbound road- and railway construction as well as aggregates in asphalt and concrete.

WRAP (2009) present a bespoke Life Cycle Inventory and Assessment for the UK aggregates industry, including crushed rock, land-won sand and gravel, marine, and recycled aggregates. This differs from other studies in that it specifically addresses quarry fine production.

Kittipongvises et al (2016) present a study for crushed granite production in Thailand, assessing the carbon cost of production prior to transport away from the source.

Renforth (2012) assesses the financial and energy costs of using milled rocks for CO_2 removal, giving the carbon emissions for transport. The figures for milling (typically to 50% below 0.05mm) are converted to the equivalent carbon emissions in Moosdorf et al (2014). As all of the other analyses in Table 1 give a particle size of nominally <5mm, Moosdorf et al's figures emphasise the carbon cost of milling.

A number of other studies, not considered here, address the carbon cost of producing secondary aggregates from crushed concrete and demolition materials (eg Pradhan et al., 2019; Rosado et al., 2019).

References

Ecoinvent (2020) Ecoinvent V3.7 [Online]. Switzerland Available: https://www.ecoinvent.org/ [Accessed 2020].

Hartmann, J., and Moosdorf, N. (2012) The new global lithological map database GLiM: a representation of rock properties at the Earth surface. Geochem. Geophys. Geosyst. 13, 1e37. https://doi.org/10.1029/2012GC004370

IFU Hamburg (2019) Umberto LCA+ software package. Life Cycle Assessment using the software package Umberto LCA+. Hamburg, Germany: 1998-2019 ifu Hamburg GmbH.

Kittipongvises, S., Chavalparit, O., and Sutthirat, C. (2016) Greenhouse gases and energy intensity of granite rock mining operations in Thailand: a case of industrial rock-construction. Environmental and Climate Technologies 18, 64-75. https://doi:10.1515/rtuect-2016-0014

Lefebvre, D., Goglio, P., Williams, A., Manning, D. A.C., de Azevedo, A. C., Bergmann, M., Meersmans, J. and Smith, P. (2019) Assessing the potential of soil carbonation and enhanced weathering through Life Cycle Assessment: A case study for Sao Paulo State, Brazil. Journal of Cleaner Production, 233, 468-481.

Moosdorf, N., Renforth, P. and Hartmann, J. (2014) Carbon dioxide efficiency of terrestrial enhanced weathering. Environmental Science and Technology 48, 4809-4816. https://doi:10.1021/es4052022

Pradhan, S., Tiwari, B., Kumar, S. and Barai, S. V. (2019) Comparative LCA of recycled and natural aggregate concrete using Particle Packing Method and conventional method of design mix. Journal of Cleaner Production, 228, 679-691.

Renforth, P. (2012) The potential of enhanced weathering in the UK. International Journal of Greenhouse Gas Control, 10, 229-243

Rosado, L. P., Vitale, P., Penteado, C. S. G. and Arena, U. (2017) Life cycle assessment of natural and mixed recycled aggregate production in Brazil. Journal of Cleaner Production, 151, 634-642.

Onnela, T. and Danielsen S. W. (2019) Mobile processing and use of short-transported construction aggregates, challenges and opportunities.

https://www.sintef.no/globalassets/project/kortreist-stein/013-kortreist-stein-report-h3-mobile-processing-and-use-of-short-transported-construction-aggregates-endelig.pdf

WRAP (2009) https://ceramics.org/wp-content/uploads/2017/05/EVA025-MIRO-Life-Cycle-Assessment-of-Aggregates-final-report.pdf

Life cycle assessment of GGRTs

The case for basalt/dolerite aggregate application

Mohammad Rajaeifar
Newcastle University

C3 A brief description

For this life cycle assessment, the Life cycle inventory (LCI) is given in Table 1, and the system defined in Figure 1.

Table 1. *LCI used in this study (per 1 tonne basalt/dolerite aggregate) (Rosado et al., 2017, Lefebvre et al., 2019).*

LCI	Unit	Value	Comment
Basalt	tonne	1.05	Basalt production - Drilling
Water	litter	0.07	Basalt production - Drilling
Loader operation	h	0.006	Basalt production - Drilling
Explosive	g	145	Basalt production - Blasting
Loader operation*	h	0.006	Basalt production - Loading
Freight transport, lorry 16-32 metric ton, EURO6	t.km	1	Transportation from quarry to cruhing unit
Lubricating oil	kg	0.004	Crushing
Electrcity	kWh	5.45	Crushing
Loader operation*	h	0.006	Basalt crushing -Loading crushed basalt
Freight transport, lorry 16-32 metric ton, EURO6	t.km	Different values see results section	Transportation from cruhing unit to the fields (sites)
Loader operation*	h	0.006	Basalt application
Diesel	kg	1.73	Basalt application

*Loader operation includes diesel and lubricating oil consumption, i.e. 1 hour loader operation consume 18.9 l diesel and 0.3 kg lubricating oil.

In all the scenarios, 70 kg CO_2/tonne removal for carbonation and 230 kg CO_2/tonne removal for EW were considered. All the background data were adopted from Ecoinvent 3.7 (Ecoinvent, 2020). In this study global warming contribution or so called ‘global warming potential (GWP)’ was considered as the main impact category to assess the carbon emissions of aggregate application. To this end, IPCC 2013 including was selected considering a 100 year time horizon (ifu Hamburg, 2019). The following results aimed at showing the carbon cost of different activities within the life cycle of basalt/dolerite application as a carbon removal technology in the UK.

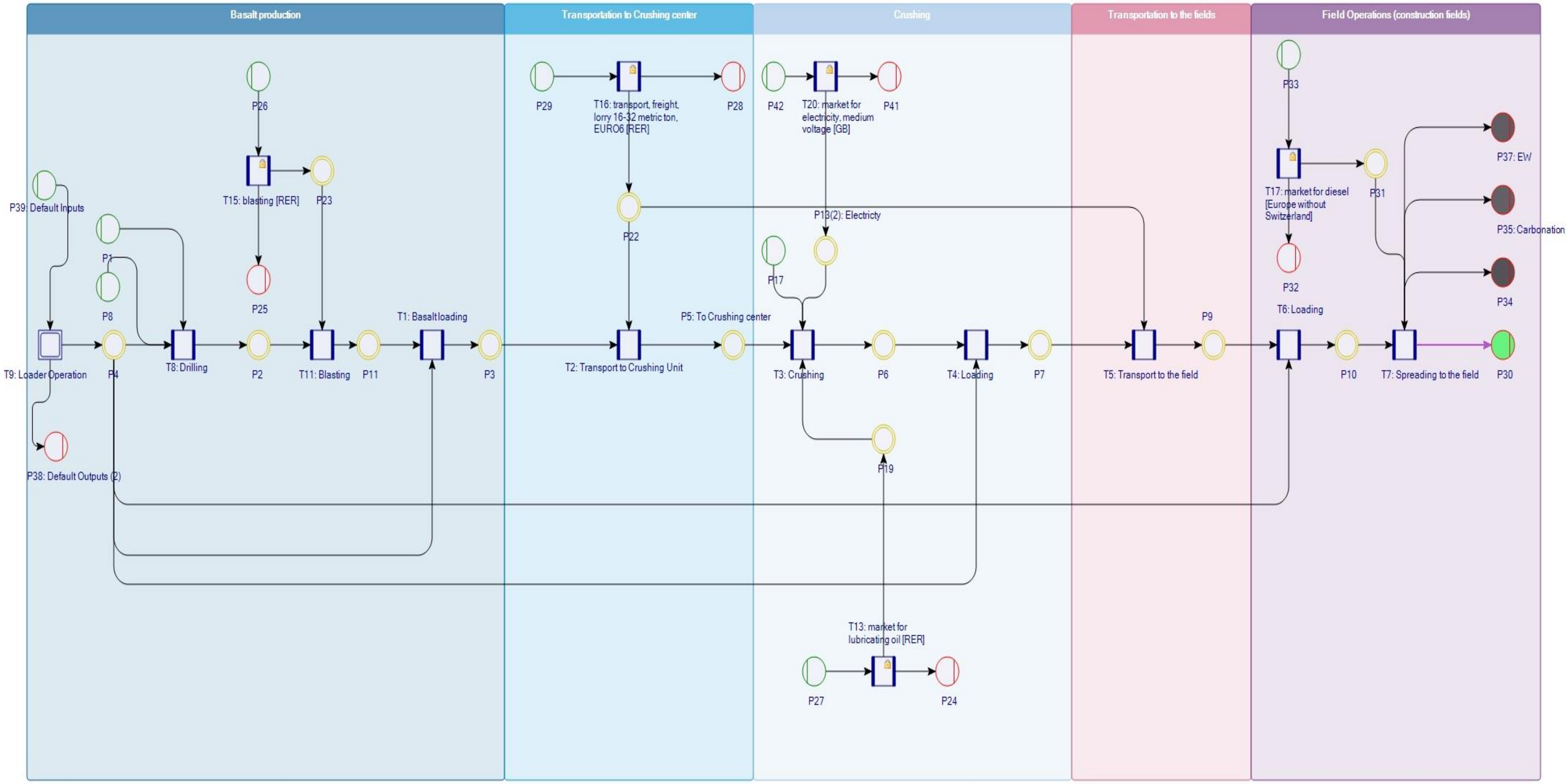


Figure 1. Scope of the current study and the modelled life cycle in Umberto LCA+ software.

C3.1 Results

Manufacture in the mine/quarry

The embedded carbon cost at the mine gate (zero transport) is shown in Figure 2.

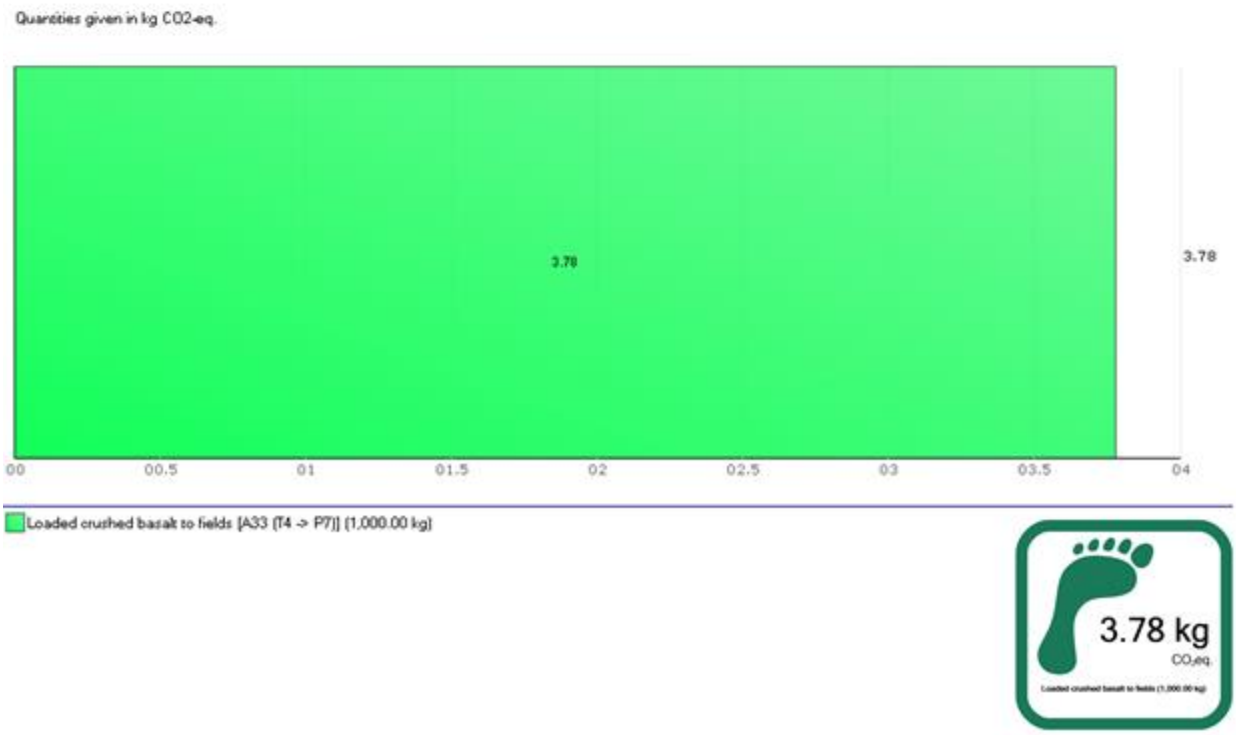


Figure 2 *The cradle to gate results for 1 tonne basalt mining (from cradle to mining gate, i.e. after crushing the extracted basalt/dolerite).*

As the results show, the global warming contribution of each tonne of basalt mining (from cradle to the end of the crushing stage) is as low as 3.78 kg CO_2-eq. Accordingly, the contribution analysis show that 'crushing and loading stage' contributed to 48.6% of the GWP, followed by 'basalt production (including Drilling, blasting and loading)' by 47.1%.

Table 2 . *Results for cradle to gate contribution analysis of 1 tonne basalt mining.*

Stage	Emission value	Unit	Contribution (%)
Basalt production	1.78	kg CO_2-eq	47.1
Transportation to Crushing centre	0.16	kg CO_2-eq	4.3
Crushing	1.84	kg CO_2-eq	48.6

The above could be easily translated to 75.6 kg CO_2-eq. per 20 tonnes basalt application per hectare, and 11340 kg CO_2-eq. per 3000 tonnes basalt application (mixed with 1000 tonnes compost) per hectare. The LCI used for the mining operation in this study were compared to (Pradhan et al., 2019) and the results were the same.

Per kilometre carbon cost for onward transport (gate-to-gate)

Transportation in LCA is usually considered as t.km (metric ton transferred per km). Here, we analysed per kilometre carbon cost of 1 tonne crushed basalt/dolerite delivered from the gate of mining facility to the fields (Table 3).

Table 3. *Results for gate to gate analysis of 1 tonne crushed basalt/dolerite transportation.*

Stage	Emission value	Unit	Contribution (%)
Basalt/dolerite Transportation (transport, freight, lorry 16-32 metric ton, EURO6)	0.16	kg CO_2-eq	100

The above corresponds to 3.2 kg CO_2-eq. per 20 tonnes basalt application per hectare providing that the transportation distance is 1 km. For a blended topsoil this corresponds to 640 kg CO_2-eq. per 4000 tons of mixed aggregate application per hectare (i.e. 3000 ton basalt/dolerite aggregate mixed with 1000 tonne of green compost), providing that the transportation distance is 1 km.

It should be noted that the return of the vehicles to the crushing centres was not considered (but obviously its carbon cost is less than the departure). The way we are dealing with transportation in this study is that we consider it as a background LCI. The values are robust, but they are average of market consumption. Therefore, transportation could be modelled based on the specific transportation scenarios for the case study.

The carbon cost for aggregate application in construction sites (gate-to-gate)

a) 20 tonnes per hectare for agriculture, which represents the top-dressing approach
   Figure 3 and Table 4 show the results of 20 tonnes application of basalt aggregate per hectare.

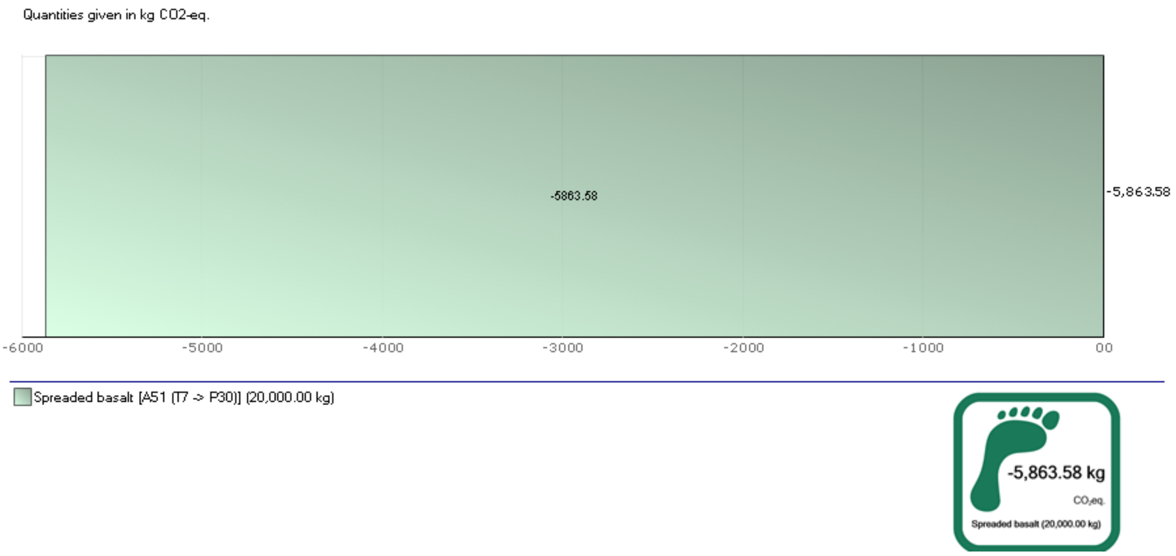


Figure 3 . *The gate to gate results for 20 tonnes aggregate application.*

Table 4. *Results for gate to gate contribution analysis of 20 tonnes basalt/dolerite application in agricultural sites.*

Stage	Emission value	Unit	Contribution (%)
Field application	-5,860	kg CO_2-eq	100

The results illustrate the removal of more than 5.8 tonnes of carbon dioxide during the field application of 20 tonnes of basalt aggregate per hectare.

b) 3000 tonnes per hectare mixed with 1000 tonnes green waste compost then spread to construction sites.

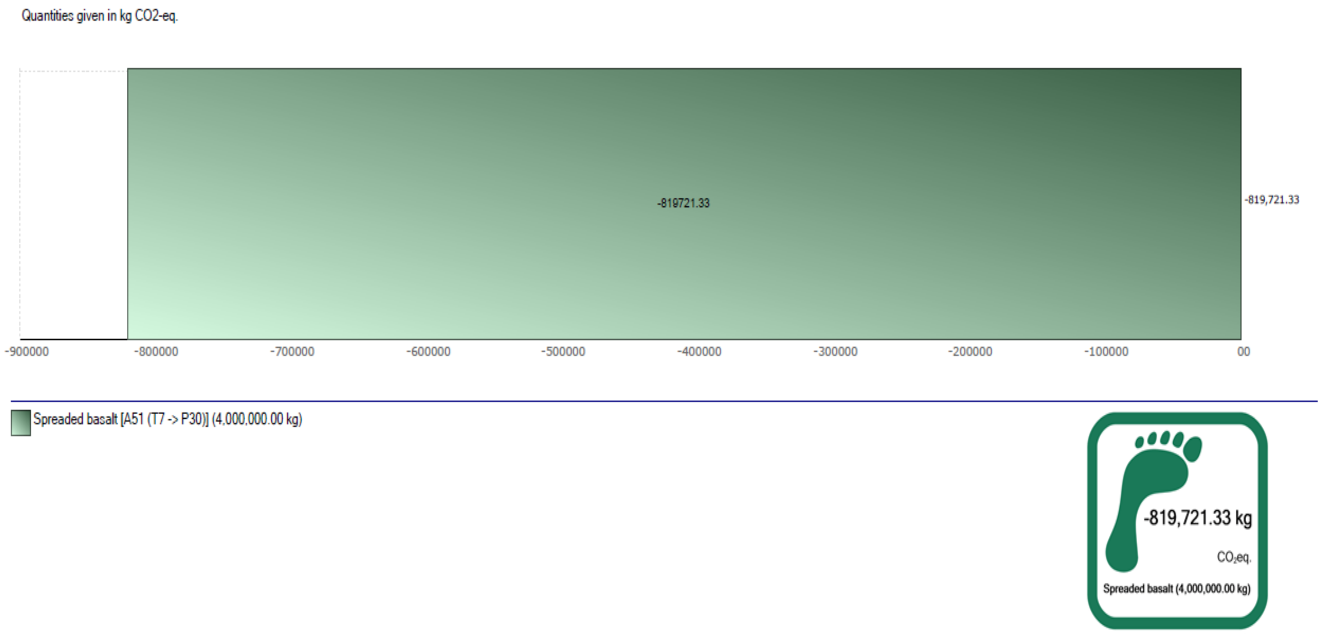


Figure 4 . *The gate to gate results for application of 3000 tonnes aggregate mixed with 1000 tonnes green compost per hectare.*

Table 5. *Results for gate to gate contribution analysis of 4000 tonnes mixed basalt/dolerite application in construction sites.*

Stage	Emission value	Unit	Contribution (%)
Field application	-819000	kg CO_2-eq	100

Since this scenario considered application of green waste compost, the environmental impact of treating organic fraction of waste for compost production should be considered. To this end, LCI for compost production were adopted from Ecoinvent 3.7 (Ecoinvent, 2020). Results show that more than 819 tonnes of carbon dioxide could be removed during the field application of 3000 tonnes basalt aggregate (mixed with 1000 tonnes compost) per hectare.

Table 6 shows the gate-to-gate results for the application stage.

Table 6. *Results for gate to gate contribution analysis of 4000 tonnes aggregate and compost application in construction sites.*

Stage	Emission value	Unit	Relative contribution (%)
Treatment of biowaste, industrial composting	53,400	kg CO_2-eq	5.7E-02
Diesel consumption	3,300	kg CO_2-eq	3.5E-03
Spreading to the field	-877,000	kg CO_2-eq	9.4E-01
Loader Operation	1,090	kg CO_2-eq	1.2E-03

It should be noted that the emissions to water and soil originated from the application of basalt and compost were not considered as it is out of the scope of the current study. Also, no CO_2 removal was considered as a result of compost application. The other issue to be considered is that all the 3000 tonnes of applied aggregate were assumed to have the potential of CO_2 removal.

The transportation of compost from compost production facilities to the sites was not considered (due to uncertain transportation distances), however, the carbon cost of such transportation could be considered as 0.16 kg CO_2-eq per km for tonne of compost transported to the field.

Assessing the whole life cycle and achieving life cycle results (i.e. from cradle to gate) in this project needs determination of some parameters such as transportation distances, etc. Here we considered four different distances, i.e. 0. 50, 100 and 150 km, from mining facilities to the construction site.

Table 7 shows the LCA results (from cradle to grave) for the application of aggregates.

Table 7. *Results for cradle to gate contribution analysis of aggregate application.*

Scenario No.	Scenario description	Emission value for the whole life cycle	Unit
1	Assuming zero transportation (0 km) from mines to the fields, for 20 tonnes of basalt aggregate application* per hectare	-5.8E+03	kg CO_2-eq per hectare (20 tonnes aggregate application)
2	Assuming 50 km transportation from mines to the fields, for 20 tonnes of basalt aggregate application per hectare	-5.6E+03	kg CO_2-eq per hectare (20 tonnes aggregate application)
3	Assuming 100 km transportation from mines to the fields, for 20 tonnes of basalt aggregate application per hectare	-5.4E+03	kg CO_2-eq per hectare (20 tonnes aggregate application)
4	Assuming 150 km transportation from mines to the fields, for 20 tonnes of basalt aggregate application per hectare	-5.3E+03	kg CO_2-eq per hectare (20 tonnes aggregate application)
5	Assuming zero transportation (0 km) from mines to the fields, for 4000 tonnes of aggregate application per hectare (basalt+compost)**	-8.08E+05	kg CO_2-eq per hectare (4000 tonnes aggregate application)
6	Assuming 50 km transportation from mines to the fields, for 4000 tonnes of basalt aggregate application per hectare (basalt+compost)	-7.76E+05	kg CO_2-eq per hectare (4000 tonnes aggregate application)
7	Assuming 100 km transportation from mines to the fields, for 4000 tonnes of basalt aggregate application per hectare (basalt+compost)	-7.44E+05	kg CO_2-eq per hectare (4000 tonnes aggregate application)
8	Assuming 150 km transportation from mines to the fields, for 4000 tonnes of basalt aggregate application per hectare (basalt+compost)	-7.11E+05	kg CO_2-eq per hectare (4000 tonnes aggregate application)

*In all the scenarios 70 kg CO_2/tonne for carbonation and 230 kg CO_2/tonne for EW were considered.
** For the sake of simplicity, the transportation distance between compost producing lants and fields were considered the same as distances between mines and fields in each scenario.

References

ECOINVENT. 2020. *Ecoinvent V3.7* [Online]. Switzerland Available: https://www.ecoinvent.org/ [Accessed 2020].

IFU HAMBURG 2019. Umberto LCA+ software package. *Life Cycle Assessment using the software package Umberto LCA+*. Hamburg, Germany: 1998-2019 ifu Hamburg GmbH.

LEFEBVRE, D., GOGLIO, P., WILLIAMS, A., MANNING, D. A., DE AZEVEDO, A. C., BERGMANN, M., MEERSMANS, J. & SMITH, P. 2019. Assessing the potential of soil carbonation and enhanced weathering through Life Cycle Assessment: A case study for Sao Paulo State, Brazil. *Journal of cleaner production,* 233**,** 468-481.

PRADHAN, S., TIWARI, B., KUMAR, S. & BARAI, S. V. 2019. Comparative LCA of recycled and natural aggregate concrete using Particle Packing Method and conventional method of design mix. *Journal of Cleaner Production,* 228**,** 679-691.

ROSADO, L. P., VITALE, P., PENTEADO, C. S. G. & ARENA, U. 2017. Life cycle assessment of natural and mixed recycled aggregate production in Brazil. *Journal of cleaner production,* 151**,** 634-642.

Appendix D - Industry Consultation

1 Introduction

The ‘Integration of GHG (Greenhouse Gas) Removal Technologies into Linear Infrastructure Projects’ (“the project”) examines the use of enhanced mineral weathering (“EMW”) techniques using quarry fines and the incorporation of biochar into earthworks and landscaping areas of infrastructure developments. Both technologies have already been shown to be effective for direct capture of CO_2e in agriculture. The ultimate ambition of the project is to demonstrate that these technologies can be upscaled for use within the UK Infrastructure sector (“the industry”).

This document provides a report on the consultation and industry engagement completed as part of the project. An overview of the status of industry is first provided to detail the challenges incumbent to the promotion of new technologies. This report predominantly details how the team has engaged with the UK engineering industry throughout the project. This was firstly to develop the possibilities for using the technologies on engineering projects, which resulted in an options review that guided the feasibility phase; secondly to research potential pilot schemes, and thirdly to begin the process of introducing the new technologies to industry.

1.1 Consultation Overview

An overview of the various types of consultation completed during the project is provided below in Figure 1 and discussed in more detail in the following sections.

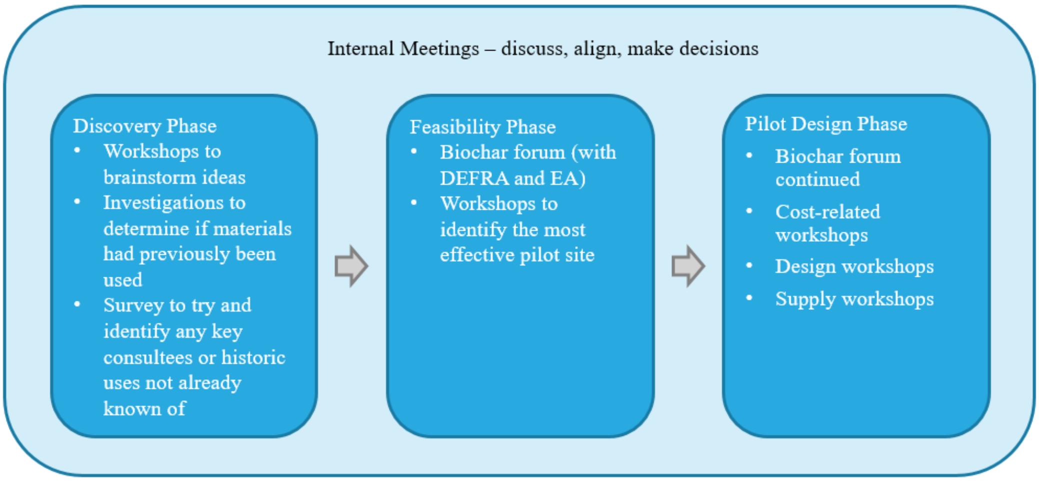


Figure 1: Overview of consultation process

A full list of all stakeholders consulted throughout the project can be found in Appendix D3.

1.2 Discovery Phase

The discovery phase took place at the start of the project. Its aim was to establish the current industry position , and to determine if there was any previous experience or track record with the use of (or intention to use) biochar and EMW for this purpose. Another important aspect of the consultation was to explore potential opportunities and risks associated with the use of biochar and enhanced mineral weathering in this context, and in particular any barriers to application, and how these might be overcome. There were three main parts to consultation in this stage:

- Workshops were held in order to brainstorm ideas for the project;
- Investigations were undertaken to determine if these materials had previously been used in any past infrastructure projects, via conversation with internal and external industry representatives; and,
- A survey was prepared and circulated to industry consultees to explore views more widely and identify any key consultees or historic uses of biochar or EMW in the context of GHG removal.

All the options raised within this phase were captured, ranked, and analysed in order to direct and refine the work during the feasibility phase (please see Appendix D5 and D6 for fuller details of this).

1.3 Feasibility Phase

The feasibility stage was used to determine the practicality of a pilot project using biochar and EMW in industry. A biochar forum attended by key stakeholders from DEFRA and the Environment Agency (EA) was established, and workshops with potential pilot projects were set up to identify the most effective pilot site for the project. See section 3.8 and Appendix D4 for more information on the biochar forum.

1.4 Pilot Design Phase

The final stage was the pilot design phase, during which the biochar forum continued to meet to discuss key regulatory issues. Workshops were also organised to further explore costing, detailed design considerations, environmental impacts, and supply chain issues for the pilot project.

1.5 Consultation Objectives

The works carried out for the project were split into three stages, which had slightly different objectives for their industry consultation:

1. The discovery phase;
    - Exploring options for the uses of the technologies;
    - Finding case studies where the technologies have previously been deployed, and identifying any best practices or lessons learned;
    - Raising awareness around the two technologies, assessing their technological readiness, and developing confidence in their use;

- Exploring the potential for the future upscaling of the technology uses;
- Identifying industry consultees to engage with; and,
- Identifying risks and opportunities associated with each of the two technologies, and developing mitigations for said risks (including where this would require further consultation).

2. The feasibility stage;
    - Engaging with industry consultees to gather further input;
    - Working with industry regulators;
    - Engaging with potential pilot projects; and,
    - Continuing with the objectives associated with the discovery phase.
3. The pilot design phase.
    - Developing the design of the pilot project;
    - Developing monitoring plans;
    - Working with industry regulators;
    - Continuing to identify risks associated with each technology use and planning how to close out the risks (possibly requiring further consultation);
    - Identifying suppliers; and,
    - Identifying and confirming governance arrangements.

1.6 Overview of Industry

For the industry consultation, a diverse range of engineering industry organisations were contacted. A simplified high-level overview of the types of industry organisations consulted is provided in Figure 2, with examples of typical individual actors in this area.

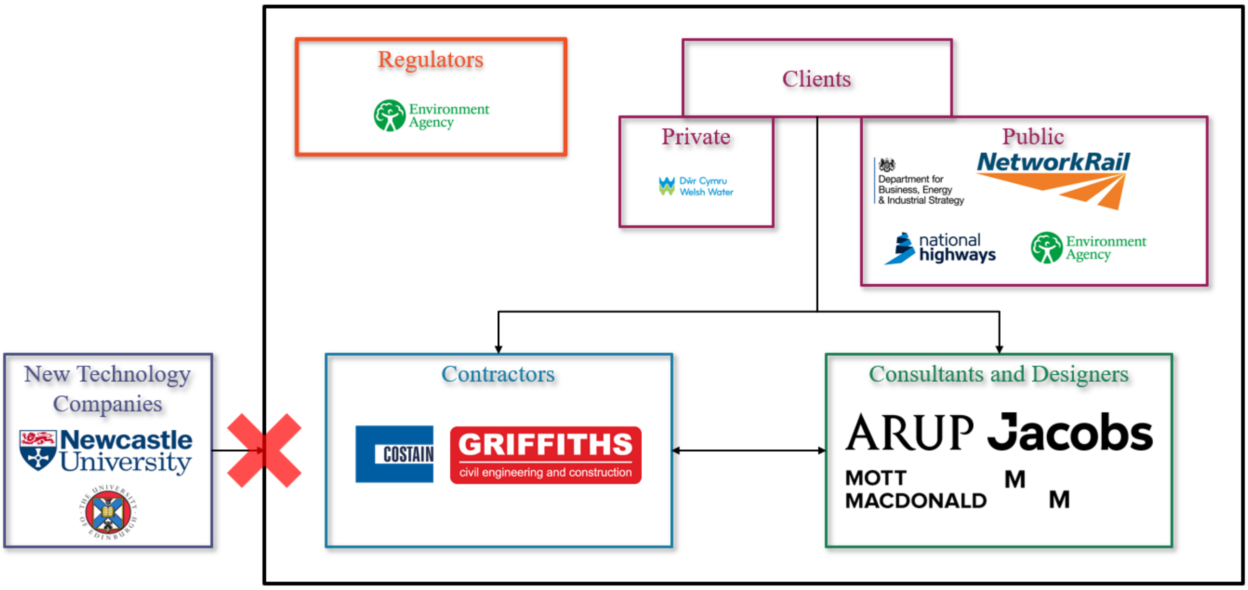


Figure 2: Overview of types of engineering industry organisations consulted with examples

1.7 Overview of Key Consultees

There are four key types of actors in the engineering industry:

- ‘Clients’ (Infrastructure scheme commissioning organisations).:
    - Governmental, Local Authority, Infrastructure operating companies and other public organisations. This is the source of the majority of major infrastructure investment in the UK.
    - Those under private ownership. Whilst less common for major infrastructure delivery, some private companies exist within the energy and water industries, such as Welsh Water, a private not for profit organisation.
- Contractor Organisations:
    - Construction companies and their supply chains, who specialise in the delivery, maintenance and decommissioning of infrastructure schemes (with some companies also operating projects for ‘clients’, such as Interserve). Alun Griffiths and Costain are typical examples of individual companies operating in this space.

  - There are a significant number of individual contracting companies in this sector.
  - Profit margins for contractors is generally very low. For the 10 largest contractors by turnover in 2021, the average profit was 1.1% (Construction News, 2021). Major infrastructure delivery in the UK is delivered by a relatively small number of larger ’principal contractors’ with large turnovers, with smaller companies providing specialist services or sub-contracted as part of an extensive supply chain of goods and services.
- Consultants and/or Designers;
  - Organisations with a focus on developing designs or work related to the development of the design for a project. This may include contractors and engineering consultants. Major infrastructure schemes in the UK are typically delivered by a relatively small number of larger multidisciplinary consultants, albeit there is a proliferation of smaller to medium sized organisations delivering more specialists services or as part of the design supply chain, and hence a significant number of potential stakeholders.
- Regulators:
  - As might be expected of an industry that represents 6.7% of the UK’s GDP (UK Government, 2021) and 13% of its carbon emissions (Institution of Civil Engineers: The Carbon Project, 2020), there are numerous regulators of the industry.
  - Regulations cover various items, for example:
    - Planning permission: a key risk for any large infrastructure project;
    - Permitting (particularly of any materials that may be considered as “waste” by the Environment Agency); and,
    - The Health and Safety Executive (which has multiple subsidiary bodies)

The organisational and contractual relationships between the ‘client’, ‘contractor’ and ‘consultants’ will vary significantly. The consultant may be contracted directly by the client, or the contractor, or a joint venture may be a combination of both contractor and consultant together bidding for client’s work. Different options may suit different project types, and critically, different types of client.

It is always a challenge to introduce new technologies where they have not been tried and tested and where they may bring additional risks and uncertainties. The typically low profitability of the contractor sector means the industry is very competitive, with cost as a persistent key driver. This can make the introduction of new technologies (particularly without an effective supply chain available) challenging.

This is compounded by the culture of the engineering industry, which is discussed further in Section 1.8. The challenge is therefore to engage as widely as possible across the industry with whatever limited resources and time are available within the project.

1.8 Culture of the Engineering Industry

Numerous reports and opinions are available on the culture of the engineering industry (see Latham (1984) and Construction Task Force (1998)).

There is no single industry representative. There are several bodies that were set up with the aim of representing certain groups within industry, for example:

- The Institution of Civil Engineers (ICE);
- The Institution of Structural Engineers (IStructE);
- Royal Institute of Chartered Surveyors (RICS); or even,
- Civil Engineers Contractors Association (CECA).

As can be inferred from the names of the above institutions, there is functional overlap between them. For example, an individual structural engineer might choose to be part of the ICE, IStructE, or even both. Furthermore, membership of any of these institutions is not mandatory, so only a small proportion of individuals are actually represented by them. For instance, the Institution of Civil Engineers is one of the largest bodies in the industry but has only 80,000 members, whereas there are 3.2 million people working withing the UK construction industry (Office for National Statistics, 2021).

Attempts have been made to provide strategies for the engineering industry, for example the recent creation of Project 13 community, or the formation of the National Infrastructure Commission (NIC). The NIC however has mostly an advisory role to the UK government on infrastructure issues, rather than representing the industry as a whole (National Infrastructure Commission, 2021).

Project 13 brought together a significant number of the key industry actors provided in Section 1.7 with the aim of improving the “low margins, low investment, and dysfunctional relationships” present within industry (Project 13, 2021). These problems were first identified by the Latham report in 1984 (Latham, 1984). This gives an indication of the lack of industry agility and suggests that these problems have persisted at least partially due to underlying problems.

Project 13 has contributed significantly to the recent government’s Construction Playbook (UK Government, 2020), which has meanwhile set out three key main objectives for what the Government expects from the construction industry: improving building and workplace safety, making progress towards the UK’s 2050 net zero carbon commitment with an emphasis on whole life carbon, and to promote social value. The expectations set out in the Playbook are mandatory for central Government and arm’s length bodies for all new public works and projects, with enforcement through Cabinet Office Spending Controls (Build UK, 2021).

At this stage, the Construction Playbook outcomes are generally at a high level and there will need to be changes within the entire industry to achieve them. For example, investing in digital and automated contracting and payment systems and ensuring prompt payment of supply chains to ensure work is as efficient as possible. To further progress towards the UK's net zero target and increase efficiency, the industry will be required to develop safe, innovative manufacturing-led solutions. However, the industry historically suffers from lack of investment and difficulty in allowing the introduction of new technologies (Project 13, 2021) (Latham, 1984).

1.9 Cost Barriers

In addition to any technical issues, the additional costs associated with the use of new technologies must be well understood, together with the balance of cost and benefit. There are currently several uncertainties around the cost of production, supply, and application of biochar and EMW which need to be more fully understood. As an example of this, the costs of production of biochar are currently relatively high, largely due to the small scale of the current supply chain capability. Reductions in these costs will be important to effectively upscale the application of biochar for GHG capture. This would be reduced with time as the supply chain develops, but in order to drive the supply chain greater uptake of biochar use and greater confidence in its effectiveness is needed.

1.10 Supply Constraints

The biochar industry is at early-stage development. There are competing uses for biomass feedstock, including other potential methods of carbon sequestration e.g., BECCS. The supply chain for quarry fines exists but is not fully utilised for GHG, as other uses exist such as asphalt binding To achieve the biochar production scale required for use across industry, supply constraints (quantity, quality, production, distribution) need to be addressed. Quarry fines supply is assured, given the long-term existing production permits, granted to the quarrying industry through the planning process (in the context of the national strategic need for supply of construction aggregates).

1.11 Regulatory Issues

There is currently a policy gap to allow large scale utilisation of biochar. For example, there are uncertainties around whether biochar should be considered to be a waste material or a product, which could restrict use and require greater investment and lead times for implementation at scale (e.g., permit application may be required).

1.12 Certification Issues

Currently, only woodland creation and upland peatland restoration have certification standards that enable them to be used for carbon offsetting in the UK. Additional R&D is needed to expand the number of nature-based and built environment offsetting schemes available (Environment Agency, 2021) International certification standards exist for biochar, but there is little guidance (and no recognised standard) for the application of EMW.

1.13 Technology Information, Validation and Promotion

The technologies are not widely understood and there is currently a lack of clear guidance to inform the industry. This may preclude their use. Ideally, the method for using the materials would be in an industry code.

Providing further details of the potential application of these new technologies, e.g. by preparing new guidance documents or updating existing guidance documents will help encourage uptake. Amendments to codes of practice would also help to promote them and their future use. In order to facilitate this, demonstration with monitoring and verification of the effectiveness of the technologies is required.

Validation is required to quantify the long-term GGR potential of EMW-processes and refine the conservative methods by which biochar is used as a GGR technology.

In order to validate the GGR potential and provide further monitoring data, in addition to the main pilot project proposed, a reference site to focus on monitoring potentially over longer periods of time was therefore also ultimately investigated during stakeholder discussions.

2 Overview of Key Industry Consultees

This section provides an overview of some of the key consultees engaged with throughout this project to help provide context in following sections.

2.1 Environment Agency (EA)

The Environment Agency (EA) is an executive non-departmental public body. It is part of the Department for Environment, Food & Rural Affairs (DEFRA) which provides most of its funding. The aim of the EA is to create better places for people and wildlife and support sustainable development. Their main business areas are: flood and coastal erosion risk management, water, land and biodiversity and the regulation of industry. There is currently a policy gap for the regulation of biochar and EMW on infrastructure schemes. Consultation with the EA was therefore critical for the project, with Appendix E examining this issue more fully.

Within England, they are responsible for managing the risk of flooding from main rivers, reservoirs, estuaries and the sea, regulating major industry and waste, treatment of contaminated land, water quality and resources, fisheries, inland river, estuary and harbour navigations and conservation and ecology.

They have around 10,600 employees and their annual expenditure for the 2019/2020 financial year was £1.4 billion. The Environment Agency secured capital funding of £10m for one year for essential work on Navigation and £29m over four years for Water Resources assets, as well as the £5.2bn (next six years) FCRM capital programme budget (Environment Agency, 2021).

2.2 National Highways (Formerly Highways England)

National Highways is a government owned company which is responsible for the operation, maintenance and improvement of England's motorways and major A roads. They are responsible for all motorways and major (Trunk) roads in England, which totals 2% of total road length in England but carries a third of all traffic by mileage and two thirds of heavy goods traffic.

National Highways work with the Department for Transport and have around 5000 employees around the country (Highways England, 2021).

They are planning to deliver £15 billion of investment on their road network as described in the government's Road Investment strategy, including £11 billion of capital funding committed between 2015 and 2020 – as set out in the Strategic Business Plan.

Due to the focus on linear infrastructure, National Highways were a key informed industry client for the project. Therefore, consultation with them was vital for this project.

2.3 Network Rail

Network Rail owns, operates and develops Britain's railway infrastructure. They own 20000 miles of track, 30000 bridges, tunnels & viaducts and thousands of signals, level crossings & stations, as well as managing the 20 largest stations (Network Rail, 2021).

National Rail's 2020/2021 revenue was £9,618m and they have 43,871 employees across the country, according to their 2021 Annual Report (Network Rail Limited, 2021).

It is an "arm's length" public body of the Department for Transport. It has no shareholders and therefore reinvests its income in the railway network.

As with National Highways, it was also essential to consult with Network Rail as they were also a key informed industry client for the project.

2.4 Alun Griffiths Contractors Limited

Alun Griffiths is a regional civil engineering and construction contractor based in Wales. Their areas of work cover eight sectors, including highways & bridges, rail, utilities & energy, surfacing, integrated transport, urban regeneration, highway maintenance and water management.

The company has an annual turnover of roughly £225m and directly employ over 1000 people. In 2018, Griffiths became part of Tarmac Plc, the UK’s leading sustainable building materials business and a wholly owned subsidiary of CRH. CRH is the world’s leading building materials companies – employing over 77,000 people across 3,100 locations worldwide and with a turnover of €26.8 billion (Alun Griffiths, 2021).

Alun Griffiths were the incumbent contractor engaged on the Banwell Bypass pilot project so consultation with them was also crucial for this project.

3 Consultation With Industry

This section provides more detail on the various industry consultation methodologies summarised in Section 1.1.

3.1 Internal Investigations

The project team reached out internally across Arup's 16,000 global employees in order to identify any case studies of previous uses of dolerite or biochar and to find any lessons learned from past experience of using carbon capture technology within infrastructure projects. Risks were identified and captured in the risk register, see Appendix J.

3.2 Workshops

During this project, workshops were undertaken to discuss ideas from across industry. Multiple workshops took place, with key workshops including:

- A stakeholder engagement workshop with internal specialists in May 2021;
- Two internal workshops focussed on the development of application options in May and June 2021; and,
- A workshop with key project leads in Costain to discuss potential pilot project options in August 2021.

Workshops were carried out remotely due to the Covid-19 pandemic. Mural online brainstorming platforms were used to help brainstorm ideas collaboratively during the workshop.

3.3 Stakeholder Engagement Workshop Results

Example screenshots from Mural of the boards produced during the Stakeholder engagement workshop with Costain are shown in Figure 3 and Figure 4 below.

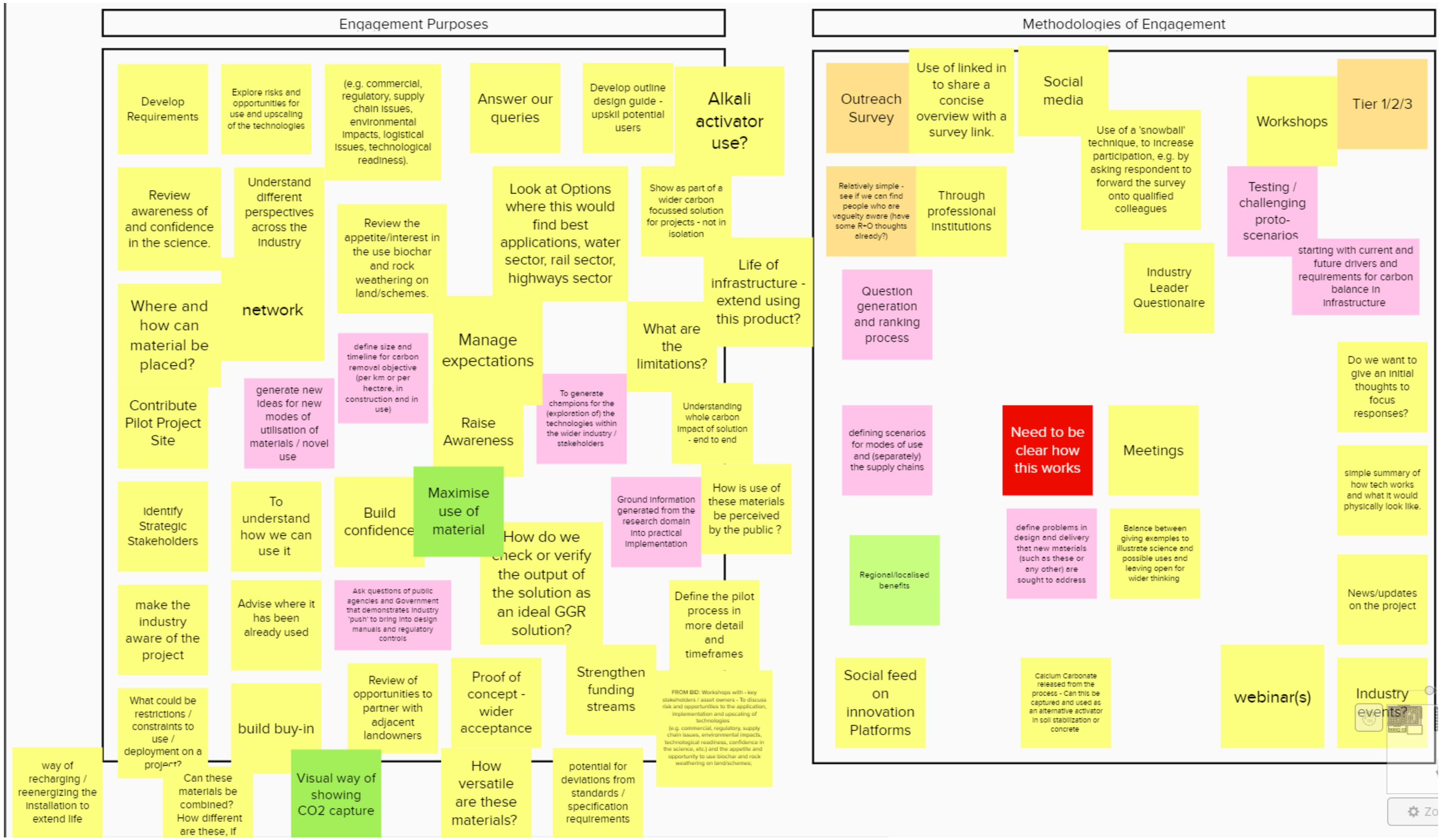


Figure 3: Stakeholder engagement workshop purposes and methodologies brainstorm

Figure 4: Brainstorm of potential stakeholders or consultees. A consultee list was maintained throughout the project, see Appendix D3 for full list.

As shown in these figures, thoughts relating to the engagement process and their methodologies were brainstormed along with further actions to be taken after the workshops. A group of potential consultees were also generated, and as many as possible were contacted throughout the project.

An industry survey was proposed during the stakeholder workshop, which was then further developed (see Section 4 and Appendix D1).

3.4 Options Review and Outcomes

Two workshops were completed to develop possible on-site applications of biochar and dolerite. The long list developed during the workshop is provided in Figure 5.

Figure 5: Long list of applications. Please see Appendix D6 for a full, appraised list.

Examples of applications with high potential include use in under street urban paving and road resurfacing by cold mixing biochar into the asphalt. The risks and key questions for each of the applications were also identified. Medium potential applications include creating hardstanding areas during the construction stage or permanently for plant, burying cells of biochar in the ground, integration into aesthetic landscaping applications, filling borrow pits and stone dusting pavements and cycleways.

The workshop discussion was condensed into a list of options and ranked, which was informed the level of technological readiness, ease of replicability, and social value. These three parameters represented the wider considerations of:

- Cost (heavily related to minimising transport requirements);
- Frequent replicability (one-off sequestrations are unsuitable, the use should be repeatable);
- Feasibility concerns that can be solved within the timeframe of the Phase 1 Design Phase;
- Ease of validation and monitoring (options that require destructive testing are undesirable);
- Social value in terms of visibility to infrastructure users.

The full version of the produced options list is tabulated in Appendix D6. The top-ranking options are presented below in Table 1.

Table 1: Table to show ranked options generated within the discovery phase (extracted from Appendix D6). The scale of 1 (worst) to 3 (best) has been used. For replicability this represents 1 = one-off, 2 = ad-hoc, and 3 = integral to infrastructure. Overall score is generated by multiplying these values.

Rank	Option	TLR	Social value/visibility (1 – 3)	Ease of monitoring (1 - 3)	Replicability (1 – 3)	Overall Score
1	Drainage – central reserves and verges	6	3	3	3	162
2	Slopes and embankments	4	3	3	3	108
3	Landscaping	6	3	3	2	108
4	Maximising biodiversity on soft estates	5	3	2	3	90
5	Traffic and pedestrian pavement construction – surface layers and subgrade integration	5	3	2	3	90
6	Non-structural concrete	5	3	2	3	90
7	Borrow-pit restoration	5	3	3	2	90

The three key options that were identified in the discovery phase were use in central reserves and verges, application to slopes and embankments, and landscaping. These uses formed the basis of research during the feasibility stage. These three application options were reviewed by an Arup specialist team. This team developed a shortlist of the practical potential applications, as shown in Table 2.

Table 2: Overview of shortlisted uses

ID	Potential Use	Biochar	Quarry fines
1	Blended with soil for drainage swale/SUDS	✓	✓
2	Substituted for filter drainage stone	✓	X
3	Substitute for unbound surfacing on access tracks (accommodation works and basins, low-loaded tracks, or paths, etc.)	X	✓
4	Substitute for Type 1 subbase/capping material	X	✓
5	Substitute for Class 1 earthworks materials	X	✓
6	Filtration of surface water drainage to improve water quality	✓	X
7	Blended with soil for topsoil	✓	✓
8	Landscape fill	✓	✓

These potential uses are explored further in Appendix I.

3.5 Pilot Project Workshop and Follow Up Review

Key project leads were invited to a presentation giving an overview of the technologies, and a follow-up discussion on whether their project was suitable for becoming the basis for the Phase 2 pilot site. Projects that were initially well-received by project leads included:

- Moreton-in-Marsh: a small site used as a training and experimental ground (this was recommended by multiple consultees, such as HE, Costain, and internal contacts);
- Banwell Bypass: a new road bypassing the small town of Banwell in Somerset;
- The M62 upgrade: this project included many relatively small individual improvements to the M62;
- The A12: an upgrade to the existing A12 trunk road in the east of England; and
- HS2: West Ruislip: A large project related to HS2 as an area for land remediation.

Following the decision to discuss the proposal for pilot sites in more detail, consultation was completed to understand several key critical success factors:

1. Whether the project strategically fit with the goals of Phase 2. A key item within this was whether the program for the project fit:
    a. In the short-term to achieve the delivery of the Phase 1 design to an acceptable level by the end of 2021; and

b. In the long-term to deliver the construction (and ideally monitoring) of the project by the end of Phase 2 by 2025.

This program issue was found to be a key differentiator for the potential pilot projects being considered.

2. Whether it was likely that value-for-money could be achieved. This was related to how effectively the technologies could be integrated with the entire project solution proposed, and whether any systematic cost benefits were likely.

3. The potential affordability of the site.

4. The expected ease of supplying the key materials (biochar and quarry fines) for the site. The estimation was based principally on the expected distances between the site and the supply of biochar and quarry fines as vital materials for the pilot projects.

5. The potential risk profile for the project option. The likely difficulty of planning permission achievement was a key part of this risk determination. This risk would be present for any potential project; however, some projects were expected to be smaller in size or have better links with the planning provisor. These projects had comparatively lower planning risk.

6. The expected alignment with local and national regulations.

A summary of the red/amber/green review of the sites is provided in Table 3 below. Following this initial development of the possible options, Moreton-in-Marsh and Banwell Bypass were taken forward for further detailed investigation. More information on these projects is provided in the main report, and Appendices G and H respectively.

The other potential pilot projects remain possibilities for using the technologies, and contact has been maintained with the M62 designers to encourage the future use of both technologies. However, a significantly larger amount of work, prohibitive programs, or planning risks were expected with these projects, so they were discounted for the purpose of Phase 2.

Table 3: Summary of potential pilot project options

Critical Success Factor (CSF)	**Option 1** Moreton-in Marsh	**Option 2** Banwell Bypass	**Option 3** M62	**Option 4** A12	**Option 5** HS2 West Ruislip
CSF 1: Strategic Fit					
CSF 2: Value for Money (benefits optimisation)					
CSF3: Potential affordability / cost					
CSF 4: Supply side capacity and capability					

Critical Success Factor (CSF)	**Option 1** Moreton-in Marsh	**Option 2** Banwell Bypass	**Option 3** M62	**Option 4** A12	**Option 5** HS2 West Ruislip
CSF 5: Potential achievability/risk profile					
CSF6: Alignment with regulatory agenda					

Assessment	**Rating**	**Recommendation**
Fully/ largely meets CSF		Option preferred
Partially meets CSF		Further analysis required to take option forward
Fails to meet CSF		Discount option

3.6 Consultees Contacted Throughout Project

A high-level list of the consultees contacted throughout this project were:

- ADAS Environmental Team and RSK Habitat Management (who were asked about the biochar railway testing that they are currently completing);
- Various pyrolysis suppliers (see Appendix B);
- Various quarries relating to the supply of quarry fines for EMW (see Appendix C);
- Various Costain project teams (to provide an overview of the technologies to, and discuss the potential for pilot projects);
- Kat Ibbotson (a key carbon champion) of the EA (who moved on to work for WSP shortly after initial contact);
- The EA at a high level following an initial talk with Kat Ibbotson, to provide an overview of the technologies, and additionally gain further contacts for more detailed talks with the industry regulator about permitting mechanisms (see Appendix E);
- HE high level technical authorities (with a workshop providing an overview of the technologies and how they could be used on HE projects – the same presentation was also given to the recommended Geotechnical Asset Owners Forum);
- HE Geotechnical Asset Owners Forum (with a workshop providing an overview of the technologies and how they could be used on HE projects);
- HS2 design teams (to provide an overview of the technologies and investigate the potential for a pilot project on HS2);
- Internal H&S specialist teams in order to gain insight on key technology risks;

- Natural Resources Wales (to provide an overview of the technologies);
- Network Rail technical authorities (to investigate the possibility of mandating the technologies for use on rail projects) and local project leads (to investigate the possibility of local pilot projects);
- Railway Industry Association (RIA) (to provide an overview of the technologies to the association and also at one of the RIA's wider events);
- Yorkshire Water (both as a typical water company, identified as a key potential industry for the technologies to provide an overview to, but also to gather lessons learned following their experience attempting to repurpose sewage sludge into biochar); and
- Welsh Water (as another key water company to provide an overview of the technologies to).

A full list of all stakeholders consulted throughout the project can be found in Appendix D3.

3.7 The Biochar Forum

Along with representatives from BEIS, Defra, and the Environment Agency, a group was established to connect other projects from within the BEIS GGR competition that are also investigating the use of biochar. Within the seven teams invited, companies such as CPL Industries, PyroCore, Biomacon, BSW Timber, and Sofies UK are represented. The forum is managed by SevernWye.

A position statement prepared for the first meeting has guided the conversation since, primarily regarding how the projects can negotiate waste regulations to define it as product. This position statement can be found in Appendix D4.

Centralising this discussion in the presence of EA and Defra representatives assists them in developing ideas and policy guidance around the varied uses of biochar. Including pyrolysis companies such as PyroCore and Biomacon also provides assurance of the growing demand for biochar and draws attention to the need for processes that produce stable biochar as well as energy output through syngas.

4 Survey

A survey was shared across various platforms requesting initial data on biochar and enhanced mineral weathering (EMW) (the "technologies"). The objectives of this survey were:

- To reach out as widely as possible to advertise the potential opportunities presented by the technologies;
- To identify any key industry stakeholders not already identified by the project team that may need to be consulted;

- To identify any risks or opportunities for the technologies not already identified; and
- To develop an understanding of the current industry position to the technologies in their current form.

Platforms across which the survey was shared included:

- LinkedIn;
- The Institution of Civil Engineers reshared the LinkedIn post on their social media pages;
- Railway Industry Association; and Via email to various internal and external contacts.

The survey questions and format were developed following multiple workshops, initially as part of the consultation engagement plan. This developed, with a focus on allowing key consultees to identify themselves for further in-depth discussions.

See Appendix D1 for more details on the industry survey results.

4.1 Pilot Design Phase

During this phase, consultation was focused on developing the selected pilot sites to achieve their objectives. More information about the pilot sites and their final designs is provided in Appendices G (Banwell Bypass: Pilot Site) and H (Moreton-in-Marsh: Reference Site).

5 Discussion

Consultation has guided decisions made throughout the project, and ultimately led to the proposal of two pilot sites: a live, scaled-up pilot at Banwell Bypass and a smaller, monitoring-focused reference site at Banwell Bypass. Many risks have also been identified for this project from consultation. These have all been summarised in Appendix I. However, a summary of the key risks identified by industry during consultation are summarised below in Table 4.

Table 4: Summary of key risks identified during stakeholder engagement

Risk	Details	Key Consultee(s)
Validation	Two pilot sites will be able to provide this validation, subject to their approval by BEIS.	Pilot schemes
Cost	Contractor costs and supply chains are not as efficient as possible.	Pyrolysis and quarry fines suppliers Contractors on pilots/future projects
Regulations	Current policy gap for the regulation of biochar and EMW on infrastructure schemes.	EA and DEFRA (biochar forum) - Refer also to Appendix F
Barriers to enter into the industry	Increasing awareness of material usage. Adding the use of these materials into a code would increase knowledge and uptake in usage.	CIRIA, possibly British Standards or Eurocode. Requires monitoring.

The most important risk for the technologies is the validation of the carbon capture potential of the materials. This demonstration of effectiveness will be essential for the development of certification schemes for the use of these technologies, which will be needed if large scale uptake is to be a realistic prospect. In order to validate the use of these materials and quantify the long-term GGR potential of EMW processes and refine the conservative methods by which biochar is used as a GGR technology, pilot projects will need to take place. This has significantly influenced the proposals for Phase 2 of the project, as detailed further in the respective Appendices G and H. The pilot site and accompanying reference site would assist with provision of the necessary validation including potential for longer-term monitoring and ability to test specific elements of the GGR processes and performance.

Another key risk for the technologies is the cost. Currently, the contractor costs and supply chain are not as efficient as they could be. The supply of the materials themselves is also currently an emerging industry. Full detail is provided in Appendix D1, however as a high-level summary the biochar industry is at early-stage development and there are competing uses for biomass feedstock. The supply chain for quarry fines exists but is not fully utilised. To achieve the biochar production scale required for use across industry, supply constraints (quantity, quality, production, distribution) need to be addressed. Dolerite supply is assured, given the long-term existing production permits, granted to the quarrying industry through the planning process (in the context of the national strategic need for supply of construction aggregates). Therefore, to reduce costs, the supply chain should be made more efficient, and the materials supply further expanded. This project, through demonstration in infrastructure, would help realise the demand potential and provide confidence for others to invest (e.g., in production facilities) that could in turn help to rapidly scale up and deliver economic and social value across the supply chain). Dolerite supply is less constrained, but validation is required along with standards on material use, sourcing, and transportation for optimal lifecycle outcomes.

A further risk is the policy gap for the regulation of biochar and EMW on infrastructure projects with the EA (refer to Appendix F). Currently, only woodland creation and upland peatland restoration have certification standards that enable them to be used for carbon offsetting in the UK. Additional R&D is needed to expand the number of nature-based and built environment offsetting schemes available (Environment Agency, 2021). International certification standards exist for biochar, but there is little guidance (and no recognised standard) for the application of EMW. Phase 2 of this project will link with other BEIS biochar projects looking at international certification standards and application in a UK context. There is also currently a policy gap for the permits to allow large scale utilisation of the technologies. Biochar is currently considered a waste material, requiring which restricts use and means greater investment and lead times for implementation at scale (e.g., permit application).

Due to the current fragmented nature of the industry, it is difficult for new companies and technologies to enter and become involved in new infrastructure schemes. This is a key risk for the use of dolerite and biochar within the industry. Therefore, to increase use, awareness of these materials to use in infrastructure schemes should be increased with the possibility of them being codified to further increase uptake within the industry.

These risks and market blockers are summarised in Table 3. In Phase 2, consultation with key industry consultants will need to continue, with the key consultant identified in Table 3 above.

References

Alun Griffiths. (2021, November 16). Retrieved from Griffiths: https://alungriffiths.co.uk/

Build UK. (2021). *The Construction Playbook: An Executive Summary.* London: Build UK.

Construction News. (2021, November 21). *CN100 2019: The top 100 UK contractors*. Retrieved from Construction News: https://www.constructionnews.co.uk/financial/cn100-2019-top-100-uk-contractors-05-09-2019/

Construction Task Force. (1998). *Rethinking Construction.* London: Department of Trade and Industry.

Environment Agency. (2021, November 16). *About us*. Retrieved from UK Government: https://www.gov.uk/government/organisations/environment-agency/about#corporate-information

Highways England. (2021, November 16). *About us*. Retrieved from UK Government: https://www.gov.uk/government/organisations/highways-england/about

Institution of Civil Engineers: The Carbon Project. (2020). *Reducing Carbon in UK Infrastructure: Are we nearly there yet?* London: Institution of Civil Engineers.

Latham, S. M. (1984). *Constructing the Team.* London: Her Majesty's Stationery Office.

National Infrastructure Commission. (2021, November 17). *About Us*. Retrieved from National Infrastructure Commission: https://nic.org.uk/about/

Network Rail. (2021, November 16). *About us*. Retrieved from Network Rail: https://www.networkrail.co.uk/who-we-are/about-us/

Network Rail Limited. (2021). *Annual report and accounts 2021.* Network Rail.

Office for National Statistics. (2021, November 16). *Productivity in the construction industry, UK: 2021*. Retrieved from ons.gov.uk: https://www.ons.gov.uk/economy/economicoutputandproductivity/productivitymeasures/articles/productivityintheconstructionindustryuk2021/2021-10-19

Project 13. (2021, November 17). *About Us*. Retrieved from Project 13: https://www.project13.info/about-project13/

UK Government. (2020). *Construction Playbook.* London: Cabinet Office.

UK Government. (2021, November 17). Retrieved from UK Government: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/229339/construction-sector-infographic.pdf

D1 Industry Survey Result

1 Objectives

As part of the consultee engagement process for the BEIS Greenhouse Gas Removal for Linear Infrastructure project, a survey was shared across various platforms requesting initial data on biochar and enhanced mineral weathering (EMW) (the "technologies"). The objectives of this survey were:

- To reach out as widely as possible to advertise the potential opportunities presented by the technologies;
- To identify any key industry stakeholders not already identified by the project team that may need to be consulted;
- To identify any risks or opportunities for the technologies not already identified; and,
- To develop an understanding of the current industry position to the technologies in their current form.

1.1 Methodology

Platforms across which the survey was shared included:

- LinkedIn;
- The Institution of Civil Engineers reshared the LinkedIn post on their social media pages;
- Railway Industry Association; and,
- Via email to various internal and external contacts.

The survey questions and format were developed following multiple workshops, initially as part of the consultation engagement plan. This was developed with a focus on allowing key consultees to identify themselves for further more in depth discussions.

The survey and its results can be accessed at the below link:

https://forms.office.com/Pages/DesignPage.aspx#FormId=QYvkSjcBmUWGYfxkH-d76vRyUrRikf9OjZ29oFqDWm9UMTZJMTRNMVFYU09EQlc1T1A0V0lURlFCVi4u&Token=03432e6575fa4b27854151d44f3994ba

Results were also downloaded at multiple intervals and saved as excel (.csv) outputs to allow more detailed analysis.

The latest review of the survey results is provided in the following section. A discussion is also provided at the end of this document.

1 Results Breakdown by Question

This section provides a breakdown of the results by question. Some questions have been grouped together where applicable; for example Q1 asks for an opinion score between 1 and 5, and Q2 provided the option for further details.

1.2 Q1/2; Decarbonising UK Infrastructure

Q1 was: *In your opinion, how well on a scale of 1 to 5 is the decarbonising of the UK Infrastructure Sector progressing? Please indicate this on a scale of 1 to 5 with 1 being no progress, and 5 being full industry engagement.*

The average score (as of 30/10/21) was 2.3. Three scores of 1 were provided (although one of these responders noted that they were not a UK citizen), otherwise scores were all 2 or 3.

Q2 was: *If you would like to please share any additional details, feel free to use this optional space.*

Responses in this section (as of 30/10/21) were generally quite unenthusiastic. Several responses noted that more could be done to "accelerate". Another common theme was that "industry seems to be at different engagement levels", with one applicant asking "Who is coordinating this?". This suggests that there is not sufficient industry penetration from any over-arching industry bodies. This is a commonly encountered theme due to the fractured nature of the engineering industry; for example the Institution of Civil Engineers is one of the largest industry representatives but only has 80,000 members globally (Designing Buildings, 2020).

A respondent from Viridis Industries noted that substantial investment and market awareness needs to be created for commercial manufacture of biochar. This agrees with the preliminary findings of the economic analysis of biochar (see Appendix D2).

There is a sense that there is a move towards incorporating carbon concerns as Business As Usual (BAU). For example; "There are positive and encouraging moves towards decarbonising but it will take a little time to filter through".

1.3 Q3/4: Known Biochar Uses in Infrastructure

Q3 was: *Are you aware of the potential for production and use of Biochar for CO2 capture and storage?*

56% of respondents (7 of 16 as of 29/10/21) were aware of the potential use of biochar for CO_2 capture.

Q4 was: *If you would like to please share any additional comments relating to your understanding of biochar's potential for CO2 capture (e.g. the level of your understanding, specific areas of risk or opportunity, or points you would like to see developed), feel free to use this optional space.*

8 of respondents provided further details. All were those who answered “yes” to Q3.

Awareness ranged from those newly aware of biochar (one noted that they had been made aware of biochar from a presentation from the consortium); to biochar plant companies.

Viridis Industries noted that they were making progress with researching “bio / organic feedstocks”. The respondent noted that Viridis Industries had plants in the “Far East, South Africa, and feasibility studies being carried out in Florida, Columbia, Suriname and Brazil”. The plants were noted to be modular and could process feedstocks of up to 2 tonnes per hour. They noted that they believed CORC’s endorsement by the UN would boost the biochar industry in the near future. It was not clear what this referred to.

Viridis Industries seem to run pyrolysis machine use, although their website is not entirely clear (Viridis Industries, 2021). They are a global company.

1.4 Q5/6: Known Biochar Uses in Infrastructure

Q5 was: *Are you aware of any situations where Biochar has been considered for use within verges, drainage, landscaping areas or for other applications within infrastructure schemes?*

Four of the 16 respondents (as of 29/10/21) responded “yes” to this question.

Q6 was: *If you would like to please share any additional details, feel free to use this optional space.*

Four respondents (as of 29/10/21) provided additional information. All were those who answered “yes” to Q5. Three reported using biochar within an infrastructure context. Uses included:

- 1 tonne into a septic system;
- Within drip lines;
- In water trenches;
- In soccer fields;
- In green roofs;
- Storm drainage filtration;
- Biofilters;
- Runoff from farms – it is assumed that this was use was to address runoff from farms, but further context was not provided.

A link was also provided to a Swedish project: “From Rest to Best” (Rest till Bast, 2021); which produced biochar from various waste streams for various uses. Most of the website’s reports were in Swedish, so it was not possible to ascertain how large the operation was, but publications were provided indicating an ambition to replicate the model globally.

This project is similar to Pyrocore, based in south-west England. Pyrocore has developed several pyrolysis machines, however their business model is based on pyrolyzing waste principally to produce energy (rather than biochar) (Pyrocore, 2021).

1.5 Q7/8: Possible Issues Preventing the Use of Biochar

Q7 was: *Are you aware of any issues which might limit the potential to use Biochar in this way?*

Five of the 16 respondents replied (as of 02/11/21) "yes" to this question, and 6 replied "Not sure".

Q8 was: *If you would like to please share any additional details, feel free to use this optional space.*

Six respondents provided additional detail in this space (as of 02/11/21). All five respondents who replied "yes" to Q7 provided a response, which included:

- Market acceptance;
- Technology awareness;
- Funding potentials;
- Energy balance in the feedstocks;
- The need to manage potential pollutants in the feedstock (waste from hospitals and industry was cited for this issue);
- The lack of standards to guide the use of biochar; and,
- Fire risk.

"Energy balance in the feedstocks" was referred to by one respondent, which is believed to relate to how much energy is required for the creation of biochar (from different feedstocks).

One respondent who replied "not sure" to Q7 asked in this space if there was any potential for biochar to leach contaminants into the soil or groundwater if used as a verge/drain/bund.

1.6 Q9: Potential for Biochar to Contribute to Decarbonise the Infrastructure Sector

Q9 was: *In your opinion, how much potential on a scale of 1 to 5 do you think Biochar has to contribute to the decarbonisation of the UK Infrastructure Sector? Please indicate this on a scale of 1 to 5, with 1 being no potential, and 5 being huge potential.*

The average score in response to this question was 3.88; indicating that generally biochar was felt to be a strong contender for contributing to the decarbonisation of the infrastructure sector. For a breakdown of the number for each score between 1 to 5 see Table 1. The results show a strong trend towards a huge perceived potential for biochar in the infrastructure industry.

Table 1: Number of respondents for scores 1 to 5 for Q9

Score	1	2	3	4	5
Number of respondents	1	1	2	7	5

1.7 Q10/11 Known EMW Uses in Infrastructure

Q10 was: Are you aware of the potential for the use of Enhanced Mineral Weathering for direct CO2 capture?

10 of the 16 respondents (as of 02/11/21) responded yes to this question (63%).

Q11 was: *If you would like to please share any additional comments relating to your understanding of Enhanced Mineral Weathering's potential for CO2 capture (e.g. the level of your understanding, specific areas of risk or opportunity, or points you would like to see developed), feel free to use this optional space.*

Six respondents provided additional detail in this space (as of 02/11/21). All six replied "yes" to Q10. Responses included:

- Using kelp feedstocks to make biochar;
- A concern that large amounts of dust applied to ecosystems could be damaging at scale;
- A concern that EMW is expensive and does not have a circular economy purpose;
- A note that landfills should be stopped and programs like EMW or other CO_2 capture in cement need to be investigated;
- Basalt weathering from Future Forest Company; and,
- Two respondents noted that they had heard of EMW via a recent presentation from the project team.

The effect of the dolerite fines on the environment is therefore worth investigating.

The Future Forest Company aims to remove CO_2 at scale from the atmosphere. The company achieves this by applying biochar and dolerite to land bought for reforestation. This combines the CO_2 capture potential of biochar, dolerite and reforestation (The Future Forest Company, 2021). The Future Forest Company is supported by BEIS and Innovate UK. The Future Forest Company was contacted separately for further engagement, as a rare instance of combining the use of biochar and EMW on a site.

1.8 Q12/13: Known EMW Uses in Infrastructure

Q12 was: Are you aware of any situations where the use of Enhanced Mineral Weathering has been considered for use within verges, drainage, landscaping areas or for other applications within infrastructure schemes?

Two respondents replied "yes" to this question (as of 02/11/21).

Q13 was: *If you would like to please share any details, feel free to use this optional space.*

One respondent provided additional detail in this space. This respondent replied "yes" to Q12. They noted that they had had an enquiry about using dolerite as part of a vegetated wall system, which they also noted could work in theory.

1.9 Q14/15: Possible Issues Preventing the Use of EMW

Q14 was: *Are you aware of any significant issues which might limit the potential to use Enhanced Mineral Weathering in this way?*

Five of the 16 respondents replied (as of 02/11/21) "yes" to this question, and 9 replied "not sure".

Q15 was: *If you would like to please share any details, feel free to use this optional space.*

Seven respondents provided additional detail in this space (as of 02/11/21). All five respondents who replied "yes" to Q14 provided a response. Two respondents who replied "not sure" to Q14 provided a response, one of which was simply to note that they were unsure. The other agglomerated responses included:

- Lack of market acceptance;
- Poor funding availability;
- Cost (including a note that a respondent did not think that EMW would be cost-competitive);
- Resources;
- Particle size (including a note that one respondent's specification required less than 8% fines overall; it is expected that this refers to clay and silt particles);
- Whole-life carbon cost being greater than carbon benefit;

- Concern that the EMW carbon removal process is too slow to justify for carbon capture purpose; and,
- Concern on how difficult it is to include EMW within the MCHW (Manual of Contract Documents for Highway Works – a key code for the design and specification of materials on highway projects).

1.10 Q16/Q17: Potential for EMW to Contribute to Decarbonise the Infrastructure Sector

Q16 was: *How much potential on a scale of 1 to 5 (with 1 being no potential, and 5 being huge potential), do you think Enhanced Mineral Weathering has to contribute to decarbonisation of the UK Infrastructure Sector?*

The average score in response to this question was 3.1; indicating that generally EMW was felt to be a good contender for contributing to the decarbonisation of the infrastructure sector. For a breakdown of the number for each score between 1 to 5 see Table 2.

Table 2: Number of respondents for scores 1 to 5 for Q16

Score	1	2	3	4	5
Number of respondents	2	3	4	6	1

Q17 was: *If you would like to please share any additional details, feel free to use this optional space.*

Four respondents provided additional detail in this space (as of 02/11/21). One respondent who provided a score of 1 to Q16 noted that they were unsure (possibly skewing the result). Two other respondents who provided a score of 2 to Q16 provided additional detail, with the only other responder providing a score of 4 to Q16. Agglomerated responses include:

- EMW could be part of a wider strategy;
- EMW would require subsidies to be viable;
- A presumption that airflow would be needed ("or 'acid rain' capture so not sure how well this sits in a roadside setting");
- A note that details of EMW has been passed on to a project team in Northumberland where it might be of use.

1.11 Q18/19: Known EMW Uses in Pilots

Q18 was: *Are you aware of any situations where a mixture of Biochar and Enhanced Mineral Weathering materials has been considered or used, within an infrastructure scheme or pilot?*

Three of the 16 respondents replied (as of 03/11/21) “yes” to this question.

Q19 was: *If you would like to please share any additional details, feel free to use this optional space.*

Three respondents provided additional detail in this space (as of 03/11/21). All were those who responded “yes” to Q18. Responses included:

- A reference to previous answers, however previous answers were focused only on biochar;
- A note that it was believed “this mixed approach is being used in the construction of roads and in cement”; and,
- The Future Forest company (discussed in 1.7).

The answers therefore do not provide definitive details of any previously unknown pilot.

1.12 Q20/21: Combining Biochar and EMW

Q20 was: *Are you aware of any issues that may occur from combining a mixture of Biochar and an Enhanced Mineral Weathering solution?*

One of the 16 respondents replied (as of 03/11/21) “yes” to this question.

Q21 was: *If you would like to please share any additional details, feel free to use this optional space.*

One respondent provided additional detail in this space (as of 03/11/21). The respondent also responded “yes” to Q18.

A question was left in this space, which was “Taking the individual comments above, is the mixture any more effective/carbon or energy efficient and is it practical in a roadside setting?” This project team has found that there are recommended limits on how much biochar should be combined with topsoil (for example); therefore by adding further EMW additional carbon removal is achieved.

Once begun, pyrolysis is a self-perpetuating process, making the production of biochar energy-efficient. Dolerite (which undergoes EMW) is a by-product from certain mines in the UK, so has no additional energy requirements for its production. Both materials have been assessed in a whole-life manner to assess their lifetime carbon removal (i.e. transport and production costs have been included), and both provide net carbon removal for the pilot sites proposed.

A key variable for sites in the future is the transportation distance of the materials, which if extremely large may cause the materials to be carbon-negative.

1.13 Q22/23: Blockers to Decarbonising the Construction and Engineering Industry

Q22 was: *Are you aware of any blockers limiting the decarbonisation of the construction and engineering industry?*

Nine of the 16 respondents replied (as of 03/11/21) “yes” to this question.

Q23 was: *If you would like to please share any additional details, feel free to use this optional space.*

Eight respondents provided additional detail in this space (as of 03/11/21). All were those who responded “yes” to Q18. Responses included:

- Precedent;
- Cost;
- Energy cost;
- The culture of the engineering industry being cost-driven, therefore unless clients specify carbon reduction measures at tender stage then uptake will be very low;
- Cement;
- Knowledge;
- Health and Safety;
- Standards;
- Planning; and,
- The possibility of planning requiring decarbonisation measures to fuel decarbonisation in engineering.

This question provides a useful insight into the state of play of the engineering industry. For example, 50% of the eight respondents mentioned cost. Three of the eight referred in some way to “culture” or the “status quo” being a blocker to the uptake of these materials. Three of the eight referred to “knowledge” in some way.

This aligns with the fragmented nature of the industry – it is quite difficult for a new technology to gain a foothold as there is no easy place to advertise it. The industry is furthermore relatively risk-averse, so precedent is extremely important as proof of concept, safety, and ideally cost-effectiveness. The industry also often works to very small profit margins, with typical materials (for example concrete) being very cheaply available, well-understood, and therefore difficult to displace.

1.14 Q24 to Q27: Respondent Details

Q24 was: *For our data analysis, could you please share your current employer?*

14 of the 16 respondents replied (as of 03/11/21) responded to this question. The current employers reported were:

- Arup;
- Ithaka Institute (an international not-for-profit research foundationinto carbon removal strategies. It has a focus on biochar, and its suggested quality codes have been examined for use on the pilot project);
- Viridis Industries (pyrolysis machinery supplier in America);
- Phoenix Biochar cic (community interest company that pyrolyzes trees affected with ash dieback);
- Institution of Civil Engineers;
- ECOERA AB (Swedish biochar production company);
- Biomass Controls PBC (American company specialising in creating biochar from farm slurry);
- PyroCore Ltd (pyrolysis machinery supplier);
- HBB Geosales Ltd (Geosynthetic reinforcement specialist);
- Vertase fli (a land remediation specialist company); and,
- Highways England (now National Highways).

Q25 was: *For our data analysis, could you please share your current role?*

14 of the 16 respondents replied (as of 03/11/21) responded to this question. Roles reported include:

- Senior Engineer;
- US Director;
- Director;
- CEO;
- Director of ICE Wales Cymru;
- Executive Chair;
- Business Development;
- Project Director;
- Geotechnical Adviser;
- Senior Geotechnical Adviser; and,
- Principal Geotechnical Adviser.

Q26 was: *We are keen to seek views of those in the industry. Would you be happy for us to get in touch with you to discuss your responses and find out more about this project?*

12 of the 16 respondents replied (as of 03/11/21) “yes” to this question.

Q27 was: *Please provide a name and e-mail address and / or contact phone number so we may talk to you further (for example: Jane Doe; jane.doe@domain.co.uk; 01234567890).*

14 of the 16 respondents provided their details in response to this question. These will not be shared to preserve data confidentiality, but the number of people keen to respond indicates a strong keenness to remain in contact with this project.

1.15 Q28: Any Other Comments

Q28 was: *Do you have any other comments?*

Seven respondents provided additional detail in this space (as of 03/11/21). Responses included:

- Notes of thanks;
- Notes with best wishes or good luck;
- Notes where the respondent felt they had limited knowledge (and were concerned about skewing the results of the survey);
- A keenness to get involved from Pyrocore (Note that they are being considered as potential suppliers of pyrolysis equipment to produce biochar for the Phase 2 Pilot Project);
- A note that “population and consumption is the real problem”;
- A strong note of support for biochar: “14 of the 17 UN SDGs are related to solutions biochar can solve. We need to be looking holistically at what solutions can have the greatest impact”; and,
- A note providing links on blogs about how biochar can be used in a landscape:
    - http://fingerlakesbiochar.com/dwelling-on-drawdown-draining-the-swamp/

      This provided a case study where a small amount of biochar was added to a site drain in America. Regulatory difficulties were referenced as providing a cap to the amount of biochar that could be legally used in the works. Whether the biochar was used as an engineering material is not clear, and the case study is not strong enough to allow industry to take up the material to a greater extent.
    - http://fingerlakesbiochar.com/dwelling-on-drawdown-part-iii-c-walls/

This provided a case study where biochar was applied to the surface of interior walls of a building in America as part of plastering. The Ithaka Institute in Switzerland was cited as inspiration for this use. This use may be less relevant for infrastructure projects, but is innovative nonetheless.

2 Results Discussion

2.1 Industry Responses

The survey was shared as widely as possible with industry and received 16 respondents in total (as of 9/11/21). While this is a disapointingly small number of respondents, it did provide evidence from a number of different industry sectors. It also provides a good example of the difficulty achieving penetration into and engagement with the industry. Despite a successful request to the Institution of Civil Engineers (ICE) (considered to be a major industry knowledge-sharing body) to reshare the survey, few responses were retrieved.

2.2 Industry Reception

The results suggest slightly higher levels of awareness and understanding of biochar than EMW. For example, the average score of 3.06 in response to Q16 (potential for EMW to contribute to decarbonisation) versus 3.88 for Q9 (potential for biochar to contribute to decarbonisation). Additionally, in the space for any other comments (Q28) two respondents noted that their expertise was in biochar, and one noted that their lack of knowledge about dolerite may skew the result of EMW-related questions. This was expected due to the comparative difference in TRL (6 for EMW, 7 for biochar).

The general survey responses to the potential use of these technologies was positive, for example the many wishes of good luck or offers for further follow-up contact. However, it is likely that the industry respondents were generally parties already aware of (or enthusiastic about) the biochar and/or EMW technologies. This is likely to have skewed the results.

Conversely, the lack of respondents also suggests that the majority of industry may not be interested in the technologies. This is not possible to confirm however, and other industry evidence suggests the opposite. For example, the recent “Carbon Champions” launched by the ICE to promote decarbonisation achievements and methodologies within the engineering industry (Institution of Civil Engineers, 2021), and the key aim of eliminating carbon emissions highlighted by various reports by the National Infrastructure Commission (National Infrastructure Commission, 2017).

This project could apply to the Carbon Champion ICE initiative, which would help advertise the technologies to industry.

2.3 Additional Consultees in Industry

A number of respondents to the survey were those running pyrolysis plants, for example Pyrocore and Viridis Industries. These respondents have been contacted for follow up discussions and also considered as potential suppliers of pyrolysis machinery for the pilot project (see Appendix B, B2 and B3 for further details).

Several respondents from Highways England (now National Highways) also provided additional information following a follow up workshop with the key technical specialists at National Highways about the potential use of the technologies (details are provided in Appendix D).

There were very few additional consultees identified from the survey. The Future Forest Company was mentioned in this survey, and have also been contacted separately (see Appendix D).

2.4 Technical Information Gained

Case Studies of Historic Uses

A key aim of the survey was to identify any instances or case studies of the use of either biochar or EMW (or both, combined) that were not already known of by the project team. While few responses were retrieved, some case studies were provided that were not previously known of:

- 1 tonne into a septic system;
- Within drip lines;
- In water trenches;
- In soccer fields;
- In green roofs;
- Storm drainage filtration;
- Removal of trees affected with ash dieback, and conversion into biochar (by Phoenix Biochar (Phoenix Biochar CIC, 2021))
- Biofilters; and,
- Using kelp feedstocks to make biochar.

These uses were all small scale or private uses of biochar. There were no previous examples of the use of EMW reported, although one respondent noted that had enquired about using EMW as part of a vegetated wall system. This was noted to work in theory, and it is assumed this was therefore not completed in practice.

Although these uses were generally on a small scale, this demonstrates that use of biochar in construction projects is something that is already occurring with early adopters. Although additional information on these uses was identified (for example as provided in Section 1.15), it generally did not include a verification of the captured carbon process. These data sets were too small to draw any conclusions. The examples therefore support a TRL of approximately 7 for biochar. The TRL for EMW therefore remains at 6.

2.5 Possible Blockers

From Q22/23, 56% of respondents were aware of blockers. Blockers identified included:

- Precedent;
- Cost;
- Knowledge;
- Health and Safety; and,
- Planning.

These items are key to almost every project within the engineering industry. Most are strongly interdependent, for example with more precedent comes increased industry knowledge, and therefore likely improved perceptions of Health and Safety. Similarly, with more precedent the supply chain is more likely to be more efficient, reducing costs long-term (see Appendix D2 examining the wider economic setting of the technologies).

Planning (or in full, “planning permission”) is a key requirement for almost all significant industry projects. The exact details required to achieve planning permission varies from region to region (and with project size), but generally entails an environmental and procedural review of the impact of the project by the local planning body (or at a higher level for particularly large projects). Achieving planning permission is never a certainty, and with recent environmental challenges by the public to infrastructure projects (for example at Heathrow Airport’s third runway) is an increasingly risky, costly goal for industry projects.

While this increased public scrutiny increases the focus of industry on new carbon-removal technologies such as biochar and EMW, without precedent and the related validation testing it may be difficult to satisfy planning requirements, or provide the information required to support the establishment of codes for application. The current regulatory mechanisms and permitting policies would also need to be developed to enable wider uptake, for example the permitting landscape with DEFRA. This is examined further in Appendix E.

A good option for raising the awareness and knowledge of a new material is by including it with relevant established codes of practice and industry guidance documentation. However, developing new codes of practice or amending existing codes and guidance will take time. The material additionally needs to be well-understood, with parameters tested and verified and potential risks well understood and documented. It will need to be demonstrated that potential risks are acceptable or can be effectively mitigated before new approaches can be considered for inclusion within any codes. It may be that neither biochar nor dolerite have a sufficient available evidence base to adequately verify their potential for carbon removal via the uses being proposed currently. Additional data is likely to be required to allow the development of definitive guidance. Monitored pilot projects are considered to be required in order to gather reliable data.

Amajor beneficial impact of Phase 2 would be providing additional data and precedent for the successful application of these technologies. This would in turn help to release other key blockers for the wider use of this technology in industry at scale.

References

Albert, R. (1938). On the use of fine debris from stone quarries for the improvement of poor forest soils. *Forstarchiv, 14*, 229-240.

Beerling, D., Kantzas, E., Lomas, M., Wade, P., Eufrasio, R., Renforth, P., . . . Bawart. (2020). Potential for large-scale CO2 removal via enhanced rock weathering with croplands. *Nature, 583*, 242-248. Retrieved from https://doi.org/10.1038/s41586-020-2448-9

Beerling, D., Leake, J., Long, S., Scholes, J., Ton, J., Nelson, P., . . . Hansen, J. (2018). Farming with crops and rocks to address global. *Nature Plants, 4*, 138-147. Retrieved from https://doi.org/10.1038/s41477-018-0108-y

Brazil. (2013). *Lei 12.890/2013 de 10 de dezembro de 2013 - Altera a Lei no 6.894, de 16 de dezembro de 1980.* Retrieved from https://www.planalto.gov.br/ccivil_03/_ato2011-2014/2013/lei/l12890.htm

Breedon. (2020). *Aggregate Property and Declared Values.* Breedon Group.

Casas, C., Schaschke, C., Akunna, J., & Jorat, M. (2019). Dissolution experiments on dolerite quarry fines at low liquid-to-solid ratio: a source of calcium for MICP. *Environmental Geotechnics*. Retrieved from https://doi.org/10.1680/jenge.19.00067

de Oliveira, P. C., & Zuquette, L. V. (2014). Evaluation of weathering of basaltic lithotypes based on pH, electrical conductivity, and point-load strength tests. *REM Revista Escola de Minas*. Retrieved from https://doi.org/10.1590/S0370-44672014000100002

De Villiers, O. (1962). Soil rejuvenation with crushed basalt in Mauritius. Part I - Consistent results of worldwide interest. *International Sugar Journal*, 363-364.

De Villiers, O. (1962). Soil rejuvenation with crushed basalt in Mauritius. Part II - The fertility of basalt and its nutritional effects. *International Sugar Journal*, 3-5.

Deneele, D., Dony, A., Colin, J., Herrier, G., & Lesueur, D. (2021). The carbonation of a lime-treated soil: experimental approach. *Materials and Structures*. Retrieved from https://doi.org/10.1617/s11527-021-01617-w

Designing Buildings. (2020, November 18). *Institution of Civil Engineers ICE.* Retrieved from Designing Buildings: The Construction Wiki: https://www.designingbuildings.co.uk/wiki/Institution_of_Civil_Engineers_ICE

Glasser, F. (2011). 4 - Application of inorganic cements to the conditioning and immobilisation of radioactive wastes. In *Handbook of Advanced Radioactive Waste Conditioning Technologies* (pp. 67-135). Woodhead Publishing Series in Energy. Retrieved from https://doi.org/10.1533/9780857090959.1.67

GOV UK. (2012). *Guidance on the Managed Aggregate Supply System.* London: Department for Communities and Local Government. Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/14721/2238394.pdf

GOV UK. (2012). *Quarry processes: process guidance note 3/08.* GOV UK. Retrieved from https://www.gov.uk/government/publications/quarry-processes-process-guidance-note-308

GOV UK. (2020, October 9). *Claim relief from Aggregates Levy for industrial and agricultural processes*. Retrieved from GOV.UK: https://www.gov.uk/guidance/claim-relief-from-aggregates-levy-for-industrial-and-agricultural-processes

GOV UK. (n.d). *Environmental taxes, reliefs and schemes for businesses*. Retrieved from GOV.UK: https://www.gov.uk/green-taxes-and-reliefs/aggregates-levy

Gribble, C. (1974). The dolerites of Ardnamurchan. *Scottish Journal of Geology, 10*, 71-89. Retrieved from https://doi.org/10.1144/sjg10010071

Guillou, G., & Davies, R. (2004). *Combination of BasalticQuarry Fines with Organic Process Residues for the Development of Novel Growing Media.* Mineral Solutions. Retrieved from http://www.mineralsolutions.co.uk/casestud.php

Hensel, J. (1894). *Bread From Stones.* Philadelphia: A.J. Tafel. Retrieved from https://archive.org/details/breadfromstones00hens

Hilf, H. (1938). The manuring of poor soils with basalt grit. *Forstarchiv, 14,* 93-101.

ifu Hamburg. (1998-2019). Umberto LCA+. Hamburg, Germany.

Institution of Civil Engineers. (2021, November 11). *ICE Carbon Champions: Send us your success stories*. Retrieved from Institution of Civil Engineers: https://www.ice.org.uk/news-and-insight/latest-ice-news/carbon-champions-send-us-your-success-stories

Kelland, M., Wade, P., Lewis, A., Taylor, L., Sarkar, B., Andrews, M., . . . Beerling, D. (2020). Increased yield and CO2 sequestration potential with the C4 cereal Sorghum bicolor cultivated in basaltic rock dust-amended agricultural soil. *Global Change Biology, 26*(6), 3658-3676. Retrieved from https://doi.org/10.1111/gcb.15089

Kolosz, B., Sohi, S., & Manning, D. (2019). CASPER: A modelling frameworkj to link mineral carbonation with the turnover of organic matter in soil. *Computers & Geosciences*, 58-71. Retrieved from https://doi.org/10.1016/j.cageo.2018.12.012

Leaman, D. (1975). Form, mechanism, and control of dolerite intrusion near Hobart, Tasmania. *Journal of the Geological Society of Australia*, 175-186.

Lefebvre, D., Goglio, P., Williams, A., Manning, D., Carlos de Azevedo, A., Bergmann, M., . . . Smith, P. (2019). Assessing the potential of soil carbonation and enhanced weathering through Life Cycle Assessment: A case study for Sao Paulo State, Brazil. *Journal of Cleaner Production, 233*, 468-481.

Lefebvre, D., Goglio, P., Williams, A., Manning, D., Carlos de Azevedo, A., Bergmann, M., . . . Smith, P. (2019). Assessing the potential of soil carbonation and enhanced weatheringthrough Life Cycle Assessment: A case study for Sao Paulo State, Brazil. *Journal of Cleaner Production, 233*, 468-481.

Lefebvre, D., Goglio, P., Williams, A., Manning, D., Carlos de Azevedo, A., Bergmann, M., . . . Smith, P. (2019). Assessing the potential of soil carbonation and enhanced weatheringthrough Life Cycle Assessment: A case study for Sao Paulo State, Brazil. *Journal of Cleaner Production,* *233*, 468-481. Retrieved from https://doi.org/10.1016/j.jclepro.2019.06.099

Li, X., Zhang, C., Xiao, H., Jiang, W., Qian, J., & Li, Z. (2021). Reducing Compressibility of the Expansive Soil by Microbiological-Induced Calcium Carbonate Precipitation. *Advances in Civil Engineering*. Retrieved from https://doi.org/10.1155/2021/8818771

Liu, N., Bond, G., Abel, A., McPherson, B., & Stringer, J. (2005). Biomimetic sequestration of CO2 in carbonate form: Role of produced waters and other brines. *Fuel Processing Technology*, 1615-1625. Retrieved from https://doi.org/10.1016/j.fuproc.2005.01.008

Manning, D. (2004). *Exploitation and Use of Quarry Fines.* Retrieved from http://www.mineralsolutions.co.uk/mist2.php

Manning, D. (2021). *Response to Department for Business, Energy and Industrial Strategy, and HM Treasury call for evidence on greenhouse gas removals.* Newcastle University.

Manning, D., & Theodoro, S. (2020). Enabling food security through use of local rocks and minerals. *The Extractive Industries and Society*, 480-487. Retrieved from https://doi.org/10.1016/j.exis.2018.11.002

Manning, D., Renforth, P., Lopez-Capel, E., Robertson, S., & Ghazireh, N. (2013). Carbonate precipitation in artificial soils produced from basaltic quarry fines and composts: An opportunity for passive carbon sequestration. *International Journal of Greenhouse Control, 17*(1), 309-317. Retrieved from https://doi.org/10.1016/j.ijggc.2013.05.012

Mitchell, C., Mitchell, P., & Pascoe, R. (2008). Quarry fines minimisation: Can we really have 10mm aggregate with no fines? Retrieved from https://core.ac.uk/display/62240

Moosdorf, N., Renforth, P., & Hartmann, J. (2014). Carbon Dioxide Efficiency of Terrestrial Enhanced Weathering. *Environmental Science Technology, 48*(9), 4809-4816. Retrieved from https://doi.org/10.1021/es4052022

National Infrastructure Commission. (2017). *Congestion, Capacity, Carbon: Priorities for National Infrastructure.* London: National Infrastructure Commission.

Phoenix Biochar CIC. (2021, November 11). *Phoenix Biochar*. Retrieved from Phoenix Biochar: https://phoenixbiocharcic.co.uk/

Pradhan, S., Tiwari, B., Kumar, S., & Barai, S. (2019). Comparative LCA of recylced and natural aggregate concrete using Particle Packing Method and conventional method of design mix. *Journal of Cleaner Production*, 679-691.

Pyrocore. (2021, October 29). *Pyrocore*. Retrieved from Pyrocore: https://pyrocore.com/

Randall, B. (1989). Dolerite-pegmatites from the Whin Sill near Barrasford, Northumberland. *Proceedings of the Yorkshire Geological Society, 47*(3), 249-265. Retrieved from http://dx.doi.org/10.1144/pygs.47.3.249

REMIN. (2018). *REMIN*. Retrieved from https://www.reminscotland.com/

Renforth, P. (2012). The potential of enhanced weathering in the UK. *International Journal of Greenhouse Gas Control, 10*, 229-243. Retrieved from https://doi.org/10.1016/j.ijggc.2012.06.011

Renforth, P. (2012). The potential of enhanced weathering in the UK. *International Journal of Greenhouse Gas Control, 10*, 229-243. Retrieved from https://doi.org/10.1016/j.ijggc.2012.06.011
Renforth, P. (2019). The negative emission potential of alkaline. *Nature*, 1-8. Retrieved from https://doi.org/10.1038/s41467-019-09475-5
Renforth, P. (2019). The negative emission potential of alkaline materials. *Nature Communications*. Retrieved from https://doi.org/10.1038/s41467-019-09475-5
Renforth, P., & Henderson, G. (2017). Assessing ocean alkalinity for carbon sequestration. *Reviews of Geophysics*. Retrieved from https://doi.org/10.1002/2016RG000533
Renforth, P., Manning, D., & Lopez-Capel, E. (2009). Carbonate precipitation in artificial soils as a sink for atmospheric carbon dioxide. *Applied Geochemistry, 24*(9), 1757-1764. Retrieved from https://doi.org/10.1016/j.apgeochem.2009.05.005
Renforth, P., Manning, D., & Lopez-Capel, E. (2009). Carbonate precipitation in artificial soils as a sink for atmospheric carbon dioxide. *Applied Geochemistry*, 1757-1764. Retrieved from https://doi.org/10.1016/j.apgeochem.2009.05.005
Rest till Bast. (2021, October 29). *Travel to Best*. Retrieved from Rest till Bast: https://biokol.org/
Rosado, L., Vitale, P., Penteado, C., & Arena, U. (2017). Life cycle assessment of natural and mixed recycled aggregate production in Brazil. *Journal of cleaner production*, 634-642.
SILL. (2021). *Whin Sill Grassland Roof*. Retrieved from SILL: National Landscape Discovery Centre: https://www.thesill.org.uk/exhibition/grassland-roof/
Sloane, D. (1991). *Some physical properties of dolerite.* Division of Mines and Mineral Resources - Report 1991/22. Retrieved from http://www.mrt.tas.gov.au/mrtdoc/dominfo/download/UR1991_22/UR1991_22.pdf
The Future Forest Company. (2021, November 2). *The Future Forest Company*. Retrieved from The Future Forest Company: https://thefutureforestcompany.com/
The Royal Society. (2018). *Report: Greenhouse Gas Removal*. Royal Academy of Engineering.
Viridis Industries. (2021, October 29). *Viridis Industries Home*. Retrieved from Viridis Industries: https://viridisindustries.com/
Washbourne, C.-L., Renforth, P., & Manning, D. (2012). Investigating carbonate formation in urban soils as a method for capture and storageof atmospheric carbon. *Science of the Total Environment*, 166-175. Retrieved from http://dx.doi.org/10.1016/j.scitotenv.2012.05.037

D2 Economics Review

1 Executive Summary

This paper provides an initial assessment of the economic viability of integrating GHG removal technologies – biochar and dolerite materials – within linear infrastructure projects. These materials have not yet been proven economically viable in an infrastructure setting at scale.

A short overview of the technologies is provided for reference but is documented more thoroughly within the "Overview of Biochar and Enhanced Mineral Weathering Technologies" note (University of Edinburgh and Newcastle University, 2021).

This economics review considers the potential cost and barriers to implementation of the technologies based on current market analysis, assessment of potential future trends and identification of key economic risks which may influence large-scale viability.

Summary: Biochar

- There is a growing consensus that soil biochar amendments are highly effective in removing CO_2 from the atmosphere. However, the chemical properties of biochar and its net carbon footprint are widely variable and depend on several things, including the feedstock used, production method, and, the resulting chemical composition.
- There is a wide cost range (£/tonne of biochar), which is reflective of the immaturity of the market and lack of established production facilities.
- Initial supplier enquires (in the UK) suggest that three hundred tonnes of biochar could be supplied at a price of £90,000 (plus VAT at 20%), indicating a price of £300 (plus VAT) per tonne of raw biochar including delivery.
- Marginal carbon abatement costs range from £-144/tCO_2 (indicating profit) when produced at the largest scales with commercial organic waste to £208/tCO_2 when produced at low scales using imported Canadian forestry (chips). (Shackley, 2011).
- Initial engagement with the market demonstrates a high price for biochar which suggests that use will be constrained to high-end specialty markets until biochar can be produced more cost effectively.
- Several barriers exist to widespread adoption, including information failures (relating to verifiable benefits) and high upfront investment costs.
- The extent to which biochar implementation can produce other benefits (including increased crop yields, increased soil water retention thus flood risk alleviation etc) not yet quantifiable, but numerous studies have shown positive effects.
- Market growth for biochar is expected to be positive but there may be feedstock supply issues with competing demands for energy generation from biomass.

- The largest challenges or risks identified, across the value chain, for biochar's application as a GHG removal technology are feedstock supply in manufacturing (given competing uses); cost effective production; and sustainable transportation and distribution of feedstock supply along with end biochar product. Creating a sustainable biochar market will require overcoming several barriers to entry and scale-up to make biochar an affordable and competitive option for use in linear infrastructure projects.

Summary: EMW

- The production of quarry fines and quarrying operation by-products is well established given they have existed in some form since quarrying's inception. Currently, there is little/no market for quarry fines due to them being regarded as waste products that quarry companies have struggled to sell.
- There is no single "quarry gate" price, with price dependent on the size of the load and delivery charge (dependent on distance to site). Additionally, there is uncertainty as to whether the Aggregates Levy, of £2 per tonne, will be applied to material that is being used for carbon capture.
- Assuming the Aggregates Levy is waived, and assuming a typical CO2 removal rate of 230kg/tonne via enhanced rock weathering, results in a cost of £50 per tonne of CO2 removed or £180 per tonne of carbon removed. The price will go up and the net CO2 removed will decrease with distance from the quarry to site. This remains the one of the biggest challenges to application of EMW to linear infrastructure projects i.e., sustainable / low carbon transportation of material from quarry to site.

Contents

2 Summary of technologies

2.1 Biochar

Biochar is a high-carbon form of charcoal that is produced by pyrolyzing organic matter (e.g., wood chips). This means heating the organic matter at extremely high temperatures in the absence of oxygen to convert the material to biochar – a stable form of carbon that can't easily escape into the atmosphere. The carbon captured through pyrolysis is estimated to reside within the biochar for between five hundred and several thousand years.

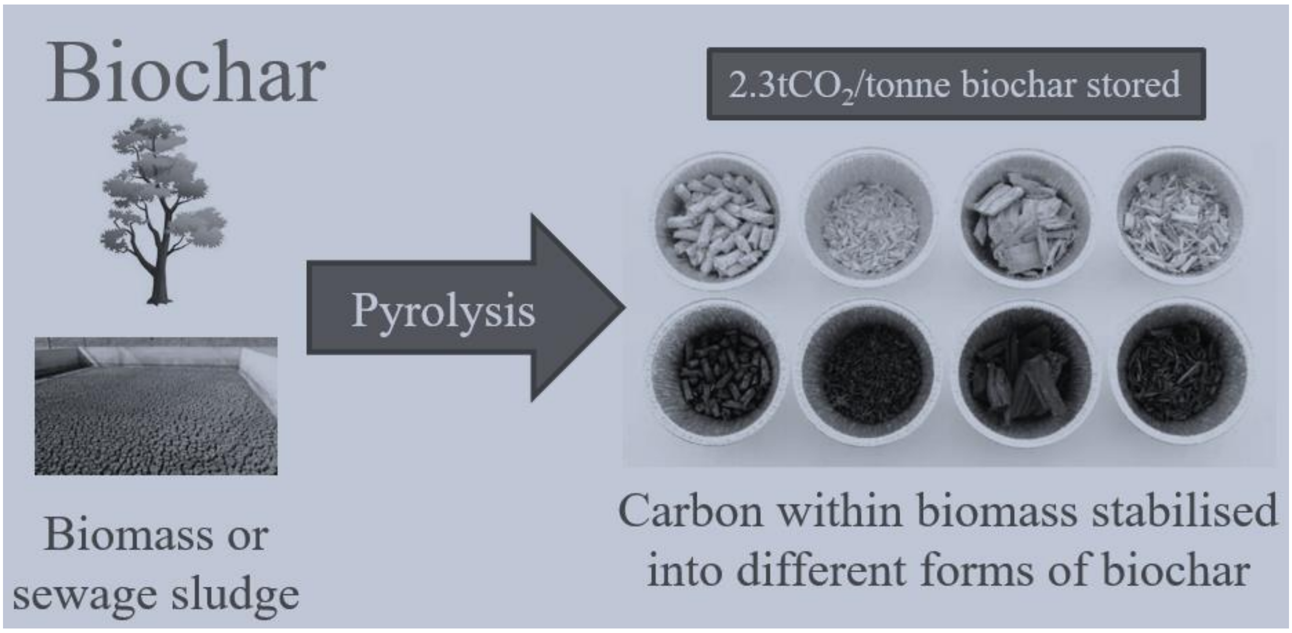


Figure 1: Overview of biochar generation process

2.2 Dolerite or Basalt (via enhanced mineral weathering)

Weathering is a natural process whereby rocks are broken down by rainwater, extreme temperatures, or human activity. The process takes place over millions of years and constitutes an important carbon sink through the natural oceanic carbon cycle. Enhanced mineral weathering is the speeding up of this natural process, whereby rocks – such as dolerite or basalt – are ground into fine particles and spread across large areas of land.

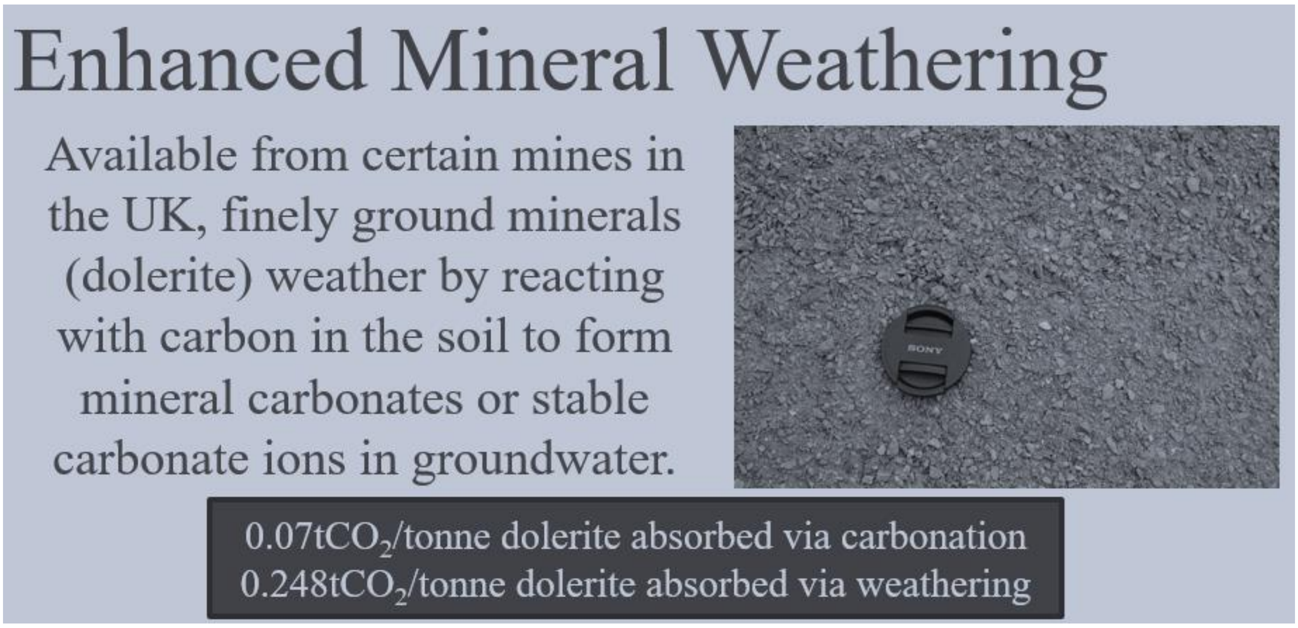


Figure 2: Overview of dolerite (or basalt) enhanced mineral weathering

2.3 Integration into linear infrastructure projects

In terms of the use of these GHG removal technologies / materials in linear infrastructure projects, two options are considered:

- Integration within earthworks: slopes, embankments, and bunds; and
- Integration within drainage and verges.

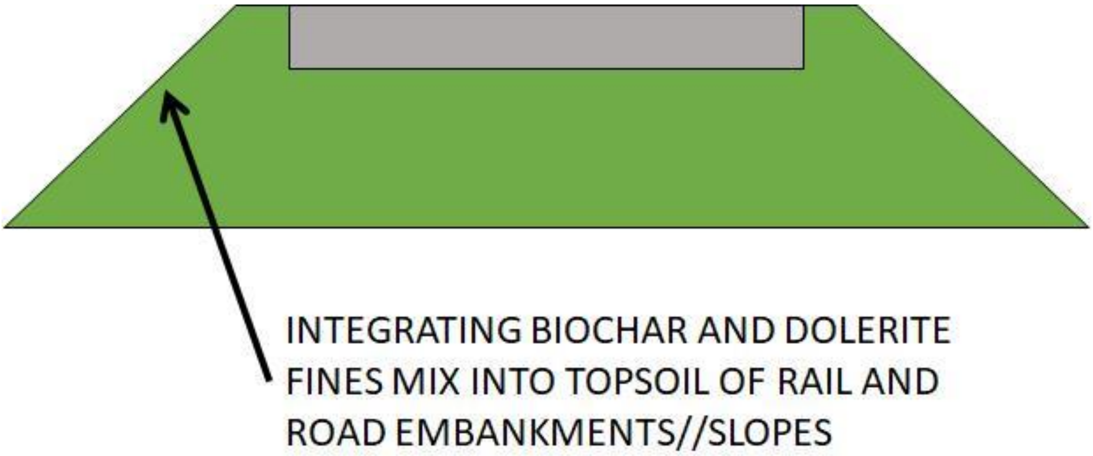


Figure 3: Overview of typical dolerite and biochar location within an embankment or slope

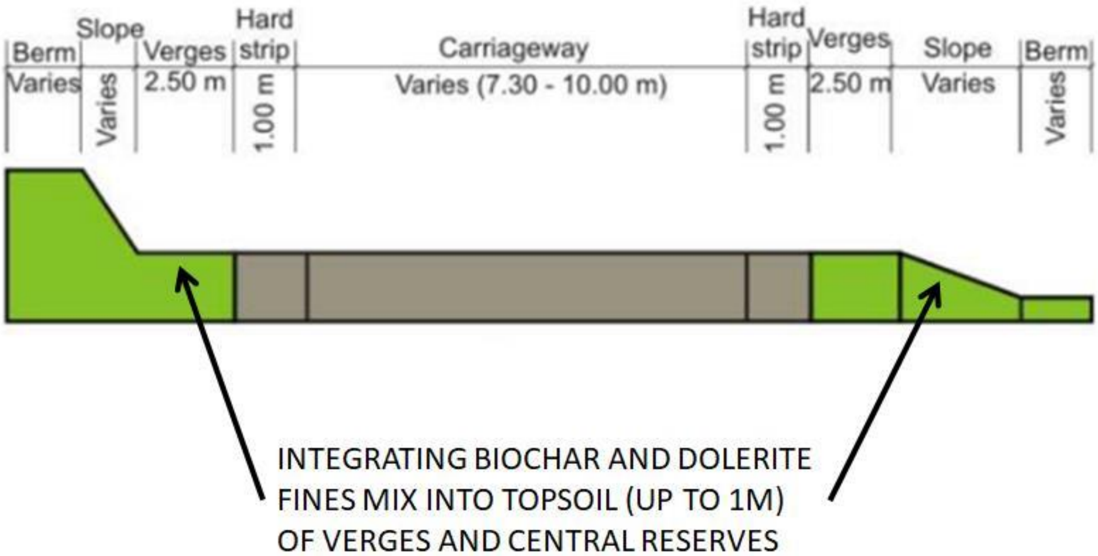


Figure 4: Overview of typical dolerite and biochar location within verges and central reserves

However, rather than potential engineering solutions, this note focuses on economic costs and barriers to implementation based on current market analysis, assessment of potential future trends and identification of key economic risks which may influence large-scale viability.

3 Biochar Market Analysis

3.1 Market maturity and value

The biochar market is at its nascent stage and is very fragmented, comprising a few small- scale producers. Nevertheless, the biochar market is of significant value and is expected to grow over the coming years.

- The European biochar market is worth £0.45 billion and is set to reach £0.56 billion by 2025 (EBRI, 2021).
- The US biochar market was valued at $97.8 million in 2019 and is expected to grow by 18.6% per annum between 2020 and 2027 (GVR Market Analysis, 2021).
- North America is currently recorded as the highest consumer of biochar. However, the Asia Pacific region is expected to witness extremely high growth owing to large, developing agriculture sectors in growing economies, such as China and India.
- The global biochar market is projected grow from $502.3m in 2020 to $699m by 2026 at 8.6% per annum (MENAFN, 2020).

Approximately 150 companies, mostly small garden supply and specialty retailers, sell biochar worldwide. There are emerging opportunities, but overall, the market is in its infancy, production is limited, and cost is at a premium (GVR Market Analysis, 2021).

A 2013 report by the IBI (International Biochar Initiative, 2013) showed that the majority of the global market share comes from the US (65%), followed by Europe (25%), Asia (7%), and Africa (3%). Ninety percent (90%) of commercial activity is focused on small specialty retail markets—mostly nursery and garden centres. A small percentage (10%) is focused on larger scale markets, such as agriculture or land remediation projects.

3.2 Market trends

Figure 5 summarises the current biochar market trends.

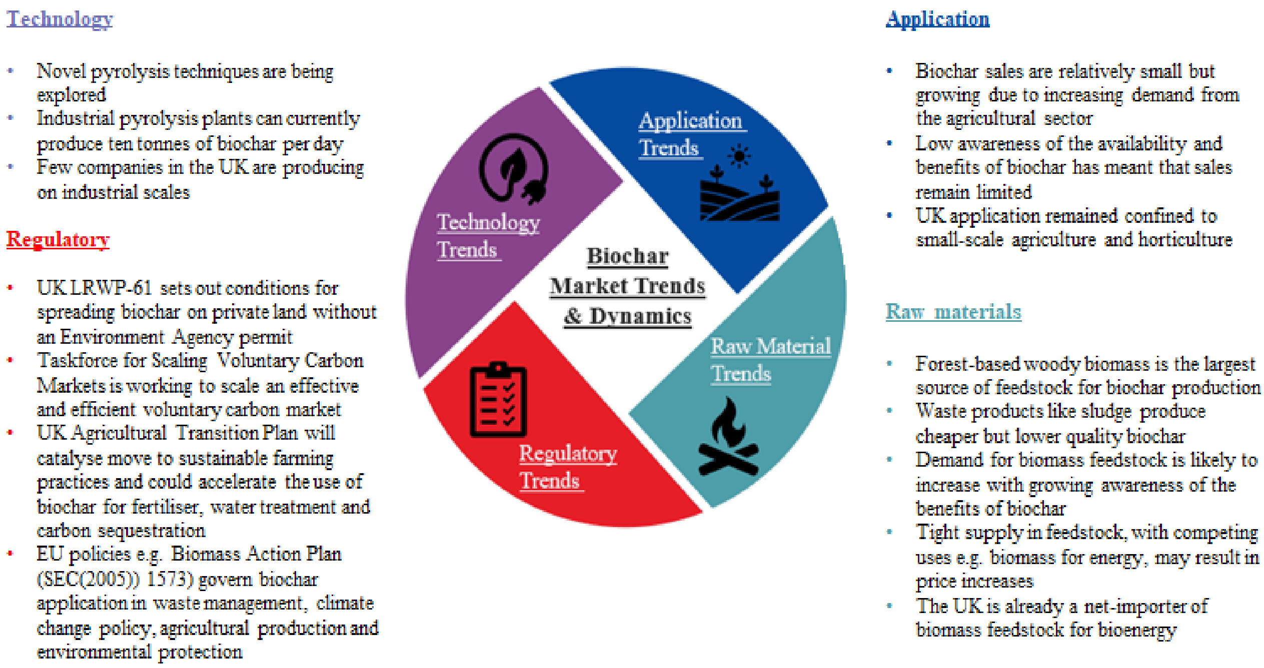


Figure 5: Biochar Market Trends Analysis

Demand & market drivers

Currently, biochar is primarily used in agriculture for its soil amending properties. Biochar provides essential benefits, such as soil carbon enhancement and sequestration, increased soil fertility and improved crop nutrient availability, reduction in nutrient leaching, increased water holding capacity, and improvements in soil aeration, porosity, and structure for agricultural productivity.

Biochar is yet to realise its full potential in the agriculture sector and is expected to be increasingly important in securing food supplies for a growing global population. Water treatment has also been identified as another important application of biochar in the near term.

Supply & Market Barriers

Biochar is an emerging sector and there are very few producers engaged in production around the globe. There are currently high barriers to entry, given (i) high upfront investment costs, combined with (ii) lack of awareness (information failures) of the benefits of biochar.

Lack of robust data on benefits is a barrier to investment, and therefore there has been little funding from banks and/or venture capitalists. Personal capital is the main source of funding biochar projects, resulting in the biochar industry being dominated by small business (entrepreneurs and start up enterprises) producing very small volumes.

The growth prospects for biochar as a product are expected to be positive owing to the high potential of biochar in agriculture and water treatment. Biochar manufacturers are expected to expand their production facilities supported by an increase in the number of pyrolysis equipment manufacturing companies (e.g., Phoenix Energy and Pacific Pyrolysis).

Lack of awareness and financial constraints, coupled with low demand in certain regions, have resulted in some companies exiting the market over the past few years. For example, Australia has witnessed the closure of biochar production facilities owing to low demand (mainly because of low adoption rates by farmers).

The cost / price difference between pure biochar products (which comprise over 95% carbon and are much more expensive to produce) and blended biochar products is expected to be a major hurdle for biochar producers.

Cost / Price Analysis

Biochar costs are comparatively uncertain, with cost dependent upon the presence of locally available feedstock. The cost of producing biochar (whole supply chain) in the UK ranges between £-148 per tonne of biochar (indicating that through electricity generation and circumvented gate fees, producing biochar could be profitable) and £389 per tonne of biochar produced (when produced at mid-scale using the most expensive form of biomass) (Shackley, 2011). This is equivalent to a provisional carbon abatement value of -£144 - £208 per tCO_2.

Initial supplier enquires (in the UK) suggest that three hundred tonnes of biochar could be supplied at a price of £90,00 (plus VAT at 20%), indicating a price of £300 (plus VAT) per tonne of raw biochar including delivery.

Biochar prices are expected to increase gradually owing to tight feedstock supply. Woody biomass, which constitutes most of the feedstock for biochar production, is an important resource for other processes e.g., heat generation, cooling, and electricity production.

In the near term, due to price point, biochar will likely only be used in high-end specialty markets, but there is growing interest in developing biochar into new products that take advantage of its unique chemical properties. For example, wastewater treatment facilities purchase thousands of tonnes of activated carbon annually to help absorb potential contaminants and reduce odours. Biochar has been shown to be a cost-effective alternative.

3.3 Market supply / value chain

The biochar value chain consists of the following:

Figure 6: Biochar Value Chain

- *Raw material and feedstock supply:* Biochar can be made from any organic feedstock with high carbon content. The most economical sources for biochar are agricultural and forest residues (wood residues are the most common feedstock). A report on the increase in tree planting/afforestation in Scotland and its effects on biomass availability for biochar production suggests an increase in available feedstock for biochar production of 75-150 per cent (Ahmed, 2011).

- *Manufacturing:* Feedstock supply can be a major issue for biochar manufacturers owing to the transportation cost and the ability to procure continuously (given small production volumes).

- *Distribution / logistics:* The logistics of wood harvesting provides economic advantages. Compared to field-by-field processing of crops, wood can be processed at centralised sawmills or chip mills. Wood residues can thereby be obtained relatively easily and cost effectively. In addition, wood is drier than most agricultural crops, making wood industry residues less expensive and more sustainable to transport.

- *End*-use *application*: biochar has many potential end-use applications. Typically, biochar can be used across four broad and overlapping objectives: waste management, soil improvement, energy production, and climate change and water pollution mitigation (Lehmann & Joseph, 2015).

    - Waste management - numerous companies such as Splainex Ecosystems in the Netherlands and PyroCore in England are orientated towards reducing material waste and the pollutant impact of sewage and non-recyclable waste through pyrolysis (Splainex Ecosystems, 2018) (Pyrocore, 2021).

    - Soil improvement - biochar properties can be tailored to specific soils and may target crop productivity through increased nutrient availability, improved soil-water properties, plant-microbe relations, and soil remediation (Lehmann & Joseph, 2015). Integration into pavement subsurface in Stockholm, Sweden, has also improved the growth of urban trees (Embren, 2016).

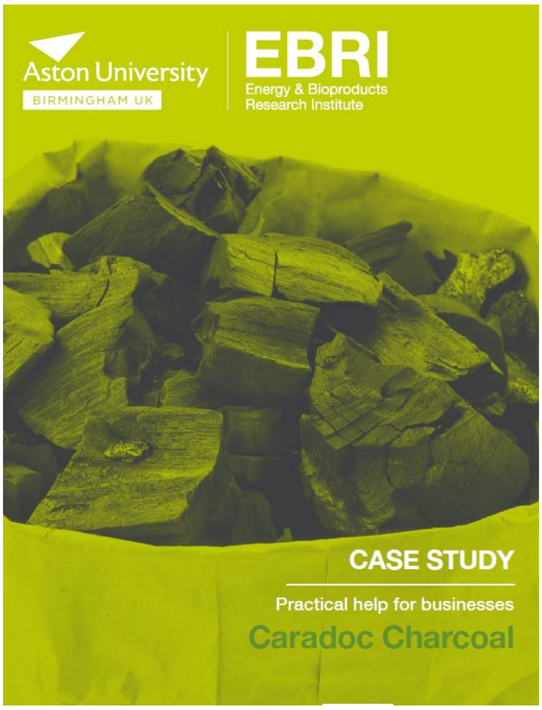
- Energy production – biochar is a flammable by-product that can be used in energy production. Before shutting down due to consequences of the Fukushima disaster, the Tokyo Sludge Pyrolysis Plant was producing 9.86 kt of biochar per year to be used as fuel in a nearby power station (Mašek, Sohi, Kiso, & Boag, 2010). The Splainex Ecosystems and PyroCore also generate energy from the processed waste, and pyrolysis can be orientated to energy production as with the BIOMACON boiler systems (BIOMACON, 2021).
- Climate change mitigation and water pollution - the carbon in biochar decomposes very slowly and is therefore suitable for sequestering carbon, with a mean residence time of approximately 556 ± 483 years (Wang, et al., 2015).

The largest challenges or risks identified, across the value chain, for biochar's application as a GHG removal technology are feedstock supply in manufacturing (given competing uses); cost effective production; and, sustainable transportation and distribution of feedstock supply along with end biochar product. Creating a sustainable biochar market will require overcoming several barriers to entry and scale-up to make biochar an affordable and competitive option for use in linear infrastructure projects.

3.4 Case Study Analysis

The case study (EBRI, 2021) provides an example of the type of support that might be required to overcome existing market barriers.

3.4.1 Caradoc Charcoal Ltd



Caradoc Charcoal Ltd – an independent family business based in the Stretton Hills, Shropshire – produces sustainably sourced British charcoal. The wood-derived biochar left over from the production process could be brought to market, increasing biochar supply as well as providing additional revenue for the business. As part of their business development, the company has explored the merits of biochar and considered new market opportunities, ranging from utilisation of biochar as a soil enhancer to pelletising it for fuel. The Energy & Biproducts Research Institute at Aston University (EBRI) supported this firm in this analysis, assessing the potential for commercialisation. EBRI found that that firm's biochar meets the criteria set by the International Biochar Initiative (IBI), Biochar Quality Mandate (BQM) and European Biochar Certification (EBC), which makes it suitable for market applications, such as soil enhancement.

Source: http://bioenergy-for-business.org/wp-content/uploads/2020/12/Caradoc-Charcoal-EBRI-Case-Study.pdf

Overcoming the information failures relating to the wider GHG benefits of biochar and potential emerging market opportunities is an important first step in increasing supply for larger-scale application in infrastructure schemes.

3.5 Risk Analysis

Risks identified include:

- Feedstock supply: Pure biomass electricity production, which already makes up 12% of total UK energy production, is likely to increase. This will increase demand for biomass feedstock, directly competing with biochar manufacturing for supply. Prices of feedstock increased by ~8% in winter compared to spring/summer (Ricardo Energy & Environment, 2018), presenting the risk of seasonal price fluctuations.
- Competition for land use: if land is purposely used to grow feedstock/biomass that will be processed into biochar, the opportunity cost will be high as the land could have been utilised a) to grow food/crops, or b) for other wider environmental benefits c) for sustainable development.
- Limited availability of pyrolysis facilities for biochar production and thus potentially high production costs. Investment into increasing the number of pyrolysis facilities is essential for biochar to be scaled and utilised effectively in infrastructure projects.
- Lack of economic and policy incentives or a guaranteed market for biochar which could limit market growth. This ties into Environment Agency guidance on biochar which allows one tonne per hectare in the absence of a permit, whereas scientific advice recommends 50 tonnes per hectare.
- Government has signalled it does not intend to offer any form of fuel cost indexation for biomass projects in the low carbon CFDs. This means increasing biomass fuel prices could greatly disadvantage the profitability of biochar operations, simultaneously shrinking private investor appetite due to volatility (Deloitte, 2020).
- Uncertainties regarding UK Government-backed certification of biochar for GHG removal.

3.6 Summary

There is a growing consensus that soil biochar amendments are highly effective in removing CO_2 from the atmosphere. However, the chemical properties of biochar and its net carbon footprint are widely variable and depend on several things, including the feedstock used, production method and the resulting chemical composition.

There is a wide cost range (£/tonne of biochar), which is reflective of the immaturity of the market and lack of established production facilities. Marginal carbon abatement costs range from £-144/tCO_2 (indicating profit) when produced at the largest scales with commercial organic waste to £208/tCO_2 when produced at low scales using imported Canadian forestry (chips). (Shackley, 2011).

Initial engagement with the market demonstrates a high price for biochar which suggests that use will be constrained to high-end specialty markets until biochar can be produced more cost effectively. Several barriers exist to widespread adoption, including information failures (relating to verifiable benefits) and high upfront investment costs. Market growth for biochar is expected to be positive but there may be feedstock supply issues with competing demands for energy generation from biomass.

4 Enhanced Mineral Weathering

4.1 Market Maturity and Value

The production of quarry fines and quarrying operation by-products is well established given they have existed in some form since quarrying's inception. Currently, there is little/no market for quarry fines due to them being regarded as waste products that quarry companies have struggled to sell. This has resulted in many quarries stockpiling quarry fines. Further, large demand for high-specification fine aggregate, and aggregate with specific shape characteristics, has resulted in an increase in fines production. Quarries in remote places find it particularly hard to find a market for fines given associated transportation costs.

4.2 Market Trends

Figure 7 summarises current EMW market trends.

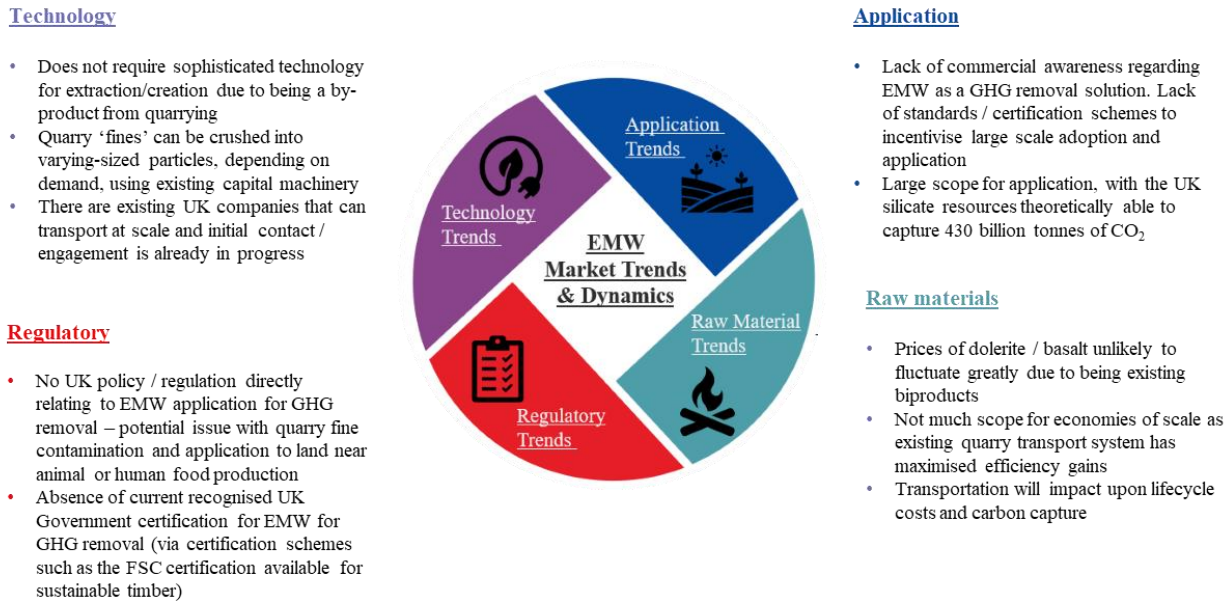


Figure 7: EMW Market Trends Analysis

Demand and Market Drivers

Taxes on waste disposal and on production of primary aggregate materials have encouraged the use of secondary materials as aggregate, but have depressed the market for quarry fines. Furthermore, large demand for high specification fine aggregate, and aggregate with specific shape characteristics, has resulted in an increase in fines production (Mitchell, 2009).

Current end uses for quarry fines include application for the purpose of:

- Soil Improvement: Dolerite and basalt fines are a commonly used as a soil remineraliser. Crushed volcanic rock for soil remineralisation is available to purchase in small quantities in the UK from REMIN (Scotland) Ltd. In October 2013, rock dust remineralisers became a category of agriculture input in Brazil by Law 12.890. Regulations were later established s for defining, classifying, specifying and guaranteeing, registering, packaging, labelling and marketing the remineralisers for agriculture (Manning & Theodoro, Enabling food security through use of local rocks and minerals, 2020).

- Climate change mitigation: enhanced terrestrial weathering and mineral carbonation were recently acknowledged by the The Royal Society Greenhouse Gas Removal report as feasible, large-scale greenhouse gas removal options (The Royal Society, 2018). Extensive field work has validated the CO_2 capture potential of weathering and carbonation processes of silicate rich materials (Manning & Renforth, 2012) (Kelland et al., 2020). The residence time of dissolved inorganic carbon in the ocean as a result of enhanced weathering is approximately 100,000 years, and the carbon dating of soil formed carbonates as a result of mineral carbonation indicates residence times upwards of 30,000 years (Renforth & Henderson, 2017).
- Cement additive: large stockpiles of quarry fines in the UK are incentivising research seeking to integrate them into mass-scale construction practices, like their use as a fine aggregate replacement in cement paste and mortar (Dobiszewska & Beycioglu, 2017).

Supply and Market Barriers

Many UK quarries have large stockpiles of quarry fines due to them not having significant economic value and therefore being regarded as a waste product (Mitchell, 2009).

In the UK there are 1,300 quarries that produce roughly 300 million tonnes of aggregates each year (BGS, 2021). These quarries also produce 50 million tonnes of quarry fines annually, and a further 20 million tonnes of quarry waste (BGS, 2021).

Due to the quarrying industry's consolidation over hundreds of years, there is not much scope for cost savings via economies of scale due to production efficiencies already being all but maximised through existing technologies and processes.

Cost / Price Analysis

There is no single "quarry gate" price, with price dependent on the size of the load and delivery charge (dependent on distance to site). Additionally, there is uncertainty as to whether the Aggregates Levy, of £2 per tonne, will be applied to material that is being used for carbon capture.

The US Geological Survey estimates a guide price of US$12 per tonne for crushed rock aggregates of any type, which is assumed to be conservative. As such, a price assumption of around £12 per tonne (plus £2 per tonne Aggregates Levy, which may be waived) is considered appropriate. Assuming the Aggregates Levy is waived, assuming a typical CO_2 removal rate of 230kg/tonne via enhanced rock weathering, results in a cost of £50 per tonne of CO_2 removed or £180 per tonne of carbon removed. The price will go up and the net CO_2 removed will decrease with distance from the quarry to site.

Risk Analysis

Risks identified include (but are not limited to):

- Feedstock supply: as outlined in section 3.2.2, there is no overall supply constrained but the 'quality' of stockpiles needs to be considered carefully with respect to land type for application.

  There are two types of land where the quarry fines are used:

  (1) As components of the bulld or as topsoil within the immediate controlled land take of the site (i.e., no unauthorised public access).

  (2) Areas adjacent to the site where faming might take place or where the public might have uncontrolled access.

  Accreditation is different depending on type of land. Stockpiled quarry fines may be contaminated and not suitable for infrastructure projects on land near food production. Some suppliers e.g.REMIN have a track record of beneficial use of dolerite and the organic certifications of safety for food production.

- Cost uncertainty: unclear whether the Aggregates Levy would apply. Additionally, there is no single "quarry gate" price with this being dependent on load and distance to site (delivery charge).

- Sustainable transportation: clearly there is a major challenge associated with transporting material sustainably from quarry to site. If there is a large distance between the two the transportation costs will be higher and particularly 'expensive' in carbon terms.

4.3 Summary

Compared to biochar, there are less supply barriers to the use of dolerite and basalt in EMW for carbon capture and GHG removal. Taxes on waste disposal and on production of primary aggregate materials have encouraged the use of secondary materials as aggregate but have depressed the market for quarry fines. This has resulted in large stockpiles of quarry fines.

However, one constraint on supply might be the quality of the fines in terms of contamination levels. If a site is close to land used for food production then more rigorous accreditation standards (relating to the quarry fines) will be required and this may result in a higher priced material, due to inability to use cost-effective stockpiled material.

Currently the price is relatively low. The US Geological Survey estimates a guide price of US$12 per tonne for crushed rock aggregates of any type, which is assumed to be conservative. As such, a price assumption of around £12 per tonne (plus £2 per tonne Aggregates Levy, which may be waived) is considered appropriate.

Assuming the Aggregates Levy is waived, and assuming a typical CO_2 removal rate of 230kg/tonne via enhanced rock weathering, results in a cost of £50 per tonne of CO_2 removed or £180 per tonne of carbon removed. The price will go up and the net CO_2 removed will decrease with distance from the quarry to site. This remains the one of the biggest challenges to application of EMW to linear infrastructure projects i.e., sustainable / low carbon transportation of material from quarry to site.

References

A.W. Jenkinson Forest Products. (2021). *Our Products*. Retrieved from A.W. Jenkinson Forest Products: https://www.awjenkinson.co.uk/sales/our-products/

ABUNDIA. (2021). Retrieved from ABUNDIA - Global Impact Group: https://www.abundiaimpact.com/

Adekiya, A., Olayanju, T., Ejue, S., Alori, E., & Adegbite. (2020). Contribution of Biochar in Improving Soil Health. In B. Giri, & A. Varma (Eds.), *Soil Health* (pp. 99-113). Springer International Publishing. Retrieved from https://doi.org/10.1007/978-3-030-44364-1_6

Ahmed. (2011). The potential role of biochar in combating climate change in Scotland: an analysis of feedstocks, life cycle assessment and spatial dimensions. *Journal of environmental planning and management*.

Amos, W. (1998). *Report on Biomass Technology*. National Renewable Laboratory. Retrieved from https://www.nrel.gov/docs/fy99osti/25885.pdf

Azzi, E., Karltun, E., & Sundberg, C. (2019). Prospective life cycle assessment of large-scale biochar production and use for negative emissions in Stockholm. *Environmental Science and Technology, 53*(14), 8466-8476. Retrieved from https://doi.org/10.1021/acs.est.9b01615

Bakshi, S. B., & Laird, D. (2018). Quantification and characterization of chemically-and thermally-labile and recalcitrant fractions. *Chemosphere*, 247-255. Retrieved from https://doi.org/10.1016/j.chemosphere.2017.11.151

Barry, D., Barbiero, C., Briens, C., & Berruti, F. (2019). Pyrolysis as an economical and ecological treatment option for municipal sewage sludge. *Biomass and Bioenergy, 122*, 472-480. Retrieved from https://doi.org/10.1016/j.biombioe.2019.01.041

Beesley, L., Moreno-Jiménez, E., Gomez-Eyles, J., Harris, E., Robinson, B., & Sizmur, T. (2011). A review of biochars' potential role in the remediation, revegetation and restoration of contaminated soils. *Environmental Pollution, 159*(12), 3269-3282. Retrieved from https://doi.org/10.1016/j.envpol.2011.07.023

BGS. (2021). *Aggregates*. Retrieved from Minerals UK: Quarry Fines (nerc.ac.uk)

Biogreen. (n.d.). *Models and Capacities*. Retrieved from Biogreen: https://www.biogreen-energy.com/industrial-pyrolysis-capacities

BIOMACON. (2021). *Downloads*. Retrieved from BIOMACON: https://www.biomacon.com/downloads?lang=en

BIOMACON. (2021). *Home*. Retrieved from Biomacon: https://www.biomacon.com/?lang=en

Biomass UK. (2021). *Home*. Retrieved from Biomas UK: https://www.biomass-uk.org/

BlackCarbon. (n.d.). *BlackCarbon unit*. Retrieved from BlackCarbon: http://www.blackcarbon.dk/Unit

Boateng, A. (2016). Rotary Kiln Minerals Process Applications. In A. Boateng, *Rotary Kilns (Second Edition)* (pp. 231-264). Butterworth-Heinemann. Retrieved from https://doi.org/10.1016/B978-0-12-803780-5.00010-1

Boateng, A., Garcia-Perez, M., Mašek, O., Brown, R., & del Campo, B. (2015). Biochar Production Technology. In J. Lehmann, & S. Joseph, *Biochar for Environmental Management* (pp. 63-87). Routledge.

Brassard, P., Godbout, S., Pelletier, F., Raghavan, V., & Palacios, J. (2018). Pyrolysis of switchgrass in an auger reactor for biochar production: A greenhouse gas and energy impacts assessment. *Biomass and Bioenergy, 116*, 99-105. Retrieved from https://doi.org/10.1016/j.biombioe.2018.06.007

Brewer, C., Chuang, V., Masiello, C., Gonnermann, H., Gao, X., Dugan, B., . . . Davies, C. (2014). New approaches to measuring biochar density and porosity. *Biomass and Bioenergy*. Retrieved from http://dx.doi.org/10.1016/j.biombioe.2014.03.059

Budai, A., Zimmerman, A., Cowie, A., Webber, J., Singh, B., Glaser, B., . . . Joseph, S. (2013). *Biochar Carbon Stability Test Method: An assessment of methods to determine biochar carbon stability*. International Biochar Initiative. Retrieved from https://www.biochar-international.org/wp-content/uploads/2018/06/IBI_Report_Biochar_Stability_Test_Method_Final.pdf

Carbon Gold. (2021). *About*. Retrieved from Carbon Gold: https://www.carbongold.com/our-story/

Carbonfuture. (2021). *Portfolios*. Retrieved from Carbonfuture: https://platform.carbonfuture.earth/balancer/portfolios

Cha, J., Park, S., Jung, S.-C., Ryu, C., Jeon, J.-K., Shin, M.-C., & Park, Y.-K. (2016). Production and utilization of biochar: A review. *Journal of Industrial and Engineering Chemistry, 40*, 1-15. Retrieved from https://doi.org/10.1016/j.jiec.2016.06.002

Chun, Y., Lim, M., & Yoshikawa, K. (2012). Development of high-efficiency rotary dryer for sewage sludge. *Journal of Material Cycles and Waste Management*. Retrieved from http://dx.doi.org/10.1007/s10163-012-0040-6

Cong, H., Mašek, O., & Zhao, L. (2018). Slow Pyrolysis Performance and Energy Balance of Corn Stover in Continuous Pyrolysis-Based Poly-Generation Systems. *Energy & Fuels*. Retrieved from http://dx.doi.org/10.1021/acs.energyfuels.7b03175

Coskun, C., Bayraktar, M., Oktay, Z., & Dincer, I. (2009). Energy and exergy analyses of an industrial wood chips drying process. *International Journal of Low-Carbon Technologies*, 224-229. Retrieved from https://doi.org/10.1093/ijlct/ctp024

Crombie, K., & Mašek, O. (2015). Pyrolysis biochar systems, balance between bioenergy and carbon sequestration. *GCB Bioenergy*, 349-361. Retrieved from https://doi.org/10.1111/gcbb.12137

Cross, A., & Sohi, S. (2013). A method for screening the relative long-term stability of biochar. *GCB Bioenergy, 5*(2), 215-220. Retrieved from https://doi.org/10.1111/gcbb.12035

Cruz, D. (2012). *Production of Bio-coal and Activated Carbon from Biomass*. The University of Western Ontario. Retrieved from https://ir.lib.uwo.ca/etd/1044/

Del Giudice, A., Acampora, A., Santangelo, E., Pari, L., Bergonzili, S., Guerriero, E., . . . Gallucci, F. (2019). Wood Chip Drying through the Using of a

Mobile Rotary Dryer. *energies*. Retrieved from http://dx.doi.org/10.3390/en12091590

Deloitte. (2020). *Knock on Wood: Is Biomass the Answer to 2020?* London: Deloitte.

Designing Buildings. (2020, November 18). *Institution of Civil Engineers ICE*. Retrieved from Designing Buildings: The Construction Wiki: https://www.designingbuildings.co.uk/wiki/Institution_of_Civil_Engineers_ICE

Dobiszewska, M., & Beycioglu, A. (2017). Investigating the Influence of Waste Basalt Powder on . *Materials Science and Engineering*.

Dong, X., Singh, B., Li, G., Lin, Q., & Zhao, X. (2019). Biochar increased field soil inorganic carbon content five years after application. *Soil and Tillage Research, 186*, 36-41. Retrieved from https://doi.org/10.1016/j.still.2018.09.013

EBC. (2012). *European Biochar Certificate - Guidelines for a Sustainable Production of Biochar.* European Biochar Foundation. Retrieved from https://www.european-biochar.org/en/ct/2-EBC-guidelines-documents-for-the-certification

EBC. (2020). *Certification of the carbon sink potential of biochar.* European Biochar Certificate - The Ithaka Institute. Retrieved from https://www.european-biochar.org/en/ct/139-C-sink-guidelines-documents

EBRI. (2021, August). *Eneegy and Bioproducts Research Institute*. Retrieved from https://bioenergy-for-business.org/charcoal-and-biochar/#.

Elliot-Smith, G. (2020). *Waste incineration and the UK Emissions Trading Scheme*. Retrieved from Zero Waste Europe: https://zerowasteeurope.eu/2020/11/waste-incineration-and-the-uk-emissions-trading-scheme/

Embren, B. (2016). Planting Urban Trees with Biochar. *The Biochar Journal*.

Embrén, B. (2016). Planting Urban Trees With Biochar. *The Biochar Journal*, 44-47. Retrieved from www.biochar-journal.org/en/ct/77

Enders, A., Hanley, K., Whitman, T., Joseph, S., & Lehmann, J. (2012). Characterization of biochars to evaluate recalcitrance and agronomic performance. *Bioresource Technology, 114*, 644-653. Retrieved from https://doi.org/10.1016/j.biortech.2012.03.022

ENplus. (2015). *Quality Certification Scheme For Wood Pellets Part 4: Sustainability Requirements.* Brussels: European Pellet Council. Retrieved from https://enplus-pellets.eu/en-in/

Environment Agency. (2009). *The Incineration of Waste (EPR 5.01).* Environment Agency. Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/297004/geho0209bpio-e-e.pdf

EU. (2010). *Directive 2010/75/EU of the European Parliament and of the Council of 24 November 2010 on industrial emissions (integrated pollution prevention and control) Text with EEA relevance.* The European Union. Retrieved from http://data.europa.eu/eli/dir/2010/75/oj

European Biochar Certificate. (2021). *Guidelines for a Sustainable Prodiuction of Biochar.* Arbaz. Retrieved from https://www.european-biochar.org/media/doc/2/version_en_9_3.pdf

European Biomass Industry Association. (2021). *Wood Pelleting*. Retrieved Jun 22, 2021, from https://www.eubia.org/cms/wiki-biomass/biomass-pelleting/wood-pelleting/

Firth, S., & Jones, V. (2019). *Rapid Evidence Assessment: Evidence Review on the effect of Pyrolysis and/or Gasification of Biosolids on Antimicrobial Resistance in the Environment.* Atkins - SNC-Lavalin. Retrieved from http://randd.defra.gov.uk/Document.aspx?Document=14768_WT15105_REA_ImpactofpyrolysisgasificationonAMR_FINAL.pdf

Forestry Comission. (2020). *Forestry Statistics 2020 - Chapter 2: UK-Grown Timber.* Forestry Commission. Retrieved from https://www.forestresearch.gov.uk/documents/7772/Ch2_Timber_FS2020.pdf

ForestryCommission. (2020). *Forestry Statistics 2020: Chapter 2- UK grown timber*. Retrieved from GOV.UK: https://data.gov.uk/dataset/2c373ffb-4e8c-4c81-8056-8c2db299ab43/forestry-statistics-2020-uk-grown-timber

Gambles, I. (2019). *GOV.UK*. Retrieved June 18, 2021, from https://forestrycommission.blog.gov.uk/2019/10/29/trees-for-zero/

GOV. (2020). *Direct Air Capture and Greenhouse Gas Removal Programme.* Department for Business, Energy & Industrial Strategy. Retrieved from https://www.gov.uk/government/publications/direct-air-capture-and-other-greenhouse-gas-removal-technologies-competition

GOV. (2021, May 24). *Projects selected for Phase 1 of the Direct air capture and greenhouse gas removal programme*. Retrieved from GOV.UK: https://www.gov.uk/government/publications/direct-air-capture-and-other-greenhouse-gas-removal-technologies-competition/projects-selected-for-phase-1-of-the-direct-air-capture-and-greenhouse-gas-removal-programme

GOV UK. (2015). *2010 to 2015 government policy: low carbon technologies.* Retrieved from https://www.gov.uk/government/publications/2010-to-2015-government-policy-low-carbon-technologies/2010-to-2015-government-policy-low-carbon-technologies#appendix-6-renewable-heat-incentive-rhi

GOV UK. (2021, August 25). *Biomass Feedstocks Innovation Programme: successful projects*. Retrieved from GOV. UK: https://www.gov.uk/government/publications/apply-for-the-biomass-feedstocks-innovation-programme/biomass-feedstocks-innovation-programme-successful-projects

GOV UK. (n.d). *Biomass Suppliers List.* GOV UK. Retrieved from https://biomass-suppliers-list.service.gov.uk/about

GVR Market Analysis. (2021). *Biochar Market Analysis 2016 - 2027.* USA: Grand View Research.

Hamedani, S., Kuppens, T., Malina, R., Bocci, E., Colantoni, A., & Villarini, M. (2019). Life Cycle Assessment and Environmental Valuation of Biochar Production: Two Case Studies in Belgium. *Energies*, *12*(11). Retrieved from https://doi.org/10.3390/en12112166

Hammond, J., Shackley, S., Sohi, S., & Brownsort, P. (2011). Prospective life cycle carbon abatement for pyrolysis biochar systems. *Energy Policy, 39*(5), 2646-2655. Retrieved from https://doi.org/10.1016/j.enpol.2011.02.033

HMSO. (1993). *Clean Air Act 1993.* GOV UK. Retrieved from https://www.legislation.gov.uk/ukpga/1993/11/section/11

IBI. (2015). *Standardized Product Definition and Product Testing Guidelines for Biochar.* International Biochar Initiative. Retrieved from https://biochar-international.org/characterizationstandard/

Institution of Civil Engineers. (2021, November 11). *ICE Carbon Champions: Send us your success stories*. Retrieved from Institution of Civil Engineers: https://www.ice.org.uk/news-and-insight/latest-ice-news/carbon-champions-send-us-your-success-stories

International Biochar Initiative. (2013). *State of the Biochar Industry 2013.* USA: International Biochar Initiative .

International Biochar Initiative. (2015). *Standardized Product Definition and Product Testing Guidelines for Biochar That Is Used in Soil.* Retrieved from http://www.biochar-international.org/wp-content/uploads/2018/04/IBI_Biochar_Standards_V2.1_Final.pdf

International Biochar Initiative. (2015). *State of the Biochar Industry: Company List from 2015.* International Biochar Initiative. Retrieved from https://biochar-international.org/state-of-the-biochar-industry-2015/

IPCC. (2014). *Fifth Assessment Report of the Intergovernmental Panel on Climate Change: Climate Change 2014 Synthesis Report.* IPCC. Retrieved from https://ar5-syr.ipcc.ch/ipcc/ipcc/resources/pdf/IPCC_SynthesisReport.pdf

Ippolito, J., Cui, L., Kammann, C., Wrage-Mönnig, N., Estavillo, J., Fuertes-Mendizabal, T., . . . Borchard, N. (2020). Feedstock choice, pyrolysis temperature and type influence biochar characteristics: a comprehensive meta-data analysis review. *Biochar, 2*, 421-438. Retrieved from https://doi.org/10.1007/s42773-020-00067-x

Ippolito, J., Spokas, K., Novak, J., Lentz, R., & Cantrell, K. (2015). Biochar elemental composition. In J. Lehmann, & S. Joseph (Eds.), *Biochar for Environmental Management* (pp. 137-161). Retrieved from https://eprints.nwisrl.ars.usda.gov/id/eprint/1590/

Irish Cement. (n.d.). *Platin Works*. Retrieved from Irish Cement: https://www.irishcement.ie/about/platin/

Joseph, S., & Taylor, P. (2014). The production and application of biochar in soils. In K. Waldron, *Advances in Biorefineries* (pp. 525-555). Woodhead Publishing.

Kelland et al., . (2020). Increased yield and CO2 sequestration potential with the C4 cereal Sorghum bicolor cultivated in basaltic rock dust-amended agricultural soil. *Global Change Biology*.

Kent, T., Kofman, P., Owens, E., Coates, E., & Cooley, S. (2009). *Harvesting and processing forest biomass for energy production in Ireland.* Coford. Retrieved from http://www.coford.ie/research/thematicareaharvestingandproducts/woodenergy/forestenergy/

Khanmohammadi, Z., Afyuni, M., & Mosaddeghi, M. R. (2015). Effect of pyrolysis temperature on chemical and physical properties of sewage sludge biochar. *Waste Management and Research*, 275-283. Retrieved from https://doi.org/10.1177%2F0734242X14565210

Koga, Y., Endo, Y., Oonuki, H., Kakurata, K., Amari, T., & Ose, K. (2007). Biomass Solid Fuel Production from Sewage Sludge with Pyrolysis and

Co-firing in Coal Power Plant. *Technical Review, 44*(2). Retrieved from https://www.mhi.co.jp/technology/review/pdf/e442/e442043.pdf

Krokida, M., Marinos-Kouris, D., & Mujumdar, A. (2015). Chapter 7 - Rotary Drying. In A. Mujumdar, *Handbook of Industrial Drying* (pp. 139-161). Taylor & Francis Group. Retrieved from https://doi.org/10.1201/b17208

Laird, A. &. (2013). Quantitative Prediction of Biochar Soil Amendments by Near-Infrared Reflectance Spectroscopy. *Soil Science Journal of America*.

Land Energy. (n.d). *Delivering the UK's renewable heat objectives through wood fuel.* Retrieved from https://www.land-energy.com/uk-production/sustainability/

Lefebvre, D., Williams, A., Kirk, G., Meersmans, J., Sohi, S., Goglio, P., & Smith, P. (2021). An anticipatory life cycle assessment of the use of biochar from sugarcane residues. *Journal of Cleaner Production*. Retrieved from https://doi.org/10.1038/s41598-020-76470-y

Lehmann, J., & Joseph, S. (2015). *Biochar for Environmental Management.* Abingdon: Routledge.

Lehmann, J., & Stephen, J. (2015). Biochar for environmental management: an introduction. In J. Lehmann, & J. Stephen, *Biochar for Environmental Management* (pp. 1-15). Routledge.

Lehmann, J., Abiven, S., Kleber, M., Pan, G., Singh, B., Sohi, S., & Zimmerman, A. (2015). Persistence of Biochar in Soil. In J. Lehmann, & S. Joseph, *Biochar for Environmental Management* (pp. 235-283). Routledge.

Leng, L., Huang, H., Li, H., & Li, J. Z. (2019). Biochar stability asessment methods: A review. *Science of the Total Environment*, 210-222. Retrieved from https://doi.org/10.1016/j.scitotenv.2018.07.402

Lindgren, M., & Hansson, P.-A. (2002). PM—Power and Machinery: Effects of Engine Control Strategies and Transmission Characteristics on the Exhaust Gas Emissions from an Agricultural Tractor. *Biosystems Engineering*, 55-65. Retrieved from https://doi.org/10.1006/bioe.2002.0099

Manning, D., & Renforth, P. (2012). Passive Sequestration of Atmospheric CO2 through Coupled Plant-Mineral Reactions in Urban soils. *Environmental Sciene and Technology*.

Manning, D., & Theodoro, S. (2020). Enabling food security through use of local rocks and minerals. *The Extractive Industries and Society*.

Mašek, O., Brownsort, P., Cross, A., & Sohi, S. (2011). Influence of production conditions on the yield and environmental stability of biochar. *Fuel, 103*, 151-155. Retrieved from https://doi.org/10.1016/j.fuel.2011.08.044

Mašek, O., Brownsort, P., Cross, A., & Sohi, S. (2013). Influence of production conditions on the yield and environmental stability of biochar. *Fuel, 103*, 151-155. Retrieved from https://doi.org/10.1016/j.fuel.2011.08.044

Mašek, O., Buss, W., Roy-poirier, A., Lowe, W., Peters, C., Brownsort, P., . . . Sohi, S. (2018). Consistency of biochar properties over time and production scales: A characterisation of standard materials. *Journal of Analytical and Applied Pyrolysis*. Retrieved from https://doi.org/10.1016/j.jaap.2018.02.020

Mašek, O., Sohi, S., Kiso, J., & Boag, K. (2010). *FCO "UK Mission to Japan – biochar".*

Matuštík, J., Hnátková, T., & Kočí, V. (2020). Life cycle assessment of biuochar-to-soil systems: A Review. *Journal of Cleaner Production, 259*. Retrieved from https://doi.org/10.1016/j.jclepro.2020.120998

MENAFN. (2020). *Biochar Market in Japan; Manufacturing, Consumption, Outlook Forecast 2020-2026.* Retrieved from Nextgenreports: https://menafn.com/1100926415/Biochar-Market-in-Japan-Manufacturing-and-Consumption-Outlook-and-Forecast-2020-2026

Mitchell, C. (2009). Quarry Fines and Waste. *Quarries and Mines*.

Mohan, D., Sarswat, A., Ok, Y., & Pittman, C. (2014). Organic and inorganic contaminants removal from water with biochar, arenewable, low cost and sustainable adsorbent – A critical review. *Bioresource Technology, 160*, 191-202. Retrieved from http://dx.doi.org/10.1016/j.biortech.2014.01.120

Mohanty, S., Valenca, R., Berger, A., Yu, I., Xiong, X., Saunders, T., & Tsang, D. (2018). Plenty of room for carbon on the ground: Potential applications of biochar for stormwater treatment. *Science of the Total Environment, 625*, 1644-1658. Retrieved from https://doi.org/10.1016/j.scitotenv.2018.01.037

Morgan, H., Sohi, S., & Shackley, S. (2020). Biochar: An Emerging Carbon Abatement and Soil Management Strategy. *Environmental Science*, 1-11. Retrieved from https://doi.org/10.1093/acrefore/9780199389414.013.550

Muñoz, E., Curaqueo, G., Cea, M., Vera, L., & Navia, R. (2017). Environmental hotspots in the life cycle of a biochar-soil system. *Journal of Cleaner Production, 158*, 1-7. Retrieved from https://doi.org/10.1016/j.jclepro.2017.04.163

National Infrastructure Commission. (2017). *Congestion, Capacity, Carbon: Priorities for National Infrastructure.* London: National Infrastructure Commission.

Neemisha. (2020). Role of Soil Organisms in Maintaining Soil. In B. Giri, & A. Varma (Eds.), *Soil Health* (pp. 313-335). Springer Nature Switzerland. Retrieved from https://doi.org/10.1007/978-3-030-44364-1_17

Neves, E., Petersen, J., Bartone, R., & Heckenberger, M. (2004). The Timing of Terra Preta Formation in the Central Amazon: Archaeological Data from Three Sites. In B. Glaser, & W. Woods (Eds.), *Amazonian Dark Earths: Explorations in Space and Time* (pp. 125-133). Heidelberg: Springer-Verlag. Retrieved from https://doi.org/10.1007/978-3-662-05683-7_9

OFWAT. (2021). *Bioresearch Market Information*. Retrieved from OFWAT: https://www.ofwat.gov.uk/regulated-companies/markets/bioresources-market/bioresources-market-information/

Ofwat. (2021). *Bioresource market monitoring*. Retrieved from Ofwat: https://www.ofwat.gov.uk/regulated-companies/markets/bioresources-market/bioresources-market-monitoring/

Ofwat. (2021). *Bioresources market information*. Retrieved from Ofwat: https://www.ofwat.gov.uk/regulated-companies/markets/bioresources-market/bioresources-market-information/

Owens, E., & Cooley, S. (2013). *Calorific value of Irish woodfuels.* Coford Connects. Retrieved from http://www.woodenergy.ie/media/woodenergy/content/woodfuelsstovesandboilers/PP32.pdf

Oxford Biochar. (n.d). *Home*. Retrieved from Oxford Biochar: http://www.oxfordbiochar.com/

Pardo, G., Sarmah, A., & Orense, R. (2019). Mechanism of improvement of biochar on shear strength and liquefaction resistance of sand. *Géotechnique*, 471-480. Retrieved from https://doi.org/10.1680/jgeot.17.P.040

Phoenix Biochar CIC. (2021, November 11). *Phoenix Biochar*. Retrieved from Phoenix Biochar: https://phoenixbiocharcic.co.uk/

Puettmann, M., & Sahoo, K. (2020). Life cycle assessment of biochar produced from forest residues using portable systems. *Journal of Cleaner Production, 250*. Retrieved from https://doi.org/10.1016/j.jclepro.2019.119564

PYREG. (2021). *Our Technology*. Retrieved from PYREG: https://pyreg.com/our-technology/

PyroCore. (2021). *Demo Facility*. Retrieved from PyroCore: https://pyrocore.com/demo-facility/

Pyrocore. (2021, October 29). *Pyrocore*. Retrieved from Pyrocore: https://pyrocore.com/

Pyrocore. (2021). *Pyrocore*. Retrieved from https://splainex.com/

Pyrum Innovations. (2021). *Downloads*. Retrieved from Pyrum Innovations: https://www.pyrum.net/en/downloads/

Rajkovich, S., Enders, A., Hanley, K., Hyland, C., Zimmerman, A., & Lehmann, J. (2012). Corn growth and nitrogen nutrition after additions of biochars with varying properties to a temperate soil. *Bio Fer*, 271-284. Retrieved from https://doi.org/10.1007/s00374-011-0624-7

Ralebitso-Senior, T., & Orr, C. (2016). *Biochar Application: Essential Soil Microbial Ecology*. Elsevier. Retrieved from https://doi.org/10.1016/C2014-0-04678-3

Rasmussen, E. (2012). *BioEnergy Lists: Biochar Mailing Lists*. Retrieved from BioEnergy Lists: http://biochar.bioenergylists.org/

Renforth, P., & Henderson, G. (2017). Assessing ocean alkalinity for carbon sequestration. *Reviews of Geophysics*.

Renforth, P., Manning, D., & Lopez-Capel, E. (2009). Carbonate precipitation in artificial soils as a sink for atmospheric carbon dioxide. *Applied Geochemistry, 24*(9), 1757-1764. Retrieved from https://doi.org/10.1016/j.apgeochem.2009.05.005

Research, G. V. (2020). *Biochar Market - Market Analysis 2016-2027.* USA: Grand View Research.

Rest till Bast. (2021, October 29). *Travel to Best*. Retrieved from Rest till Bast: https://biokol.org/

Reza, M., Lynam, J., Vasquez, V., & Coronella, C. (2012). Pelletization of biochar from hydrothermally carbonized wood. *T-C Biomass*, 225-234. Retrieved from https://doi.org/10.1002/ep.11615

Ricardo Energy & Environment. (2018). *Blobal Biomass Markets.* BEIS.

Ringer, M., Putsche, V., & Scahill, J. (2006). *Large-Scale Pyrolysis Oil Production: A Technology Assessment and Economic Analysis.* National Renewable Energy Laboratory. Retrieved from https://www.nrel.gov/docs/fy07osti/37779.pdf

Rittl, T. (2015). *Challenging the claims on the potential of biochar to mitigate climate change.* Wageningen: Wageningen University. Retrieved from https://edepot.wur.nl/346239

Robb, S., & Dargusch, P. (2018). A financial analysis and life-cycle carbon emissions assessment of oil palm waste biochar exports from Indonesia for use in Australian broad-acre agriculture. *Carbon Management, 9*(2), 105-114. Retrieved from https://doi.org/10.1080/17583004.2018.1435958

Roberts, K., Brent, A., Stephen, J., Scott, N., & Lehmann, J. (2010). Life Cycle Assessment of Biochar Systems: Estimating the Energetic, Economic, and Climate Change Potential. *Environment Science Technology, 44*, 827-833. Retrieved from https://cpb-us-e1.wpmucdn.com/blogs.cornell.edu/dist/8/4308/files/2015/04/Life-Cycle-Assessment-of-Biochar-Systems-Estimating-the-Energetic-Economic-and-Climate-Change-Potential-22b0fyd.pdf

Roy, P., & Dias, G. (2017). Prospects for pyrolysis technologies in the bioenergy sector: A review. *Renewable and Sustainable Energy Reviews, 77*, 59-69. Retrieved from https://doi.org/10.1016/j.rser.2017.03.136

Schmidt, H.-P., & Taylor, P. (2014). Kon-Tiki flame curtain pyrolysis for the democratization of biochar production. *the Biochar Journal*, 14-24. Retrieved from http://www.biochar-journal.org/en/ct/39

Shackley. (2011). The feasibility and costs of biochar deployment in the UK. *Carbon Management*.

Shackley, S., & Sohi, S. (2010). *An assessment of the benefits and uses associated with the application of biochar to soil.* DEFRA. Retrieved from http://sciencesearch.defra.gov.uk/Default.aspx?Menu=Menu&Module=More&Location=None&Completed=0&ProjectID=16168

Shackley, S., Ibarrola, E., Hopkins, D., & Hammond, J. (2014). *Biochar Quality Mandate (BQM) version 1.0.* Retrieved from https://www.research.ed.ac.uk/en/publications/biochar-quality-mandate-bqm-version-10

Sharifzadeh, M., Sadeqzadeh, M., Guo, M., Borhani, T., Konda, N., Garcia, M., . . . Shah, N. (2019). The multi-scale challenges of biomass fast pyrolysis and bio-oil upgrading: Review of the state of art and future research directions. *Progress in Energy and Combustion Science, 71*, 1-80. Retrieved from https://doi.org/10.1016/j.pecs.2018.10.006

Society, R. (2016). *Greenhoue Gas Removal.* Royal Society.

Soentgen, J., Hilbert, K., von Groote-Bidlingmaier, C., Herzog-schröder, G., Erich Pabst, E., & Timpf, S. (2017). Terra preta de índio: Commodification and Mythification of the Amazonian Dark Earths. *GAIA - Ecological Perspectives for Science and Society, 26*(2), 136-143. Retrieved from https://doi.org/10.14512/gaia.26.2.18

Sohi, S., Krull, E., Lopez-Capal, E., & Bol, R. (2010). A Review of Biochar and its Use and Function in Soil. In *Advances in Agronomy* (pp. 47-82). Academic Press. Retrieved from https://doi.org/10.1016/S0065-2113(10)05002-9

Soka, O., & Oyekola, O. (2020). A feasibility assessment of the production of char using the slow pyrolysis process. *Heliyon*. Retrieved from https://dx.doi.org/10.1016%2Fj.heliyon.2020.e04346

Splainex Ecosystems. (2016). *Sewage Sludge Pyrolysis*. Retrieved from Pyrolysis Eco Thermal Technology: https://www.pyrolysis.biz/index.html

Splainex Ecosystems. (2018). *Industrial Pyrolysis*. Retrieved from Splainex Ecosystems: https://splainex.com/

Splainex Ecosystems. (2018). *Pyrolysis Plants*. Retrieved from Splainex Ecosystems: https://splainex.com/waste-pyrolysis-technology.html

Terlouw, T., Bauer, C., Rosa, L., & Mazzotti, M. (2021). Life cycle assessment of carbon dioxide removal technologies: a critical review. *Energy and Environmental Science, 14*(4), 1701-1721. doi:http://dx.doi.org/10.1039/D0EE03757E

The Future Forest Company. (2021, November 2). *The Future Forest Company*. Retrieved from The Future Forest Company: https://thefutureforestcompany.com/

The Royal Society. (2018). *Report: Greenhouse Gas Removal.* Royal Academy of Engineering.

Tigercat. (2021). *Products*. Retrieved from Tigercat: https://www.tigercat.com/product/6050-carbonator/

Tomczyk, A., Sokolowska, Z., & Boguta, P. (2020). Biochar physicochemical properties: pyrolysis temperature and feedstock kind effects. *Reviews in Environmental Science and Bio/Technology*, 191-215. Retrieved from https://doi.org/10.1007/s11157-020-09523-3

Twidale, S. (2021, July 7). *Global banks to launch voluntary carbon offset market platform*. Retrieved from Reuters: https://www.reuters.com/business/sustainable-business/global-banks-launch-voluntary-carbon-offset-market-platform-2021-07-07/

UK Biochar Research Centre. (2019). *Standard Biochars*. Retrieved June 22, 2021, from https://www.biochar.ac.uk/standard_materials.php

UK BRC. (2019). *Standard Biochars*. Retrieved June 22, 2021, from UK Biochar Research Centre: https://www.biochar.ac.uk/standard_materials.php

UK Environment Agency. (2015). *Product comparators for materials applied to land: non-waste biochar.* Retrieved from https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/404761/Product_comparators_for_materials_applied_to_land_-_biochar.pdf

UKBRC. (2021). *Standard Biochars*. Retrieved from UK Biochar Research Centre: https://www.biochar.ac.uk/standard_materials.php

UKWIN. (2021). *Why Oppose Incineration*. Retrieved from The United Kingdom Without Incineration Network: https://ukwin.org.uk/oppose-incineration/

University of Edinburgh and Newcastle University. (2021). *Overview of Biochar and Enhanced Mineral Weathering Technologies*. Bristol: Arup.

Viridis Industries. (2021, October 29). *Viridis Industries Home*. Retrieved from Viridis Industries: https://viridisindustries.com/

Wang, H., Zhang, W., Chen, L., Xu, Q., Jiang, Y., & Sun, B. (2019). Biochar induced negative priming effect on soil organic carbon mineralisation by changing the microbial community structure across plant growth stages. *Journal of Soils and Sediments*, 3340-3350. Retrieved from https://doi.org/10.1007/s11368-020-02662-8

Wang, J., Chen, Z., Xiong, Z., Chen, C., Xu, X., Zhou, Q., & Kuzyakov, Y. (2015). Effects of biochar amendment on greenhouse gas emissions, net ecosystem carbon budget and properties of an acidic soil under intensive vegetable productio. *Soil Use and Management*.

Wang, J., Xiong, Z., & Kuzyakov, Y. (2015). Biochar stability in soil: meta-analysis of decomposition and priming effects. *Global Change Biology Bioenergy*, 512-523. Retrieved from https://doi.org/10.1111/gcbb.12266

Wang, J., Xiong, Z., & Kuzyakov, Y. (2015). Biochar stability in soil: meta-analysis of decomposition and priming effects. *GCB-Bioenergy*. Retrieved from https://doi.org/10.1111/gcbb.12266

Woods, W., Teixeira, W., Lehmann, J., Steiner, C., WinklerPrins, A., & Rebellato, L. (2009). *Amazonian Dark Earths: Wim Sombroek's Vision.* Springer. Retrieved from http://dx.doi.org/10.1007/978-1-4020-9031-8

Woolley, S., & Hallowell, B. (2018). *Biochar: An Overview.* Biomass Controls PBC. Retrieved from https://biomasscontrols.com/biochar-overview/

Xiang, W., Zhang, X., Chen, J., Zou, W., He, F., HU, X., . . . Gao, B. (2020). Biochar technology in wastewater treatment: A critical review. *Chemosphere*. Retrieved from https://doi.org/10.1016/j.chemosphere.2020.126539

D3 Stakeholder Register

The Stakeholder Register has been removed due to confidentiality issues.

D4 Integration Biochar and Dolerite into Linear Infrastructure Projects

1 Introduction

As part of the BEIS-funded Direct Air Capture and other Greenhouse Gas Removal technologies competition, a number of the project teams have worked together to coordinate and set up a forum for examining the issues associated with the potential use of biochar within these projects. The set up of this forum was managed by SevernWye, and its intention is to work with BEIS, Defra and the Environment Agency to help develop the necessary regulatory framework for the use of biochar for the purpose of carbon sequestration.

This document provides a high-level overview of this project's understanding of the regulatory issues associated with the use of biochar, and presents specific topics that we feel need to be discussed and resolved at/by the forum.

2 Current Proposed Use of Biochar

In the context of this project, which is examining the opportunities and constraints to using biochar to enhance carbon sequestration, Table 1 presents the currently identified opportunities for the application or use of biochar within linear infrastructure schemes.

Table 1: Summary of opportunities for biochar application on linear infrastructure schemes.

ID	Potential Use	Biochar	Notes
1	Blended with soil for drainage swale	ü	
2	Substituted for filter drainage stone	ü	Potential to add Biochar to drainage stone in filter drains.
3	Substitute for unbound surfacing on access tracks (accommodation works and basins, low-loaded tracks or paths, etc.)	×	It may be possible to use some types of biochar for this, although it is assumed to be negligible amounts for the purpose of this study.
4	Substitute for Type 1 subbase/capping material	×	Unsuitable
5	Substitute for Class 1 earthworks materials	×	It may be possible to use biochar in earthworks, however biochar is inherently variable and its physical properties vary with the source material used. Biochar will not be considered as a Class 1 earthwork material for the purpose of this study.
6	Filtration of surface water drainage to improve water quality	ü	
7	Blended with soil for topsoil	ü	
8	Landscape fill	ü	General landscaping fill, e.g. Class 4

3 Current Regulatory Position Regarding Use of Biochar

A key issue for the use of biochar is its waste status. The status of the materials as a waste or a non-waste is based on a number of factors including:

- Feedstock – whether this is a waste or not;
- The status of the process – whether this is considered a waste treatment; and
- The use, or not, of the product – and whether there is an intention or requirements to discard it.

Biochar is produced by the process of high temperature thermal decomposition (pyrolysis) of biomass in the absence of oxygen. The nature of the biomass feedstock varies, from biomass (such as wood chips and pellets) produced to produce energy, to sludges from sewage treatment. The biochar is a by-product of these processes, and it is currently likely to be considered a waste, and therefore subject to waste regulations, with consequent limitations on its potential use.

It should be noted, that for situations where pyrolysis is undertaken with the express purpose of producing biochar, and where the feedstock is not a waste, that biochar would not be considered a waste.

It is noted that there are a limited number of companies that produce pyrolysis plant to use waste biomass to produce biochar as a product and enabling carbon sequestration, however we are not currently aware of the regulatory position on this, and whether these companies are active in the UK.

From initial discussions with EA specialists, including Matthew Davis (land and biodiversity soil protection team (biochar expert)) it was their expectation that currently the EA would consider Biochar as a waste.

Consequently, it is our understanding that currently biochar produced through energy production or waste treatment (e.g. sewage sludge) would be considered a waste and therefore its potential re use limited.

However, there are a number of regulatory vehicles that exist, or could be called upon, to consider biochar as not a waste:

- End of waste protocol – whereby it would be necessary to demonstrate;
- The EA/Defra position statement;
- Waste exemption; and
- Standard rules environmental permit.

The above are not expected to be addressed in a short timescale and therefore any plans in the short term, i.e., the pilot project will need to consider that the biochar is likely to remain considered as a waste. However, positively the Matthew Davis indicated that for the purpose of the pilot scheme would be possible/reasonable to assume the approach would be a position statement from the EA to allow this to move forward. It will be necessary to understand what the EA require to progress this.

In the longer term, where the importance of carbon sequestration, with the associated increased value in the production of biochar, and the recognition of its societal benefit, we can envisage the possibility where a clean sourced feedstock is produced for the production of biochar, and this can be debated as a non-waste, and therefore be outside of the waste regulatory framework.

3.1 Geo Environmental Considerations

The quality of the biochar will be impacted by a number of factors, and in particular the quality of the feedstock.

Our literature review has indicated that numerous studies have been undertaken that have indicated the potential benefits of the application of biochar in the context of carbon capture.

In particular, where the biochar is produced using a good quality virgin feedstock through a well-controlled pyrolysis process it is considered the contamination issues associated with its use will be negligible, subject to further review and this will be further validated through the pilot project.

Where the quality of feedstock is lower and non-virgin feedstocks are used (for example sewage sludge) the following potential contaminants associated with the use of biochar have been identified:

- Metals (including lead, cadmium, chromium, copper and zinc);
- Polycyclic aromatic hydrocarbons (if carbonaceous materials are present);
- Persistent contaminants such as furans and dioxins (if chlorine/plastics present in the feedstock), although these are not currently covered by the Persistent Organic Pollutant legislation.

Our initial review suggests that these are likely to be at relatively low concentrations, and in relation to human health are likely to be below published assessment criteria. However, the environmental standards applicable to controlled waters are very low and therefore the potential impact of these species would need to be investigated further, and particularly in areas of sensitive controlled waters receptors detailed risk assessment would be required. This would be considered as part of any project design.

4 General Queries for the Forum

- Organisational momentum - how will this group perpetuate itself beyond Phase 1 with the selection of a few projects for further funding? Will further industry stakeholders be invited in?
- Framework development - can this group coordinate with EA and DEFRA to create a framework for biochar applications? This will prevent ad-hoc

exemptions and provide a better way of incorporating biochar into both agriculture and infrastructure.

- Flexible material - the groups that comprise this forum each have a different relationship to biochar. Some cease involvement at its creation, whilst others focus upon its application into infrastructure and agriculture. The unity of this forum must not be confused with the material, biochar is a highly variable material and any outcomes of the forum must have the flexibility to reflect this.
- Purpose - what is the strict purpose of this organisation? Is it a useful convergence of the projects into one voice for EA/DEFRA/BEIS, and/or might funding be sought at some point to produce some further collaborative work?
- Is there the opportunity for the development of a certification scheme in relation to carbon sequestration potential, what are the issues to resolve to allow us to achieve this?
- During our initial discussions with the EA it was reasonably likely that a Regulatory Position Statement may be achieved for pilot trials, the project needs to understand:
    - What information does the EA require to support their development of an RPS?
    - What is the expected duration of such a process, will it allow for establishment of pilot trials in early 2022, with pilot trials extending to 2025?
    - What interaction with EA/Defra is required from the forum, e.g. which departments in the EA should we be engaging with?
- Development of a biochar protocol/exemption/Standard Rules permit for the use:
    - What information from any proposed pilot schemes or trials would be required or useful to support the wider societal beneficial use of biochar and upscaling of application in the medium to long term in the UK?
    - How, as a project team, can we best map out the process required to achieve this wider regulatory position in the UK?

D5 Options Note and Review

Contents

1 Introduction

This note summarises the ideas taken from a series of stakeholder engagement workshops to present and evaluate the options available for integrating biochar and enhanced mineral weathering and carbonation technology into linear infrastructure. The options documented herein, along with their respective risks and opportunities, were critical for guiding the research undertaken during the early stages of Phase 1.

To contextualise these options a brief review is made of alternative greenhouse gas removal (GGR) removal options, with a range of costs per ton of CO_2 removed given for each technology. These values have been taken from the Royal Society's 2018 GGR Report (The Royal Society, 2018).

The discussion of three workshops is then condensed into a list of options and ranked in terms of risk, which is informed by the level of technological readiness, ease of replicability, and social value. The full version of this is tabulated in Appendix D6. Three key options are then recommended from this list.

These key options are then discussed and elaborated upon.

2 Greenhouse Gas Removal (GGR)

As defined by the Royal Society GGR involves the intentional capture and removal of a greenhouse gas from the atmosphere, and the storage of that gas in a form that prevents it from returning to the atmosphere for an extended period (The Royal Society, 2018).
These are typically in the form of:

1. Increasing biological uptake and storage – for example biochar and bioenergy carbon capture and storage (BECCS), or afforestation.
2. Accelerated inorganic reactions – enhanced mineral weathering and carbonation (EMW+C).
3. Engineered removals – for example direct air capture (DAC) may be accompanied with a solution for carbon storage (DACCS).

The pre-eminent GGR options laid out in the Royal Society's 2018 GGR Report are tabulated in an accompanying Excel file, and have been condensed overleaf. The options are listed in order of lowest uncertainty, measured by estimate range for cost per tonne of CO_2 removed.

Table 1: Table to show GGR options (The Royal Society, 2018)

GGR	TLR (1-9)	Cost per tonne CO_2 removed (£)			CO_2 removed per hectare per year (tonnes)	Source
		Low estimate	High estimate	Range		
Afforestation	9	10	21	11	0.1	(The Royal Society, 2018)
Soil carbon sequestration	9	3	18	15	0.11 – 3.65*	(The Royal Society, 2018) (Lovett, Sunnenberg, & Dockerty, 2013)
Wetland, peatland, and coastal habitat restoration	9	7	70	63	0.4 – 18	(The Royal Society, 2018)
BECCS	7 - 9	100	200	100	2.35 – 8.24*	(The Royal Society, 2018)
Biochar	5 - 9	12	120	108	115.5** (one-off)	(The Royal Society, 2018) (Sohi, Krull, Lopez-Capal, & Bol, 2010)
Low carbon concrete	6 - 8	35	215	180	-	(The Royal Society, 2018)
Quarry fines (EMW+C)	5 - 9	15	361	346	17.6***	(The Royal Society, 2018) (Manning, Renforth, Lopez-Capal, Robertson, & Ghazireh, 2013)
DACCS	5 - 8	70	450	380	-	(The Royal Society, 2018)

* these are calculated from the UK wide per annum estimates over the 8.5Mha available land not excluded by UKERC constraints (Lovett, Sunnenberg, & Dockerty, 2013), though this value is much higher than the 0.93 – 3.63 MHa estimate provided by 2012 GOV Bioenergy Strategy (GOV UK, 2012).
** this is calculated from a 50 t p.ha application with an assumed 90% persistence after 100 years and 70% carbon content by mass, and is a one-off deposit not a rate.
*** lower bound as considering only carbonation, also dependent upon applied mass of quarry fines (Manning, Renforth, Lopez-Capal, Robertson, & Ghazireh, 2013).

The GGR options with the lowest cost uncertainties are typically also those with the lowest potential for CO_2 removal per hectare per year. Unlike BECCS or DACCS, biochar and EMW+C are not wholly plant based, and their abatement potentials are contingent upon material supply chains. Scenario based life cycle assessments conducted for both technologies for Sao Paulo State, Brazil, found that transport was the principal detriment to EMW+C carbon offsetting potential (Lefebvre, et al., 2019), and that electricity required to maintain pyrolysis in the absence of full combustion was the principal detriment to biochar carbon offsetting potential (Lefebvre, et al., 2021). It should be noted that the biochar scenario considers on-site pyrolysis and spreading operations, so travel considerations are diminished (Lefebvre, et al., 2021).

Options that consistently reduce the transport requirements of each technology will therefore be most valuable, and this can be done by demonstrating their integration into linear infrastructure schemes that are close to quarry fines and biomass sources.

3 Options

Stage 1 bids must demonstrate the applicability of the proposed GGR in the UK, and whilst likely smaller in scale, the ultimate objective is to identify removals at the MtCO2 scale or greater, at a cost of <£200 per tonne of CO2 removed. The project is lot 2 and will therefore need to demonstrate a minimum capacity of 1k tCO_2 pa (per annum) within the pilot project by 2025. Highest considerations are given to the projects that demonstrate 50k t CO_2 pa in the UK setting by 2030.

Considerations for discriminating between options at the pilot-stage are:

- Cost (heavily related to minimising transport requirements);
- Frequent replicability (one-off sequestrations are unsuitable);
- Feasibility concerns that can be solved within the timeframe of the Phase 1 Design Phase;
- Ease of validation and monitoring (options that require destructive testing are undesirable); and
- Social value in terms of visibility to infrastructure users.

The top-ranking options are:

1. Drainage – central reserves and verges;
2. Slopes and embankments;
3. Landscaping;
4. Maximising biodiversity on soft estates;
5. Traffic and pedestrian pavement construction – surface layers and subgrade integration;
6. Non-structural concrete; and
7. Borrow-pit restoration.

3.1 Drainage

Incorporating biochar and dolerite fines into verges and linear infrastructure drainage is the most promising use of the material. Integration into topsoil is easily monitored and small-scale testing suggests the potential for regulating stormwater runoff and pollution control. Advantages include:

- High visibility to users and potential for promotion;
- Access for monitoring and validation;
- Best dual use of material that exploits each technology's material properties;
- Integral to linear infrastructure so pilot creates a reliably scalable solution;
- If drainage and noise-cancelling properties could be established from the pilot, then this opens up the use for aviation infrastructure, acoustic bunds, and borrow-pit restoration; and
- Flood management schemes often seek to improve the permeability and vegetation establishment of catchment scale areas.

3.2 Cuttings and Embankments

A mix of fines and biochar would promote strong plant growth for stabilisation and drainage for embankments and slopes that have a highly constrained topsoil depth. Advantages include:

- Incorporates well established fertiliser use with newer, semi-structural application;
- Visible to infrastructure users;
- Slopes and embankments are highly integral to both rail and road infrastructure so an established use would facilitate a reliable wide-scale use;
- If a topsoil application could demonstrate improved structural stability then this application would extend into coal-tip stabilisation and bunds; and
- Cuttings generate high groundwater flow so would benefit from improved drainage properties and promote enhanced rock weathering.

3.3 Landscaping

The established agricultural use of biochar and dolerite fines makes their use in landscaping one of high technological readiness, however, extensive landscaping is not integral to linear infrastructure and does not necessarily establish a new use for the technology. Advantages include:

- High visibility.
- Ease of monitoring.

However:

- Is not a crucial aspect of linear infrastructure, so the technology become an ad-hoc curiosity and an integral use is not demonstrated.

- Agricultural applications have already demonstrated that biochar and fines mix promote plant growth, so again new use is not being demonstrated.

3.4 Maximising biodiversity on soft estates

MPI-85-102020 sets out the means to maximise biodiversity opportunities on soft estates. These are the areas used by the Highways Agency to describe the natural habitats surrounding motorways and trunk roads, totalling some 30,000 ha of land nationally, the largest unofficial nature reserve in Britain (Chell, 2013). Guidance to this end includes finishing with subsoil or bare substrate like chalk, rotavating the surface once geotechnically stable to form suitable growing surface, and options for establishing vegetation on nutrient poor soils (natural colonisation, green hay, local seed, commercial seed). This recommendation suggests the suppression of fast-growing grasses will save money and Carbon by reducing the maintenance requirements. Lean nutrient soils are proposed as a means to these ends. Alternatively, a custom mix of biochar and quarry fines may be used to control weed establishment via pH and promote specific wildflowers, expanding upon the Carbon abatement potential of MPI-85-102020, and integrating well due to the proposed use of rotavators on the soil. Biochar's capacity to adsorb soil contaminants may also be used to curb the effect of eutrophication, and the provision of pore space encourages mycorrhizal fungi. Quarry fines also promote mycorrhizal fungi, and together they can improve the rhizosphere of some soils, promoting microbial diversity. Biochar can also be used to improve the soils of low nitrogen environments, as nitrogen is typically present on the surface of biochar as C-N heterocyclic structure and has a low bio-availability (Adekiya, Olayanju, Ejue, Alori, & Adegbite, 2020). Dolerite also has 0% nitrogen content, and can be used for land reclamation and biodiversity establishment in poor-fertility conditions, evidenced by the healthy establishment of nitrogen-fixing plants in low nitrogen soils (Manning, Renforth, Lopez-Capal, Robertson, & Ghazireh, 2013) (Guillou & Davies, 2004). Potential advantages include: -

- High visibility and large amount of potential land;
- Planting with wildflower seeds would promote biodiversity and good wildflower growth;
- Recommended use of rotavator allows easy integration of biochar and fines onto land.

However:

- Biochar can increase the biomass of plants grown upon it, if this is not specific to the desired species then it counteracts the aims of MPI-85-102020.
- high costs associated with biochar are likely to limit uptake.

3.5 Traffic and Pedestrian Pavement Construction

Biochar could potentially be integrated into both asphalt surface finishing and within subgrade layers:

- Well established integration of biochar into cold mix asphalt;
- Biochar could be stored in the subgrade layer when compaction is undertaken.

However

- Enhanced mineral weathering of the quarry fines is unlikely to occur effectively if these materials are sealed from groundwater flows and the root systems of vegetation;
- Potential for volume changes associated with enhanced mineral weathering which could be detrimental to the function of pavements if enhanced mineral weathering process are able to take place;
- Due to the sealing, monitoring and verification would be expensive and difficult to incorporate into infrastructure;
- High costs associated with biochar are likely to limit uptake.

3.6 Non-structural Concrete

Biochar could be mixed into concrete in different concentrations to either strengthen the material or optimise biochar storage in low-grade concrete. Potential advantages include:

- Addition of biochar affords multiple uses;
- Likely to increase the stability of the biochar through the protection of the concrete.

However:

- Similarly, to the case of pavement construction there is unlikely to be any opportunity to incorporate quarry fines/enhanced mineral weathering processes in this context;
- Monitoring and verification of long-term biochar health would require destructive or intrusive measures such as concrete cores; and
- Concrete aggregate already very cheap and high costs associated with biochar are likely to limit uptake.

3.7 Borrow-pit Restoration

The Crewe-Birmingham HS2 plans require 154ha of borrow pits to be restored to healthy soil conditions and good drainage. Fines and biochar stand to perform this function perfectly. Potential advantages include:

- Very well defined, large areas of restoration to provide ideal large-scale test of biochar and fines dual use.
- Ideally situated in South West of England near suitable quarry sites.

However:

- Considerable borrow pits are typically avoided through cut/fill balances and are therefore perhaps not as reliable as a scalable pilot as integration into the infrastructure itself.
- Is not establishing a novel use for the technology.

3.8 Pipeline Backfill

Water companies are producers of sewage sludge and major constructors of linear pipeline infrastructure. They therefore represent both a source and use for biomass/biochar and are distributed uniformly enough across the country to be close to suitable quarries. Potential advantages include:

- Complete minimisation of required transport for biomass and biochar;
- Clients reduce the cost and environmental impact of both sludge disposal and construction in direct substitution for backfill material;
- Minimal risk of disturbance combined with a long design life of sewage infrastructure.

However:

- As with other backfill uses requires extensive suite of geotechnical testing, even minor settlements unacceptable in this application;
- Ideal small-scale test, but yearly constructed areas of pipelines may not be sufficient to demonstrate adequate sequestration potential.

4 Key Points

- Due to the requirements of yearly sequestration, the pilot must prioritise applications that demonstrate a reliable, scalable use for both technologies. In this way ideas like coal-tip stabilisation are excellent one-off applications but retain little possibility for growth in that specific area.

- The pilot should demonstrate that the technologies have a use value beyond a simple burial//sequestration function, as this ensures they will be meaningfully integrated into future infrastructure.

- Ideas that are limited to a sealed-off deposits of biochar and fines do not create opportunities for monitoring, and limit what can be learned from the pilot. For instance, incorporating biochar into concrete, pavement subgrade, or a fines and biochar mix into gabion baskets requires a destructive testing method that hinders the pilot's key function – data gathering.

- Drainage and cuttings/embankments are integral aspects of both road and rail infrastructure, the growth of which is relatively constant and reliable. Both applications can be readily monitored and can provide information for new and further uses. Successful integration into these two areas would demonstrate a reliable technological as well as carbon off-setting usage, they are therefore the most promising on-site applications to explore.

- The MPI-85-102020 document represents both a key challenge and opportunity for integrating biochar and quarry fines into soft estates for highway schemes. The emphasis upon promoting biodiversity in these areas has been coupled with the drive to economise on site mowing, and consequentially the reduction of biomass. If biochar and fines can be shown to specifically target the desired wildflowers and suppress undesired species then an opportunity is created with further potential for Carbon saving, but an indiscriminate increase in biomass and growing rate will be unfavourable in light of MPI-85-102020.

References

Adekiya, A., Olayanju, T., Ejue, S., Alori, E., & Adegbite. (2020). Contribution of Biochar in Improving Soil Health. In B. Giri, & A. Varma (Eds.), *Soil Health* (pp. 99-113). Springer International Publishing. Retrieved from https://doi.org/10.1007/978-3-030-44364-1_6

Capitals Coalition. (2021, November). *The Capitals Approach*. Retrieved from Capitals Coalition: https://capitalscoalition.org/capitals-approach/

Chell, E. (2013). *Soft Estate.* Canterbury: UK Research and Innovation. Retrieved from https://gtr.ukri.org/projects?ref=AH%2FJ005797%2F1

Construction Innovation Hub. (2021). *Value Toolkit*. Retrieved from https://constructioninnovationhub.org.uk/value-toolkit/

GOV UK. (2012). *UK Bioenergy Strategy.*

Guillou, G., & Davies, R. (2004). *Combination of Basaltic Quarry Fines with Organic Process Residues for the Development of Novel Growing Media.* Mineral Solutions. Retrieved from http://www.mineralsolutions.co.uk/casestud.php

HM Government. (2020). *The Construction Playbook.*

Lefebvre, D., Goglio, P., Williams, A., Manning, D., Carlos de Azevedo, A., Bergmann, M., . . . Smith, P. (2019). Assessing the potential of soil carbonation and enhanced weatheringthrough Life Cycle Assessment: A case study for Sao Paulo State, Brazil. *Journal of Cleaner Production, 233*, 468-481.

Lefebvre, D., Williams, A., Kirk, G., Meersmans, J., Sohi, S., Goglio, P., & Smith, P. (2021). An anticipatory life cycle assessment of the use of biochar from sugarcane residues. *Journal of Cleaner Production*.

Lovett, A., Sunnenberg, G., & Dockerty, T. (2013). The availability of land for perennial energy crops in Great Britain. *GCB Bioenergy*, *6*(2), 99-107.

Manning, D., Renforth, P., Lopez-Capal, E., Robertson, S., & Ghazireh, N. (2013). Carbonate precipitation in artificial soils produced from basaltic quarry fines and composts: An opportunity for passive carbon sequestration. *International Journal of Greenhouse Control, 17*(1), 309-317.

Sohi, S., Krull, E., Lopez-Capal, E., & Bol, R. (2010). A Review of Biochar and its USe and Function in Soil. In *Advances in Agronomy* (pp. 47-82). Academic Press.

The Royal Society. (2018). *Report: Greenhouse Gas Removal.* Royal Academy of Engineering.

D6 Options Review

Application	Description	TLR	Blockers	Key Questions	Existing trials or Pilots	Current Practice	Social Value/Visibility (1-3)	Ease of monitoring (1-3) (3 relatively easy/non-destructive monitoring)	Replicability (One-off = 1, ad-hoc = 2, or integral = 3)	Overall Score	Rank
Soil improver	Biochar fines to increase bulk permeability of the soil and improve drainage of wet soils Biochar and fines as soil improver	3	. Untried . Permeability is dependent upon the biochar structure which is fragile to communition, this may change upon compaction . Difficulty in mixing biochar into an already wet soil . Would require fines for this purpose as a quick drying solution	How consistent are the permeability characteristics of biochar from fines to pelleted form? Is a surface application sufficient or does this function require mixing, and if it does, is cost prohibitive?		. Lime stabilisation chemically removes water into hydrated lime . Earth exhumed and left to dry as option . Cementitious materials added to the soil to mechanically enhance the properties	1	3	2	18	26
Biochar and fines in new (traffic) pavement construction	Surface layer	5	. Required design life 40 years (CD 225)	Does mixing into asphalt halt the long term communition of biochar?	. Cold and hot-mix biochar asphalt in various pilot-scale tests	. Asphalt	3	2	3	90	4
	Subbase layer	4	. Required design life 40 years (CD 225)			. Incinerator bottom ash used already HBM category B material (non-combustible residue from combustion processes)	3	1	3	36	16
	Capping layer (if short-term subgrade surface modulus < 50 MPa)	4	. Required design life 40 years (CD 225)			. Incinerator bottom ash used already HBM category B material (non-combustible residue from combustion processes)	3	1	3	36	16
	Subgrade	5	. Required design life 40 years (CD 225) . Require long and short term subgrade surface modulus $E = 17.6(CBR)^{0.64}$	What is the CBR of typical soils mixed with various forms of biochar? What is the residence time of biochar when it is sealed off from typical groundwater flows and interaction with vegetation? What is the optimum moisture content of biochar?	. Very simple to demonstrate s/t feasibility - incorporate at different wt(%) into typical soils and test CBR . Long term typically requires lower CBR due to temporary construction loads	. Typically uses existing ground and compacted . Requires mixing with existing ground, must demonstrate this is worth the cost to the project	3	1	3	45	15
Biochar and fines in new (footway and cycleway) pavement construction	Surfacing	5	. Required design life 40 years (CD 239)	Does mixing into asphalt halt the long term communition of biochar?	. Cold and hot-mix biochar asphalt in various pilot-scale tests	. Asphalt . Pavers/setts . Flags/slabs . Concrete	3	2	3	90	4
	Subbase	4	. Required design life 40 years (CD 239)			. Imported aggregate, either bound (binder added) or unbound	3	1	3	36	16
	Subgrade	4	. Required design life 40 years (CD 239) . Assessed in terms of CBR (CD 239) if < 2.5% must be improved . Where mean annual frost index is geq 50 all material within 450mm of surface must be non-frost suscpetible, if lower this reduces to 350mm		. Use in Stockholm with load-bearing 100-150mm rocks	. Existing soil . Sometimes amended if not suitable	3	1	3	36	16
	Paver protection	8	. If unprotected could scatter and make monitoring impossible			. Use stone dust	2	1	3	48	14
Biochar as lightweight fill to replace expanded polystyrene (EPS) geofoam	EPS is a recyclable foam with excellent strength to weight properties, predictable behaviour, and homogeneity	2	. Biochar tech currently stands out in contrast to all the properties that make EPS desirable, namely extreme predictability and long term stiffness . Typically used in quantities unavailable in the UK (e.g. switching 1400m³ used in viaduct stabilisation, Warrington, would require approx 448 tonnes) . EPS approximately 10 times lighter than biochar [https://www.jablite.co.uk/application/jablite-fillmaster/]	What is the optimum moisture content of biochar? Does biochar's compaction to a maximum dry density affect its residence time in the soil? How does biochar content by weight of fill affect the shear strength of soil?			3	2	3	36	16
Acoustic and visual bunds	Incorporating biochar and fines into surfaces of bunds	5	. Is more expensive than simply erecting a fence . Demonstrate value where this interferes with cut/fill balance	How does biochar and rock fine content by weight of soil change the sound adsorption coefficient? Can sufficient noise cancelling be obtained through integration into topsoil or is compaction required?	. Anecdotal evidence that use underneath a roundabout in Stockholm reduced noise . Addition of biochar to concrete considerably increases sound adsorption coefficient across 200 - 2000Hz [https://doi.org/10.1016/j.biombioe.2018.11.007]	. Typically formed from soils to hand	2	3	2	60	12
Integrate biochar with concrete	Structural	4	. To maintain high structural performance wt% must be kept low, reducing the offset value of the practice . Aggregate and sand are both already incredibly cheap, would have to demonstrate value . Issue of structure lifetime and ambiguity around eventual destination of biochar post demolition . Is a univocal application in neglecting dolerite fines	What is the typical destination of demolished concrete, and would this simply degrade the embodied biochar?	. At low wet% can retain water during mixing, the slow release of which promotes secondary curing . At approximately 1-2%wt the biochar can help block the propagation of cracks	. Would be replacing aggregate or sand	3	1	3	36	16
	Non-structural	5	. High wet% increases water required to maintain concrete workability, by approximately 1L per kg added . Is a univocal application in neglecting dolerite fines . Replacing aggregate and sand - already cheap materials . Issue of structure lifetime and ambiguity around eventual destination of biochar post demolition	Is the value of sequestered carbon high enough to displace already cheap aggregate?		. Would be replacing aggregate or sand	3	2	3	90	4
Hardstanding	Use of biochar+fines for temporary and permanent hardstanding areas	6	. If temporary, EMW will not have a chance to work, and contractors unlikely to want to incur any extra costs for this . For long-term hardstanding, their use may promote undesired plant cover . If plant growth discouraged, washout and therefore verification becomes a problem	What is the average hardstanding area per km of road?			1	3	2	36	16
Embankments and cuttings	Road and rail embankments, where biochar+fines mix can promote plant growth and slope stabilisation within an environment where topsoil may be limited. Cuttings generate groundwater that contribute to the enhanced weathering process	4	. Untried . Permeability is dependent upon the biochar structure which is fragile to commination, this may reverse upon compaction . Difficulty in mixing biochar into an already wet soil	What is the optimum moisture content of biochar? How quickly could the B+F mix produce a stabilising vegetated layer? Does this layer afford a quantifiable resistance to shear-slip failure? Does biochar's compaction to a maximum dry density affect its residence time in the soil? How does biochar content by weight of fill affect the shear strength of soil? Does biochar change the maximum gradient of any slopes? Embankments suscpetible to heavy rainfall, is erosion a problem? What are the maintenance requirements of a slope? What is its resilience to climate change and ground-related hazards			3	3	3	108	2
Gabion baskets	Adding biochar and fines to gabion baskets	3	. Settlement//commination of tech here likely irrelavant as rocks take force network . Risk of washout if not properly integrated, pelleted biochar may help this . Metal cage makes probing and verification very difficult . Likely to not replace any rocks, so would have to demonstrate the value of its addition on to an otherwise cheap thing . Issue of how to effectively mix rock with the mixture			. Machine-filled with large rocks	1	1	3	9	28
Drainage	Attenuation ponds	3					3	3	3	81	10
	Central reserves and verges	6	. Is there a contamination risk after localising so many heavy metals . Potential waste status . Precipitate blockage of drain	Is there a contamination risk after localising so many heavy metals? Need to understand leaching risks What is the expected lifetime of a B+F amended verge before pollutant concentration becomes too high? Does an end of life "disposal" plan need to be created after immobilsing so many run-off elements, and is this a high contamination/cost risk? Are specific plant species limited due to elevated metals in biochar Precipitates clogging up ground drains over time - experiences in iron rich ochreous precipitates How to avoid the label of waste, and with it, having to avoid designing to waste protocols and end of waste protocol How do biochar and quarry fines react to constant wetting/drying cycles? Is there a risk of washout in an area with such high sub-surface flow? Does it create a risk of pollution incidents downstream?	. American pilot found significant reduction in stormwater runoff and control of heavy pollutants . Significant public and organisational support for promoting biodiversity in highway verges	. CD 127	3	3	3	162	1
	Sustainable drainage systems, Swales	5		Reducing water flow/runoff may limit the need for further attentuation downstream Is there a risk of the tech impacting the plants and trees here?			3	3	2	90	4
	Flood area management	3	. Biochar and fines along the embankments of such schemes . Oftern have wider measures assosciated with them, such as improving infiltration characteristics and improving tree growth - catchment wide add-ons				3	3	2	54	13
Coal-tip stabilisation	Use of this mix and tree seeds to promote strong root growth and stabilise surface, as well as immobilise heavy metal pollutants and reduce water pollution Over 2,100 waste tips in Wales that require stabilisation with total value of £500 million	3	. Tangential from linear infrastructure, very few coal tips left as active sites . Delivery of mix would be difficult	Is the coal-tip stable enough for typal delivery practice? How quickly could the B+F mix produce a stabilising vegetated layer? How much resistance does this layer afford to shear-slip failure? Is a surface layer enough to resist deeper, internal shearing?		. Restoration via vegetation cover to reduce infiltration and enhance stability . Drainage channels	3	2	2	36	16
Quarry fines for maritime tidal zone – terabit seawalls and beach nourishment		2	. Washout seems likely in this case				3	3	2	36	16
Aviation infrastructure	Large grassy areas and huge tracts of concrete for inclusion, possible affinity of EMW with increased CO_2 air content	5	. No new airports planned in UK, but expansion is constant . Need for construction speed in minimising delays may deter contractors	Would the potentially accelerated vegetation growth be undesirable?		. Even small airports have several hundred acres of grass . These areas have a runoff function also, and are desired for noise absorption . Optimum grass length is six inches	3	3	2	90	4
Vegetated geotextiles		4	Seems ideal for erosion control in promoting plant growth				3	3	2	72	11
Buried biochar and fines	Buried cells	6	. Would need to demonstrate the advantage this has over simpler removal tech . Massive concentrations of uncompacted biochar could lead to highly localised subsidence	Would this be classified as landfill? Would the mixture need to be buried in a load bearing case to prevent subsidence?			1	1	2	12	27
	Filling borrow pits	3	. Requires geotech verification for such a large fill . Likely difficult to demonstrate that this is cheaper than . Due to borrow pit size this could be a major subsidence problem				2	2	2	24	25
	Borrow pit restoration, needs good drainage	5		How much control does the leasing landowner have over the amendments to their site?		. Backfill then recoat with set aside topsoil . [https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/627178/E30_CT_009_000_WEB.pdf]	3	3	2	90	4
Landscaping	Easy integration into aesthetic landscaping applications, as both technologies are already well established as agricultural fertiliser	6	. Contamination checks . Prove that any change to drainage regime will be positive	In terms of constructed road area, what proportion is taken up by landscape design?	. Wealth of literature validating both fines and biochar as a soil fertility aid	. LD 117 gives very qualitative guidance regarding landscape design	3	3	2	108	2
Pipe Backfill	Close to sewage plants for ease of biomass sourcing, and pipe systems widespread enough to be close to quarry Client also gets free disposal of their waste and clear cutting of imported backfill costs	3	. As with other filling purposes, suitable structural testing is required	What is the yearly constructed area of such works?			3	3	3	81	10
Maximise biodiversity on soft estates	Represent 30,000 ha of space Tailor made biochar to limit the growth of fast growing weeds Encourage slower growing species	5	. Associations with nutrient improvement unhelpful for trying to establish a nutrient lean soil	Can biochar be tailored specifically enough to limit the growth of weed species	Biochar can have incredibly varied effects on soil	MPI-85-102020 sets out the new lean soil policy for Highways England	3	2	3	90	4

Phase	TRL	Stage	Description
Operations	TRL9	Operations	The technology is being operationally used in an active facility
Deployment	TRL8	Active Commissioning	The technology is undergoing active commissioning
	TRL7	Inactive Commissioning	The technology is undergoing inactive commissioning. This can include works testing and factory trials but it will be on the final designed equipment, which will be tested using inactive simulants comparable to that expected during operations. Testing at or near full throughput will be expected
Development	TRL6	Large Scale	The technology is undergoing testing at or near full-scale size. The design will not have been finalised and the equipment will be in the process of modification. It may use a limited range of simulants and not achieve full throughput
	TRL5	Pilot Scale	The technology is undergoing testing at small to medium scale size in order to demonstrate specific aspects of the design
	TRL4	Bench Scale	The technology is starting to be developed in a laboratory or research facility.
Research	TRL3	Proof of Concept	Demonstration, in principle, that the invention has the potential to work
	TRL2	Invention and Research	A practical application is invented or the investigation of phenomena, acquisition of new knowledge, or correction and integration of previous knowledge
	TRL1	Basic principles	The basic properties have been established

Appendix E - Regulatory Review

Contents

1 Regulatory context of Use of Biochar and Dolerite Rock Dust

1.1 Introduction

The application of biochar and dolerite rock dust will be significantly influenced by whether these products are considered wastes (or not) by the regulatory authorities. The definition of waste is defined in the Waste Framework Directive (WFD). The WFD defines waste as “any substance or object which the holder discards or intends or is required to discard”. The meaning of the word ‘discard’ under the WFD has a special meaning and is not necessarily the same as the dictionary meaning. It is necessary to define if the material in a particular situation:

- is waste i.e. it has or is required to be discarded; or
- It was never waste, and it meets the ‘by-product’ test or the ‘reuse’ requirements; or
- It has stopped being waste and it meets the ‘end of waste’ test.

The process of deciding if the material is a waste, non-waste or a by-product is complex and there is extensive guidance and consultation necessary, plus legal precedents that must be considered. These are not explained in this document.

The disposal, recovery and use of wastes is controlled by various regimes and typically require an environmental permit, exemption from permitting, end of waste protocol or other mechanism. The permitting system is regulated by the Environment Agency (EA) in England.

This appendix presents our current understanding of the regulatory position in this regard.

1.2 Regulation and waste status of Dolerite fines

Dolerite rock fines are produced as a by-product from quarrying of these materials. As such the fines might be considered to be waste. However, there is an existing market for the use of dolerite fines within construction. It is used in asphalt plants for coated aggregates and as a road surface dressing, and it is subject to the Aggregates Levy. Consequently, it is currently considered likely that specific rock dust products should not be defined as a waste, and therefore its use on this project should not be subject to waste regulation.

Both the Pilot Site and the Reference site will be subject to planning requirements and therefore must demonstrate that the use of these materials will not present a risk to human health or the environment in the context of the proposed developments. A site-specific risk assessment and appropriate construction mitigation methodology will be required.

1.3 Regulation and waste status of Biochar

Biochar is typically produced by high temperature thermal decomposition (pyrolysis) of biomass in the absence of oxygen. The nature of the biomass feedstock varies, from biomass (such as wood chips and pellets) to sludges from sewage treatment. As the Biochar is currently consider a by-product of the process of pyrolysis, typically for heat generation, its status as a waste or a non-waste is based on several factors including:

- Feedstock; whether this is a waste or not;
- The status of the process; whether this is considered a waste treatment; and
- The use, or not, of the biochar and whether there is an intention or requirement to discard it.

Where pyrolysis is undertaken with the intention of producing biochar, for example with for carbon sequestration, and where the feedstock is not a waste, then there is a proposition that biochar should not be considered a waste.

Based on various discussions with the EA, who would be the regulator, have indicated that they consider it likely that Biochar will be considered a waste, and therefore subject to waste regulations and permitting. It is noted that the current proposal for the Pilot and Reference sites is to manufacture the Biochar for the sole purpose of use on the Pilot and Reference sites, however the EA were quite clear that currently the regulatory route to use of the material, in the volumes proposed, is through waste permitting. This may change in the future as the market matures but is the current base position for progressing the Pilot and Reference site.

There are several regulatory mechanisms that may be applied to facilitate the use of waste, including:

- Waste exemptions.
- End of waste protocol.
- Regulatory position statement.
- Standard rules environmental permit; usually with an associated volume limit, defined controls, and limitations, and specific to the use and type of waste for a particular purpose.
- Bespoke environmental permit which can cover a wider array of situations than a standard rule permit but is more complex with applicable supporting risk assessments and controls etc.

Currently there are no waste exemptions or end of waste protocols applicable to biochar in the UK. There are currently two low risk waste positions (LRWP) relating to Biochar:

- Storing and treating waste to make Biochar: LRWP 60; this indicates that if the intention is to store and treat waste to make biochar from the following waste streams then the EA consider that this can be undertaken without an environmental permit for a waste operation:

  - 02 01 03 - untreated plant tissue waste from agriculture, horticulture and forestry activities.
  - 02 01 07 - untreated wood waste from forestry activities.
  - 02 03 04 - vegetable waste unsuitable for consumption or processing.
  - 03 01 01 - untreated waste bark and cork.
  - 03 01 05 - untreated sawdust, wood shavings and wood cuttings.
  - 03 03 01 - untreated waste bark and wood.

- Storing and spreading of Biochar to benefit land: LWRP 61; the EA consider that an environmental permit for a waste operation is not required for the storage and spreading of one tonne of biochar per hectare over any twelve-month period from the following feedstocks:
  - 02 01 03 - untreated plant tissue waste from agriculture, horticulture and forestry activities.
  - 02 01 07 - untreated wood waste from forestry activities.
  - 02 03 04 - vegetable waste unsuitable for consumption or processing.
  - 03 01 01 - untreated waste bark and cork.
  - 03 03 01 - untreated waste bark and wood.

The application rate is significantly less than that proposed for the use of biochar in linear infrastructure developments, which likely a 70 tonnes/ha as a one-off application. In addition, LRWP relate to a specific purpose of the improvement of soil quality, and consequently, these LRWPs are not applicable to the proposed use of biochar for sequestration.

It is expected that the regulatory mechanism to be applied for Biochar use will be an environmental permit for a waste operation. Discussion have been undertaken with the EA and the Biochar forum to understand the route map to achieving a regulatory position on the use of Biochar which are summarised in the following section.

1.4 Discussions with Environment Agency

The project has undertaken liaison with the Environment Agency and Defra, In order to understand the regulatory position with respect to the use of rock dust and biochar through the following:

- Direct discussion with specific departments of the EA including Mathew Davis (Land and biodiversity soil protection team) and Caitlin Burns (Decarbonisation and net zero team, climate Change and energy). Mathew was involved in the development of the existing LRWP but noted that his views and opinions represented his understanding and area of expertise, and that a broader cross department EA opinion and consultation would be required (including the various waste teams).

- Attendance and presenting at the Biochar forum, that the EA and Defra are members too. The Biochar Forum has been formulated by a number of BEIS projects and interested parties to allow for discussion of the issues associated with the use of Biochar and enable information dissemination and cooperation.

Representatives from Defra present at one of these meeting did not express a particular view on the matter and were not present at the second meeting.

The discussions have indicated the following:

- There is currently a recognised policy gap in the regulation of Biochar, and biochar does not have a waste code, and therefore does not have an entry in the List of Wastes, which can also make permitting a challenge.
- Currently there is no single point of contact within the EA and Defra with regarding Biochar and its use and regulation. A cross cutting agreement should be sought to ensure the greatest societal benefit can be realised.
- It will be necessary to confirm from a regulatory perspective whether Biochar itself is a product or a production residue. If considered a production residue then the EA will likely consider Biochar to be a waste and regulate it accordingly.
- Currently it is likely that the regulatory standpoint of the EA is that Biochar is a production residue, unless the driver for the pyrolysis is to produce biochar for a purpose, rather than a by-product from energy generation, and it is being manufactured to a particular specification. Consequently, it is likely that biochar would be considered as a waste and the use of biochar will be subject to waste regulation. There are provisions for exempting wastes from the requirement for permitting if a benefit to agriculture can be demonstrated: biochar is not presently exempted.
- The EA recognise that there are several regulatory mechanisms as alternative to permitting that could be applicable as follows:
  - An end of waste protocol. These define the point at which waste ceases to be waste and can be used as a product without the requirement for waste management controls. There is no current applicable end of waste protocol for waste biochar for sequestration. It was noted that an end of waste protocol has been agreed in Europe related to use of biochar in fertiliser for soils, but this has not been adopted by the UK government and Defra is considering their own policy in this regard.
  - EA/Defra position statement. These define specific situations where the EA is not currently enforcing the need for an environmental permit in specific cases for some activities.
  - A waste exemption. Specific exemptions to permitting must be registered with the Environment Agency or other relevant authorities. The exemptions apply to specific activities and maximum quantities of waste. There are no current exemptions for use of biochar for sequestration.

None of these currently exist for biochar and for sequestration and are not expected to be addressed or developed in a relatively short timescale necessary to consent and implement the Reference and Pilot site. Therefore, the base assumption is that an environmental permit will be required.

- Positively, it was recognised by the EA represented in the Forum that there is a clear societal benefit to the use of biochar for carbon sequestration, and therefore the EA should be open to considering this, and the importance of carbon sequestration, and the associated increased value in biochar. This would require a suitable policy steer on land-based sequestration. This forms the basis of a longer-term goal of defining a bespoke non-waste process for biochar from the various types of feedstock, and therefore the use of biochar may eventually fall outside the waste regulatory framework.

- The existing LWRPs were put in place by the EA as there is no exemption for biochar land spreading. However, it is recognised that without a change in the EA's position on the application rate and unless the application of biochar to land is of benefit to the crop or similar, the existing LWRPs would not enable use of the use of biochar for carbon sequestration without a permit.
- The current advice from the EA consulted in the Forum is that the appropriate approach for the use of biochar in the pilot project is likely to be a bespoke environmental permit. This permit will either be a waste recovery or disposal operation.
- The EA present in the Forum proposed that the use of the biochar might be considered a waste recovery operation (which is preferential to disposal). Based on the existing permitting, options this would comprise permit R10 Operation, Land treatment resulting in benefit to agriculture or ecological improvement". To follow this route, and demonstrate recovery rather than disposal, it will be necessary to show benefit (and pass the substitution test) and that it can be applied without unacceptable impact on the land. However, it should be noted that this will be a relatively novel application and use of this type of permit and will require some relatively new lines of evidence and the cooperation of the EA in that regard, taking account of the genuine intention to result in environmental improvements (carbon sequestration etc).
- The EA provided recommendations on the approach to progressing the environmental permit, and how to liaise with the EA during this process. In summary this comprises:
    - Undertake a pre application consultation with the local Environment Agency team and request that they log a National Help Desk enquiry relating to the pre application.
    - This will facilitate a discussion at national level within the EA to drive the decision making.

1.5 Regulatory approach for the project

It is currently likely that biochar will be considered to be a waste, and therefore the regulatory vehicle for its use on the Pilot Scheme will be an environmental permit. A key aspect of the Pilot site is that the use of the biochar is as a permanent "addition" to the scheme. However, the use of biochar on the Reference site is more nuanced, in that currently it is not confirmed whether the proposed Reference site scheme would be a permanent development. The reference site will be used to provide supporting data for the wider use of Biochar in carbon sequestration and will be set up to provide several trials to demonstrate the success of the biochar application. It is possible that these trials will be dismantled at the end of the trial period, some ten years, and therefore there is no permanent deposition of waste biochar, and therefore the potential of it being considered a disposal operation is reduced.

However, it is recognised that the placement of waste on land, for ten years, although not permanent, is likely to require a level of regulatory control. The EA is likely to have reservations of “storage” of a waste for such a duration. Regulatory mechanisms, other than environmental permits for the storage of waste on land are limited, and generally do not go past twelve months, and therefore it is assumed that an environmental permit will be required.

For both the pilot and reference projects it will be necessary to assume at this stage that an environmental permit will be required for the use of Biochar. There are two potential permits:

- Use of waste in a deposit for recovery operations (construction, reclamation, restoration or improvement of land other than by mobile plant).
- Disposal of waste.

The preferred approach is to pursue a waste recovery permit where we will be proposing to use a waste material (biochar) instead of a non-waste which is one of the requirements of demonstrating disposal. The alternative of permitting a large area of an infrastructure project as ‘disposal’ (i.e. landfill) and agreeing the controls for such disposal could be problematic and complex.

To support this type of permit application the following is required:

- Pre application discussion with the EA to confirm information required with the permit application, and confirmation of applicability of proposed permit.
- Preparation of a waste recovery plan that demonstrates that the proposed activity will meet the waste recovery test. If we are unable to satisfy the EA that the proposed operation is waste recovery, then it will be necessary to apply for a waste disposal permit instead.

Although the R10 standard rules permit seems applicable to the project this does not list Biochar in its list of applicable wastes. Consequently, it is considered that bespoke Waste Recovery permits will be required for the use of Biochar on the two projects.

1.5.1 Waste recovery plan

The waste recovery plan is key in providing reassurance to the EA that the activity is recovery and not a ‘sham’ recovery. It is necessary to demonstrate that the same activity would be carried out using a non-waste material. The waste recovery plan provides design and financial evidence to support this, and this is known as the substitution test.

Evidence that can support the argument that the proposals are the recovery of waste are:

- Financial gain; it is necessary to demonstrate that if a non-waste was used instead the project would benefit from a net financial gain or benefit.

- Obligation to complete the scheme; evidence that there is an obligation to carry out the scheme; this does not include planning permission but could be a planning condition or other imperative.
- Demonstrate that the waste will serve a useful purpose and that the waste is suitable for the intended purpose and will not cause pollution. This could be in the form of appropriate risk assessments to demonstrate this.
- Demonstrate that if you could not use a waste material for the proposed operation, you would use non waste materials.

Other information that we should include within the waste recovery plan includes:

- Purpose of the work; what the scheme's function is, why it is needed and how it will be carried out
- Quantity of waste needed to carry out the function that would otherwise be provided by non-waste and demonstrate that only the amount of waste needed to carry the function provided by the non-waste is used. This will need to be supported drawings and sections of the proposed scheme.

The permit will need to be supported by:

- A management system that details waste acceptance procedures for accepting the biochar on to the sites
- The environmental setting of the sites
- Risk assessments to demonstrate whether the use of the biochar on the schemes will present a risk to controlled waters or human health.
- Evidence of how the schemes are authorised in planning terms, i.e. have planning permission.

The EA may require a benefit statement to demonstrate that a soil quality benefit is achieved by addition of the biochar. Highways England (HE) require that the topsoil along their road schemes should be low nutrient, and this may be a route to demonstrating this, in that the addition of biochar to existing topsoil could reduce the nutrient content.

In addition, for both sites it is proposed to a create a manufactured topsoil (of biochar, dolerite and existing topsoil at the site) and therefore it is necessary to confirm with the EA how this process will be permitted as it is likely to be considered as a waste treatment.

1.5.2 Waste recovery screening

The following indicators may be useful to demonstrate that the proposals are a waste recovery activity:

- The biochar will serve a useful purpose; as well as achieving carbon sequestration it will be as a substitute for additional topsoil. Currently it is estimated that the biochar will replace 50% (by volume) of the topsoil. Depending on the volume of site won topsoil this may prevent the import of a specific volume of topsoil from other sources.

- The assessment of the potential contaminative nature of the biochar has demonstrated that it is not expected to have an impact on controlled waters or human health.
- The addition of the proposed volumes of biochar is expected to support HE's requirements for a low nutrient topsoil.

1.5.3 Proposed program

The construction phase of the Pilot site starts six months later than that of the Reference site. It would be efficient to progress both the permit applications, including the pre application discussions with the EA, at the same time; there is likely to be economies and efficiencies in the discussions with the EA and in production of the supporting information.

It is proposed that the following process is followed.

1. Meet with Mat Davis and Caitlin Burns of the EA, who are both contributors to the Biochar Forum, to discuss/confirm our strategy for pre application discussions with the EA permitting team.
2. Contact the local EA permitting officers to arrange a pre application meeting and confirm their initial requirements for that meeting.
3. Prepare a pre application package to present the proposed schemes and the context of the use of the biochar and rock dust on them. This will include the environmental settings of the sites and the identified risks from the proposed use (likely negligible or very low environmental and human health risk). This will also set out the initial principles describing the requirements for the waste recovery plan, and evidence of substitution.
4. Meet with the EA permitting team for a pre application meeting. This will introduce the two projects, detail the benefits and scope of the project, and agree the proposed permitting strategy and ensure that the permitting officers are aware of the need to engage with the SMEs in the EA through the EA Helpdesk. This would also confirm the requirements for the reference site, and any principles regarding the soil blend manufacture.
5. Complete waste recovery plans and submit to the EA to ensure that they agree that the proposed activities are waste recovery.
6. Once recovery plan is agreed prepare the permit applications, whilst maintaining ongoing review and liaison with the EA to ensure any developments on the permitting of Biochar are incorporated into our permit applications.
7. Meet with the EA for a final pre application review of the permits' documentation and confirm any outstanding works required.
8. On completion of any amendments further to the above meeting we will then submit the permit applications to the EA for determination.

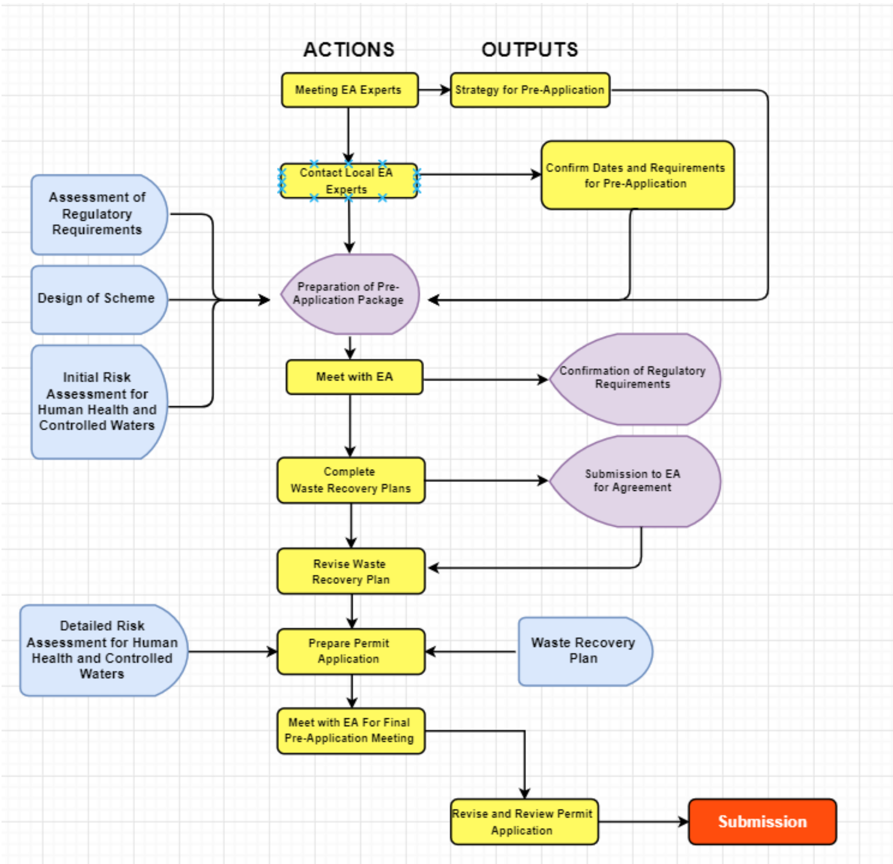
The proposed program for the preparation of the permits is presented below in Table 1.

Table 1:Shows the proposed program for the preparation of the permits.

		Month												
		1	2	3	4	5	6	7	8	9	10	11	12	13
Task	Meet with Mat Davis et al													
	Prepare pre application package													
	Initial Pre App meeting with EA													
	Complete Waste Recovery Plans													
	Preparation of Permit Applications													
	Meet with EA for final Pre App													
	Revise Permit Applications													
	Submit Applications for Determination													
	Permit Determination by EA													

The programme above allows a six-month determination period. This could be shorter. After the permit is submitted the EA review the documents and conform if it has been ‘duly made’. If that is not the case, they may request additional information which rerestarts the application time once the updated documentation is submitted. Below in Figure 1Figure 1 is a summary of the workflow for delivery of the permits.

Figure 1: shows a summary of the workflow for delivery of the permits.



1.6 Non-Permit Route to Implementation

As discussed in Section 1.4, currently the expectation for the implementation of the Pilot and Reference sites is that they will both require a bespoke Waste Recovery Permit based on the R10 Standard Rules permit.

However, the long term ideal is that the use of biochar will not require a waste recovery permit, or permit of any type, and its use be “regulated” through say:

- An end of waste protocol. These define the point at which waste ceases to be waste and can be used as a product without the requirement for waste management controls. There is no current applicable end of waste protocol for waste biochar for sequestration.
- EA/Defra position statement. These define specific situations where the EA is not currently enforcing the need for an environmental permit in specific cases for some activities.
- A waste exemption. Specific exemptions to permitting must be registered with the Environment Agency or other relevant authorities. The exemptions apply to specific activities and maximum quantities of waste. There are no current exemptions for use of biochar for sequestration.

All of these options would need to be developed by the EA and Defra, and would require internal discussions. It is considered that the Biochar Forum and the outputs from the Pilot and Reference sites will have significant impact on the success of achieving these non-permit routes.

Appendix F - Social Value

Contents

F1 BEIS: Integration of GHG Removal Technologies in Linear Infrastructure Projects, Social Value Report

F1.1 Introduction

This report examines how the use of Greenhouse Gas Removal (GGR) technologies, namely biochar and quarry fines (via enhanced mineral weathering, EMW) in linear infrastructure projects could deliver social value.

These technologies offer significant potential benefits in the UK's drive to achieve Net Zero by 2050 and their use in the infrastructure sector provides a substantial market and social value opportunity.

Infrastructure's purpose is to meet fundamental societal needs; such as roads, public transport, low carbon energy supply, clean water and flood protection. There is currently significant focus on improving infrastructure delivery in the UK, and the recent and emerging value-based infrastructure delivery models seek to improve efficiency and productivity and drive innovation to achieve better outcomes for society including delivering greater social value.

In addition, government, public sector institutions and corporates are under pressure to ensure their investments reflect genuine value to society and demonstrate their corporate social responsibility agendas. Interest in the concept of social value is growing as organisations increasingly want to show social responsibility leadership, further embed sustainable practices, or simply find other ways to improve how they do business and benefit their communities.

Government and local authority commissioners will be able to use the policy procurement note PPN 06/20 to drive the demand for measures that are delivering outcomes such as 'effective stewardship of the environment' and 'tackling of economic inequality.'

Construction companies have more information than ever at their disposal to help develop local sourcing strategies and improve the social value of their supply chains. This would include an opportunity to specify low carbon materials and/or carbon sequestering materials, such as biochar and dolerite (via EMW). Sourcing these materials locally could offer additional economic, social and environmental benefits including supporting local production, reducing transportation costs and carbon emissions and helping develop new markets.

Investment in UK Infrastructure

Over the next year between £16 billion and £25 billion of economic (transport, energy and digital) infrastructure contracts will be brought to market. There is a projected £250 billion spend over the next 10 years (within a total £650 million of economic and social infrastructure investment) (IPA, 2021). Encouraging and driving innovation in a sustainable manner that aligns with the path to Net Zero by 2050 is central to the Government's infrastructure ambitions.

The £650 billion of economic and social infrastructure investment is critical to the Government's achievement of its long-term ambitions for the UK, including to level up the country, strengthen the union and meet the United Nations Sustainable Development Goals (UNSDGs).

The UK's Transforming Infrastructure Performance (TIP) roadmap to 2030 describes a vision that links societal outcomes defined by UNSDG priorities, with value-based policy leading to system level decisions and using the data and technology to see them through (Infrastructure and Projects Authority, 2021).

Drivers for Social Value

With such significant infrastructure investment planned for the UK, matched with severe socio-economic challenges across the country heightened by Covid-19, there is now more need than ever for infrastructure projects to create additional social value over their lifecycle and help to build local economies and deliver on a low carbon agenda.

The essence of social value is to identify the wider benefits of public decisions and business activities for people, the economy and the environment. If infrastructure is to play a key role in the levelling up agenda, social value creation must be integral to all stages of an infrastructure project including funding, planning decisions and delivery.

The societal benefits that infrastructure projects can generate are not limited to delivering basic functionality. By focusing on delivering broader social outcomes, not just engineering outputs, infrastructure projects can create additional 'social value'. For example, they can help address local socio-economic issues and inequalities; create jobs for previously unemployed people; buy local opportunities; provide opportunities for small and medium enterprises; promote low carbon economies and ultimately increase the quality of life of people involved in or impacted by an infrastructure project.

The UK policy environment has shifted significantly since the Public Services (Social Value) Act 2012 which required public bodies to "consider" social value in the services they commission and procure. There is now a range of government measures driving the need for social value to be articulated and implemented.

HM Treasury Green Book recommends the Five Case Model business case as a means of developing proposals in a holistic way that optimises the social/public value produced using public resources (HM Government, 2020). The Green Book update (2020) addresses social or public value as all significant costs and benefits that affect the welfare and wellbeing of the population e.g. environment, cultural, health, social care, justice and security and not just market effects.

In January 2021, the implementation of PPN 06/20 (a public policy guidance note) set the requirement for all central Government procurement to explicitly evaluate social value, with a 10% minimum weighting. This is driving the infrastructure sector to demonstrate the additional societal benefits that can be achieved in the delivery of Government contracts. PPN 06/20 defines social value across a framework of five themes and eight outcomes (see Figure 1). Its roll out is reinforcing the aspirations set out in the Construction Playbook (HM Government, 2020).

Themes		Policy outcomes
Theme 1	COVID-19 recovery	Help local communities to manage and recover from the impact of COVID-19
Theme 2	Tackling economic inequality	Create new businesses, new jobs and new skills
		Increase supply chain resilience and capacity
Theme 3	Fighting climate change	Effective stewardship of the environment
Theme 4	Equal opportunity	Reduce the disability employment gap
		Tackle workforce inequality
Theme 5	Wellbeing	Improve health and wellbeing
		Improve community cohesion

Figure 1: PPN 06/20 Themes and Outcomes

The Construction Playbook (HM Government, 2020) sets out the requirement that all contracting authorities should set out strategies and plans for achieving net zero GHG emissions by, or ahead of 2050, for their whole estate and portfolio, including the use of PAS 2080 (HM Government, 2020). HM Treasury has now published a revised remit for the National Infrastructure Commission (NIC) that adds a fourth objective of supporting climate resilience and the UK's transition to net zero carbon emissions by 2050 (McNaught, 2021). This adds to the existing objectives of supporting sustainable economic growth across the UK, improving competitiveness, and improving quality of life and increases the opportunities for the use of low carbon technologies and materials in built environment projects.

All the above build on the commitment made in the Government's 2017 Industrial Strategy Construction Sector Deal to embed a 'procure for value' approach in public procurement (BEIS, 2018; Construction Leadership Council, 2018). The CLC responded to this deal with their report in 2018 on 'Procuring for Value'.

These commitments have led to the development of The Value Toolkit (Construction Innovation Hub, 2021) which enables value-based decision making focused on driving better social, environmental and economic outcomes. Launched in May 2021, the toolkit is designed to change the way that the construction industry makes decisions from project/programme inception through the full investment lifecycle. It uses the Capitals Coalition's model (Capitals Coalition, 2021) of four capitals (Produced, Natural, Human, and Social) to enable organisations to make informed decisions to create value for nature, people and society, alongside business and the economy.

Commissioning for social value

The Social Value Act (2012) and PPN06/20 has empowered central Government and local authority commissioners to use social value to maximise their purchasing power and secure as much benefit as possible for their local area. Social value can include a range of outcomes, such as leaving a skills legacy by employing locally and creating sustainable apprenticeships, boosting local small, medium and micro businesses and social enterprise by ensuring that they form a core part of the supply chain and that a high proportion of the project spend goes to local suppliers.

Commissioners have the opportunity to be ambitious, demanding value creation and low carbon outcomes through the use of low carbon or carbon-sequestering materials such as biochar and dolerite. To deliver these outcomes, it is essential that the demand for social value outcomes is fully embedded into an infrastructure project's business case or strategic brief. Without this, it will always be considered an "add-on" and opportunities will be lost.

A project's design stage is critical in making sure that social value outcomes set out in the strategic case are taken forward. Collaboration with designers is key during this stage to ensure they are familiar with a project's social value priorities, targets, outcomes, and indicators.

Construction companies have more information than ever at their disposal to help develop local sourcing strategies and improve the social value delivered throughout their supply chains. This would include an opportunity to specify carbon sequestering materials such as biochar and dolerite. In addition to environmental benefits, use of biochar and dolerite could deliver particular social value in the expansion of networks and connections through the establishment of new markets, the creation of jobs, and the development of new skills and knowledge.

When done well, procurement can enable social value delivery and provides opportunities to engage local suppliers and SMEs, building local capabilities, and ensuring that the supply chain is diverse and reflects the local cultural mix. Sourcing locally could offer economic, social and environmental benefits including supporting local production, reducing transportation and carbon emissions and help to channel investment towards new markets. Using locally produced materials could help imbue infrastructure projects with a sense of place and cohesion.

The procurement stage provides a valuable opportunity to deliver social value by ensuring that supply chains are engaged and committed to contributing to the defined social outcomes of a project. Engagement and collaboration i.e. pre-procurement market engagement with potential suppliers before developing the tender will offer an opportunity to design a commission that enables the supply chain to be prepared for success and delivering clear social value. By communicating expected outcomes (those ideally set out in an infrastructure project's business case) and discussing the commission before with potential bidders, before tender, will ensure a more inclusive bidding process, provide insight and unlock creativity and innovation in the supply chain.

Good practice is that any social value opportunities agreed in a project's planning and design phase are set out within contractual requirements to ensure clarity and delivery. Best practice is to set out a social value delivery plan – articulating the approach to social value outputs and outcomes expected at all project stages.

To deliver more social value it is essential to communicate a project's social value ambitions in the procurement tender information as well as include evaluation criteria for social value and a percentage scoring weighting. This will make clear the importance of delivering social value and the supply chain can respond accordingly.

When designing a tender, a set of contract requirements that are aligned with the projects' priorities and outcomes is a clear way to get supply chain commitment to delivery of social value. However, it is important to strike a balance between clear requirements and giving bidders, particularly SMEs, the flexibility to show capability and innovative ways to deliver social value. Early supplier engagement will help determine this balance.

To maximise social value, it is important that that contract opportunities are opened to SMEs and the voluntary, community and social enterprise sectors (VCSEs) and that the supply chain has the chance to form collaborations to fulfil the tender requirements. Innovative suppliers will work in partnership to go beyond provision of jobs and apprenticeships, i.e. by delivering social value in creative ways, working with local community groups or organisations who specialise in addressing local need. They may, for example, offer job and training opportunities to those furthest from the labour market and involve social enterprises with local knowledge and local networks to do this. Community is one area where businesses, especially SMEs and VCS organisations wishing to add value, can provide tangible benefits as they are more likely to have vision, knowledge and skills to engage with and deliver social value in communities.

Finally, best practice is also to track social value achievements through reporting on progress in the social value plan at each stage of a project. Targets/expectations should also be shared with supply chains. In larger contracts supply chain forums can be set up to share best practice, transfer knowledge and celebrate good practice.

F1.2 The critical importance of the pilot project

The pilot project – the £38 million Banwell Bypass design and build project and the associated 'reference' site at Moreton-in-Marsh – will provide a significant opportunity for these technologies to be tested and delivered operationally. This will allow a better assessment of social value achievement including the following:

- Embedment of the technology into the design of the project, to contribute to the future specification of these technologies.
- Assessment of the social value contribution of the pyrolysis of materials to make biochar, including an assessment of job creation.
- Evaluation of the operational logistics of the supply and installation of the technologies into linear infrastructure including the use of mobile plant. This will allow for a detailed assessment of the job potential within the infrastructure sector and identification of any skills gaps, including as an example, material testing.
- Supply chain engagement opportunities and understanding potential synergies and wider benefits.
- Monitoring of the carbon capture effectiveness.

F1.3 Scaling up industry wide

With the value of planned infrastructure investment in the national pipeline running into the hundreds of billions of pounds, it is imperative that the demand for social value outcomes is fully embedded into early-stage project design. For the Banwell scheme, a Needs Analysis and Social Value Action Plan has been completed by the Social Value Portal (The Social Value Portal, November 2020), with estimated additional social and local economic value between £2.9 million - £5.9 million, representing 7.5% - 15% of the contract value.

Priority needs to be addressed include: (i) high employment deprivation in Banwell village centre (ii) high level transport CO2 emissions per capita in North Somerset, and (iii) high percentage of physically inactive adults. The Social Value Action Plan recommendations include: providing employment opportunities for local people (particularly those further from the job market; including NEET0s and long-term unemployed), subsidised sustainable transport opportunities and volunteer support to community events. The Social Value Action Plan developed during Phase 2 inception would build on this plan further and consider potential to link into community events.

Engagement with the supply chain will provide additional opportunity to explore social value and wider benefits. For example, as set out in Appendix G, this project would give PyroCore the ability to further investigate the options open to the capturing and sequestration of carbon from various sources. Through the use of PyroCore technology, the project could generate bioenergy, produce biochar (the quality and type of which can be controlled for specific applications) and potentially look to extract hydrogen in the future.

F1.4 Conclusion

This project taps into the planned £650 billion infrastructure investment as a market for the emerging innovative technologies of biochar and dolerite. This market is supported by a significant policy drive for increased social value which includes the GGR properties, the opportunities for creating value through new innovative supply chain networks, the creation of high-quality meaningful jobs in a wide range of locations across the UK, and the development of new skills and knowledge.

The policy environment and marketplace are further supported by the commitments of major suppliers, and their supply chains, to delivering a corporate responsibility – sustainability agenda. This commitment is driven by government, investors, regulators and stakeholder demand for responsible investment and the delivery of social value including progression to net zero.

The pilot stage of the project will provide data on the potential social value opportunity of the infrastructure market for both biochar and dolerite. It has the potential to embed the use of these technologies into linear infrastructure and play a part in the global drive to achieve a just transition to net zero carbon.

References

BEIS (2018) *Construction sector deal*. Available online: https://www.gov.uk/government/publications/construction-sector-deal [Accessed 5/11/2021].

Capitals Coalition (2021) *Capitals Coalition a global collaboration redefining value to transform decision making*. Available online: https://capitalscoalition.org/ [Accessed 5/11/2021].

Construction Innovation Hub (2021) *Construction Innovation Hub Value Toolkit*. Available online: https://constructioninnovationhub.org.uk/value-toolkit/ [Accessed 5/11/2021].

Construction Leadership Council (2018) *Procuring for value*. Available online: https://www.constructionleadershipcouncil.co.uk/news/procuring-for-value/ [Accessed 5/11/2021].

Costain (n.d.) *Costain being a responsible business*. Available online: https://www.costain.com/our-culture/being-a-responsible-business/ [Accessed 5/11/2021].

Costain (n.d.) *Costain joins the COP26 Race to Zero and signs The Climate Pledge*. Available online: https://www.costain.com/news/news-releases/costain-joins-the-cop26-race-to-zero-and-signs-the-climate-pledge/ [Accessed 5/11/2021].

Costain Group PLC (2021) *Interim results for the half year ended 30 June 2021*. Available online: https://www.costain.com/media/599553/full-results-statement-for-the-half-year-ended-june-2021.pdf [Accessed 5/11/2021].

Government Commercial Function (2020) *Social value model quick reference table* (3 December 2020). Available online: https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/940828/Social-Value-Model-Quick-Reference-Table-Edn-1.1-3-Dec-20.pdf [Accessed 5/11/2021].

Hey, N. (2020) The Green Book review – what do the changes to government appraisal mean? *What Works Wellbeing*. 9 December. Available online: https://whatworkswellbeing.org/blog/the-green-book-review-what-do-the-changes-to-government-appraisal-mean/ [Accessed 5/11/2021].

HM Government (2020) *Procurement policy note 06/20 – taking account of social value in the award of central government contracts*. Available online: https://www.gov.uk/government/publications/procurement-policy-note-0620-taking-account-of-social-value-in-the-award-of-central-government-contracts [Accessed 5/11/2021].

HM Government (2020) *The construction playbook*. Available online: Guidance overview: https://www.gov.uk/government/publications/the-construction-playbook [Accessed 5/11/2021].

HM Government (2020) *The Green Book: appraisal and evaluation in central government.* Available online: https://www.gov.uk/government/publications/the-green-book-appraisal-and-evaluation-in-central-governent [Accessed 5/11/2021].

HM Treasury (2021) *Green book supplementary guidance wellbeing*. Available online: https://www.gov.uk/government/publications/green-book-supplementary-guidance-wellbeing [Accessed 5/11/2021].

Infrastructure and Projects Authority (2021) *Transforming infrastructure performance: roadmap to 2030*. Available online: https://www.gov.uk/government/publications/transforming-infrastructure-performance-roadmap-to-2030 [Accessed 5/11/2021].

McNaught, D. (2021) Why the National Infrastructure Commission's new net-zero objective is good news for infrastructure planning. *Institution of Civil Engineers*. 1 November. Available online: https://www.ice.org.uk/news-and-insight/the-infrastructure-blog/november-2021/why-nic-net-zero-good-news-infra-planning (ice.org.uk) [Accessed 5/11/2021].

National Highways (2021) *A12 Chelmsford to A120 widening scheme*. Available online: https://highwaysengland.co.uk/our-work/east/a12-chelmsford-to-a120-widening-scheme/ [Accessed 5/11/2021].

Appendix G - Banwell Bypass

Appendix G has been removed due to confidentiality issues.

G1 Banwell Strategy

Appendix G has been removed due to confidentiality issues.

G2 Banwell PSSR

Appendix G has been removed due to confidentiality issues.

G3 Banwell Drawings

(1) BNWLBP-ARP-HML-X_BB_02-SK-CH-100013

(1a) BNWLBP-ARP-GEN-X_BB_Z-DR-CH-900001

(1b) BNWLBP-ARP-GEN-X_BB_Z-DR-CH-900002

(1c) BNWLBP-ARP-GEN-X_BB_Z-DR-CH-900003

(1d) BNWLBP-ARP-GEN-X_BB_Z-DR-CH-900004

(2) BNWLBP-ARP-HML-X_SL_Z-SK-CH-000004

(2a) BNWLBP-ARP-HGN-X_BB_Z-DR-CH-000005

Appendix G has been removed due to confidentiality issues.

G4 Environmental Considerations

Appendix G has been removed due to confidentiality issues.

G5 Material requirements and Landtake

Appendix G has been removed due to confidentiality issues.

G6 PyroCore Feedstock Trial Proposal

Appendix G has been removed due to confidentiality issues.

G7 RAMS Earthworks Embankment

Appendix G has been removed due to confidentiality issues.

Appendix H - MIM Specification of Works

1 Introduction

1.1 Project background

Arup have been appointed by the Department for Business, Energy, and Industrial Strategy (BEIS) to assess the effectiveness of incorporating quarry fines and biochar ('the materials') for carbon sequestration (CO_2) within linear infrastructure projects. Both technologies have previously been used in agriculture for soil improvement. The potential for use of the materials for Greenhouse Gas Removal (GGR) on linear infrastructure projects is currently a novel concept. The information collated through literature reviews has indicated that the use of these materials presents a viable opportunity for carbon sequestration in linear infrastructure projects.

To assess the performance of carbon sequestration of the materials within linear infrastructure projects, their use would be incorporated into a real-world application on a pilot linear infrastructure project site. The Banwell Bypass has been identified as a suitable site for the main pilot scheme.

To provide evidence of benefit and a risk-based assessment of the proposed activities on the pilot site, it is also proposed that the materials would be used on a reference site. Moreton-in-Marsh (MiM) has been identified as a suitable location for the reference site.

The purpose of the reference site would be to mimic the proposed uses on the pilot site as closely as possible, within a controlled environment, that would allow for monitoring of the carbon benefits, the geotechnical and geo-environmental properties, and general material behaviours. The objective of the reference site would be to ensure that the effectiveness of carbon removal, behaviour of the materials, monitoring requirements and applications during construction (e.g., mixing) are understood in a controlled environment.

This note presents a high-level design of the works proposed at the reference site and states any requirements for monitoring and testing of carbon removal and material behaviours.

1.2 The need for the reference site

During the development of this specification of works, it has been concluded by the Project Team that a reference site would be of benefit to the overall study. Although a reference site would incur increased costs, there are significant benefits of having a reference site for the application of these material technologies.

The benefits of having a reference site, in the context of these material technologies, are listed below:

- The facility at the reference site would allow for the assessment of the effectiveness of Enhanced Mineral Weathering (EMW) and understanding monitoring requirements prior to use in a live site; e.g., monitoring the effectiveness of EMW in sequestering carbon dioxide (CO_2).

- The reference site would allow the construction methodologies to be refined, including methodologies for the mixing the materials with topsoil and placement of materials.
- The reference site would demonstrate the feasibility of the use of these materials and potential impacts (e.g., potential impacts on plant growth, and slope stability), which would be useful in obtaining agreement for implementing a pilot scheme at Banwell Bypass.
- The reference site would offer the opportunity for longer term monitoring, which would be beneficial to the pilot site as the construction of the pilot site would be up until 2025.
- The proposed reference site (MiM) is currently operational as a controlled testing facility, owned by Capita. This offers a controlled site for monitoring and for construction. Relevant stakeholders (e.g., National Highways) currently utilise MiM for their own testing purposes (e.g., smart motorway testing), and using MiM as a reference site would allow increased exposure of the use of these materials and their benefits. This would benefit the possibility of future applications. Capita have provided a letter of support for use of the MiM site, provided in the back of this note.
- The reference site offers the possibility to integrate highly specific testing concerns that are not practically examined at the pilot site.
- The reference site would allow greater flexibility for amendments to be made to the pilot site proposals, e.g., to further explore unexpected results.
- The use of a reference site promotes increased awareness of the material applications and technologies, promoting their use in future linear infrastructure projects.
- A safely accessible reference site is an invaluable tool in the long-term for disseminating the project to future stakeholders; tactile engagement with the materials is more reassuring than photos or data sheets.

2 Uses of biochar and quarry fines

An overview of the material types biochar and quarry fines (Enhanced Mineral Weathering) is provided in Appendix B and Appendix C respectively. This includes a review of what the materials are, how they are generated/processed, their properties (structural, chemical, and carbon removal capabilities), and existing uses in society.

This section of Appendix H provides a high-level summary of the potential uses of these materials in linear infrastructure projects. This includes identified uses during this study, which are to be implemented, monitored, and compared between the pilot site (Banwell Bypass) and the reference site (MiM).

2.1 Summary of current applications of the materials

The materials have established uses for soil improvement within agriculture and have been examined in detail by the academic community. Integration into farming systems is typically based on small doses over large areas. Civil engineering projects might allow more concentrated application, allowing the incorporation of much larger volumes of usable carbon removal technologies into available land areas, integrated within the confines of project sites. Quarry fines have been used in green landscaping (e.g., Newcastle Helix), in green roofs (e.g., The Sill) and in community ‘carbon capture gardens’.

See Appendix B and Appendix C for further details.

2.2 Potential uses in linear infrastructure projects

High-level view

From review of published literature (presented in Appendix B and Appendix C), a number of possible opportunities for the use of biochar and quarry fines within linear infrastructure projects have been identified. These are presented in Table 1. These uses have been defined based on individual technical discipline understandings (e.g., civil, and geotechnical engineering) of typical material applications along linear infrastructure projects (e.g., materials required for earthworks within highways schemes).

Table 1: Potential uses of biochar and quarry fines within linear infrastructure projects

ID	Potential Use	Biochar	Quarry fines
1	Blended with soil for drainage swale/SUDS	✓	✓
2	Substituted for filter drainage stone	✓	X
3	Substitute for unbound surfacing on access tracks (accommodation works and basins, low-loaded tracks, or paths, etc.)	X	✓
4	Substitute for Type 1 subbase/capping material	X	✓
5	Substitute for Class 1 earthworks materials	X	✓

ID	Potential Use	Biochar	Quarry fines
6	Filtration of surface water drainage to improve water quality	✓	X
7	Blended with soil for topsoil	✓	✓
8	Landscape fill	✓	✓

Banwell Bypass material placement scenarios

Based on the current scheme design at Banwell Bypass, the following material use scenarios for biochar and quarry fines are presented below. These are further expanded upon in Appendix G of this report:

- Within topsoil on embankments with 1 in 2 slope gradients (including adjacent drainage swales).
- Within topsoil on embankments with 1 in 3 slope gradients (including adjacent drainage swales).
- For use in adjacent flatter areas/verges alongside of embankments.

It may also be feasible to use quarry fines as drainage filter stone, or as surround to service ducts, subject to the design confirmation.

The material uses at the reference site (Moreton-in-Marsh) would look to emulate the material placement scenarios at the pilot site (Banwell Bypass), as to provide the best possible means of validating the material behaviours and expected carbon removal in similar conditions. This would include trialling the use of these materials within topsoil on the slopes of 1 in 1.5 and 1 in 3 embankment slopes, to understand how the materials behave on steeper slope gradients.

2.3 Regulatory requirements

Regulation of use of biochar

Refer to Appendix E for the regulatory position for the use of biochar and quarry fines respectively.

3 Reference site: Moreton-in-Marsh

3.1 Introduction

The reference site which is proposed for use as part of this specification of works is located in the town of Moreton-in-Marsh, a small market town located in the Evenlode Valley in Gloucestershire, England. The site is currently purposed as a testing facility associated with the Fire Service College and highways services, and the site is typically used for fire-related training (e.g., large scale aviation fuel burning).

The site would allow for the safe trials of new technologies or processes on a non-live highways site. The site would be ideal for monitoring of the application and use of the two materials in a safe, easily accessible environment. This would allow for the testing and subsequent monitoring of the proposals which are to be implemented at the pilot site (Banwell Bypass), and as such would look to mitigate potential risks to the pilot site, such as future perceptions of risk of the use of these materials in a highways scheme.

This section of the note provides an information summary of the reference site; for example, general site characteristics such as the topography and the geological conditions. This is important as it allows for comparisons and differences to be drawn with the pilot site (Banwell Bypass), which should be considered when forming the basis of the experiments and monitoring at the reference site. This section also comments on the procedural aspects associated with the reference site, for example, any planning permission or permits that may be required as part of the development. It should be noted that the Project Team have been notified by the site owners (Capita) that there are no exemptions from planning on the site, and as such, it is important to note that it is expected that planning permission would be required for any development works on the site that would normally require planning permission.

3.2 Site information

A summary of the pertinent information relating to the site is provided in Table 2.

Table 2: Summary of site information

Site characteristic	Summary
Site location and description	The site is situated at the Fire Service College, east of the town Moreton-in-Marsh, in Gloucestershire. The site is centred round National Grid coordinates SP 225 325. The surrounding site area is occupied by residential housing associated with the town of Moreton-in-Marsh (west), the A44 road (south), woodland and agricultural land (east, and a large unnamed road which connects the A429 and the A3400. The south east of the site is currently occupied by buildings associated with the Fire Service College, including numerous ancillary buildings such as the Fire Service College Library. These buildings including building reception areas, teaching rooms, accommodation, and living areas (e.g., kitchens). The remaining site comprises bisecting hardstanding road surfaces (1st to 5th Ave), with the road bisections creating individual isolated segments of grassed surfaces which have triangular geometries. The road surfaces are currently used for testing and training

Site characteristic	Summary
	purposes such as accident management planning. Adjacent to the road surfaces are smaller buildings, vehicles, and general infrastructure (e.g., reservoirs). Regular routine fire drills take place at the site.
Current site operations	The site plan for the Fire Service College is shown on Figure 3. The site comprises an incident ground which is where testing is undertaken. This includes infrastructure such as a fire station, rail carriages and track, drill towers, and specific vehicle testing areas. The facility also houses an area used for accommodation and general facilities, administration, and training room areas. These are located to the south east of the site. A chemistry lab is also located on site.
Topography	The site is generally quite flat with the elevation of the ground ranging between 130m and 135mAOD.
Site history	The site history has been summarised from a review of the available historical mapping on the National Library of Scotland data inventory. Only historical mapping dating between 1919 and 1923, 1955, and 1966 were available to review. In summary, between 1919 and 1923, the site itself was occupied by agricultural fields and farmland associated with Batsford Heath Farm. A footpath traversed the site from ENE to WSW. A surface watercourse traversed the site from north to south. Surrounding the site, the town of Moreton-in-Marsh was well established (west). A forested area annotated as 'Lemington Heath Coppice' was present (east), which formed the larger forested area of Wolford Wood. By 1955, the whole site was occupied by an area annotated as 'airfield', and the section of the surface watercourse within the site had been removed (still present to the south). There had been little change to the surrounding area. According to Heritage Gateway[1] information, Moreton In Marsh Airfield opened in 1941 and closed in 1955; however, work had begun on the construction of the facility in 1940. An associated military camp was also present at the airfield site during its operational years. Until 1959, the site was used by the RAF for training reservists in firefighting techniques. By 1966, the airfield that occupies the site was marked as 'disused'. Building development to the south east of the airfield had taken place, which resembled the configuration of the present-day facility.
Published geological records	The British Geological Survey GeoIndex database indicates that the site is underlain by the following: • **Superficial geology (1:50,000):** Moreton Member (sand, silt, and clay) and Wolford Heath Member (sand and gravel). • **Bedrock geology (1:50,000):** Charmouth Mudstone Formation (Jurassic, Lower Lias) underlain across the site. Several historical BGS exploratory hole logs are located within the extent of the site, all of which are available for this review. A summary of the encountered ground conditions within the borehole logs is presented below. **SP23SW6/A-E:** Topsoil above intermittent bands of sand, gravel, and clay generally down to 20 – 25m bgl (holes located within the mapped extent of the Moreton Member).

[1] Heritage Gateway: https://www.heritagegateway.org.uk/Gateway/Results_Single.aspx?uid=1406464&resourceID=19191

Site characteristic	Summary
	Very stiff poorly laminated, fissured, silty CLAY generally encountered between 25 – 30m bgl, which is likely to represent weathered rock. Mudstone encountered at 29m bgl in SP23SW6/E. **SP23SW4:** Borehole terminated 11m bgl. Turf over topsoil (0 – 0.2m bgl) and intermittent bands of sand, gravel, and clay down to 11m bgl (hole located within the mapped extent of the Moreton Member). **SP23SW8:** Trial pit, terminated 2.7m bgl. Made Ground (0 – 1.5m bgl) above Glacial Deposits (1.5 – 2.7m bgl). The Made Ground comprises black and yellowish-brown CLAY with cobbles and boulders (concrete blocks, tarmac, and flint). In summary, the exploratory hole logs indicate that the ground conditions comprise topsoil/Made Ground above superficial deposits, which likely represents the Moreton Member. The superficial deposits have been proven to a maximum depth of 29m bgl, below which mudstone has been encountered, which likely represents the Charmouth Mudstone Formation.
Hydrogeology	The following aquifer designations have been assigned to the geological formations present beneath the site: • Wolford Heath Member: Secondary A aquifer. • Moreton Member: Secondary B aquifer. • Charmouth Mudstone Formation: Secondary (undifferentiated). The ground investigation data (below) indicates that groundwater may be located at shallow depth within the superficial deposits.
Hydrology	A small tributary of the River Evenlode is located immediately south of the site. The configuration of this watercourse is similar to that identified from the 1919 to 1923 historical mapping. The section of this watercourse that traversed the site was not present after the construction of the site as an airfield and was likely removed during this time. Several watercourses are present directly east of the site associated with Lemington Heath Coppice and appear to drain towards a tributary of the River Evenlode.
Rainfall and wind direction	According to data obtained from Climate-Data.org, the average annual precipitation rates in Moreton in Marsh is 763mm. The prevailing wind direction is typically from south west to north east.
Environmental sensitivity	**<u>Statutory</u>** The Wolford Wood and Old Covert Special Site of Scientific Interest (SSSI) is located approximately 700m to the east of the site. The eastern part of the site lies within a SSSI Impact Risk Zone. Sites that lie within a SSSI Impact Risk Zone may be required to assess planning applications for likely impacts on SSSIs/SACs/SPAs and Ramsar Sites in England. The site is located within the Evenlode (Bledington to Glyne confluence) Nitrate Vulnerability Zone (NVZ) for surface water. **<u>Non statutory</u>** The site lies within an area designated as a Drinking Water Safeguard Zone for surface water, under safeguard zone name "Thames_SWSGZ4015, 4016_Cookham Teddington & Wey. This is on account of the following pollutants: • Benzo(a)pyrene. • Nitrite. • Pesticide 2-4 D.

Site characteristic	Summary
	• Pesticides (11 species). • Turbidity.
Unexploded Ordnance (UXO)	**Evidence of previous military land-use** A search of available online resources and historical OS mapping, including Zetica risk maps, indicates that the site was used as an airfield and military camp. **Potential for aerially delivered ordnance** The Zetica risk maps shows the site to be in an area of low risk. However, the site itself was deemed to be an area classified as a 'Luftwaffe Target' during the Second World War. No UXO finds have been documented on and within 5km of the site. **Consideration of additional factors** Industrial development of the site took place during the Second World War and had a defined purpose as a military and airfield base during and post Second World War. As the site was deemed to be a Luftwaffe Target, it is possible that the site may have been subject to Second World War bombings. According to the Geotechnical Engineering Limited (GEL) ground investigation report[2], the site was in fact subject to bombings during the Second World War. **Overall consideration of risks** On account of the information above, the site is deemed to be high risk with respect to UXO. The Project Team are aware that the site owners are aware of the potential risks associated with UXO and are in possession of relevant UXO site assessment information. The findings of this assessment will be factored into any of the minor engineering works required for this development.
Previous ground investigations	A ground investigation was undertaken at the site by Geotechnical Engineering Limited (GEL) for Costain acting on behalf of Highways England. This was undertaken on 21st March 2019. The ground investigation was commissioned to determine the ground conditions in an area of the site where it was proposed to construct a gantry and a mast structure at the Fire Service College. **Scope of ground investigation** The ground investigation comprised the following: • Boreholes MM01 (0.15m bgl), MM01A (20.35m bgl), and MM02 (5.45m bgl). MM01 was terminated at 0.15m bgl due to a concrete obstruction encountered across the pit and reattempted approximately 2m to the south as MM01A. Standard Penetration Tests (SPTs) were undertaken in all boreholes. • The site was subject to aerial bombing during the Second World War. Consequently, on-site monitoring was provided by a specialist in unexploded ordnance (UXO) from Brimstone Site Investigation (downhole magnetometer testing was used at regular intervals as the hole was advanced). • Samples were obtained and scheduled for geotechnical classification and chemical laboratory testing. • No installations were constructed within boreholes for groundwater and/or ground gas monitoring. **Findings of the ground investigation** Pertinent findings of the ground investigation are summarised below:

[2] Geotechnical Engineering Limited (2019): SMP Moreton Ground Investigation, factual report on ground investigation.

Site characteristic	Summary
	• Ground conditions are typically aligned to those identified from the published geological review, comprising thin Made Ground above superficial deposits. Superficial deposits comprise dominant CLAY with intermittent SAND and GRAVEL layers. • During drilling, groundwater was encountered at 1.9m bgl in MM01A, which rose to 1.32m bgl after 20 minutes. In MM02, groundwater was intersected at 3m bgl, rising to 2.9m bgl after 20 minutes. Groundwater was encountered in both boreholes corresponding to strata comprising of sandy gravelly CLAY. • No UXO anomalies were identified in the deeper boreholes (MM01A and MM02). • Concentrations of contaminants within the soil are generally low given the type of the development being industrial/commercial (and no asbestos was detected from the laboratory analysis).

The rainfall and wind direction align closely with the reported values for Banwell Bypass, which has expected rainfall of 830mm and the same prevailing wind direction from south west to north east (see Appendix G).

It should be noted that due to the frequent flammability tests and fire drills that are conducted at Moreton-in-Marsh, this site is likely to have higher levels of pyrogenic carbon present in the topsoil and surface waters than typical greenfield sites.

Similarly, due to the recorded presence of Made Ground in previous ground investigations, the site's previous role as an airfield, and the current industrial/commercial status of the site, it is likely that crushed concrete is present in the topsoil at higher rates than would be found in greenfield sites.

A baseline should be established to determine the approximate carbonate and pyrogenic carbon content of the soil arising from pre-existing processes.

3.3 Planning and regulation

As stated in Section 3.1 of this note, the Project Team have been notified by the site owner (Capita) that there are no exemptions from planning for any developments that are to take place on the site. The site owner is to discuss these development proposals with the relevant Local Planning Authority (LPA), to understand if there would be any permitted conditions relating to this development.

For the regulatory position of the use of biochar at the reference site, see Appendix E. At this stage, it is assumed that a waste recovery permit will be required for the proposed operations (see Appendix E).

An Environmental Impact Assessment (EIA) is unlikely to be required for the proposed development, given that the development will only require small-scale engineering works (see Section 4). To demonstrate that an EIA would not be required, an EIA screening document should be prepared and submitted to the relevant planning authority.

4 Monitoring at the reference site

4.1 Introduction

This section of Appendix H presents the proposed trials that would be undertaken at the reference site, Moreton-in-Marsh. The trials would look to validate factors such as carbon sequestration potential from the different material applications, and monitor soil and water properties over a longer-term monitoring period (planned to be undertaken over a 3-year period). This would help inform the requirements for material placement and monitoring at the pilot site (Banwell Bypass); see Appendix G of this report. Below are the specific objectives of the trials, the proposed methodology and rationale, and any monitoring requirements.

4.2 Objectives

The general objective of the trials at the reference site would be to provide a means of validating the design and material placement scenarios which are proposed at the pilot site (Banwell Bypass). The specific objectives of the proposed trials at the reference site are listed below.

- To monitor the carbon sequestration potential of the different blended ratios of topsoil, quarry fines, and biochar (e.g., blended topsoil in topsoil of embankments), or as standalone materials (e.g., quarry fines plots). This is to understand which blend would be the most effective in terms of carbon removal, to inform future applications.
- To understand the geotechnical and structural behaviour of the proposed placement scenarios, and how different blended ratios of topsoil, quarry fines, and biochar behave in different earthworks. Comparisons between 1 in 3 slopes for the main embankment batters and 1 in 1.5 slopes for the embankment battered end slopes.
- To understand the geo-environmental implications of the proposed placement scenarios, and how different blended ratios of topsoil, quarry fines, and biochar may contribute to water quality (e.g., infiltrating water) and leaching potential of the soil.
- Understanding in greater detail how the materials (biochar and quarry fines) are handled and applied at infrastructural scales, given their previous isolation of use in agricultural practices. Specifically, this would include how the materials would be handled and blended during construction. This would be crucial in informing the mixing process during construction at the pilot site.
- Characterising the combined effect of biochar and quarry fines upon the soil structure over time, and how this varies with different concentrations (blended ratios) in the soil.
- To validate the rates of Enhanced Mineral Weathering within the quarry fines, to assess the effectiveness of this mechanism of carbon sequestration. In addition to this, understanding how weathering of the quarry fines might impact the geotechnical/structural properties of the topsoil containing quarry fines.
- To provide a well-controlled monitoring scenario for the performance of the above factors (e.g., carbon sequestration) in a controlled environment on the testing site, which may help to refine the monitoring proposals being implemented at the Banwell Bypass pilot site and other future applications.

4.3 Potential constraints

A number of potential constraints have been identified with respect to the project and Moreton-in-Marsh (MiM). This section will provide a summary of the main potential constraints.

Table 3: Key risks and opportunities for Moreton-in-Marsh

Risk or opportunity	Description	Impact	Mitigation/further action
Risk: Programme alignment with the pilot site (Banwell Bypass)	It is possible that the alignment of programme for Moreton-in-Marsh (MiM) and the identified live pilot project's (Banwell Bypass) completion may not be aligned.	Completion may be delayed beyond the 2025 date required for demonstration of the 1,000tCO_2/annum target.	The trials at MiM will aim to demonstrate the value of these technologies as a whole, benefitting future applications. The trials at MiM will align with the Banwell Bypass programme with respect to mixing trials and overlap with the monitoring intervals, and therefore providing an overall benefit.
Risk: Likeness between reference site and live infrastructure projects	The reference site is purposed as a testing facility and offers a 'controlled' environment with few restrictions in terms of accessibility, which is not strictly analogous to the pilot site.	The differences in setting may have a bearing on the feasibility of use of these materials (e.g., different accessibility constraints for monitoring between reference and live pilot site).	The trial plots (Table 5) have been designed so that they mimic the conditions of the pilot site (e.g., linear embankments with similar slope gradients and vegetation).
Risk: Validation and monitoring	The carbon benefits and behavioural characteristics of these materials have been postulated in the literature, however, monitoring of these behaviours is in some cases a novel concept (e.g., monitoring structural/geotechnical changes associated with quarry fines as a result of weathering).	There is a potential risk that monitoring material behaviours may be difficult to validate, and unexpected problems may arise that have not previously been accounted for (e.g., sampling and testing issues).	The primary purpose of these trials at MiM is to validate the material behaviours and monitoring, to streamline this process during the pilot site and future applications.
Risk: Planning permission and permitting	As stated in Section 3.3 of this appendix, the development is not exempt from planning permission and there is likely to be a requirement for some regulatory control for the use of biochar, for example, a waste recovery permit (Appendix E).	This may incur additional costs to the development.	Relevant stakeholders for regulatory positioning on biochar (e.g., the Environment Agency) have been engaged throughout the process (Appendix E). If required, necessary permits will be obtained. Understanding of planning permission requirements

Risk or opportunity	Description	Impact	Mitigation/further action
			have been discussed with the site owner (see Section 3.3).
Risk: Grass fires at Moreton-in-Marsh	Large scale fire drills at Moreton-in-Marsh can spread cinders across the site, which can start small grassfires during long periods of dry weather.	There is a potential risk that these fires could interfere with vegetation growth measurements and alter the topsoil chemistry.	The placement of the monitoring cells at Moreton-in-Marsh will consider the location of high-risk fire activities and will be sited away from these and upwind of them. Additionally, during dry periods where fires are more likely to start and spread, stringent grass management will ensure that this risk is minimised.
Risk: Land transaction and transfer at Moreton-in-Marsh	Land is regularly transacted at the Fire Service College in order to facilitate site developments.	The placement of plots on land that is later sold may result in the plots being demolished for future building and jeopardise the potential for long term monitoring of carbon and environment performance.	Placement of monitoring plots will be sited in ‘key’ areas of the site, e.g., close to key site assets that are not likely to be sold. This information has been provided by the Site Manager.
Risk: Vandalism	There is an ongoing issue with trespassing at the site, as the site is considered to be of interest to local vandals, and urban explorers.	There is a risk that future trespassing may result in the vandalism of the plots, which would significantly impact the integrity of the monitoring.	The site is currently in the process of implementing a highly sophisticated radar telemetry system for their personal CCTV. This will ensure that trespassing is kept to a minimum.
Opportunity: Longer term monitoring	Moreton-in-Marsh offers the potential for longer term monitoring of carbon removal, and environmental/engineering/ ecological impacts associated with the materials.	Significantly benefit validating the carbon performance of the materials, and to refine any monitoring needs should this be required. Refinements could be implemented/assist Pilot Site studies (Banwell Bypass).	The potential for longer term monitoring could be a key opportunity for using Moreton-in-Marsh as the reference site.
Opportunity: Practical **s**takeholder engagement	Moreton-in-Marsh offers the opportunity for stakeholders to view the applicability of the materials within a regulated environment.	Allows the relevant stakeholders to have a tactile appreciation of how the materials would be applied to linear infrastructure in the field.	The reference site would allow the Project Team to demonstrate how the materials could be applied in a variety of ways to stakeholders, as opposed to purely theoretical, written reporting.
Opportunity: Onboarding National Highways early on	Having Moreton-in-Marsh is important to get National Highways on board with	National Highways will be aware of the development of these technologies and the results of monitoring	National Highways would be in a better position to appreciate the next steps that would need to be

Risk or opportunity	Description	Impact	Mitigation/further action
	the use of these materials for carbon removal.	as and when it happens, as National Highways currently operate within Moreton-in-Marsh (e.g., through smart motorway development).	taken to integrate the materials into standard highways design.

4.4 Methodology and rationale

The proposed trial plots are shown on Figure 1. It is important to note that the locations of all of the plots are indicative and are subject to changes in location within the site (subject to formal agreement with the site owner).

The land take required for the plots is summarised in Table 4. Plot(s) 1 to 4 would comprise of four individual embankments with a five-metre separation between them. Embankment sketches are provided as Figure 2.

Table 5 outlines the justification for each individual plot required.

Figure 1: Proposed methodology at Moreton-in-Marsh

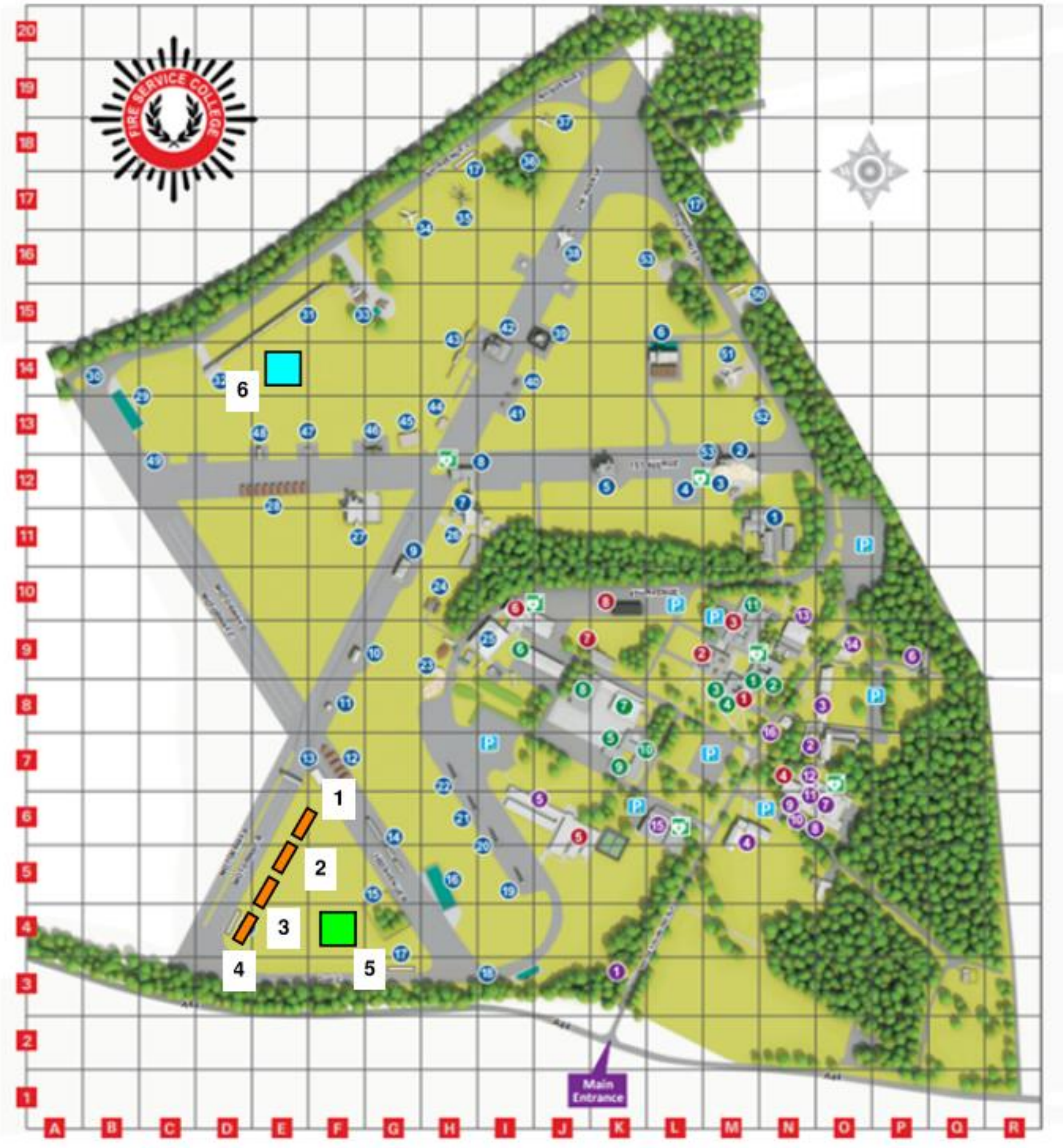


Table 4: Land take and material requirements

Plot	Structure	Total land take required	Specialist materials required	Other materials required
1 (Banwell)	Each embankment: 16.94m (L) x 1.5m (H) x 11m (W); total length of embankment includes embankment ends	186.38m^2	**Biochar:** 2.6t (10.48m^3) **Fines:** 26.37t (9.77m^3) **Topsoil:** 34.42t (20.24m^3)	**Embankment materials:** Class 1 Embankment Fill (136m^3 per embankment); Pozidrain: **Option 1:** 120m^2 of Pozidrain **Option 2:** 186.38m^2 of Pozidrain
2 (Control)		186.38m^2	**Biochar:** 0t **Fines:** 0t **Topsoil:** 68.83t (40.49m^3)	
3 (Low rate)		186.38m^2	**Biochar:** 1.05t (4.19m^3) **Fines:** 10.55t (3.9m^3) **Topsoil:** 55.1t (32.4m^3)	
4 (High rate)		186.38m^2	**Biochar:** 3.93t (15.72m^3) **Fines:** 39.6t (14.7m^3) **Topsoil:** 17.2t (10.12m^3)	
5	Treatment area	451.1m^2	-	-
6	Fines area	30m^2	**Fines:** 40.5t (0 – 6mm fraction)	**Topsoil:** 6m^3

Embankment design considerations: Plot(s) 1 to 4

Sketches of the embankment design required for Plot(s) 1 to 4 is shown on Figure 4. This includes embankment cross section, longitudinal view and view of the embankment ends. It should be noted that Figure 4 includes two embankment cross sections: Option 1 Pozidrain directly beneath topsoil and Option 2 Pozidrain base. Both options are being considered as it is the intention to have the embankment as a ‘contained system’ (see Table 5), and costs should be obtained for both design options.

Pozidrain will be used to provide to allow for the containment of infiltrating water as it is impermeable. Due to the small slope heights proposed at MiM, the risk of topsoil instability is unlikely if Option 1 is to be considered. Pozidrain will not be placed on embankment ends.

The Class 1 Embankment fill should be free of any anthropogenic content, carbonaceous, and calcite materials to ensure that the embankment fill has no bearing on the infiltrating water quality. (Drainage stone should be free of carbon content, e.g., limestone is not suitable – Trent Valley river gravels would be suitable).

The remaining details relating to the embankment design (e.g., drainage and containment system) are described per individual plot in Table 5 of this Appendix.

Figure 2: Plot(s) 1 to 4 embankment plots. **NOTE:** These are high-level sketches only, design to be confirmed.

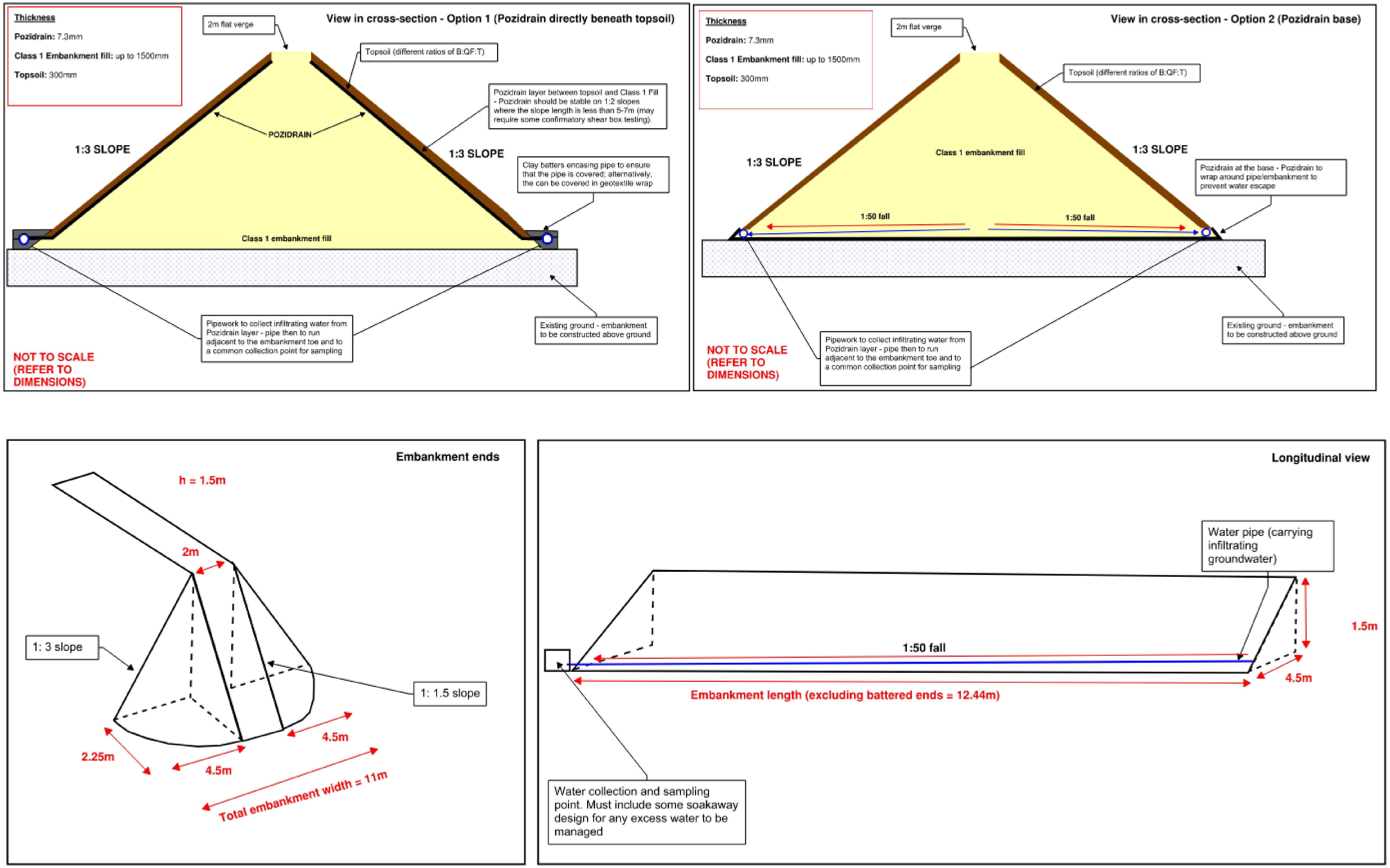


Table 5: Justification for proposed experiment at Moreton-in-Marsh

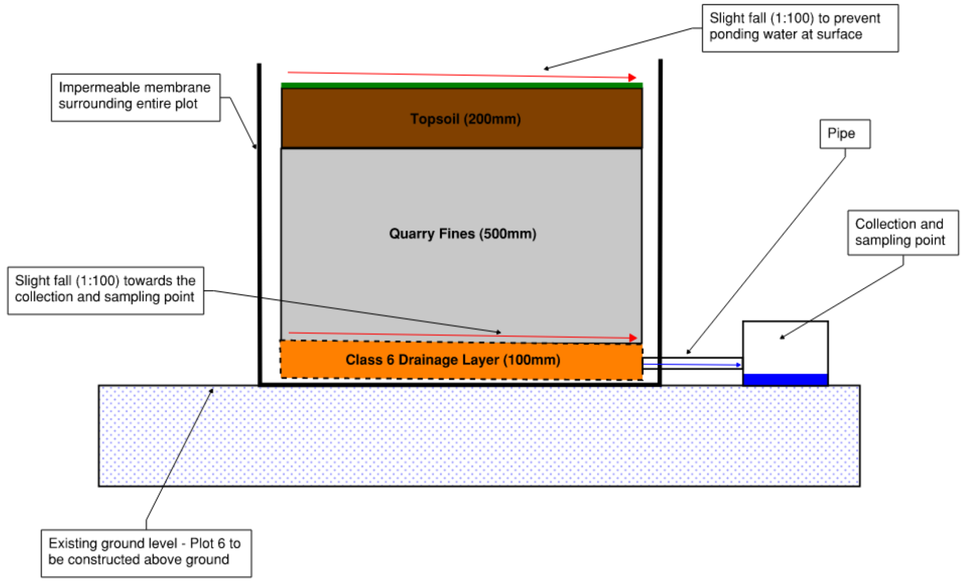
Plot	Test	Biochar (% total weight)	Fines (% total weight)	Topsoil (% total weight)	Description, placement purpose and rationale
1	Banwell replica	4.13	41.59	54.28	**<u>Description:</u>** Plot 1 comprises an embankment, which would be constructed to the dimensions and specification shown on the sketch (Figure 4). For the main embankment batters (1 in 3 slope) and battered end slopes (1 in 1.5 slope), the top 300mm of the 1 in 3 slopes and top 150mm of the 1 in 1.5 slopes would comprise a blended topsoil, with the % total weight of the blended material components indicated in the columns to the left ('Banwell replica'). The embankment would comprise either Pozidrain at the base (Class 1 embankment fill above) or directly beneath topsoil (Class 1 embankment fill below). The embankment would be a contained system, to allow for the containment and subsequent sampling of infiltrating water through the embankment. Option 1 (Pozidrain beneath topsoil) would be preferred, as it would allow for the direct capture of infiltrating water through topsoil without any diluting impacts from other material (e.g., Class 1 embankment fill). As shown in cross section (Figure 4), if Option 2 was considered, there would be a slight fall (symmetrically) of the embankment from its centre (1 in 50 fall) to allow for water to drain through the drainage layer into pipework. The pipework would collect infiltrating water from the embankment and would run longitudinally along the toe of the main embankment batter face to a water collection and sampling point. To do this, for both options there would also be a slight fall longitudinally along the main embankment batter face (1 in 50 fall) towards the water collection and sampling point. The water quality would then be monitored (Table 6). **<u>There would be a requirement for consideration of a soakaway type design to adequately manage the concentration of water at the collection point, so that they do not flood the site.</u>** **<u>Plot to be sewn with the same seed mix that is proposed at Banwell, and at the same rate.</u>** **<u>Placement purpose:</u>** The purpose of this embankment on the reference site would be to mimic the proposed earthworks at the pilot site (Banwell Bypass). The embankment would have an additional benefit at the reference site (Moreton-in-Marsh) as it would provide screening between the residential housing (west) and the testing facility (east). **<u>Rationale:</u>** The primary purpose of Plot 1 would be to validate the carbon removal at pilot site (Banwell Bypass). Mix is 50% topsoil by volume to ensure that published quarry fine weathering rates can be used. Biochar amendment rates of ~5%wt in

Plot	Test	Biochar (% total weight)	Fines (% total weight)	Topsoil (% total weight)	Description, placement purpose and rationale
					clayey soils have been found to improve aggregation. Seed sewing also permits comparison of blend mix effect upon vegetation establishment across four application rates (Banwell replica, unamended, low rate, and high rate).
2	Unamended	0	0	100	**Description:** Plot 2 comprises an embankment, which would be constructed to the dimensions and specification shown on the sketch (Figure 4). For the main embankment batters (1 in 3 slope) and battered end slopes (1 in 1.5 slope), the top 300mm of the 1 in 3 slopes and top 150mm of the 1 in 1.5 slopes would comprise unamended topsoil ONLY ('unamended'). The embankment would comprise either Pozidrain at the base (Class 1 embankment fill above) or directly beneath topsoil (Class 1 embankment fill below). The embankment would be a contained system, to allow for the containment and subsequent sampling of infiltrating water through the embankment. Option 1 (Pozidrain beneath topsoil) would be preferred, as it would allow for the direct capture of infiltrating water through topsoil without any diluting impacts from other material (e.g., Class 1 embankment fill). As shown in cross section (Figure 4), if Option 2 was considered, there would be a slight fall (symmetrically) of the embankment from its centre (1 in 50 fall) to allow for water to drain through the drainage layer into pipework. The pipework would collect infiltrating water from the embankment and would run longitudinally along the toe of the main embankment batter face to a water collection and sampling point. To do this, for both options there would also be a slight fall longitudinally along the main embankment batter face (1 in 50 fall) towards the water collection and sampling point. The water quality would then be monitored (Table 6). **There would be a requirement for consideration of a soakaway type design to adequately manage the concentration of water at the collection point, so that they do not flood the site.** **Plot to be sewn with the same seed mix that is proposed at Banwell, and at the same rate.** **Placement purpose:** The embankment would benefit the reference site (Moreton-in-Marsh) as it would provide screening between the residential housing (west) and the testing facility (east). It is also important to note that this plot is best placed next to Banwell replica so that the risk of cross interference is absolutely minimised for the highest priority plot (Plot 1).

Plot	Test	Biochar (% total weight)	Fines (% total weight)	Topsoil (% total weight)	Description, placement purpose and rationale
					Rationale: The purpose of Plot 2 would be to validate that any measured carbon removal is a result of the added materials (as this is unamended). Seed sewing also permits comparison of blend mix effect upon vegetation establishment across four application rates.
3	Low rate	1.57	15.82	82.60	**Description:** Plot 3 comprises an embankment, which would be constructed to the dimensions and specification shown on the sketch (Figure 4). For the main embankment batters (1 in 3 slope) and battered end slopes (1 in 1.5 slope), the top 300mm of the 1 in 3 slopes and top 150mm of the 1 in 1.5 slopes would comprise a blended topsoil, with the % total weight of the blended material components indicated in the columns to the left ('Low rate'). The embankment would comprise either Pozidrain at the base (Class 1 embankment fill above) or directly beneath topsoil (Class 1 embankment fill below). The embankment would be a contained system, to allow for the containment and subsequent sampling of infiltrating water through the embankment. Option 1 (Pozidrain beneath topsoil) would be preferred, as it would allow for the direct capture of infiltrating water through topsoil without any diluting impacts from other material (e.g., Class 1 embankment fill). As shown in cross section (Figure 4), if Option 2 was considered, there would be a slight fall (symmetrically) of the embankment from its centre (1 in 50 fall) to allow for water to drain through the drainage layer into pipework. The pipework would collect infiltrating water from the embankment and would run longitudinally along the toe of the main embankment batter face to a water collection and sampling point. To do this, for both options there would also be a slight fall longitudinally along the main embankment batter face (1 in 50 fall) towards the water collection and sampling point. The water quality would then be monitored (Table 6). **There would be a requirement for consideration of a soakaway type design to adequately manage the concentration of water at the collection point, so that they do not flood the site.** **Plot to be sewn with the same seed mix that is proposed at Banwell, and at the same rate.** **Placement purpose:** The embankment would provide benefit at the reference site (Moreton-in-Marsh) as it would provide screening between the residential housing (west) and the testing facility (east). **Rationale:** The primary purpose of this plot would be to explore the sensitivity of carbon removal to topsoil volume ratio and compare the efficacy of carbon removal with the other amendment rates. Mix is 80% topsoil by volume, biochar: quarry fines

Plot	Test	Biochar (% total weight)	Fines (% total weight)	Topsoil (% total weight)	Description, placement purpose and rationale
					ratio same as Banwell blend (1). Seed sewing also permits comparison of blend mix effect upon vegetation establishment across four application rates.
4	High rate	6.48	65.17	28.35	**Description:** Plot 4 comprises an embankment, which would be constructed to the dimensions and specification shown on the sketch (Figure 4). For the main embankment batters (1 in 3 slope) and battered end slopes (1 in 1.5 slope), the top 300mm of the 1 in 3 slope and top 150mm of the 1 in 1.5 slopes would comprise a blended topsoil, with the % total weight of the blended material components indicated in the columns to the left ('High rate'). The embankment would comprise either Pozidrain at the base (Class 1 embankment fill above) or directly beneath topsoil (Class 1 embankment fill below). The embankment would be a contained system, to allow for the containment and subsequent sampling of infiltrating water through the embankment. Option 1 (Pozidrain beneath topsoil) would be preferred, as it would allow for the direct capture of infiltrating water through topsoil without any diluting impacts from other material (e.g., Class 1 embankment fill). As shown in cross section (Figure 4), if Option 2 was considered, there would be a slight fall (symmetrically) of the embankment from its centre (1 in 50 fall) to allow for water to drain through the drainage layer into pipework. The pipework would collect infiltrating water from the embankment and would run longitudinally along the toe of the main embankment batter face to a water collection and sampling point. To do this, for both options there would also be a slight fall longitudinally along the main embankment batter face (1 in 50 fall) towards the water collection and sampling point. The water quality would then be monitored (Table 6). **There would be a requirement for consideration of a soakaway type design to adequately manage the concentration of water at the collection point, so that they do not flood the site.** **Plot to be sewn with the same seed mix that is proposed at Banwell, and at the same rate.** **Placement purpose:** The embankment would provide benefit at the reference site (Moreton-in-Marsh) as it would provide screening between the residential housing (west) and the testing facility (east). **Rationale:** The primary purpose of this plot would be to explore the sensitivity of carbon removal to topsoil volume ratio and compare the efficacy of carbon removal with the other amendment rates. Mix is 25% topsoil by volume, biochar: quarry fines

Plot	Test	Biochar (% total weight)	Fines (% total weight)	Topsoil (% total weight)	Description, placement purpose and rationale
					ratio same as Banwell blend (1). If successful and structurally stable, offers greater net removal per unit volume than Banwell blend (1). Seed sewing also permits comparison of blend mix effect upon vegetation establishment across four application rates.
5	Mixing trials	-	-	-	**<u>Description:</u>** Plot 5 would comprise of a 451.1m^2 mixing area, located adjacent to Plot(s) 1 to 4. The plot area would account for the required space needed to trial the mixing process (rotovating) of topsoil, quarry fines, and biochar, which would then be placed on top of the slopes of the embankments. This would include areas for stockpiling materials, accounts for rotovator mixing depth, a buffer for vehicle turning, and designated area required for mixing. **<u>Placement purpose:</u>** This plot would be placed so that it is adjacent to the areas where the mixed topsoil would be placed (e.g., as topsoil on the embankments Plot(s) 1 to 4). **<u>Rationale:</u>** The primary purpose of this plot would be to trial the mixing process of the three material types (biochar, quarry fines, and topsoil). This is integral as it is imperative to ensure that the blend is homogenous and mixing of these material types into a homogenous blend has not previously been trialled. Importantly, analysing the behaviour of biochar during the blending process is important to understand, to ensure that it is mixed appropriately without damaging its structural integrity. The mixing process would comprise the following: 1. Obtain an area of land for processing (e.g., Plot 5) 2. Strip topsoil from site and move to processing area 3. Import quarry fines and biochar and stockpile in processing area 4. Place layer of topsoil 5. Cover with layer of quarry fines 6. Cover with layer of biochar 7. Rotovate with tractor mounted rotovator, until mixed thoroughly 8. Excavate mixed product and place in stockpile 9. Test the product (PSD or similar) and review findings (e.g., amend steps 4 to 7 above if necessary) 10. Repeat this process to produce a larger stockpile 11. Excavate from stockpile, transport, and place product on embankment side slopes.

Plot	Test	Biochar (% total weight)	Fines (% total weight)	Topsoil (% total weight)	Description, placement purpose and rationale
					Biochar and quarry fine storage on site during construction should be identical to that proposed at Banwell Bypass, specified in section 4.3 of Appendix G.
6	Fines fill	-	100	-	**Description:** Plot 6 would comprise of a 30m^2 plot (6m x 5m). The plot would be constructed above ground. The plot would comprise quarry fines above a basal drainage layer (Class 6, 100mm thickness). The quarry fines would be 0.5m in thickness, therefore a total volume of 15m^3 would be required. Above the quarry fines would be topsoil (0.2m thickness) and a layer of vegetation. Similar to Plot(s) 1 to 4, this should also be a contained system (e.g., surrounding membrane) to allow for the collection of infiltrating water which is then to be sampled (Table 6). **There would be a requirement for consideration of a soakaway type design to adequately manage the concentration of water at the collection point, so that they do not flood the site.** **Placement purpose:** Situated far away from Plot(s) 1 to 5, with the main benefit of this placement opportunity being the realisation of CO_2 sequestering potential from just quarry fines alone. **Rationale:** The primary purpose of this plot would be to understand the CO_2 sequestering potential just from quarry fines. Importantly, this plot would also provide an in-situ source of weathered fines. Monitoring of the weathered fines over the monitoring interval would allow for the structural/geotechnical properties of weathered fines to be understood. 

4.5 Further requirements

Material application considerations

To ensure that the blended ratios of the materials are effective for the sequestration of carbon when applied, there are a number of factors to consider. Additionally, in the interest of construction related health and safety requirements, there are also factors relating to the material applications that would need to be considered. These considerations are summarised below.

- To ensure the protection of the pelleted biochar, and the even provision of CO_2 to the quarry fines within the blended ratios of topsoil, the materials should be blended as homogeneously as possible (e.g., a batch mixing process).
- Ensuring blend homogeneity at both reference and pilot site substantiates the comparison between them and increases confidence in the carbon removal at the live pilot site.
- To minimise the damage incurred to the pelleted biochar, it is recommended that biochar be added into this mix last to minimise direct contact between the biochar and the mixing apparatus.
- During the pouring and mixing of the batch there is a risk of dust generation from both biochar and quarry fines. The blend should be wetted to prevent this. Wetting should also be used when applying the blend to the embankment slope to limit dust generation.

Monitoring

Monitoring and testing requirements proposed at Moreton-in-Marsh are presented in Table 6.

Table 6: Monitoring and testing requirements

Monitoring	Commentary
Carbon sequestration performance (biochar and quarry fines) – Plot(s) 1, 2, 3, 4, and 6 and existing topsoil	• It is proposed that for each plot, two sets of triplicate samples be taken by hand auger or shallow trial pit per year, 6 months apart. • One set of triplicate samples should also be taken from an unamended portion of the scheme (Plot 2). • It is recommended that samples be taken to amendment depth + 10 cm to assess the prevalence of downward or upward migration of biochar. • The extracted cores are to be divided into increments of 10cm, and formed into composite samples, sorted by depth, along with the other samples from their plot (e.g., one plot would have a 0 – 10cm composite sample formed of three sub-samples). This should also be done for Plot 2 (unamended). These composite samples should be dated and labelled according to their depth. For a sample depth of 20cm then, a plot would generate a total of 2 composite samples; a 0-10cm composite sample and a 10-20cm composite sample. • If the amendment depth is 15cm, begin with an initial composite sample of 5cm and then proceed as before in increments of 10cm. • Each composite sample should then be air dried and milled to < 0.5mm so as to further reduce heterogeneity before testing. Material for each of the following tests is to be taken from these milled composite samples. • This procedure should be undertaken on Moreton-in-Marsh topsoil before construction begins to determine the latent carbonate and pyrogenic carbon content of the topsoil

<table>
<tr><th>Monitoring</th><th>Commentary</th></tr>
<tr><td></td><td>
The following testing is recommended for each depth increment composite sample for plots 1, 2, 3, and 4:
<table>
<tr><th>Material</th><th>In-situ Process</th><th>Sampling Method</th><th>Proposed Test</th><th>Output</th><th>Use</th></tr>
<tr><td>Biochar</td><td>Vertical migration and mass loss</td><td>Hand auger</td><td>Hydrogen Pyrolysis</td><td>Pyrogenic carbon content of sample with depth</td><td>Verify and quantify biochar content,
and measure biochar migration</td></tr>
</table>
The following testing is recommended for each depth increment composite sample for plots 1, 2, 3, 4, and 5:
<table>
<tr><th>Material</th><th>In-situ Process</th><th>Sampling Method</th><th>Proposed Test</th><th>Output</th><th>Use</th></tr>
<tr><td>Quarry Fines</td><td>Carbonation</td><td>Hand auger</td><td>Eijelkamp Calcimeter and Isotope Ratio Mass Spectrometry</td><td>Calcium carbonate content of soil and source of removed CO_2</td><td>Quantify calcium carbonate formation in soil and the source of CO_2 it has removed and verify the occurrence of weathering.</td></tr>
</table>
The Total Organic Carbon (TOC) and Total Inorganic Carbon (TIC) should be determined separately, independently, and summed to give Total Carbon for each depth increment also.
</td></tr>
<tr><td>Material parameters (biochar and quarry fines) – Plot(s) 1, 2, 3, 4, and 6</td><td>

It is proposed that for each plot, one set of triplicate undisturbed samples be taken by hand driven sample tube per year.
One set of triplicate samples should also be taken from an unamended portion of the scheme (Plot 2).
These samples should be taken down to the amendment depth only.
These samples should be split in the same way as above, so as to correspond to the depth of composite samples taken for carbon removal. That is, if the amendment depth is 15cm, begin with an initial sample of 5cm and then proceed as before in increments of 10cm.
Composite samples are not to be made here.
These samples are to be subsequently reconstituted for bulk and dry density testing.

</td></tr>
<tr><td>Chemical properties of the soil (soil dry weight and leachate analysis)</td><td>
To assess the potential impacts of the use of biochar and quarry fines in topsoil on the soil chemistry, and how this may impact human health and/or controlled waters.
Testing of blends prior to placement:

Three tests of each blend (Plot(s) 1, 3, and 4) should be undertaken, analysing the blends for soil dry weight determinands and soil leachate determinands. It is assumed that the constituent materials comprising the blend (topsoil, biochar, and quarry fines), should they be imported, would be accompanied with chemical data which is statistically representative.
The soil general suite would include Metals (total: As, Cr, Co, Cu, Pb, Hg, Mo, Ni, Se, and Zn), pH, chloride (2:1 water soluble), Total Organic Carbon, Loss on Ignition at 440ºC, PAH (USEPA 16), and PCB (WHO 12).
The soil leachate suite would include pH, Metals (total: As, Cd, Ca, Cr, Cu, Fe, Pb, Mg, Mn, Hg, Ni, K, Se, Na, and Zn), nitrate, and sulphate. Soil leachability testing for purposes other than waste classification using method BS EN 12457 Part 1 – single stage 2:1.

No additional soil testing (dry weight or leachability) would be required prior and during the monitoring interval.
</td></tr>
</table>

<table>
<tr><th>Monitoring</th><th>Commentary</th></tr>
<tr><td></td><td></td></tr>
<tr><td>Biochar and Enhanced Mineral Weathering (quarry fines) – Plot(s) 1, 3, and 4</td><td><u>Water analysis</u>
As part of the embankment construction, a drainage system would be installed either to collect surface run-off, substructure drainage or a combination of both.

The collected water should be analysed to review any assess of impact of the material blends on infiltering water. The water should be analysed for the following determinands: Metals (total: As, Cd, Ca, Cr, Cu, Fe, Pb, Mg, Mn, Hg, Ni, K, Se, Na, and Zn), hardness, pH, anions/cations, electrical conductivity, Dissolved Inorganic Carbon, Dissolved Organic Carbon, Particulate Organic Carbon, charge balance, PAH (USEPA 16), and PCB (WHO 12).

When analysing water (as above), perform a quality check by submitting e.g., known mineral water with each batch as an unknown sample.

The frequency of water sampling/testing would be as follows:
Year 1: Quarterly (four samples per year) per plot in Plot(s) 1, 3, and 4.
Year(s) 2 to 4: Bi-annually (two samples per year) per plot in Plot(s) 1, 3, and 4.
Year(s) 5 to 10: Annually (one sample per year) per plot in Plot(s) 1, 3, and 4.
The testing frequency may be reduced after Year 4, should the water quality show no discernible impact from the blended ratios.</td></tr>
<tr><td>Enhanced Mineral Weathering (quarry fines) – Plot 6</td><td><u>Water analysis</u>
Plot 6 would also be a closed system, allowing for the containment and subsequent sampling of infiltrating water through the quarry fines.

The collected water should be analysed to review any assess of impact of the material blends on infiltering water. The water should be analysed for the following determinands: Metals (total: As, Cd, Ca, Cr, Cu, Fe, Pb, Mg, Mn, Hg, Ni, K, Se, Na, and Zn), hardness, pH, anions/cations, electrical conductivity, Dissolved Inorganic Carbon, Dissolved Organic Carbon, Particulate Organic Carbon, charge balance, and PAH (USEPA 16). When analysing water (as above), perform a quality check by submitting e.g., known mineral water with each batch as an unknown sample.

The frequency of water sampling should follow the same as listed for the plots above.</td></tr>
<tr><td>Plant Growth and Microbial Communities (Biochar and Quarry Fines) – Plot(s) 1, 2, 3, and 4</td><td><u>Vegetation analysis</u>
Vegetation coverage and growth to be measured quarterly across all plots.
Measuring method contingent upon plant type – presume wild grass.
Three 0.1m^2 quadrats placed randomly across each plot, measure height by hand.
Cut, record fresh weight, and record dry weight to obtain kg of dry matter per hectare.
<u>Microbial analysis</u>
Small jar samples of soil to be taken annually for visual inspection of microbial growth</td></tr>
<tr><td>Qualitative field observations</td><td>For the stability of the slopes, the slope faces would be inspected to assess for any signs of instability of the topsoil blends.</td></tr>
</table>

4.6 Cost plan

A detailed cost plan for the MiM site proposals is presented in Appendix J. This includes planning, construction, and monitoring costs over a three-year period.

Appendix I - Risks and Opportunities

1 Opportunities and Development

This section considers the opportunities for using biochar and quarry fines within infrastructure schemes. The uses identified herein have been extracted by Arup specialists from the broad uses that were suggested during the discovery phase, recorded in Appendix D6 and discusses in section 3.3 and 3.4 of Appendix D. Their suitability for the purposes that have been identified is influenced by whether the geotechnical behaviour of the materials (e.g., strength, stiffness, settlement, permeability) meet the requirements of the intended use, and whether changes to these materials over time may result in unacceptable degradation of the asset. A preliminary summary of the key geotechnical considerations is presented below in Table 1.

Table 1: Possible opportunities for the use of biochar and quarry fines in geotechnical applications

ID	Potential Use	Biochar	Quarry fines
1	Blended with soil for drainage swale	✓	✓
2	Substituted for filter drainage stone	✓	×
3	Substitute for unbound surfacing on access tracks (accommodation works and basins, low-loaded tracks or paths, etc.)	×	✓
4	Substitute for Type 1 subbase/capping material	×	✓
5	Substitute for Class 1 earthworks materials	×	✓
6	Filtration of surface water drainage to improve water quality	✓	×
7	Blended with soil for topsoil	✓	✓
8	Landscape fill	✓	✓

1.1 ID 1 - Blended with soil for drainage swale and attenuation basins

Swales are grassed ditches in the highway verges which are used for drainage. They provide water quality benefits through the percolation of highway surface water runoff through the grass, which encourages the removal of suspended sediments and particulate pollutants. They also provide amenity benefits by reducing the visual corridor width with green space.

Attenuation basins are typically located at the end of a drainage network and are used to treat surface water runoff for pollutants and to reduce the peak outflow rates into surrounding watercourses. Basins commonly have a layer of topsoil to allow planting and treatment of sediment.

It is proposed to blend biochar and quarry fines with topsoil for swales and basins for both carbon removal and their technical functionality. This option would utilise the advantage of biochar in pollutant control for surface water runoff (Imhoff, 2017) and the increased mineral weathering of quarry fines through transportation of water over the surface.

Biochar degradation rate is higher for a wet/dry cycle commonly experienced in a swale or basin than when compared to being permanently saturated or dry (Wang, Xiong, & Kuzyakov, 2015). It is possible that there may be an increased amount of suspended solids generated by its use. It is suggested that regular water quality monitoring is undertaken during the operation period at the operational site to confirm if there is a significant increase in suspended solids compared to a baseline. Approval may also be required by Environment Agency if there is a significant amount of discharge expected. If discharge is to an ordinary watercourse, the Lead Local Flood Authority would also require notifying. The validity of this concern is to be explored in the testing proposed at Moreton-in-Marsh, by monitoring the groundwater for particulate and dissolved organic carbon (see Appendix H).

Regular saturation of quarry fines may provide an improvement of its performance. The carbonation and enhanced mineral weathering which sequesters carbon is dependent on regular contact with water, which commonly occurs in a drainage situation. This is therefore seen as an advantage of using quarry fines in this application.

Biochar has a low unit weight, typically of between 0.1 and 0.5 t/m^3, and is therefore susceptible to flotation when submerged below water (Adekiya, Olayanju, Ejue, Alori, & Adegbite, 2020). High water conditions within swales present the risk that the biochar component of the topsoil mix may separate and wash out due to floatation effects. This risk may be mitigated using quarry fines however, as the carbonation processes expected to occur within the timespan of a year (see section 1.3.3 of Appendix C) provides interparticle adherence (Casas, Schaschke, Akunna, & Jorat, 2019). Moreover, biochar has been found to improve aggregation within soils through the deposition of fine fractions in its pores, so the biochar will become integrated into the dense soil matrix over time (Sun & Lu, 2013) (Zong, Chen, & Lu, 2014). The greatest risk of floatation is therefore likely to be at the time of application. To avoid this risk, suitable topsoil mixes with a cohesive/binding effect may need to be developed to ensure that the topsoil mix remains stable during operation of the swales. The application and monitoring of different material blends at Moreton in Marsh (see Appendix H) should allow for this risk to be better understood and for mitigating refinements to be developed before full scale deployment at the Banwell Bypass.

The use of quarry fines at the near surface for use within swales and attenuation ponds presents few if any geotechnical challenges. The potential for reduced permeability arising from carbonation processes in the soil may be prevented in the first place by the constant movement of water through the amended soil, as dissolved bicarbonates may not be static enough to precipitate and form calcium carbonate (see section 1.2.4 of Appendix C).

1.2 ID 2 - Substituted for filter drainage stone

One option which could be considered is a partial replacement of filter drain material (single size stone 20mm) with biochar to a certain ratio (90% stone, 10% biochar for example). This would allow significant reduction in processed and quarried stone material. However, there is a cost benefit ratio which would need to be considered for the stone compared to the biochar material. It is also possible that regular exposure to water may cause a deterioration of the biochar which may cause an unacceptable level of suspended solids and other pollutants to discharge into existing watercourses.

A limit to this use may also be found in the application method, as mixture with stone is abrasive and would break down the biochar into finer fragments, whereas placement of biochar in an uninterrupted layer creates the risk of settlement due to biochar comminution. There is the risk that over time the mass may undergo comminution which could lead to settlement of the ground surface above, which may be unacceptable in some settings that rely on the stiffness of the pipe bedding to provide structural support to the filter drain pipework. It may be the case that this consideration can be addressed through the specification of suitably robust pipework that can accommodate the likely long-term changes to the biochar-filter drain mix. The biochar should be manufactured to a size whereby it cannot be washed out of the filter drain mix, but is also interstitial, so it is not part of the load-bearing matrix and therefore cannot create settlement should it degrade.

The susceptibility of biochar to flotation when filter drains become saturated presents the risk of displacement and rearrangement of the filter drain particles during operation, which could result in the filter drains not performing as intended. For such a use to be effective would require compatible gradings for both the drainage stone and the biochar. The drainage stone would need to act as a filter to the biochar to prevent it from migrating upwards under flotation pressures.

1.3 ID 3 - Substitute for unbound surfacing on access tracks

There are commonly requirements for unbound surfacing for accesses to highways assets such as attenuation basins and for farmland access. The material for this is generally Type 1 sub-base, but basalt fines, have been shown to be potentially suitable for use as an alternative to this material (Manning D. , 2004).

Unbound surfacing for access tracks requires inherent strength and stiffness to provide support to vehicle loading. Whilst quarry fines generally comprise high strength particles, quarry fines (and basalt) can in some instances comprise a more weathered clay-like formation, and such weaker particles should be avoided for this use. However, quarry fines are typically produced from fresh and unweathered rock so the clay mineral content is extremely low. Whilst the precipitate that forms from carbonation is likely to be of high strength, the longer-term strength and stiffness characteristics of the overall mass of the residual material, including the weathered quarry fines particles, would need to be better understood. Consideration would need to be given to whether the weathering of the quarry fines surfacing may result in increased maintenance requirements, a reduced design life and therefore a requirement for more frequent replacement compared to more traditional materials.

Consideration would similarly need to be given to risks surrounding the generation of airborne dusts with this use, especially during periods of dry weather. There is also a risk that when isolated from the CO_2 rich environment of soils, the carbonic acid that weathers the rock cannot form and subsequent carbonation and EMW cannot take place or may occur at significantly lower rates.

1.4 ID 4 - Substitute for Type 1 subbase/capping material

Type 1 subbase is commonly used across highways for the unbound formation prior to the asphalt being laid. The grading requirements for Type 1 sub base are given below in Figure 1.

Sieve size, mm	Percentage by mass passing		
	Overall grading range	**Supplier declared value grading range**	**Tolerance on the supplier declared value**
63	100		
31.5	75 – 99		
16	43 – 81	54 – 72	± 15
8	23 – 66	33 – 52	± 15
4	12 – 53	21 – 38	± 15
2	6 – 42	14 – 27	± 13
1	3 – 32	9 – 20	± 10
0.063	0 – 9		
Grading of individual batches – differences in values passing selected sieves			
Retained sieve size, mm	Passing sieve size, mm	Percentage by mass passing	
		Not less than	Not more than
8	16	7	30
4	8	7	30

Figure 1: Table to show grading of Type 1 sub base – From DMRB MCHW Series 800 Clause 803.

There is an opportunity for quarry fines material to be used either within the Type 1 sub base, or as a replacement in areas where the material testing requirements are not as significant. Quarry fines are typically 6mm down (see section 1.2.3 of Appendix C), and therefore would only be able to provide a maximum of 53% of the material substitution for sub base. This would need to be tested to ensure that there is no detriment to the subbase through using this substitution.

There is also an opportunity for quarry fines to be used within the highway formation as part of the subbase. The performance of quarry fines and its ability to capture carbon should be considered if it forms part of a highway formation. The proposed trials at Moreton-in-Marsh explore this use through an isolated testing cell that allows the weathering rate of quarry fines to be monitored when they are used as a general fill in construction (see section 4.4.1 of Appendix H for more information).

Capping which forms the finished earthwork surface, and the sub-base which forms the first layer above this, are selected to provide high strength and stiffness characteristics. These strength and stiffness characteristics govern the thickness and quantities of the specialist materials that form the highway above, which have the potential to contain high levels of embodied CO_2e. Whilst many sources of quarry fines are likely to have favourable characteristics for use as capping and sub-base, should poorer quality materials be selected, there would be a consequential increase in materials that may be needed to form the highway structure above, with an associated increase in CO_2e. Therefore, appropriate selection of high-quality material with a sufficiently high CBR value is critical for the effective use of quarry fines for capping and sub-base.

Whilst the original in-situ characteristics of the quarry fines may be suitable or even favourable for construction of capping and sub-base, the long-term changes in the geotechnical nature of the material as a result of weathering processes would need to be considered. The precipitate that would form within the inter-particle pores from the process of carbonation is likely to have high strength and stiffness characteristics. The deterioration of the weathered quarry fines could potentially affect the strength and stiffness characteristics of the residual mass, and there may be potential for volume changes which could impact its performance as a road foundation. Whilst quarry fines are widely used as a Type 1 sub-base in UK, the sub-base is kept drained to limit the potential for saturation which can lead to its degradation and damage to the road above. Highway construction is therefore typically designed to prevent the movement of water through the sub base, and therefore adequate flows are unlikely to be available to allow weathering of the material to take place

1.5 ID 5 - Substitute for Class 1 general fill (Quarry Fines)

Should quarry fines be suitable for use as general fill (engineered fill) this could present the potential for adoption on a much larger scale than other uses. In particular, the volumes for use as general fill could be much greater for highway works where large-scale new-build schemes are more commonplace than other forms of infrastructure such as rail.

Weathering of quarry fines and the formation of precipitate are likely to be more effective for general fill placed close to groundwater, for example, where existing soft ground is to be excavated and replaced prior to construction of embankments above, rather than for construction of embankments above original ground surface level. Similarly, the use of quarry fines for general fill at shallow depths across embankment shoulders, where more susceptible to weathering, is likely to prove more effective – although less practical to construct using standard earthworks practices.

In its natural state there is no reason to preclude the use of quarry fines as general fill so long as its geotechnical characteristics such as gradings, drained shear strength and moisture content meet the specific requirements of its end use. However, further consideration is needed into how the characteristics may vary over time, in particular, in relation to possible volume change, strength and stability as a result of weathering. Furthermore, the compatibility between weathering and strength should be established to determine if these proposed functions are mutually exclusive. The proposed trials at Moreton-in-Marsh explore this use through an isolated testing cell that allows the weathering rate of quarry fines to be monitored when they are used as a general fill in construction (see section 4.4.1 of Appendix H for more information).

1.6 ID 6 - Filtration of surface water drainage to improve water quality

Activated charcoal is commonly used in filters for drinking water. It can provide filtration of suspended solids and sediments through the material containing a high number of micro pores (Xiang, et al., 2020).

Figure 2: Photo to show biochar amended verge (Imhoff & Nakhli, Reducing Stormwater Runoff and Pollutant Loading with Biochar Addition to Highway Greenways , 2017)

It is proposed to blend biochar and quarry fines with topsoil for swales and basins. The high porosity of biochar means its amendment to typical topsoils and soils of lower porosity results in an increase in total porosity and water retention (Imhoff & Nakhli, Reducing Stormwater Runoff and Pollutant Loading with Biochar Addition to Highway Greenways , 2017). A field-scale experiment in Delaware amended the sandy-loam soil of a live verge along a four-lane highway with pine derived biochar, at a rate of 4% by weight. They found that over 74 storm events in 2016/17, the biochar amendment reduced the average stormwater runoff volume and peak flow rate by 84 and 77%, respectively, compared to unamended verges (Imhoff & Nakhli, Reducing Stormwater Runoff and Pollutant Loading with Biochar Addition to Highway Greenways , 2017). Increasing the water residence time in soil also reduces the pollutant loading of stormwater by providing greater time for evapotranspiration and microbial transformation of pollutants.

It may be possible to allow biochar to perform a similar effect for highway drainage runoff. Suspended solids and sediments are a significant pollution issue for water courses from highway drainage. Biochar could potentially be used as part of the treatment system for surface water drainage to intercept these pollutants and provide higher quality surface water drainage.

As with ID1 and ID2, the properties of biochar once exposed to water will need to be considered. Furthermore, there would need to be regular surface water quality monitoring upstream and downstream of any filter device to determine if this is able to make a positive impact.

1.7 ID 7 - Blended with topsoil

Blending of biochar and quarry fines into topsoil for use across embankment shoulders and grass verges presents few geotechnical challenges. Standard earthworks specifications that are in use within the UK, including the specification for highway works, provide few constraints on permitted constituents of topsoil, the nature of which is generally determined on a bespoke basis for each site - largely governed by landscape and ecological considerations.

Work that explicitly reviews the effect of quarry fines and basalt fines upon soil strength are lacking, but some comparisons can be made with studies that discuss soil stabilisation via carbonation processes. In a recent study that sought to stabilise clays through microbiologically induced carbonate precipitation, it was found that the carbonate precipitation filled in pores between soil particles and provided inter-particle adherence, and a lowering of the fines content of the soil mix through aggregation (Casas, Schaschke, Akunna, & Jorat, 2019).

Biochar amendment to sandy and clayey soils has also been found to improve aggregation through the settlement of finer fractions in the pores (Sun & Lu, 2013) (Zong, Chen, & Lu, 2014). It is also frequently observed in incubation studies that clay minerals bind to the biochar, thereby increasing frictional resistance against interparticle movement (Sadasivam & Reddy, 2015). With targeted applications biochar can therefore potentially help mitigate against soil degradation in erosion prone soils.

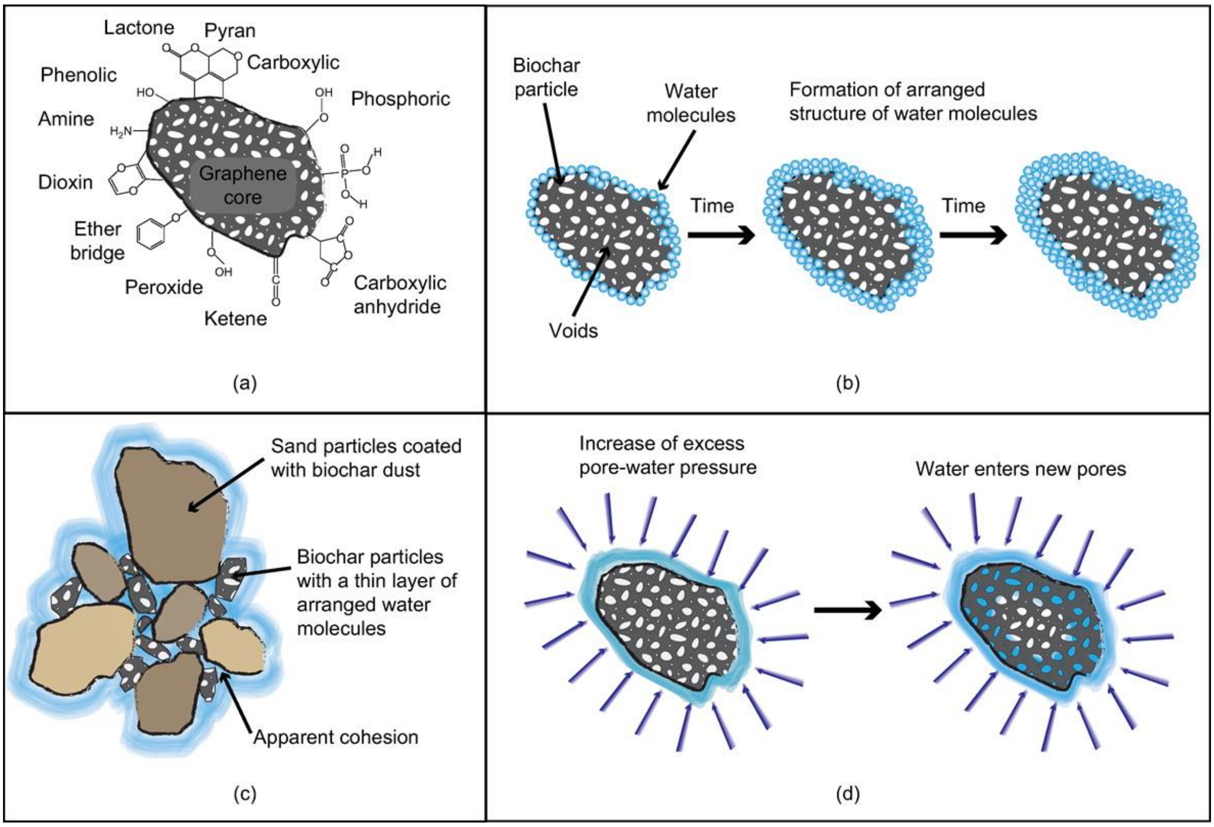


Figure 3: Figure to show mechanism by which biochar micropores can reduce excess pore water pressure during shearing (Pardo, Sarmah, & Orense, 2019).

This study investigates the use of biochar in sand as a means of increasing the liquefaction resistance and shear strength of sand. A commercial silica sand was amended with biochar at rates of 3 and 5% by weight of sand. The biochar was produced using fast pyrolysis at 470°C with residence time of 10 minutes, average particle diameter of 150 μm. Water was added, cylindrical samples were prepared, and the sample was stabilised overnight. It was found that the samples with biochar showed relatively higher drained shear strength at low confining pressures (<100 kPa),and required more cycles to deform to the same level of shear strain – thus demonstrating a higher resistance to liquefaction (Pardo, Sarmah, & Orense, 2019). The mechanism of improvement is thought to be due to the volatiles on the surface of the biochar that act hydrophobically and hydrophilically at different times. The network of pores act as a pressure valve during shearing; high pore water pressures are reduced as the water is forced into previously inaccessible biochar pores. This delays the increase in pore water pressure, increasing effective stress and therefore shear resistance. However, this effect is likely due to the micro-scale of the used biochar and has not been investigated for meso or macro-scale pelleted biochar. Examining the suitability of biochar and quarry fines for use in topsoil does not require methods like drained triaxial tests that are sensitive enough to quantify this behaviour. Whilst the topsoil behaviour will be characterised at both Moreton-in-Marsh and the Banwell Pypass, this mechanism will not be investigated, however it is recommended as an area of further specialist research.

1.8 ID 8 - Use as landscape fill (biochar & quarry fines)

Landscape fill is earth fill that is often used extensively across major infrastructure schemes for landscaping purposes, where no reliance is placed on the fill to provide structural support to earthworks or structures. There are few geotechnical restrictions on the geotechnical composition or characteristics of landscape fill, so long as it meets the specific requirements of its intended end use. Key considerations are whether the fill has sufficient strength to remain stable in the long term at the intended slope angles and whether settlement under its self-weight is acceptable for the landscape feature that it forms. The potential for deterioration of geotechnical properties over time is a consideration, although this is likely to be of limited effect for landscape fill and could be accommodated by design. The use of biochar and quarry fines present few significant geotechnical challenges for such a use and the use of biochar may be beneficial where nutrient enhancement or modification is desirable (e.g. this could be to promote plant growth or to help achieve lower nutrient soils which may help to contribute to greater biodiversity within infrastructure verges and landscaping areas). The behaviour of biochar and quarry fines when incorporated into topsoil at different ratios will be characterised at Moreton-in-Marsh (Appendix H), and application of these blends upon embankments will allow for their slope stability to be assessed, also.

2 Geotechnical Risks and Mitigation

The following risks associated with the use of biochar and quarry fines within infrastructure were identified through research and stakeholder engagement. They are characterised here in depth before a summary is made of the available research and mitigation proposals are given.

2.1 Nutrient Lean Soft Estates

2.1.1 Introduction

MPI-85-102020 sets out the means to maximise biodiversity opportunities on soft estates (Hewlett, 2020). Soft estates are the areas used by the National Highways to describe the natural habitats surrounding motorways and trunk roads, totalling some 30,000 ha of land nationally, the largest unofficial nature reserve in Britain (Chell, 2013). Guidance to this end includes finishing with subsoil or bare substrate like chalk, rotavating the surface once geotechnically stable to form suitable growing surface, and options for establishing vegetation on nutrient poor soils (natural colonisation, green hay, local seed, commercial seed). It recommends that the suppression of fast-growing grasses will save money and Carbon by reducing the maintenance requirements, and nutrient lean soils are proposed to these ends. The MPI is to be implemented forthwith on all projects providing specifications of new grassland plots and safety critical areas on soft estates on the strategic road network.

Following stakeholder engagement, the perception of biochar and quarry fines as “nutrient rich” was identified as a key risk to their integration into highway works that are being planned under this new project initiative. This concern is addressed below to show that both biochar and quarry fines are compatible with MPI-85-102020.

In topsoil the natural balance in organic Carbon, Nitrogen, Phosphorous compounds and many other compounds and minerals influence what naturally grows on the soil. Subsoils typically have less microbial and mycorrhizal life and comprise organic compound and mineral compositions more closely related to the characteristics of the underlying less-weathered parent material. When considering grassland creation and biodiversity outcomes, the soil composition, notably nutrient levels of Nitrogen, Phosphorous, and Potassium are key. Nitrogen in particular is a key determinant of grassland typology.

2.1.2 Biochar

Typical nutrient contents of biochar derived from the two considered feedstocks are given below in Table 2.

Table 2: Typical nutrient contents of anaerobically digested sewage sludge and softwood derived biochar, pyrolysed at peak pyrolysis temperatures of 550°C and 700°C (UK BRC, 2019)

Feedstock	PPT (°C)	Total N (wt.% db.)	Total P (wt.% db.)	Total K (wt.% db.)
Anaerobically digested sewage sludge	550	3.75	2.29	0.34
	700	3.79	2.50	0.42
Softwood	550	<0.10	0.06	0.25
	700	<0.10	0.07	0.28

Sludge based biochar typically contains much higher N concentrations than virgin biomass like softwood due to the elevated protein content. The N concentration by weight of softwood biochar (<0.10%) is lower than lowest nitrogen concentration bracket given for topsoils by the UK Centre for Ecology and Hydrology (<0.25%) (UKCEH, n.d). Furthermore, nitrogen is typically present on the surface of biochar as C-N heterocyclic and has a low bioavailability, and this is similarly true for phosphorous, though most of biochar's potassium is water soluble and thus available to plants (Adekiya, Olayanju, Ejue, Alori, & Adegbite, 2020). The differences in nutrient concentrations between feedstocks are therefore minor when considering their actual bioavailability, which is low.

Biochar's effect on crop yield is as variable as the material itself and the environmental conditions that it is deployed in, but an extensive review of field-scale trials showed that benefits to crop yield are most firmly established in degraded tropical soils (Vijay, et al., 2021). From a meta-analysis of 60 studies biochar amendment was found to have a negative effect on grass productivity (-10% productivity), though the uncertainty crosses 0% change and is therefore not significant (Jeffery, Abalos, Spokas, & Verheijen, 2015). This effect in the specific context of infrastructure schemes has been proposed for exploration within the pilot and reference site, through monitoring vegetation establishment over time (see Appendix G and H, respectively).

It should also be noted that a key consideration for establishing biodiverse grassland is the associated microbial community. Biochar provides favourable habitats for soil biota due to the abundant macropores, affording them protection from predators like mites and nematodes. Condensed volatiles in the labile fraction of biochar also serve as energy sources for microbe growth (Adekiya, Olayanju, Ejue, Alori, & Adegbite, 2020). The effect of the proposed material blend may be explored through the proposed monitoring at Moreton-in-Marsh, as samples obtained from the plots can be examined for microbe establishment (see section 4.5.2 of Appendix H).

Whilst the adsorption potential varies between biochar due to different feedstock and pyrolysis conditions, according to most studies biochar decreases nutrient leaching in soils via improved adsorption capacities, though (Gronwald, Don, Tiemeyer, & Helfrich, 2015). Tested in a laboratory batch experiment, biochar produced from digestate, miscanthus, and softwood showed the ability to retain nitrate, ammonium, and phosphate in silty loam and sandy loam soils, at amendment rates equivalent to approximately 100t biochar/ha. Softwood derived biochar typically showed the highest removal rates relative to the control, and all feedstocks showed lower removal rates as ion concentration in the added nutrient solutions increased. After 7 months of field incubation however, repeating the laboratory tests found that 60 to 80% of this adsorption capacity was lost, potentially due to microbial degradation or blocking of binding sites with organic matter or mineral particles like clay (Gronwald, Don, Tiemeyer, & Helfrich, 2015). Upon application then, softwood derived biochar can be expected to reduce the short-term (6-7 months) nitrate, ammonium, and phosphate leaching in sandy and silty loams, partly mitigating against the effects of stormwater runoff that lead to excess nutrients and undesired plant growth.

The physical form of the deployed biochar also effects its in-situ effects. As can be expected, the smaller the mesh size of biochar fines, the larger the interface between biochar, soil, and the circulating solution due to higher surface-volume ratio (Maienza, Genesio, Acciai, & Miglietta, 2017). A three-month pot experiment upon tomato seedlings in silty sand found that the soil amended with pelleted biochar (74.3% pellet retained at 2mm mesh, compared to 48.2% fines retained at 2mm mesh) produced 37.5% less total fresh fruit than unpelleted biochar, and that plant height was similarly reduced by approximately 5% across the duration of the experiment (Maienza, Genesio, Acciai, & Miglietta, 2017).

2.1.3 Quarry Fines

Typical nutrient contents of quarry fines are given below in Table 3.

Table 3: Nutrient content of quarry fines (see Appendix C for chemical analysis)

Source	Total N (wt.% db.)	Total P (wt.% db.)	Total K (wt.% db.)
Cragmill	<0.01	0.098	0.14
Divet Hill	0.04	0.016	0.16

Table 3 shows that the N concentration by weight of Divet Hill quarry fines (0.04%) is six times smaller than lowest nitrogen concentration bracket given for topsoils by the UK Centre for Ecology and Hydrology (<0.25%) (UKCEH, n.d).

The suitability of quarry fines for land reclamation and biodiversity establishment in low nitrogen conditions is evidenced by the healthy establishment of nitrogen-fixing plants in low nitrogen soils amended by quarry fines (Guillou & Davies, 2004). A variety of composts with differing Nitrogen contents were blended 50:50 with four rock types (two types of Basalt, Felsite, and Whin Sill Quarry fines) and sewn with a grass seed mixture composed of ryegrass, fescue, meadow grass, bent, wild white clover (nitrogen fixer) and birdsfoot trefoil (nitrogen fixer) in pots. The addition of quarry fines or basalt did not prevent the establishment of nitrogen-fixing clover or birdsfoot trefoil, and is therefore compatible with the maintenance of low nitrogen soils. From grass nutrient analysis it was actually shown that in nitrogen rich soils, basalt appeared to restrict the nitrogen supply (Guillou & Davies, 2004).

Quarry fines have been used to establish a species-rich grassland upon a low-nutrient green roof, called the Whin Sill Grassland Roof, constructed in 2017 (SILL, 2021). The roof (approximately 1000m^2) uses a blend of quarry fines chippings (<6mm; from Tarmac's Barrasford quarry), a 'soil' developed in a quarry fines quarry (Swinburne Quarry, dolerite fines on the quarry floor in 'The Cut' that had started to become vegetated), conifer bark (Westland) and bracken compost (Dalefoot) (see Appendix 3). The vegetation has been cut at the end of the season in 2017, 2018, and 2019. No cutting was done in 2020 and has yet to be decided upon in 2021; this diminishing need for cutting reflects the addition of fertiliser in 2017, as the removal of growth each year draws down the nutrients. Measurements of the CO_2e removal have not been made. No amendments have been made to the soil since construction, and the successful establishment of plants such as Sheep's fescue, Common bent, Sweet vernal-grass, and Thyme are demonstrative that quarry fines are highly compatible with the low nutrient policy initiative (SILL, 2021).

2.1.4 Summary

The identified measures for reducing nutrient loading from biochar in soils aligns with the carbon removal objectives of this project, namely the use of pelleted biochar, the use of wood derived feedstock, and minimising the ash content of the produced biochar. Quarry fines have also previously been used to successfully establish a low-nutrient green roof, and typically contain trace amounts of N, P, and K. Further verification of this is expected from monitoring proposed at Moreton-in-Marsh, as various biochar-quarry fine-topsoil blends should be tested and the subsequent effect on vegetation establishment recorded against an unamended baseline (see Appendix H).

2.2 Flammability Risk

2.2.1 Introduction

Pyrolysis can be used to increase the fuel mass energy density of biomass into a more efficient fuel (Abdullah & Wu, 2009). Biochar has been used as a combustible product for this end to generate power in a sludge processing plant in Tokyo (Mašek, Sohi, Kiso, & Boag, 2010), so flammability risk is addressed here to inform the production, storage, and application of biochar.

2.2.2 Production

From flammability tests conducted upon 34 different biochar samples, it was found that none of them qualified as flammable substances as defined by the UN Manual of Tests and Criteria, part III N, 1 Test for readily combustible solids § 33.2.1.4.3.1 (Zhao, Enders, & Lehmann, 2014). Samples were laid out along the length of a trough and the end was exposed to the oxidising portion of a bunsen burner flame, either until the sample ignited, or for a maximum of 2 minutes. The distance travelled by the combustion front along the length of the trough in 2 minutes was recorded (combustion front propagation distance). To be recognised as a flammable substance, the combustion front propagation distance had to meet or exceed 200mm travelled in 2 minutes. The tested biochar had zero moisture content, finely milled, and unbroken by soil matrix, and the testing conditions were open-air and with a naked flame, so the method represents a worst-case testing scenario compared to the material use prescribed herein (Zhao, Enders, & Lehmann, 2014). Biochar with low $H:C_{org}$ ratios showed low combustion front propagation, while those with high ratios had both high and low front propagation (Zhao, Enders, & Lehmann, 2014). Five out of the seven stored (2 years under argon gas) fast pyrolysis biochars (71%) showed front propagation, compared to only five out of the twenty-four biochars from slow pyrolysis (20%), all of which were manure derived (Zhao, Enders, & Lehmann, 2014). The long-term flammability of biochar was found to increase with volatile matter and correlate with fast pyrolysis biochar (Zhao, Enders, & Lehmann, 2014). A slow pyrolysis process with a high peak temperature (≈ 600°C) reduces flammability risk by producing biochar with low $H:C_{org}$ ratios and minimal volatile content, aligning with the project aims of maximising stability and carbon content of the produced biochar.

2.2.3 Storage

Oxidisation is the mechanism that can lead a large body of biochar to self-heat, creating temperature hotspots which cause local increases in the rate of oxidisation (Naujokas, 1985). Biochar therefore represents the highest flammability risk when it is first exposed to air because at no other point in its "life" is so much of its surface area unoxidized. The amount of carbon that is available for this oxidisation process runs inverse to the pyrolysis temperature, because biochar produced at low pyrolysis temperature has a less-ordered microstructure with more reactive microsites than high temperature biochar, and therefore oxidises faster (Cross & Sohi, 2013). When storing biochar, large, unbroken deposits should be avoided, and the surface area of any deposits maximised. As the storage unit size increases the ambient critical ignition temperature reduces, because the ratio of heat lost to the environment to heat generated by oxidation decreases (Restuccia, Rein, & Mašek, 2018). It should also be noted that for pyrolysis temperatures of 600°C, softwood derived biochar is less prone to self-heating than the original feedstock, and ambient critical ignition temperature for all biochar generally increases along with peak pyrolysis temperature (Restuccia, Rein, & Mašek, 2018). The risk of self-heating through oxidisation is therefore minimised within the biochar itself through a high peak temperature pyrolysis process. The risk of self-heating is mitigated during storage through the maintenance of low ambient temperatures, controlled oxidisation methods such as sample disturbance, and the maximisation of material surface area by using multiple, smaller biochar containers.

2.2.4 Application

There are currently no widely available results for flammability tests conducted upon biochar that have been integrated into the soil. This is where it is likely to encounter the longest exposure to heat, for example from a stationary, flaming car. The widely used geoengineering material of expanded polystyrene (EPS), Jablite, or "geofoam" is used in large and unbroken volumes to form embankments and replace structural fill. Jablite has a Euroclass E flammability rating that means it forms a major contribution to fire upon combustion (Jablite, 2017). EPS typically also has a much higher HHV (Higher Heating Value) value than the proposed biochar (40 MJ/kg compared to 13.27 MJ/kg and 33.10 MJ/kg for sewage sludge and softwood derived biochar, respectively), and whilst its volumetric heating value is lower (540MJ/m^3 compared to 6901.64 MJ/m^3 and 5626.82 MJ/m^3 for sewage sludge and softwood derived biochar, respectively), biochar still compares very favourably to cellulosic products (7150 MJ/m^3 to 10400MJ/m^3) such as fibre, insulating board, or timber (EPS, 2002). Jablite has a flaming ignition heat flux value of 20 kW/m^2 which is lower than the value for rice husk biochar (25 kW/m^2) before it has even been integrated into the soil matrix (Maiti, Dey, Purakayastha, & Ghosh, 2006) (EPS, 2002). As well as having comparatively favourable flammability characteristics against typical construction materials, the biochar should be dispersed within a moist soil matrix, and a flame front will be unable to propagate as through a dry, unbroken mass of biochar. Numerous studies have also demonstrated that biochar promotes aggregation within clayey and silty soils; its macro and mesopores provide spaces that capture the finer fractions of its host soil (Sadasivam & Reddy, 2015). The structure of the biochar therefore becomes closely integrated within the soil and can no longer be thought of as a flammable material distinct from the soil.

2.2.5 Summary

The means by which biochar's flammability risk is reduced align perfectly with the pre-existing aims of the project, namely the use of high temperature (~700°C) slow pyrolysis to minimise $H{:}C_{org}$ ratio and volatile content of the produced biochar. This has been shown to slow combustion front propagation in "pure" biochar samples, as well as reducing the risk of self-heating by minimising the reactive sites that are available for rapid oxidisation (Zhao, Enders, & Lehmann, 2014) (Cross & Sohi, 2013). Storage options are easily tailored to control any self-heating risk via the maintenance of low ambient temperatures where practically possible, and the selection of multiple storage options over one, unbroken mass of biochar (Restuccia, Rein, & Mašek, 2018). However, indulging the perception of biochar as a fire risk should be restrained, as for pyrolysis temperatures of 600°C, softwood derived biochar is less prone to self-heating than the original feedstock, and it is considered that it can be safely stored in volumes of up to 1m^3 which has been recommended as a storage option for the Banwell Bypass (see section 4.3 of Appendix G) (Restuccia, Rein, & Mašek, 2018). Furthermore, given the current industry practice of using highly flammable and ignitable EPS materials as geotechnical fills at rates far beyond those proposed for biochar application, the flammability risk of biochar once dispersed into the topsoil is comparatively very low. Testing performed under the worst-case conditions (zero moisture content, finely milled, highly concentrated sample, open-air, and with a naked flame) did not identify biochar as flammable, because even if ignition was achieved, it did not spread. It can therefore be assumed with a high level of confidence that when dispersed within topsoil, biochar presents a low risk of both piloted and unpiloted ignition, even during extended periods of dry weather (Zhao, Enders, & Lehmann, 2014). This risk becomes negligible during parts of the year when the topsoil is exposed to rain and groundwater flow.

2.3 Biochar Migration

2.3.1 Introduction

In addition to processes which mineralize biochar to CO_2 and decompose biochar to other organic materials, there is the parallel process of physical comminution, water-transport, and vertical migration of biochar within the soil that it is applied to (Rumpel, Leifeld, Santin, & Doerr, 2015). The mechanisms behind these processes and potential ameliorating processes have been investigated to inform design.

2.3.2 Review

Both vertical and horizontal transport processes involve the movement of biochar mass (particulate, dissolved, or dislodged) with water, ending up either further down into the subsoil, or carried by surface runoff into streams and rivers (Rumpel, Leifeld, Santin, & Doerr, 2015). Transport of micronized biochar through rivers for eventual deposition at the floors of lakes and oceans is actually a favourable outcome as these environments are anoxic, and PyC MRTs of >6,000 years have been calculated (Coppola, Ziolkowski, Masiello, & Druffel, 2014). The movement of dissolved and particulate biochar into the subsoil is similarly beneficial; subject to less disturbance from flora, fauna, and weather, these layers have much slower turnover times than the topsoil (Schmidt, et al., 2019).

The current understanding of biochar migration is primarily informed by applications of biochar to agricultural surfaces and the study of naturally produced biochar found in soils (Rumpel, Leifeld, Santin, & Doerr, 2015). Agricultural soils in particular experience high levels of disturbance from tillage, annual crop cycles, fertilisation, and harvesting. These mechanisms greatly accelerate comminution of biochar, facilitating overland transport and leaching, compared to an untouched roadside embankment where the biochar is mixed into the topsoil. The rates of biochar transport can confidently be expected to be much slower for an infrastructural application than an agricultural one.

Studies of migration are also typically based upon trials that use un-pelleted biochar, which is typically finer than pelleted biochar. During periods of intense rainfall, finer fractions of materials are easier to dislodge from the topsoil surface, and more easily transported in overland flow and groundwater flow as particulate content. Conversely however, finer fragments may react more easily with soil minerals to create stable organo-mineral complexes that integrate the biochar more effectively into the soil.

For both Banwell Bypass and Moreton-in-Marsh (defined in Appendices G and H respectively), it is proposed that biochar be integrated into topsoil along with quarry fines. From field testing on soils upon basaltic rock, it has been demonstrated that short range order mineral content correlates well with black carbon concentration ($R^2 = 0.46$, n=44, $p < 0.05$) (Cusack, Chadwick, Hockaday, & Vitousek, 2012). The provision of bonding sites retains the biochar and enhances the physical protection provided by the soil (Major, Lehmann, Rondon, & Goodale, 2010) (Cusack, Chadwick, Hockaday, & Vitousek, 2012). The relationship between mineral content and biochar migration will be assessed over various blend ratios at Moreton-in-Marsh (see section 4.4.1 of Appendix H), by taking topsoil samples and measuring the change in the distribution of biochar throughout the topsoil.

2.3.3 Summary

Compared to agricultural applications, road-side embankments represent a disturbance-free environment where the processes of comminution and subsequent transport (horizontal and vertical) are significantly slowed, improving the local retention of the applied biochar. The use of pelleted biochar should increase resistance to the physical processes of dislodging and particulate transport, but may restrain reactions between biochar fragments and minerals in the soil. The transport of biochar does not necessarily equate to a loss of carbon removal capacity; indeed, if the biochar is high quality $H:C_{org}<0.4$ (as proposed in section 1.3.2 of Appendix B) then this should actually delay oxidation and microbial degradation, albeit to the detriment of local monitoring. The combination of biochar with pedogenic materials such as quarry fines (quarry fines/basalt) can be expected to improve the retention of biochar (against an area unamended with quarry fines) within the area it's applied to by bonding the biochar to the surrounding soil matrix.

Measuring biochar content variation with depth and monitoring the POC/DOC (particulate and dissolved organic carbon) of runoff water should quantify the loss mechanisms within the reference site, allowing for improvement in subsequent applications (see Appendix H).

References

Abdullah, H., & Wu, H. (2009). Biochar as a Fuel: 1. Properties and Grindability of Biochars Produced from the Pyrolysis of Mallee Wood under Slow-Heating Conditions. *Energy and Fuels*, 4174-4181. Retrieved from https://doi.org/10.1021/ef900494t

Adekiya, A., Olayanju, T., Ejue, S., Alori, E., & Adegbite. (2020). Contribution of Biochar in Improving Soil Health. In B. Giri, & A. Varma (Eds.), *Soil Health* (pp. 99-113). Springer International Publishing. Retrieved from https://doi.org/10.1007/978-3-030-44364-1_6

Casas, C., Schaschke, C., Akunna, J., & Jorat, M. (2019). Dissolution experiments on dolerite quarry fines at low liquid-to-solid ratio: a source of calcium for MICP. *Environmental Geotechnics*. Retrieved from https://doi.org/10.1680/jenge.19.00067

celtest. (2017). *Laboratory Test Report (Cragmill).*

celtest. (2020). *Laboratory Test Report (Divet Hill).*

Chell, E. (2013). *Soft Estate.* Canterbury: UK Research and Innovation. Retrieved from https://gtr.ukri.org/projects?ref=AH%2FJ005797%2F1

Coppola, A., Ziolkowski, L., Masiello, C., & Druffel, E. (2014). Aged black carbon in marine sediments and sinking particles. *Geophysical Research Letters*, 2427-2433. Retrieved from https://doi.org/10.1002/2013GL059068

Cross, A., & Sohi, S. (2013). A method for screening the relative long-term stability of biochar. *GCB Bioenergy, 5*(2), 215-220. Retrieved from https://doi.org/10.1111/gcbb.12035

Cusack, D., Chadwick, O., Hockaday, W., & Vitousek, P. (2012). Mineralogical controls on soil black carbon preservation. *Global Biogeochemical Cycles*. Retrieved from https://doi.org/10.1029/2011GB004109

EPS. (2002). *Behaviour of EPS in case of fire.* European Manufacturers of EPS. Retrieved from https://eumeps.construction/content/8-downloads/4-documents/1-fire-safety/eps-behaviour-in-case-of-fire.pdf

Gronwald, M., Don, A., Tiemeyer, B., & Helfrich, M. (2015). Effects of fresh and aged chars from pyrolysis and hydrothermal carbonization on nutrient sorption in agricultural soils. *SOIL*, 475-489. Retrieved from https://doi.org/10.5194/soil-1-475-2015

Guillou, G., & Davies, R. (2004). *Combination of BasalticQuarry Fines with Organic Process Residues for the Development of Novel Growing Media.* Mineral Solutions. Retrieved from http://www.mineralsolutions.co.uk/casestud.php

Hewlett, B. (2020). *MPI-85-102020 Low Nutrient Grassland* . Highways England.

Imhoff, P. (2017). *Reducing Stormwater Runoff and Pollutant Loading with Biochar Addition to Highway Greenways.* Washington: Innovations Deserving Exploritary Analysis Programs.

Imhoff, P., & Nakhli, S. (2017). *Reducing Stormwater Runoff and Pollutant Loading with Biochar Addition to Highway Greenways* . Newark: Transportation Research Board.

Jablite. (2017). *Fillmaster Geofoam*. Jablite. Retrieved from https://www.jablite.co.uk/wp-content/uploads/2017/10/Fillmaster-Geofoam-Datasheet.pdf

Jeffery, S., Abalos, D., Spokas, K., & Verheijen, F. (2015). Biochar effects on crop yield. In J. Lehmann, & S. Joseph, *Biochar for Environmental Management* (pp. 301-325). Routledge.

Maienza, A., Genesio, L., Acciai, M., & Miglietta, F. (2017). Impact of Biochar Formulation on the Release of Particulate Matter and on Short-Term Agronomic Performance. *Sustainability*. Retrieved from http://dx.doi.org/10.3390/su9071131

Maiti, S., Dey, S., Purakayastha, S., & Ghosh, B. (2006). Physical and thermochemical characterization of rice husk charas a potential biomass energy source. *Bioresource Technology*, 2065-2070. Retrieved from http://dx.doi.org/10.1016/j.biortech.2005.10.005

Major, J., Lehmann, J., Rondon, M., & Goodale, C. (2010). Fate of soil-applied black carbon: downward migration,leaching and soil respiration. *Global Change Biology*, 1366-1379. Retrieved from https://doi.org/10.1111/j.1365-2486.2009.02044.x

Manning, D. (2004). *Exploitation and Use of Quarry Fines.* Manchester: Mineral Solutions Ltd.

Manning, D. (2021). *Site Report: The Sill.*

Mašek, O., Sohi, S., Kiso, J., & Boag, K. (2010). *FCO "UK Mission to Japan – biochar".*

Naujokas, A. (1985). Spontaneous Combustion of Carbon Bed. *Plant/OPerations Progress*, 120-126. Retrieved from http://dx.doi.org/10.1002/prsb.720040214

Pardo, G., Sarmah, A., & Orense, R. (2019). Mechanism of improvement of biochar on shear strength and liquefaction resistance of sand. *Géotechnique*, 471-480. Retrieved from https://doi.org/10.1680/jgeot.17.P.040

Restuccia, F., Rein, G., & Mašek, O. (2018). Quantifying self-heating ignition of biochar as a function of feedstock and the pyrolysis reactor temperature. *Fuel*, 201-213. Retrieved from https://doi.org/10.1016/j.fuel.2018.08.141

Rumpel, C., Leifeld, J., Santin, C., & Doerr, S. (2015). Movement of biochar in the environment. In J. Lehmann, & S. Joseph, *Biochar for Environmental Management* (pp. 283-299). Routledge.

Sadasivam, B., & Reddy, K. (2015). Engineering properties of waste wood-derived biochars and biochar-amended soils. *International Journal of Geotechnical Engineering*, 521-535. Retrieved from https://doi.org/10.1179/1939787915Y.0000000004

Schmidt, H.-P., Anca-Couce, A., Hagemann, N., Werner, C., Gerten, D., Lucht, W., & Kammann, C. (2019). Pyrogenic carbon capture and stroage. *Bioenergy*. Retrieved from https://doi.org/10.1111/gcbb.12553

SILL. (2021). *Whin Sill Grassland Roof*. Retrieved from SILL: National Landscape Discovery Centre: https://www.thesill.org.uk/exhibition/grassland-roof/

Sun, F., & Lu, S. (2013). Biochars improve aggregate stability, water retention, and pore-space properties of clayey soil. *Journal of Plant Nutrition and*

Soil Science, 26-33. Retrieved from https://doi.org/10.1002/jpln.201200639

UK BRC. (2019). *Standard Biochars*. Retrieved June 22, 2021, from UK Biochar Research Centre: https://www.biochar.ac.uk/standard_materials.php

UKCEH. (n.d). *Reports and Data: Soil nitrogen*. Retrieved from UK Centre for Ecology & Hydrology: https://eip.ceh.ac.uk/naturalengland-ncmaps/reportsData

Vijay, V., Shreedhar, S., Adlak, K., Payyanad, S., Sreedharan, V., Gopi, G., . . . Aravind, P. (2021). Review of Large-Scale Biochar Field-Trials for Soil Amendment and the Observed Influences on Crop Yield Variations. *Frontiers in Energy Research*. Retrieved from https://doi.org/10.3389/fenrg.2021.710766

Wang, J., Xiong, Z., & Kuzyakov, Y. (2015). Biochar stability in soil: meta-analysis of decomposition and priming effects. *Global Change Biology Bioenergy*, 512-523. Retrieved from https://doi.org/10.1111/gcbb.12266

Xiang, W., Zhang, X., Chen, J., Zou, W., He, F., HU, X., . . . Gao, B. (2020). Biochar technology in wastewater treatment: A critical review. *Chemosphere*. Retrieved from https://doi.org/10.1016/j.chemosphere.2020.126539

Zhao, M., Enders, A., & Lehmann, J. (2014). Short- and long-term flammability of biochars. *Biomass & Bioenergy*. Retrieved from http://dx.doi.org/10.1016/j.biombioe.2014.07.017

Zong, Y., Chen, D., & Lu, S. (2014). Impact of biochars on swell–shrinkage behavior, mechanical strength, and surface cracking of clayey soil. *Journal of Plant Nutrition and Soil Science*, 920-926. Retrieved from https://doi.org/10.1002/jpln.201300596

I1 Risk Register

Title	Risk Type	Risk detail	High, Medium or Low Risk Rating (Probability x Impact)	Mitigation Actions	Mitigated Risk (P x I)	Phase 1 member, BEIS, transfer to Phase 2
Possibility of inaccurate carbon sequestration estimate	Technical risks	Data exists for both quarry fines and biochar sequestration, but reported values have a wide range. It is possible that the feasibility study may narrow this range, but to values that do not support economic GGR.	High	We have collaborated with notable academic experts in the field who are familiar with the literature and remain confident in the feasibility of economically applying the technology. Site specific life cycle carbon analyses have been applied to Banwell Bypass which validate the removal potential of both technologies. An independent analysis and summary has been developed by Arup specialists. The analysis gave a range of possible carbon capture figures, which were similar to those previously measured or calculated in academia. The amount of carbon captured is therefore expected to be within the ranges identified by the note. Additionally, a dual monitoring campaign has been developed for the pilot site and at a reference site that allows longer term monitoring to be conducted. This will validate the amount of carbon removed by the technologies in similar settings, should long term monitoring at the pilot site become unfeasible. This develops confidence in the techniques for future, large-scale projects. Conservative assumptions have been used for estimating the carbon removal of each technology, see sections 1.3 and 1.4 of both Appendix B and C.	Low	Phase 1 - Arup, University of Edinburgh, Newcastle University, Costain
Possible surface flooding risk increase following carbonation	Technical risks	Carbonation following the weathering of quarry fines may result in deposition of carbonates which could reduce the permeability of the soils and increase risk of surface flooding.	Low	Assessment of risk and potential mitigations were explored at Phase 1. The ultimate application of quarry fines in Phase 1 is the amendment into embankment topsoil, precluding the possibility surface flooding. Quarry fines are being used in tandem with the highly porous biochar, which have been shown to reduce surface water runoff in amended roadside verges. Water-logging has never been encountered in field trials that incorporate quarry fines into soils, some of which last for 5 years. Furthermore, carbonation is one of two possible routes of carbon removal.	Low	Phase 1 - University of Edinburgh, Newcastle University
Rotary kiln potential progression for biochar is less established technology	Technical risks	Large scale biochar production is likely to transition to rotary kiln configurations. This is a change in the pyrolysis plant technology and may encounter unforeseen problems.	High	Assessment of risk and potential mitigations explored at Phase 1 feasibility stage. Rotary kilns are already in use by commercial pyrolysis companies, and the technological maturity of rotary kilns is high in other sectors. However will not be trialled on pilot projects due to potential rotary kiln suppliers not operating on the short term leasing basis required for Phase 1 (please see section 1.5 of Appendix B). Residual risk may become relevant in the future (beyond 2025 depending on industry growth and maturity) and will be further considered in planned doc of Phase 3.	Low	Others (transfer beyond Phase 2)
Quarry owner changes	Economic and market factors	Dolerite quarries changing hands and new business priorities not aligning with the project.	Low	More than one potential quarry has been identified as suitable for use, so other options exist. Mitigate by value in the market, and a supply contract agreed at Phase 2.	Low	Phase 1 - Arup, Costain, University of Edinburgh, Newcastle University
Older kilns may be used as industry use becomes more widespread	Economic and market factors	At high scales of material placement, the increased number of transport and placement machines needed will result in old second hand machines kept in use for longer.	Low	A specification for a leased or localised kiln will be used to ensure quality of the kiln. This is not expected to be a significant risk for the pilot project, however may become more important at the scale required for the pipeline to 2030. If older equipment is used, the carbon removal calculations can be changed to update the net carbon removal capacity of the biochar, and material quantities altered accordingly.	Low	Others (transfer beyond Phase 2)
Biochar/feedstock supply insufficiencies	Economic and market factors	Increases in demand for Biochar and its feedstock could outstrip supply as technologies mature and implementation becomes embedded, with associated supply chain sourcing challenges and price rises. There are risks also associated with variation in feedstock supply as a consequence of this competition, as using two different sources of biochar in the project may compromise monitoring outcomes.	High	Consultation with PyroCore indicates that pyrolysis availability aligns with supply required up to 2025. Further upscaling may be required beyond this point. Multiple pelleted biomass suppliers have been contacted, and a list of supply options has been drawn up in section 1.6 of Appendix B. A potential local Ash (Fraxinus excelsior) source has also been identified, and discussions have taken place between the source owner and the Phase 2 contractor, Alun Griffiths. Use may be made of parallel biochar and biomass projects under the same BEIS funding. Further mitigation regarding the securing of a long-term feedstock supplier will be required by the organisation that carries Phase 2 forward.	Medium	Phase 1 - Arup, Costain, University of Edinburgh, Newcastle University

Title	Risk Type	Risk detail	High, Medium or Low Risk Rating (Probability x Impact)	Mitigation Actions	Mitigated Risk (P x I)	Phase 1 member, BEIS, transfer to Phase 2
Quarry fines cost uncertainty	Economic and market factors	Costing the quarry fines as a by-product. Once a use-value is established the supply and cost of a previous waste material could prove unpredictable.	Medium	Quarry fines have been examined as part of the economics analysis and the geo-environmental regulations. Quarry fines are expected to require the aggregate tax levy, but otherwise be very cost-effective in the short-term, please see section 1.5 of Appendix C. In the long term (beyond the pilot study), if the pipeline to 2030 is realised the demand may drive up the cost for quarry fines. Through market research it has been found that the quarry fines are not a by-product, but are readily priced and even used for asphalt production at some quarries. This risk is therefore considered closed for the pilot project, but likely worth considering in later Phases.	Low	Others (transfer beyond Phase 2)
Regulatory uncertainty	Legislative/regulatory changes	Unknown Regulations/Legislation (additionally legislation may not already be in place).	High	Lead constant review of risk register, try to consider possible scenarios to identify unknowns. A regulation review has been completed within Appendix E. This has identified key regulations that will need to be applied for. There is a policy gap around biochar, which is being addressed through collaboration with other biochar centred projects in the biochar forum.	Medium	Phase 1 - Arup
Planning permission lead times	Legislative/regulatory changes	Planning permission for linear projects may be set at start of Phase 2, and GGR cannot be included under the existing planning.	High	Amendments and getting GGR material into the earthworks specification so it can come into the project via the agreed specifications. This may require variations, particularly with planning departments (which may be costly/program-critical). Pilot projects that bypass this risk by including the pilot scheme at an early project stage (i.e. before planning permission) have been targeted. This may not be possible due to project-specific infrastructure timeframes. Pilot project by the end of this project to have an "approval in principal" from the site owner, so they will need to have an understanding and familiarity with the products and site. The site selected will need an understanding of the processes needed to gain planning (timeframes are key, costs are key, any verification processes required). This would bypass this risk entirely (this risk has therefore been downgraded to low).	Low	Phase 1 - Arup/Costain
Project team risks	Human resources (e.g. loss or disability of key personnel)	The skills of the team are in some instances very specialized and also in demand across numerous projects - risk of key team members leaving the team. This risk meets a critical juncture at the beginning of Phase 2, as the staff developing Phase 1 may not be free to continue into the next stage of work.		A dedicated team has been identified to deliver the proposals. Furthermore, both Arup and our collaboration partners are able to draw on a wide pool of experts and other resources in the event of any unexpected changes to the structure of the proposed team. The requirements of the Phase 2 works have been developed by the Phase 1 team so as to identify potential skill-gaps. Handover activities for any potential team member replacements may be required as part of this. Difficult risk to control: communication on availability of all team members key: organise regular check ins.	Medium	Phase 1 - Arup, Costain, University of Edinburgh, Newcastle University
IP may cause delays	IP risk (challenges)	It is possible that any specialized plant developed to realise the technologies might attract patents and excessive costs for other firms.	Medium	Monitor potential that IP may cause program/cost issues - this is considered unlikely as no novel techniques for either technology are currently required or expected.	Low	Phase 1 - University of Edinburgh, Newcastle University
Quarry fines dust health issue	Planning and permitting	Use of quarry fines may result in health and safety concerns during construction, e.g. wind-blown dust could present a risk to construction workers.	Medium	Risk and appropriate risks mitigation measures to be identified as part of feasibility study assessments. Quarry fines are not a novel material, and quarries have best working practices for this exact risk that can be replicated. Should also be covered as part of EIA.	Low	Phase 1 - Arup
Quarry fines dust EIA planning impact	Planning and permitting	Use of finely ground dolerite/basalt rock may result in health and safety concerns and/or concerns to sensitive ecological/hydrological receptors e.g. due to presence of small quantities of metals within the dolerite dust and the finely ground nature of the material.	Medium	Risk and appropriate risks mitigation measures to be identified as part of feasibility study assessments. Good working practices likely to cover this appropriately. Should also be covered as part of EIA.	Low	Phase 1 - Arup

Title	Risk Type	Risk detail	High, Medium or Low Risk Rating (Probability x Impact)	Mitigation Actions	Mitigated Risk (P x I)	Phase 1 member, BEIS, transfer to Phase 2
Biochar vandalism/flammability potential	Health and Safety	Vandalism. Low pyrolysis temperature biochar is flammable, and there is a risk of large areas of it being 'quarried' by vandals to feed a campfire, or a deposit to be deliberate set alight.	High	Risk mitigation measures are immanent in the proposed application method, as the biochar is diluted by the quarry fines and topsoil blend. The wood derived biochar used within this project is less flammable than the original feedstock, due to high PPT. For full review of this risk, please see section 2.2 of Appendix I.	Low	Phase 1 - Arup, Costain, University of Edinburgh, Newcastle University
Materials moved, preventing successful carbon monitoring	Monitoring	For a site requiring monitoring, there is the additional risk of site disturbance, movement of material in soil or later construction will redistribute the sequestered material, making it difficult to prove and therefore driving up 'assumed' losses in storage.	Medium	Validation of carbon removal now separate from concerns of interference due to the use of a controlled reference site as well as a live pilot site.	Low	Phase 1 - Arup, Costain, University of Edinburgh, Newcastle University
Quarry fines net carbon removal sensitivity to transport distance	Technical risks	For the Dolerite fines, depending on transport distances and processing methods, a proportion of their GGR capacity is required to supply and place the materials. This could result in no pilot site being within reasonable range of a dolerite quarry.	Medium	To be assessed as key part of Phase 1 assessments. Current published data suggests that travel distances of up to 500km are likely to be feasible. Ten Dolerite quarries have been identified already, spread over the UK. Sourcing suitable material for the Phase 2 pilot study is therefore considered feasible. A good mitigation is ensuring pilot site is in a workable location. This risk is now downgraded to low as latest pilot project news is that they will be highly favourable locations for dolerite (and biochar). A review made of quarries local to the pilot site has identified suitable sources within reasonable distances (approx. 100km) and the carbon cost of transport has been included in the material requirements, please see section 1.5 of Appendix C.	Low	Phase 1 - Arup, Costain, University of Edinburgh, Newcastle University
Transportation carbon	Process integration	A key integrator technology for this project is the logistics sector. Biomass, Biochar and quarry fines all required transportation and being placed and these need to be efficient journeys.	Medium	Risk to be considered as part of the Phase 1 feasibility assessment. Experience with electrified plant on recent large infrastructure projects including HS2 and expected future trends will be considered. This risk is minimal for quarry fines but requires consideration when the feedstock source is located. Transportation carbon has been included within the LCA for both biochar and quarry fines, please see sections 1.4 and 1.6 of Appendix B and sections 1.4 and 1.5 of Appendix C, respectively.	Medium	Phase 1 - Arup, Costain, University of Edinburgh, Newcastle University
Pyrolysis plant cost	Resource issues	Pyrolysis plant design or purchase is expensive, and could consume too much of the phase 1 and phase 2 budgets. Timescales to setup and design a new pyrolysis plant incompatible with Phase 1 time line.	High	A review of commercial pyrolysis suppliers has been conducted, please see section 1.5 of Appendix B. Through frequent discussions PyroCore has stressed confidence in their ability to provide the pyrolysis process for both the reference site and the pilot site, and has been honest in sharing operational costs and scaling plans.	Medium	Phase 1 - University of Edinburgh, Newcastle University
Sewage sludge competition	Economic and market factors	The potential use of sewage sludge as a feedstock faces competition from existing power generation and agricultural spreading applications.	Medium	Integrate these existing uses into the supply forecast. Confirm as part of the economist scope, if not universities to investigate. Engage with sludge providers to understand availability further. On initial review this is not expected to be a significant risk for the pilot project, however may be a risk for future Phases or the wider pipeline if momentum is gained. The regulation of sewage sludge is likely to be a much more significant blocker to this (see risk 50), so sludge derived biochar has not been considered for this project. Availability of sludge for pyrolysis likely to increase as stricter waste-to-land regulations demand new approaches for sludge use, please see section 1.2.2 of Appendix B.	Low	Phase 1 - Arup, Costain, University of Edinburgh, Newcastle University

Title	Risk Type	Risk detail	High, Medium or Low Risk Rating (Probability x Impact)	Mitigation Actions	Mitigated Risk (P x I)	Phase 1 member, BEIS, transfer to Phase 2
Aggregate levy may become applicable to dolerite	Legislative/regulatory changes	It has been assumed for this entry that the Aggregates Levy does not apply to dolerite quarry fines that are used for GGR. It may be possible that this is ruled otherwise, or that the process of reclaiming the levy is so slow and expensive that the business model will not work.	Medium	Economic review has shown that the aggregate levy is likely to apply. This is a relatively small cost to the project as shown in section 1.5 of Appendix C, so the mitigated risk has been downgraded to low. The aggregate levy may be useful in providing an official means of recording the amount of quarry fines deployed at a site, useful for carbon accounting.	Low	Phase 1 - Arup, Costain, Newcastle University
Product competition with existing products	Competition	All of the value added products are going up against existing products in conservative markets. They may be superior, but fail to be adopted.	Medium	It will take experience, connections and multiple attempts for the products to achieve significant penetration. Adoption across major projects will increase familiarity and reduce the perceived risk of a new project. We will advertise the use, disseminate internally and externally, but this is otherwise out of direct control. Extensive stakeholder engagement has raised the profile of both technologies within the infrastructure industry, please see Appendix D for more details.	Low	Phase 1 - Arup/Costain
Biochar plants seen as incineration plants (planning opposition)	Planning and permitting	Widespread public opposition to incineration plants occurs in the UK, and a pyrolysis plant should be assumed to have the same challenges.	High	Risk reduction options followed as part of the Phase 1 feasibility assessment, including:- . Leasing an existing plant (PyroCore) that already has existing permissions in place. . Early engagement with planning/EIA required to communicate correctly and minimise this risk on a project. . Industry engagement completed on a public platform; advertisement of the benefits to a wide audience therefore begun.	Low	Phase 1 - Arup, Costain, University of Edinburgh, Newcastle University
Stakeholder miscommunication	Stakeholder engagement	Risk that stakeholders do not understand the proposed technologies, so are not able to contribute fully.	Medium	The following has been completed: -Develop graphic/"cartoon"-style overview of the technologies -Develop concise, clear summary -Consider methods of engagement" -Follow Consultation Plan This is expected to mitigate this risk, however it is not completely within this project's control. There is considered to be a risk that despite the above, stakeholders may still not understand the proposed technologies unless they are well presented, so this risk shall be kept as "Medium" to emphasise its importance. The consultation plan and stakeholder register are live and should be referred to and updated throughout the course of the project. Stakeholder miscommunication has not materialised as a significant risk. This is demonstrated by the interest expressed in the technologies as part of the stakeholder engagement plan outlined in Appendix D.	Medium	Phase 1 - Arup, Costain, University of Edinburgh, Newcastle University
Stakeholder expectations managed	Stakeholder engagement	Risk that stakeholder engagement gives incorrect expectations for the technologies.	Medium	The following has/will be completed: -Develop graphic/"cartoon"-style overview of the technologies -Develop concise, clear summary -Consider methods of engagement" -Develop and follow stakeholder engagement plan. -Engage with Arup CRM to gain insights as to how to connect with stakeholders most effectively. -Align internally before committing to anything. - Cyclic engagement with stakeholders (give them back updates) Please see Appendix D for a full review of stakeholder engagement methodology.	Low	Phase 1 - Arup, Costain, University of Edinburgh, Newcastle University
Stakeholder relationship damaged	Stakeholder engagement	Risk of poor impression from stakeholder engagement damaging future prospects of the technology.	Medium	The following has/will be implemented: -Develop graphic/"cartoon"-style overview of the technologies -Develop concise, clear summary -Consider methods of engagement" -Develop and follow stakeholder engagement plan. -Engage with Arup CRM to gain insights as to how to connect with stakeholders most effectively. -Align internally before committing to anything. -Consider any communication carefully and review internally prior to sending communication (for workshops do complete a strong preparation prior to the workshop). Please see Appendix D for a full review of stakeholder engagement methodology.	Low	Phase 1 - Arup, Costain, University of Edinburgh, Newcastle University
UK carbon market uncertainty	Economic and market factors	UK Carbon market in its infancy. Volatility and uncertainty makes it difficult to officiate offsets.	Medium	Reviewed as part of economics review. The wider industry is beyond the scope of this project, however its impacts have been assessed as further risks (e.g. see risk row 4, 5, 18, among others). This risk will be left as medium as it is quite difficult to forecast the changes to UK carbon market in the near term. Discussions surrounding the carbon accreditation of biochar within the UK are being progressed through the biochar forum also, please see Appendix D for details.	Medium	Outside scope

Title	Risk Type	Risk detail	High, Medium or Low Risk Rating (Probability x Impact)	Mitigation Actions	Mitigated Risk (P x I)	Phase 1 member, BEIS, transfer to Phase 2
Biochar creation at scale may be difficult	Technical risks	After consulting with a biochar engineering specialist. There is a risk that biochar qualities at small-scale tests become harder to implement en-masse, and that academic/laboratory conditions do not practically scale to infrastructure.	High	A study of biochar creation has been completed, biochar generation expected to be achievable at the levels required for the 2025 BEIS requirements. Upscaling required to reach 2030 requirements and this is also covered in risk 4, please see section 1.5 of Appendix B for more information. The responsibility for upscaling the nascent UK biochar market to industrial scales is outside the scope of this project, however assurance of demand may be given to suppliers through the efforts of the biochar forum, see Appendix D.	Low	Others (transfer beyond Phase 2)
Misconception of biochar and dolerite as for agricultural purposes	Stakeholder engagement	Risk that the established agricultural use of biochar and quarry fines prevents meaningful stakeholder engagement with regards to their possibilities within infrastructure.	Medium	The actions completed as part of other stakeholder engagement risks are expected to help mitigate this risk to be low (see examples below): -Develop graphic/"cartoon"-style overview of the technologies -Develop concise, clear summary -Consider methods of engagement" -Develop and follow stakeholder engagement plan. -Engage with Arup CRM to gain insights as to how to connect with stakeholders most effectively. -Align internally before committing to anything. -Consider any communication carefully and review internally prior to sending communication (for workshops do complete a strong preparation prior to the workshop). Opportunities for use within infrastructure for both technologies have been validated by Arup specialists, and these uses have been disseminated to industry stakeholders through careful presentations.	Low	Phase 1 - Arup, Costain, University of Edinburgh, Newcastle University
Variability of biochar (will depend on feedstock)	Technical risks	The plethora of feedstock options makes a firm characterisation of biochar's geotechnical properties quite difficult, and could come across as unwanted uncertainty to a potential contractor. Non-virgin feedstocks also have lower carbon stability.	Medium	Feedstock options were limited to sewage sludge and sawmill co-products, and further refined to sawmill co-products when the regulatory barriers around sludge derived biochar were found to be outside the capacity of the project. Feedstock consistency is guaranteed by pelleted biomass suppliers as covered in section 1.6 of Appendix B, and the identified source local to Banwell is consistent also. PyroCore experienced pyrolysis suppliers also, and testing of feedstock is required as standard (please see Appendix G6).	Low	Phase 1 - Arup
Cost implications of dolerite grinding	Resource issues	Site requirements for finely ground dolerite rock hinder the GGR potential of technology due to the exponential relation between decreasing particle size and energy requirements in rock flour milling.	Medium	Applications have been identified that bypass the requirement for rock milling, and 0-4mm fines are readily available from quarries as an existing product as outlined in section 1.5 of Appendix C. Typical crushed dolerite availability will be reviewed against DMRB Manual Types to confirm if further grinding required.	Low	Phase 1 - University of Edinburgh, Newcastle University
Intrusive sampling may reduce pilot site carbon removal	Technical risks	Potential requirements to break ground to maintain permeability through precipitation and disturbance incumbent in monitoring - both present risk of disturbing the biochar, compromising its stability in the soil.	High	See risk 3 also. Breaking ground will likely not be required to maintain permeability as previous field trials have never encountered this problem. The use of Moreton-in-Marsh as a reference site means that monitoring no longer compromises the carbon removal objectives of the pilot site.	Low	Phase 1 - Arup, Costain, University of Edinburgh, Newcastle University
Reputational damage from poor stakeholder engagement	Stakeholder engagement	Risk of poor impression from stakeholder engagement damaging reputation of all collaborators.	Medium	Experts Saran and David have significant experience, contacts, and are used to significant stakeholder engagement as integral to their work. They have a good reputation, and good contacts. All parties have an interest in maintaining their high reputations and spreading enthusiasm for the project. Follow CEP and align internally prior to reaching externally. See also risks 24, 25, and 26, and Appendix D for details of stakeholder engagement processes used throughout the project.	Medium	Phase 1 - Arup, Costain, University of Edinburgh, Newcastle University
Potential impact on controlled waters	Technical risks	Impact on controlled waters (particularly any pH or chemical changes, or amount of nitrates, metals in the soil). The impact on any abstractions may be important to understand	Medium	Contamination and soil health teams need to review this for the pilot site, following guidance on what key risks exist as detailed within the Specialists' note. The EA has been contacted about this risk, however ultimately the pilot project will mitigate this risk by a site-specific geo-environmental review and provision of necessary risk mitigation. This is not expected to be a regulatory blocker with the EA, however monitoring or alternative risk mitigation may be specified as part of site-specific reviews or planning requirements. GeoEnvironmental testing proposed for both Moreton-in-Marsh (section 4 of Appendix H) and the Banwell Bypass (section 5 of Appendix G).	Medium	Phase 1 - Arup

Title	Risk Type	Risk detail	High, Medium or Low Risk Rating (Probability x Impact)	Mitigation Actions	Mitigated Risk (P x I)	Phase 1 member, BEIS, transfer to Phase 2
Potential impact on groundwater	Technical risks	Impact on groundwater (particularly any pH or chemical changes, or amount of nitrates, metals in the soil).	Medium	Contamination and soil health teams need to review this for the pilot site, following guidance on what key risks exist as detailed within the Specialists' note. The EA has been contacted about this risk, however ultimately the pilot project will mitigate this risk by a site-specific geo-environmental review and provision of necessary risk mitigation. This is not expected to be a regulatory blocker with the EA, however monitoring or alternative risk mitigation may be specified as part of site-specific reviews or planning requirements.	Medium	Phase 1 - Arup
Soil health impacts unknown	Technical risks	Soil health impacts are currently unknown.	Medium	Effects on nutrient lean soft estates are mitigated through a comprehensive review in section 2.1 of Appendix I. Impacts on soil health are outlined through literature review. The methodology of this review is outlined in Appendix B4, and the reviews themselves are captured in section 1.2.6 of Appendix B and section 1.2.5 of Appendix C for biochar and quarry fines, respectively.	Low	Phase 1 - Arup, University of Edinburgh, Newcastle University
Wash-out of materials in a drainage solution	Technical risks	A drainage option for these technologies may not be suitable. High water-flow in these applications may washout integrated biochar and quarry fines.	Medium	Options for drainage use are covered in Appendix I, and plots of varied material application rates are proposed in Appendix H to develop the understanding of their hydrogeological properties over time.	Low	Phase 1 - Arup, Costain, University of Edinburgh, Newcastle University
Earthworks may not be suited to these technologies	Technical risks	A slope and earthworks option for these technologies may not be suitable.	Medium	Use of a reference site allows the short term stability of blend upon 1:2 embankments to be verified before application to the Banwell Bypass. This is most critical for embankment placements due to short term pore water pressure build-up following material placement. Discussion with geotechnical experts within Arup has not raised any issues regarding application of the blend to 1:2 embankment slopes.	Low	Phase 1 - Arup, Costain, University of Edinburgh, Newcastle University
Impact on ecological receptors	Technical risks	Impact of the technologies on ecological receptors.	Medium	To be considered as part of a site-specific EIA and contamination. These reviews to determine if further ecological advice is necessary.	Medium	Phase 1 - Arup
Effect of materials on different plants likely to be different	Technical risks	Technologies are known to improve soil for certain plants, however conversely the materials may negatively other plants (ecological receptors).	Medium	This has been reviewed following stakeholder consultation. Certain plants are expected to work better in a nutrient-rich or nutrient-poor environment, which different proportions of biochar or dolerite can provide. This risk has therefore been downgraded to low, as the materials can be designed for the requirements of the plants that would be preferred for the location being considered. For full review of effect of materials on nutrient lean soft estates, please see section 2.1 of Appendix I.	Low	Phase 1 - Arup
Potential competition for pyrolysis plant could affect cost and availability	Resource issues	Biochar sourcing is predicted based on buying or leasing a pyrolysis plant from existing suppliers. This BEIS competition, with many projects on the same timetable and a narrow range of technologies, could trigger a short term shortage and price hike. Limited availability of pyrolysis facilities for biochar production and thus potentially high production costs may price-out investors/clients.	Medium	BEIS may choose to support a range of different technologies, or choose to coordinate the competition members to share resources over a staggered time frame (achieving more for the public purse). It is expected that this may be a topic for discussion within the forum developed by BEIS. Contact established with pyrolysis suppliers: understanding of pipeline for pyrolysis has been developed through ongoing discussions with PyroCore.	Medium	Phase 1 - Arup, University of Edinburgh, Newcastle University
Effect of dolerite alkali runoff on surroundings	Environmental risk	Sustained and intense application rates of dolerite fines could generate amounts of alkali runoff that are harmful to confined coastal ecosystems.	Low	Reference site allows for the quality of any leachate to be examined before full-scale application to pilot site. Application of the quarry fines is one-off also. There is no evidence of alkali run-off from quarry fines unless they are contaminated by concrete, but careful supply chain management can avoid this.	Low	Phase 1 - University of Edinburgh, Newcastle University, Arup
Decommissioning cost	Technical risks	Decommissioning of products (cost in).	Low	This cost is often overlooked: cost in.	Low	Phase 1 - Arup, Costain, University of Edinburgh, Newcastle University
Combined effect of dolerite and biochar on soil health/environment unconfirmed	Technical risks	Greatest unknown with regards to soil health and processes within the soil is the combined effect of the two technologies. Field studies exist for biochar and EMW as individual amendments, but studies of their combined use are scarce if existent at all.	Medium	Varied joint application rates of both materials at the reference site allows for well controlled monitoring of soil behaviour over time as a result of their combination, please see Appendix H.	Low	Phase 1 - Arup, University of Edinburgh, Newcastle University

Title	Risk Type	Risk detail	High, Medium or Low Risk Rating (Probability x Impact)	Mitigation Actions	Mitigated Risk (P x I)	Phase 1 member, BEIS, transfer to Phase 2
Electric fire on biochar	Technical risks	Electric car fire cannot be put out: ensure this possible flame will not affect the biochar. Flammability risk of biochar.	High	See Risk 15 also. Risk mitigation measures are immanent in the proposed application method, as the biochar is diluted by the quarry fines and topsoil blend. The wood derived biochar used within this project is less flammable than the original feedstock, due to high PPT. For full review of this risk, please see section 2.2 of Appendix I.	Low	Phase 1 - Arup, University of Edinburgh, Newcastle University, Costain
Quality of biochar	Technical and environmental risk	If biochar is sourced from a process where it is not the primary product there is a risk it will be of an inconsistent quality, and may also create delays in the supply chain. This also risks attracting the label of waste.	Medium	Biochar is rarely the primary product/aim of many pyrolysis systems, but monitoring feedstock and pyrolysis conditions with a specification should make this irrelevant. Feedstock streams have been identified that allow for careful chain of custody monitoring and consistent feedstocks give consistent biochar. Through this project and the wider biochar forum, a use for biochar will be established that should help with regulation processing.	Low	Phase 1 - University of Edinburgh, Newcastle University
Pollutant testing on a potential non-live site	Technical risk	If a non-live site is used (e.g. Moreton-on-Marsh) there is a risk the pollutant amelioration potential of biochar will not be properly tested, due to the lack of live traffic. The lack of live traffic also reduces CO2 concentration in the air, and limits the detail of the investigation.	Medium	Converse with the HE team and determine their testing methods for similar technologies. Moreton-on-Marsh is a stepping stone from lab-scale to full-scale rollout for technologies within HE, so there is a well-defined process of implementation for use at the Banwell Bypass. Moreton-on-Marsh is a test site for HE, so while it does not have the traffic weight of a live road, it has various complicating factors present making it an excellent (with the ability to control risk better than a live site) initial trial site. Integration of materials into a live pilot site at the Banwell Bypass allows for this to be investigated also.	Low	Phase 1 - Arup, Costain, University of Edinburgh, Newcastle University
Nutrient-lean preference (e.g. of HE) versus perception of materials as nutrient-rich	Stakeholder engagement and technical risk	MPI-85-102020 calls for nutrient-lean soils as a means to improve biodiversity, reduce the biomass of soft estate vegetation, and subsequently reduce maintenance of HE land. If biochar and quarry fines cannot be shown to target the desired plant species, then their potential as soil fertilisers will be undesirable. Conversely if their function can be tailored to this end, soft estates represent 30,000 ha of land in the UK and a key opportunity. Non-virgin feedstock typically high in nutrients.	Medium	Determined that nutrient-lean soil can be designed, please see section 2.1 of Appendix I. Specify capping layer of cultivated, untreated site-won subsoil as growing medium. Dolerite has 0% N content. Virgin feedstock (sawmill coproduct) now selected as sole feedstock, so high nutrients associated with high ash content biochar is ruled out. Varied joint application rates of both materials at the reference site allows for well controlled monitoring of plant growth over time as a result of their combination, please see Appendix H. Ensure communication with potential clients clearly represents the potential for materials in both nutrient-poor and nutrient-rich scenarios.	Low	Phase 1 - Arup, Costain, University of Edinburgh, Newcastle University
Sewage sludge regulations difficulty	Economic Risk	Biochar from waste streams (sludge etc) limits where/how it could be stored as well as involving more hidden costs & regulations. Biochar from waste products also fundamentally has its supply constrained to the amount of waste that is produced, which could create a convoluted situation where more waste is produced unnecessarily to satisfy biochar's input requirements (if waste route is pursued).	High	Two separate but relatively parallel markets for biochar; one for virgin feedstock one for non-virgin. Virgin feedstock has been chosen to progress this project forward due to regulatory constraints around non-virgin sources. Contact has been established with the EA to discuss this issue. From initial discussions, it is expected that biochar from sewage sludge would be considered a waste. However material from a non-waste feedstock (e.g. virgin wood, tbc), would not. There are other avenues of obtaining a permit for either or both waste and non-waste options. This shall be discussed in further detail as part of the biochar forum BEIS has developed, please see Appendix D.	Low	Phase 1 - Arup, Costain, University of Edinburgh, Newcastle University
Feedstock plantations in future could prevent other uses	Economic Risk	Competition for land use; if land is being siphoned off to grow feed/biomass that will be turned into biochar, the opportunity cost will be high as the land could've been utilised a) to grow food/crops, or b) for other carbon sequestration techniques. This may result in negative societal perceptions forming.	Medium	Review the location surrounding pilot project location to ascertain the extent to which public may have negative perceptions of biochar. Feedstocks must have their sustainability assured by replanting or guarantee of its status as a waste stream.	Low	Phase 1 - Arup, Costain, University of Edinburgh, Newcastle University
Biomass energy production competing with biochar development	Economic Risk	Pure biomass electricity production, which already makes up 12% of total UK energy production, is likely to increase thus increase its demand for biomass feedstock, directly competing with biochar for supply.	Medium	Explore possibility of mid-long term contract with feedstock/biomass suppliers to cover pilot project length. Gemserv curated the Biomass Supplier List (BSL) which is a gov list of registered biomass suppliers, see section 1.6 of Appendix B for more information. This may be an issue for the pipeline beyond Phase 2 if it is realised.	Low	Phase 1 - Arup

Title	Risk Type	Risk detail	High, Medium or Low Risk Rating (Probability x Impact)	Mitigation Actions	Mitigated Risk (P x I)	Phase 1 member, BEIS, transfer to Phase 2
Seasonal variation in biochar feedstock price	Economic Risk	Prices of feedstock increase by ~8% in winter compared to spring/summer (Ricardo Energy and Environment, 2018), presenting the risk of seasonal unprofitability/requirement of partial government support.	Medium	Multiple feedstocks to be considered, as captured in section 1.6 of Appendix B. Long-term costs of feedstocks to be agreed for pilot project. Consider floating idea of seasonal subsidy to BEIS, funded through reduced subsidy to fossil fuel sector / siphon some of the already huge subsidy biomass/energy currently receives. Would also be mitigated by increased use of sludge in winter months due to cheaper cost, but whether that conforms to regulations is currently unknown. This may be an issue for the pipeline beyond Phase 2 if it is realised.	Low	Phase 1 - Arup, Costain, University of Edinburgh, Newcastle University
Long-term upscaling of biochar production	Economic Risk	Investment into increasing number of pyrolysis facilities is essential for biochar to be scaled and utilised effectively in built-environment infrastructure projects, which requires capital expenditure, operational costs and the inherent risks associated with large scale infrastructure development- cost, build time/overrunning's, scope, inadequacy, interruption of funding, resource conflicts with other projects.	Medium	Opportunity to investigate funding streams for upscaling future biochar supply, depending on success of this project. Contact has been established with pyrolysis suppliers to understand their existing pipeline and development plans. The barriers to effective scaling can be openly discussed and mitigated within the biochar forum. This may be a risk if the pipeline succeeds beyond Phase 2, and biochar capacity does not increase with the demand. From talks, the biochar production pipeline is keen to grow and is being developed as part of other BEIS-funded projects, however this is outside the direct control of this project. The risk has therefore been downgraded for the pilot project, but may be greater for those beyond the pilot.	Low	Others (transfer beyond Phase 2)
Woodland establishment of biochar/dolerite not adequately understood or reported	Environmental Risk	Lack of available evidence on the successful establishment of trees, woodland, hedgerow and grasslands on soils ameliorated with Biochar or Dolerite.	Medium	See risk 44 also. Further research into case studies and other sources of evidence use to design a series of planting and establishment trials at the reference site in Moreton-in-Marsh (see Appendix H for further information). Case study in Stockholm reports that trees grew well in urban soils amended with biochar.	Low	Phase 2
Biochar flammability (particularly if stockpiled)	Environmental Risk	Stockpiling of biochar on-site for construction may be necessary to meet pilot demand. This could represent an acute flammability risk.	High	Pellet the biochar or use chipped feedstock to increase mechanical durability and reduce dust formation. Use feedstocks that produce biochar with low ignition potential, i.e. softwoods. Use of wetting to reduce ignition risk. Just-in-time production technique reduces the amount of pure biochar that is left sitting at any one time. Control the biochar oxidation during storage, material mixing to disperse hotspots. Use high pyrolysis temp (approx. 700 C) to minimise volatile content and long term flammability. Avoid large unbroken deposits of biochar and maximise deposit surface area, to increase the ratio of heat loss to the environment to heat generated by chemical reactions. Please see section 2.2 of Appendix I.	Medium	Phase 1 - Arup, Costain, University of Edinburgh, Newcastle University
Engineering conservatism	Technical risks	Reluctance of engineering industry to use materials.	Medium	Expectations of potential clients need to be managed (e.g. while our materials could be used as Class 1, this may difficult to enact in practice due to engineering cultural reluctance). Advertise products as widely as possible (including results post pilot-project), see Appendix D for stakeholder plan. Complete testing to satisfy regulatory requirements and start establishing track record of materials (vital in establishing new materials in industry), see Appendix H for proposed reference site testing. Early engagement with EA regulator. The above actions may mitigate this risk, however the risk is out of the direct control of the individuals of this project. This risk shall therefore be left as medium.	Medium	Others (transfer beyond Phase 2)
Opportunity to combine with PFAs or GGBS as a powdered mixture	Technical risks	Opportunity: combine with PFAs or GGBS as a powered/slurried admixture.	Low	To be considered in geotechnical review. This may be too detailed and specific a use to attempt at this stage of material development.	Low	Phase 1 - Arup, Costain, University of Edinburgh, Newcastle University

Title	Risk Type	Risk detail	High, Medium or Low Risk Rating (Probability x Impact)	Mitigation Actions	Mitigated Risk (P x I)	Phase 1 member, BEIS, transfer to Phase 2
Infrastructure lifecycle	Monitoring	The typical life expectancy of an infrastructure scheme is lower than the 100 years that is generally considered necessary for a carbon sink to be effective in combatting climate change.	High	Discuss lifespan expectations with pilot-site owner. Include specifications for decommissioning.	Low	Phase 1 - Arup, Costain, University of Edinburgh, Newcastle University
Social impact difficult to quantify	Economic Risk	The social impacts of this project are currently difficult to asses, as depend on many variables.	High	Full review of impact on job creation conducted as part of economic review, please see section 3.3 of main report. Social value has been reviewed in Appendix F.	Low	Phase 1 - Costain
Certification	Technical risks	Risk of multiple certification providers, and confusion on which is preferred.	Medium	Existing biochar certification presented in section 1.2.5 of Appendix B. Certification through existing body not necessarily required so long as regulatory requirements are met and material testing is thorough enough to support the LCA.	Medium	Phase 1 - Arup, Costain, University of Edinburgh, Newcastle University
Infrastructure timeframes	Project risk	It is possible that an identified infrastructure live pilot project's completion may be delayed beyond the 2025 date required for demonstration of the 1,000tCO2/annum target.	Medium	This may be beyond the power of this project to control. Pilot projects will be selected that are considered to have the best chance of succeeding/completing by 2025. Multiple projects should be developed into a pipeline and supported in order to provide resilience against this risk. This risk has been communicated to site owners of the pilot projects and will need to be accepted prior to moving forward with the full pilot project design. This risk has ultimately been mitigated through the deployment at Banwell Bypass, where construction is expected to finish in 2024.	Low	Phase 1 - Arup, Costain, University of Edinburgh, Newcastle University
Certification	Technical risk	Enhanced mineral weathering relies on the transportation of bicarbonate ions to the ocean. It is not static, and it is therefore harder to quantify than carbonation or biochar degradation in the soil. This may make it difficult to certify the sequestration potential of dolerite.	Medium	Develop testing methods that can be used to estimate the rate of enhanced mineral weathering, these are laid out in section 4 of Appendix H and section 5 of Appendix G. The use of a reference site with controlled conditions maximises capture of groundwater from the applied blends, and allows the rate of bicarbonate transport to be directly monitored. A material uncertainty factor of 1.2 has been used when calculating the quantity of quarry fines required for removal, as stated in section 3 of Appendix G.	Low	Phase 1 - Arup, Costain, University of Edinburgh, Newcastle University
Infrastructure project uncertainty	Project risk	The importance of integrating the technologies into a project at an early design phase means that contracts may not have been awarded yet.	High	Honest dialogue with the pilot site owners to understand their level of confidence in their bid. This may be beyond the power of this project to control. Multiple projects should be developed into a pipeline and supported in order to provide resilience against this risk.	Medium	Phase 1 - Arup, Costain, University of Edinburgh, Newcastle University
Dolerite considered as a waste	Planning and permitting	There is a risk that quarry fines may be considered as a waste by regulators. This will hinder its use significantly.	Low	Already sold as product, so the material has purpose and is not classified as waste. Already used in construction.	Low	Phase 1 - Arup, Costain, University of Edinburgh, Newcastle University
Biochar migration	Technical and monitoring risk	If biochar is not integrated securely into soil there is a risk that physical transport may occur and reduce the measurable mass of the in-situ biochar, jeopardising measurable removal.	Medium	Most studies on migration are conducted upon highly active agricultural soils and are therefore overestimates compared to engineering schemes. Integration with quarry fines may provide cementation effect through carbonation. Rainfall and wind effects are easily designed out by incorporating into the soil - not just making a surface application that is typical of agriculture. Migration is prevented considerably by use of pelleted biochar or chipped feedstock. Please see section 2.3 of Appendix I for full review and mitigation of this risk.	Low	Phase 1 - Arup, Costain, University of Edinburgh, Newcastle University
Site contamination at MiM	Technical and monitoring risk	MiM as a fire college testing facility may contain higher than average levels of pyrogenic carbon in the soil. Made ground reported at site presents risk of latent calcium carbonate formation through crushed concrete. Reuse of MiM topsoil presents risk of compromising control plot.	High	Use of imported topsoil from Banwell maximises the validity of comparison between reference and pilot site. Banwell is a greenfield site with limited historical activity (bar agricultural) so imported topsoil carries little risk of this material being present. Baseline levels of PyC content can be established upon material application at MiM.	Low	Phase 1 - Arup, Costain, University of Edinburgh, Newcastle University
Banwell topsoil	Technical and monitoring risk	Excavation not set to start until early 2023 at the Banwell site, risk that topsoil not available for use at Moreton-in-Marsh.	Medium	Site conditions at Banwell are characterised in section 2 of Appendix G so similar topsoil can be imported if necessary.	Medium	Phase 1 - Arup, Costain, University of Edinburgh, Newcastle University

Title	Risk Type	Risk detail	High, Medium or Low Risk Rating (Probability x Impact)	Mitigation Actions	Mitigated Risk (P x I)	Phase 1 member, BEIS, transfer to Phase 2
Quarry fine sourcing	Planning and permitting	Both Clee Hill and Leaton quarry almost exclusively use their quarry fines in on-site asphalt production. Supply is irregular and only in small quantities. This has negative implications for the scaling up of demand, if incorporation into asphalt is typically more popular than stockpiling.	High	Other local quarries have been identified in section 1.5 of Appendix C, so supply can be maintained. Demonstration of value when incorporated into infrastructure schemes may reverse these existing practices.	Medium	Phase 1 - Arup, Costain, University of Edinburgh, Newcastle University
Pyrolysis availability	Planning and permitting	PyroCore has shared uncertainties regarding the availability of their pyrolysis units, so the exact model and location of pyrolysis is as yet unknown.	High	Continuing discussions with PyroCore to understand their uncertainties and limitations. Pyrolysis location set to be at Avonmouth facility, and they have provided the requirements for feedstock testing prior to full-scale pyrolysis in Appendix G6.	Medium	Phase 1 - Arup, Costain, University of Edinburgh, Newcastle University
Pilot site timeline	Planning and permitting	The early stages of the pilot site design means that some information is lacking, for example the precise area breakdown of the site, and the extent of land being acquired for the scheme. Exact placement of the materials on the site is therefore at risk of change, accompanied by the risk of abortive speculative work.	High	Through continuing discussion with the Banwell Bypass design team, information is made available as soon as practically possible. Where they are unavoidable, these gaps have been highlighted clearly within the report. Further detail to be provided in the Phase 2 bid document.	Medium	Phase 1 - Arup, Costain, University of Edinburgh, Newcastle University
Baseline data	Planning and monitoring	The early stages of the pilot site design means that the exact locations of the topsoil that is to be used for the material blend are unknown. The extent to which testing will be possible in Phase 2 when these locations are identified is also uncertain. The strength of the required baseline monitoring is therefore at risk.	High	Discussion with the Banwell team to integrate baseline monitoring requirements as far as practically possible into ongoing ground investigation. This will provide a backup data set should further testing not be possible in Phase 2.	Medium	Phase 1 - Arup, Costain, University of Edinburgh, Newcastle University
Feedstock sourcing	Technical and planning risk	Costing of locally available feedstock with associated planning and environmental permits is not feasible for Phase 1, although a source has been identified. Risk that commercial feedstock is more expensive, driving up biochar cost.	High	Basic costing for commercially available pelleted feedstock has been undertaken and captured in section 1.6 of Appendix B.	Medium	Phase 1 - Arup, Costain, University of Edinburgh, Newcastle University
Material movement	Technical and planning risk	Unbound applications of quarry fines may result in high levels of dust generation, and biochar use in drainage areas may degrade the material faster and increase the amount of suspended solids in egressing waters. This could lower the measurable rates of carbon removal.	High	Avoid the use of quarry fines in unbound applications, carbon removal likely to be lower for these anyway. Monitor particulate and dissolved carbon content in the water of controlled cells at Moreton in Marsh (see Appendix H) to determine if biochar washout is a problem (see also section 2.3 of Appendix I).	Low	Phase 1 - Arup, Costain, University of Edinburgh, Newcastle University
Grass fires at Moreton in Marsh	Technical, monitoring, and planning risk	Large scale fire drills at Moreton in Marsh can spread cinders across the site, which can start small grassfires during long periods of dry weather. This would interfere with vegetation growth measurements and alter the topsoil.	High	Place the monitoring cells upwind of large buildings where fires are started at Moreton in Marsh. Mow the grass if a dry period persists and a large scale fire test is planned.	Low	Phase 1 - Arup, Costain, University of Edinburgh, Newcastle University
Land transfer at Moreton in Marsh	Technical, monitoring, and planning risk	Potential land sale at the reference site may result in the plots being demolished for future building, and jeopardise the long term monitoring potential.	High	Place monitoring cells close to key site assets that are not likely to be sold. Identify areas that are likely to be sold with site manager and avoid them for material placement.	Low	Phase 1 - Arup, Costain, University of Edinburgh, Newcastle University
Disturbance from trespassing	Technical, monitoring, and planning risk	MiM is a site of high interest that is bordered by residential areas, so trespassing is common. Trespassers could possibly disturb materials on the embankments or tamper with any testing equipment left in-situ, compromising monitoring.	Medium	MiM is deploying a radar monitoring system to catch and subsequently deter future trespassers.	Low	Phase 1 - Arup, Costain, University of Edinburgh, Newcastle University
Material stability upon slope	Technical and monitoring risk	Due to the application of materials upon embankments at the Banwell Bypass, there is a risk that if the blend is not adequately bonded with the subsoil a shear surface could form and the material may become unstable.	Medium	The surface of the embankment may need to be scarified to increase the surface area of contact between the applied blend and the subsoil material.	Low	Phase 1 - Arup, Costain, University of Edinburgh, Newcastle University

Appendix J - Cost Plan Supporting Information BEIS

APPENDIX J
ACTIVITY SCHEDULE

Item	Description	Quantity	Unit	Cost	OB %	OB (£)	Total		
A	**PROJECT MANAGEMENT**	1	SUM	£ 862,000	23%	£ 199,000	£ 1,061,000		
B	**PRE CONSTRUCTION ACTIVITIES**	1	SUM	£ 1,219,000	46%	£ 561,000	£ 1,780,000		
C	**CONSTRUCTION ACTIVITIES**	1	SUM	£ 913,000	23%	£ 210,000	£ 1,123,000		
D	**POST CONSTRUCTION**	1	SUM	£ 365,000	23%	£ 84,000	£ 449,000		
E	**RISK**	1	SUM	£ 337,000	0%	£ -	£ 337,000	**£ 4,750,000**	Excl VAT
G	**VAT @ 20%**	1	SUM	£ 888,000	0%	£ -	£ 888,000		

£ 5,638,000 Inc VAT

APPENDIX J
MiM SITE
ACTIVITY SCHEDULE

Item	Description	Quantity	Unit	Rate	Cost	Risk	Potential Risk Commentary	Totals
A	**PROJECT MANAGEMENT**							
	ARUP & Universities	1	sum	£ 283,000	£ 283,000	£ 29,000	10% risk allowance included	£ 312,000
	Costain	1	sum	£ 76,000	£ 76,000	£ 6,000		£ 82,000
B	**PRE CONSTRUCTION ACTIVITIES**							
	ARUP & Universities	1	sum	£ 68,000	£ 68,000	£ 7,000	10% risk allowance included	£ 75,000
	Costain	1	sum	£ 6,000	£ 6,000	£ 1,000		£ 7,000
	Supply of Materials	1	sum	£ 74,000	£ 74,000	£ 7,000		£ 81,000
	Leasing of Land	1	sum	£ 312,000	£ 312,000	£ 26,000		£ 338,000
C	**CONSTRUCTION ACTIVITIES**							
	ARUP & Universities	1	sum	£ 37,000	£ 37,000	£ 4,000	10% risk allowance included	£ 41,000
	Costain	1	sum	£ 91,000	£ 91,000	£ 8,000		£ 99,000
	Testing during construction	1	sum	£ 5,000	£ 5,000	£ 1,000	10% risk allowance included	£ 6,000
D	**POST CONSTRUCTION**							
	ARUP & Universities	1	sum	£ 48,000	£ 48,000	£ 5,000	10% risk allowance included	£ 53,000
	Costain	1	sum	£ -	£ -		Pure contingency figure until Costain amounts received.	£ -
	Testing & monitoring post construction	1	sum	£ 81,000	£ 81,000	£ 7,000	10% risk allowance included	£ 88,000
					£ 1,081,000	**£ 101,000**		**£ 1,182,000**

BEIS (Direct Air Capture and GGR Programme)

APPENDIX J
BANWELL SITE
ACTIVITY SCHEDULE

Item	Description	Quantity	Unit	Rate	Cost	Risk	Potential Risk Commentary	Totals
A	**PROJECT MANAGEMENT**							
	ARUP & Universities	1	sum	£ 491,000	£ 491,000	£ 49,000	10% risk allowance included	£ 540,000
	Alun Griffiths	1	sum	£ 12,000	£ 12,000	£ 1,000	Based on two week slippage on 20 week programme for inclement weather etc.	£ 13,000
B	**PRE CONSTRUCTION ACTIVITIES**							
	ARUP & Universities	1	sum	£ 94,000	£ 94,000	£ 10,000	10% risk allowance included	£ 104,000
	Alun Griffiths	1	sum	£ 430,000	£ 430,000	£ 38,000	Based on two week slippage on 20 week programme for inclement weather etc.	£ 468,000
	Supply of Materials	1	sum	£ 235,000	£ 235,000	£ 46,000	Inflation of raw material costs	£ 281,000
C	**CONSTRUCTION ACTIVITIES**							
	ARUP & Universities	1	sum	£ 46,000	£ 46,000	£ 5,000	10% risk allowance included	£ 51,000
	Alun Griffiths	1	sum	£ 725,000	£ 725,000	£ 63,000	Based on two week slippage on 20 week programme for inclement weather etc.	£ 788,000
	Testing during construction	1	sum	£ 9,000	£ 9,000	£ 1,000	10% risk allowance included	£ 10,000
D	**POST CONSTRUCTION**							
	ARUP & Universities	1	sum	£ 151,000	£ 151,000	£ 15,000	10% risk allowance included	£ 166,000
	Alun Griffiths	1	sum	£ 80,000	£ 80,000	£ 7,000	Based on two week slippage on 20 week programme for inclement weather etc.	£ 87,000
	Testing & monitoring post construction	1	sum	£ 5,000	£ 5,000	£ 1,000	10% risk allowance included	£ 6,000
					£ 2,278,000	**£ 236,000**		**£ 2,514,000**