Greenhouse Gas Removal

Mersey Biochar – Executive Summary

FINAL SUBMISSION

31/12/2021

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1. Introduction

This is the FINAL report for the Mersey Biochar project as part of the BEIS funded Direct Air Capture and Greenhouse Gas Removal programme. The aim of the programme is to research approaches (technological and commercial) to removing CO_2 and greenhouse gases from atmosphere at a cost as low as possible below £200/tCO_2e with a demonstration of reaching over 50ktCO_2e/yr scale by 2030.

The project is undertaken by a consortium of partners including;

- Severn Wye Energy Agency (lead) – community energy organisation and biochar specialist
- Pure Leapfrog (partner) – community energy development and finance
- Pyrocore (partner) – pyrolysis plant innovation and supply
- Vital Energi (s/c) – heat network and energy generation contractor/consultant
- Cheesecake Energy (affiliate) – Technology Provider
- Mersey Forest (s/c) – charity community woodland organisation
- Stobart Forestry (s/c) – woodland and forestry management and contracting/logistics
- Element Energy (s/c) – carbon capture and storage consultancy
- The Environment Partnership (s/c) – GIS mapping and data specialists

This paper acts as an executive summary for the entire project which comprises a technical and commercial feasibility study with multiple components. These are contained in more detailed annexes to this summary document and we have provided a number of these in draft form. The complete suite of documents will be provided in the final draft in December.

2. Executive Summary of Project

The Mersey Biochar project concept has evolved during the feasibility study from that submitted during the application. The core concept of a negative-carbon district heating project remains, and the project will be removing carbon from atmosphere via stable biochar generation. However, unlike in the original application we will not be specifying carbon capture (CCUS) of the flue gas. The rationale is elaborated on in later sections but CCUS is generally not deemed not feasible at this scale in all but very specific (and restrictive) geographical circumstances. The second change was to switch a simple Organic Rankine Cycle power generation technology for a thermal energy storage system.

It is important to the understanding of our proposal to understand that this is not only a greenhouse gas removal or biochar generation concept, but a more complete solution; a carbon-negative flexible heat and power concept. The distinction is important as we are developing a solution to more than just one of the energy transition challenges and to differentiate from other carbon removal technologies.

This 20-page summary report is structured along the lines of the 9 supplemental annexes, the detailed bulk of the report that support it as follows.

In Annex 1.1 **Biochar Generation & Use** we give an overview of the biochars we will generate based on results from pyrolysis tests using our proposed feedstocks. We discuss the suitability of these chars to different applications, use cases and the resulting market potential. Application to land is a possible route but logistically demanding, use in animal feed another good potential, but we have done particular investigation into the potential of use in construction.

The following two sections cover the core technologies of the concept. In Annex 1.2 **Pyrolysis Plant** we discuss the pyrolysis technology that is being designed and would be supplied by partner Pyrocore. Ours is a comparatively large scale fast pyrolysis unit and is being optimised for flexibility and energy recovery, as well as scaled up from 140 to 500 kg/h feed. In the associated annex we describe the scope of supply and provide the engineering drawings. In the second technology paper Annex 1.3

Flexible Power & Heat, we talk about the different options considered for energy recovery and in detail about the chosen technology, a novel Compressed Air Energy Storage (CAES) system. This is a core innovation to our concept that not only creates additional revenues allowing carbon removal costs to be reduced, but also provides valuable services to the decarbonisation of the wider energy system including zero carbon heat and electricity system flexibility and storage.

The fourth paper Annex 1.4 **CCUS Assessment** an assessment of the feasibility of carbon capture, utilisation and storage of flue gas carbon. In the original application we proposed utilising mineralisation technology (Carbon8) as the CCUS to further capture carbon from the process. As part of the feasibility we decided to undertake a study into a wider range of possible CCUS options and pathways. Our determination now is that generally at this scale CCUS is not feasible across all the technologies studied except for a few exceptions 1) capture for transportation and sequestration where plants are located in clusters and 2) mineralisation where plants are located adjacent to alkaline residue sources. These are highly geographically limiting to a concept that seeks scale though multiple UK deployments and whose ethos is to supply community heat and power needs alongside carbon removal, and therefore in general we do not foresee CCUS featuring in community scale biochar and CCUS will not feature in the pilot project.

In the fifth paper Annex 1.5 **Feedstock Strategy** we talk about the feedstocks we consider appropriate for the concept, the sources of the feedstock and the potential local to the pilot and across the UK. Bioresource projects need robust feedstock supply proposals to get built and scaled. We are developing a long term strategy around procurement, partnering and acquisition of local feedstock. Here we determine the sourcing strategy that will enable stable and sustainable procurement for future projects and support diversification and biodiversity.

Annex 1.6 covers a **Social Value, Employment & Natural Capital** assessment, the value of the project beyond the financial. The central tenet of our project is to maximise local value where possible across jobs and environment. The main lever through which this will act via through the sourcing of local sustainable feedstock with value flowing into the local community woodland and agriculture sector. This will support woodland creation and management, creating new green and amenity spaces for people and increasing natural capital, designed by our woodland charity partner Mersey Forest, and the diversification of agriculture and new revenue stream to help farmers to survive.

Annex 1.7 (to be supplied later) covers **Project Economics & Financial Modelling**, here we talk through the financial model and the economic considerations and assumptions that went into this to arrive at the cost of removal.

Annex 1.8 **Market Potential, Carbon Markets and Scaling to 2030** talks through the roadmap to reaching the 50 ktpa removal requirement for 2030. As a small scale concept, our approach is multiple deployments, here we discuss how this can be achieved.

Finally, Annex 1.9 (also to be supplied later) **Pilot Project Proposal** describes in more detail the pilot project location and assembly description of the pilot project, costs and location.

In summary, we have forecast a removal cost of £170/tonne 2020s falling towards £70/tonne 2030s with a clear plan to scale to the 50 ktpa by 2030s. However, as we have stressed ours is more than simply a carbon removal project by providing a number of wider system benefits. **Decarbonising Heat** – the biggest challenge in the energy transition is decarbonising heat, our concept can deliver zero carbon heat, which will be highly beneficial to the energy system. We will be able to provide heat below the cost of low-carbon alternatives. **Energy Storage and Flexibility** – enabling the increased penetration of intermittent renewable power generation onto the energy system is going to become increasingly challenging over the next 10 years. Technologies that can support energy system flexibility will be highly beneficial to the energy transition. **Community or Municipal Ownership** – we see an increasingly important role for place-based activity in energy, particularly involvement from community and municipal actors. Future projects that we promote will be created under alternative models of ownership (e.g. Bencom & C.I.C).

Each site we develop would both displace fossil fuel, and provide critical flexibility and energy services to a decarbonising power system. This is in addition to meeting the core aim of this competition, which is to remove carbon directly from the atmosphere. We will also be generating a valuable product in the form of biochar.

3. Biochar Generation & Use

As part of the project's attempts to maximise the benefit of the production process a selection of feedstocks were identified which are either well established (woodchip), marginalised (Whole Tree Chip(WTC)), short rotation coppice (Willow) or developing (Miscanthus and eucalyptus). As well as being in differing phases of availability and sustainability all carry differing properties which impact the characteristics of the biochar produced.

Biochar was produced at both 400°C and 800°C for each feedstock to provide equivalent data for both a slow and fast pyrolysis process.

Analysis was completed by an accredited laboratory of these biochars to the same levels required for European Biochar Certification, one of two existing keys standards recognised globally along with the International Biochar Initiative. In all cases the biochar produced met the highest level of compliance and therefore under guidance associated with the accreditations could be viable for use as, animal feed additives, organic agricultural application, standard agricultural application and material applications.

Parameter	Regulation/Standard	Compliance
Emissions, inc. particulates and PFAS	DIRECTIVE 2010/75/EU	✓
Destruction of Pathogens	DIRECTIVE 86/278/EEC	✓
Heavy Metals: As, Cd & Hg	• European Biochar Certification • International Biochar Initiative Certification	✓ Class I-IV ✓
Heavy Metals: Cr, Cu, Pb, Ni & Zn	• European Biochar Certification • International Biochar Initiative Certification	✓ Class I-IV ✓
Organic Contaminants, inc. PCB and PFAS	• European Biochar Certification • International Biochar Initiative Certification	✓ Class I-IV ✓
Destruction of Micro/Nanoplastics	No comprehensive Law: • DIRECTIVE 2010/75/EU • REGULATION (EU) 2019/1009 - Fertilising Products Regulation	✓

It is also important to note that in all cases the feedstocks are products of the agricultural and forestry sectors and are listed as approved feedstocks for application to land without requirement for permits or waste licences.

3.1. Viable Char Uses

There are many reported uses of biochar across a wide range of sectors, notably in agriculture, horticulture, industrial production and construction. The characteristics of the biochar are key in determining the best use of the biochar. Very low contaminants such as heavy metals and Polycyclic Aromatic Hydrocarbons (PAHs) are required in biochar's for use in agriculture and horticulture whilst key characteristics such as stability, specific surface area and cation exchange are key in biochar's for use in construction and agricultural fertilisers.

Both the Willow and WTC 800 biochars analysed have significantly increased rates of plant available Phosphorus and Potassium both of which are valuable and key components of fertilisers and compost. Cost of fertiliser is increasing at present, and it is likely the market for biochar fertilisers will emerge in the agricultural sector to not only increase soil carbon but to offset existing fertiliser costs.

The Miscanthus biochars have different characteristics, with a higher ash content and reduced plant available nutrients. As such they would not be as suitable a feedstock for agricultural application to land directly. However, Miscanthus and its biochar have excellent absorption qualities which make it suitable as an animal feed additive. Research also suggests that animals such as sheep and cattle will ingest more biochar if it is of a similar nature to its existing feedstock, in this case grass and straw, when compared against pelleted animal feed biochar additives.

A major challenge however to the scaling up of our model is the existing limits on application of biochar to agricultural land with a limit of up to 1 tonne of biochar per hectare over any 12 month period. The average farm in England is estimated to be 87 Hectares. As the 1 module unit will produce in the region of 680Tonnes of biochar per annum this would require in the region of 8 farms to spread biochar on all their land every year to be able to utilise the available product.

Likewise, for animal feed additives only small quantities are required. If an average UK dairy herd of 143 cows consumed 500g per day of biochar additive this would equate to approximately 26 tonnes per annum assuming and all year-round diet. This would require in the region of 26 dairy farms to meet the pilot's requirement.

With both these products there is potential for strong market demand in the future however when considering the requirement to scale the operation up to 2030 targets this would require a significant increase in demand and continuing low uptake of production in the UK, neither of which can be guaranteed, with the latter expected to be highly unlikely.

Both agricultural and horticultural markets offer significantly higher value per tonne of biochar with the market currently established in the region of £600 - £800 per tonne dependent on the product. However, this is not a stable market and without changes to regulation and increased uptake in the sector could crash in value.

Therefore, as part of the pilot process we are developing a key partnership to utilise the biochar in the sustainable housing sector, in particular local, community and social housing. We have developed relationships with both a local community run housing scheme and also a large-scale concrete construction firm in order to pilot and prove concept for bio-concrete products and bio-plasters suitable

Masonry Uses			
Product	***Type of biochar***	***Quantity of biochar***	***Replacement***
Cement fly ash blocks	Corn stover	2-4-6-8% 550 °C	Filler material
Cement paste and mortar composites	Wood chips	2wt% 700°C	Filler and substitue for cement powder
Cement	Rice husk and bagasse	0-5-10% 700°C	Pozzolan
Eco friendly building material red clay	Rice husk	2.5-5.7.5-10- 450°C	Filler material
	Coconut shell	2.5-5.7.5-10-800°C	Filler material
	Bamboo	2.5-5.7.5-10-1000°C	Filler material
Masonry joints	wood ash	10-20-30-40-70-100%	Lime mortar

for use in all forms of construction. Building and construction are responsible for 39% of all carbon emissions in the world (Global Status Report 2017). Therefore, reducing the number of carbon emissions by using sustainable materials could have a significant reduction.

Detailed analysis of the science behind this concept is provided in the full report (Annex 1.1), however the tables above and below provide an overview of the existing scientifically proven uses of biochar in the construction sector.

The UK cement industry produces in the region of 9 million tonnes per annum. At an average application rate of 5% biochar this means the industry could potentially sequester in the region of 450,000 tonnes of biochar per autumn, equivalent to 661 of our pilot units.

In addition, we are looking to work with Warrington Council during the pilot to supply biochar for addition to asphalt for their highways and pathways management. Again, detailed analysis of the science behind this concept is provided in the full report however the table below provides an overview of the existing scientifically proven uses of biochar in Asphalt products.

Asphalt Uses			
Product	***Type of biochar***	***Quantity of biochar***	***Replacement***
Asphalt cement	Switchgrass	10wt.%	Activated carbon as asphalt binder
Asphalt modification	Crop straw	6%	Bitumen addititve
Asphalt binder in pavement	Mesua ferrea seed cover waste	0-5-10-15-20%	Asphalt extender (Bitumen)
Asphalt mixture	Switchgrass	up to 10% 400°C	Binder
Petroleum Asphalt	Woody biochar	2-4-8% tested- 4% best	Modifier for asphalt binder
Removing VOC from asphalt	Pig manure- Waste wood- Straw **Waste wood** best adsorption performance	2-4-6-8% 500°C	Remove Alkanes, PAHs and sulphide compounds because of its carbon negativity and porosity
Ashpalt for paving	Cypress waste wood (Sawdust)	5% 500°C	Bioasphalt replacing petroleum asphalt

In all these applications it is expected that a value of £250 - £500 per tonne is achievable in both a sustainable and long-term market without risk of fluctuation or variations of the agricultural sequestration methods.

The pilot will aim to demonstrate that the quantity of biochars produced could easily be sequestered into these markets once scaled to the required 2030 levels and also provide the industry confidence in the research by developing real industry products in the UK.

4. Technology Overview

The Mersey Biochar concept is a combination of core technologies to create a negative carbon community scale flexible power and heat process. The vision is that small scale biochar processing facilities would be connected onto communal and district heat networks, decarbonising heating and providing flexible dispatchable power into the grid. Therefore, the process concept not only removes carbon from atmosphere, but critically it also enables decarbonisation of the energy system. There are three main technology components to the concept:

Pyrolysis Engine - The biochar generation pyrolysis technology designed and supplied by Pyrocore

Energy Capture/CAES Technology - The flexible energy and power storage CAES technology

Energy Centre & Heat Network Infrastructure – the balance of plant and piping infrastructure that distributes the heat

4.1. Pyrolysis Technology

N.B. The report of the pyrolysis plant that *Mersey Biochar - Feasibility Report - 1.1 Technology Pyrolysis Plant* contains significantly more detail on the technology that we provide here. That report contains a detailed description of the process, the equipment scope of supply, biochar testing methodology and the results of a series of tests and preliminary technical drawings of the new equipment.

Partner Pyrocore is the designer/supplier of the pyrolysis plant. The pyrolysis plant is the heart of the negative carbon community energy project. It generates the biochar from biomass feedstock providing negative emissions, as well as providing additional decarbonisation potential and revenue streams in the form of low carbon energy. Pyrocore has a track record of supplying smaller (150 kg/hour feedstock) pyrolysis systems in to waste management use cases. For this project Pyrocore has been engineering a biochar optimised solution that will maximise both the biochar and energy yield. The system is also being scaled up to 500kg/h (the pilot project capacity) and a larger 1,000 kg/hour version is being planned which will further reduce CAPEX costs in the future.

The engineering challenge of the pyrolysis plant is threefold; firstly, to maximise the yield of durable and stable biochar, secondly to maximise the yield and value of by-product energy generation, and finally to lower to cost of supply, and we discuss these here. Further detail on plant performance can be seen in section on Heat Balance Diagram of the Annex 1.2 pyrolysis report.

Biochar Generation – the unit is fast pyrolysis type but can operate and modulate easily between 400°C -800°C. The intention would be to operate the unit at 800°C the majority of the time, this maximises the unit throughput, the carbon capture in char yield (see table 1) and the energy generation. In the summer months when less energy is useable we have the option of de-rating the unit and operating at 400°C.

Each unit will generate 87.5 kg/hr of biochar with a carbon-in-char value of 93% equating to 81.7kg/h of carbon (see table 1). This equates to a CO_2 removal rate of 300 kg/h and over the circa 7800 operating hours we forecast per year around 2,400 tonnes per year of carbon removal for each pyrolysis unit that is installed. In section 11 we discuss our approach to scaling to the 50ktpa required by 2030.

Energy Performance – the pyrolysis process under which biogenic material is heated generates a syngas composed of hydrogen, methane, carbon monoxide and dioxide, oxygen, tars and other minor compounds. This gas has a moderate calorific value and is combusted in the thermal oxidiser releasing around 1.8-2 MWth of heat energy. Around 20% of this is used to maintain the pyrolysis process (self-sustaining), the remaining heat equating to around 1.5-1.7MWth is a by-product to be captured and used. The heat balance below shows this process. The heat is to be recovered in the Compressed Air Energy Storage (CAES) technology stage as described in the next section under energy technology.

Cost Reduction – the existing Pyrocore technology is optimised for waste pyrolysis for incineration operation and is sized at around 140kg/h of input material. As part of this project the technology is being re-engineered and optimised for use with biomass feedstock and scaled up. The primary change is the removal of the Waste Incineration Directive (WID) compliance standards, this has reduced the size and cost of the oxidation system and the flue gas clean-up/emissions handling and control system.

Pyrolysis Parameters (per unit)

Operational Temperaure		800
Feedstock Rate	kg/h	500
Char	%wt	17.5
Soot	%wt	0
Water	%wt	6.8
Tars	%wt	10
Syngas	%wt	65
Char	kg/h	87.5
Soot	kg/h	0
Water	kg/h	34
Tars	kg/h	50
Syngas	kg/h	325
Carbon in Char		
Carbon in Char	%wt	93%
Carbon in Char	kg/h	81.7
CO2 : C	ratio	3.67
t-CO2/t-biochar	ratio	3.43
CO2 removal	kg/h	299.81
CO2 removal	tpa	2318.0
Annual Char Output	tpa	676.5

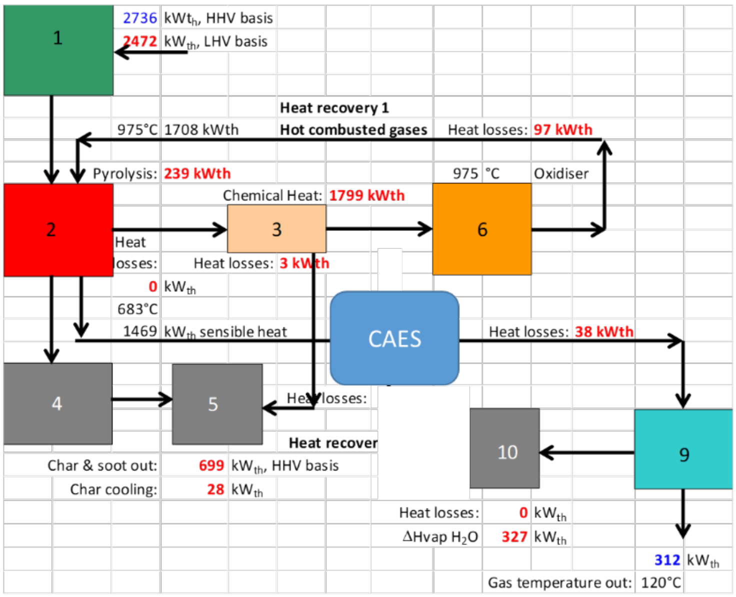


Table 1 - Pyrolysis parameters

BOX: Feedstock is received via the kiln hopper (Stage 1) and is fed via screw auger through the pyrolysis kiln (Stage 2) where pyrolysis takes place. Hot gasses are released from biomass and passed through a cyclone filter (Stage 3) where any char particles are removed to storage (Stage 5). At the same time the then fully pyrolised solid material in the kiln is not fully converted to char. It is cooled (Stage 4) before passing to storage (Stage 5). The now filtered 'syngas'is fully combusted with additional air in a thermal oxidiser (Stage 6), and the high temperature gas exhaust is passed over the kiln cylinder to self-sustain pyrolysis (Stage 2). Exiting the outer sleeve of the kiln the cooled hot gas is fed through the energy recovery unit (the CAES system or the heat exchanger), before passing through a final filter (Stage 9) and to stack (Stage 10).

Within the annex 1.2 the pyrolysis technology and process is described in more detail along with heat balances. The equipment scope of supply is also provided along with the preliminary technical drawings. We have also included there the pyrolysis testing methodology and test results that were described in previous sections.

TRL - At present the Pyrocore pyrolysis technology is at TRL 7/8 for this scaled up biomass optimised unit. The technology is commercially viable for industrial and medical waste processing but requires re-engineering to allow commercial operation when aiming to generate a biochar for a carbon removal market.

4.2. Flexible Power & Heat Technology

See A*nnex 1.3 Power and Heat Technology* for more detail on this section.

The pyrolysis plant will generate the carbon removal through biochar generation. A by-product of the process is a chemical energy in syngas that is converted to heat in the oxidiser with a heat output of around 1.4-1.7MWth (depending on the feedstock CV and dryness). This heat is carried in a fully oxidised flue gas at a temperature of around 680 Celsius.

Working with Pyrocore we undertook an assessment of different options around how best to utilise the energy arising from the pyrolysis process. This assessment considered available and emerging technologies and the revenue streams and markets that they operated within (see below). The assessment is included as an annex to the main report Annex 1.3.

Markets, Revenue Streams & System Benefits

When considering how best to utilise the energy we started by considering the markets and revenue streams both that exist today and that will exist in future as deployments increase. The values of these markets and their commodities will evolve over time some becoming less important and some more important. We will cover this in detail in section 9.

With the technologies that we have specified in the flexible power and heat approach including the heat network and compressed air energy storage system, we are able to access the following revenue streams:

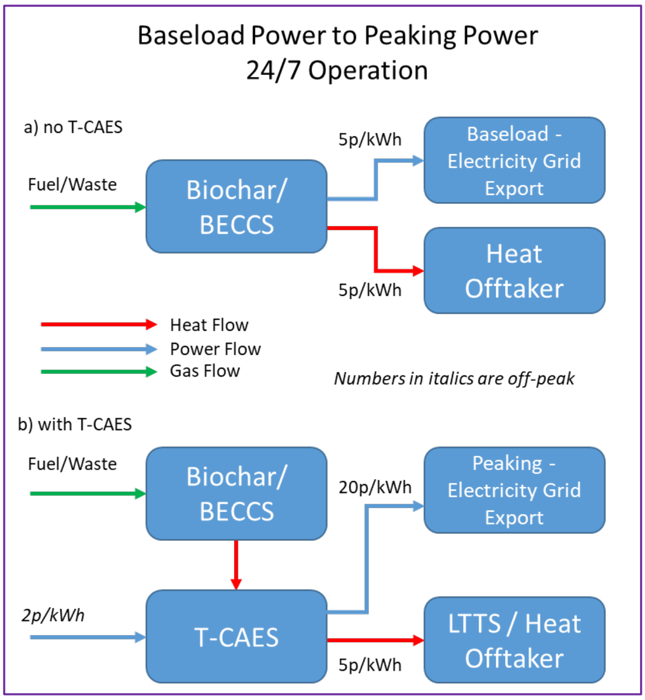
- **Heat Energy Sales** – the sale of heat at around 80C into networks for space heating and cooling. The main revenue stream from the project will be the sale of zero-carbon heat into a network to supply a communal/district system. Maximising the utilisation of heat output is key to economic viability. We believe we can achieve between 60%-80% of heat offtake depending on site type.
- **Energy Arbitrage** – buying in and storing electricity at low market price, exporting and selling at high prices and capturing the arbitrage value. This revenue stream is the second biggest available to us through the CAES energy system. It is important to not, this this approach is technically the storage of power rather than generation of power (the two streams below) in order to target much more favourable prices. The system captures the heat and converts it to power, in combination with compressed air (charged using off-peak grid electricity) to deliver the same amount of electrical power but over very specific, and more systematically useful (and therefore more revenue generative) timeframe.
- **Baseload Electrical Power Export** – the sale of zero carbon electrical power into the grid (or offsetting of import) at baseload (i.e. 24 hrs a day) and sold at baseload power prices.
- **Peaking Electrical Power Export -** the sale of power during peak periods when power process is high, usually occurring weekday evenings, but likely to be more frequent and less predictable as the energy system transitions to renewables.
- **Ancillary Services** – power generation systems can supply certain services to the electricity grid including frequency support, operating reserve and the emerging requirement of system inertia. Our project would be well placed to supply inertia, although its value is not yet established.

This is a key differentiator of our approach to other projects. Specifically using pyrolysis to remove carbon directly from the atmosphere gives rise to particularly well aligned additional low carbon energy opportunity, leveraging its effect yet further. This concept supports the wider energy decarbonisation objective by supplying zero carbon flexible and dispatchable power and heat to the energy system. It also provides grid services that supports the deployment and penetration of more intermittent renewables.

The need for such capabilities across the energy system are highlighted throughout UK Government[1] and Ofgem[2]. Alternate options such as DAC and BECCS could add challenges to the system through their operational inflexibility.

Compressed Air Energy Storage (CAES)

The preferred option for the energy recovery technology is Compressed Air Energy Storage (CAES) technology. Unlike some of the other technologies reviewed, CAES is not an electrical power generation technology per-se, but a power storage technology. Energy is stored as potential energy in the form of compressed air. When deployed in combination with thermal plant like pyrolysis, the heat is used to improve the energy storage efficiency, this stands it apart from traditional BECCS system that use heat to generate power typically using steam turbine, or Allam cycle.



Rationale - The motivation behind this approach considers the relative value of the commodities produced; future baseload power prices will be lower than those today as very low marginal cost renewables are deployed onto the grid. Conversely market price volatility will greatly increase owing to the intermittency of those same renewables, this creates an opportunity for power that can be concentrated to export at peak times, or for solutions that import during low power prices and export during high power prices.

This is the approach we will take utilising a thermally driven CAES system, we will switch power export from baseload (typically 5p/kwh) to peak power (arbitraging at around 18p/kwh).

The CAES Technology

The following section describes the function of the process flow diagrams below. The main components of the system are:

- **High Temperature Thermal Store (HTTS):** stores the high grade heat from pyrolysis
- **Low Temperature Thermal Store (LTTS):** stores the low grade heat of compression
- **Compressed Air Store:** stores the air from compression
- **Generator/Motor:** G alternator that operates as a generator and motor
- **HP/IP/LP machines:** diesel engines converted to act as compression/expansion machines
- **Heat Exchangers (HX):** to extract heat during compression, introduce heat during expansion

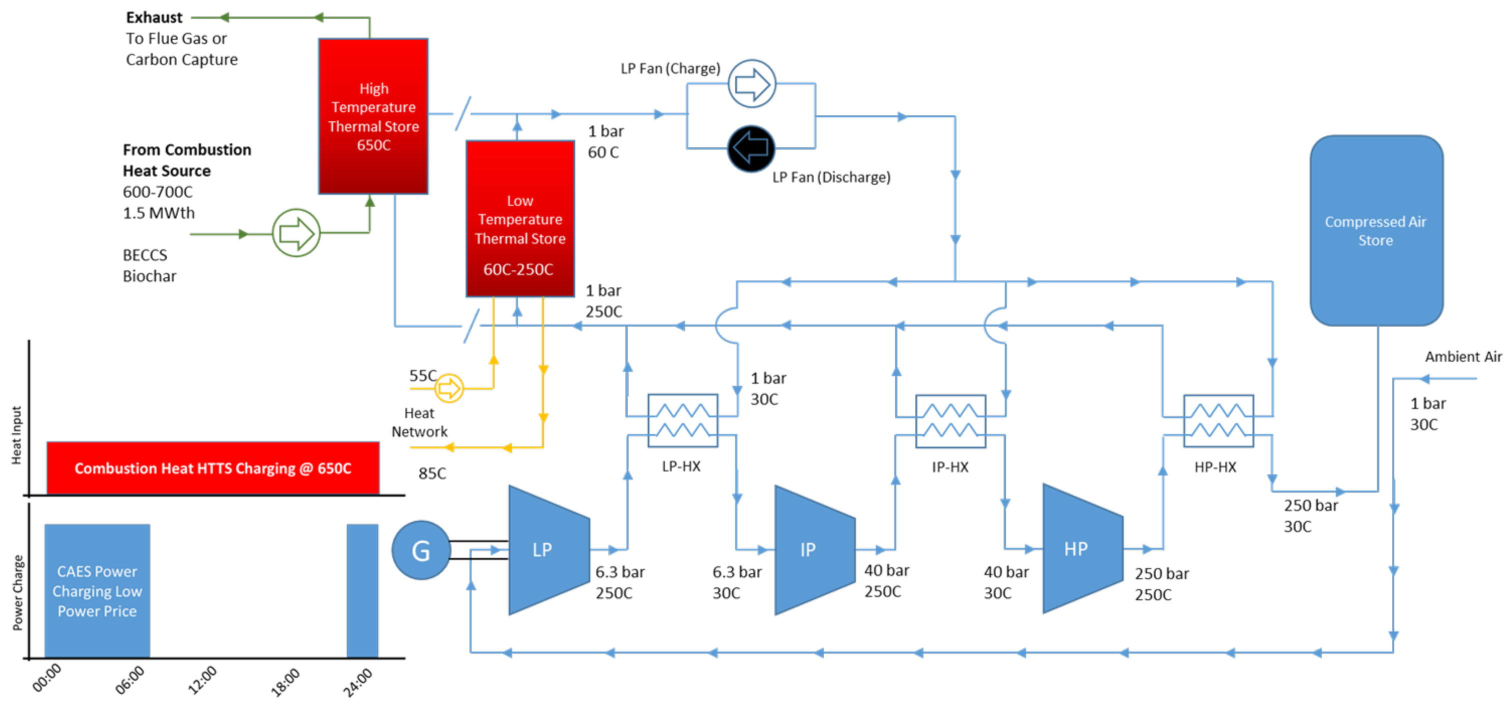
[1] Energy White Paper - https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/945899/201216_BEIS_EWP_Command_Paper_Accessible.pdf

[2] Transitioning to a net zero energy system Smart Systems and Flexibility Plan 2021 - https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1003778/smart-systems-and-flexibility-plan-2021.pdf

Charging Cycle:

The charging cycle occurs during low grid power price periods, when renewables are abundant, power is imported from the grid. The alternator (G) drives the HP/IP/LP machines compressing atmospheric air from 1 bar to 250 bar (high pressure). As the air is compressed, the heat from compression is exchanged into a separate circuit and stored in the LTTS at around 200C. The air is stored in the compressed air tank.

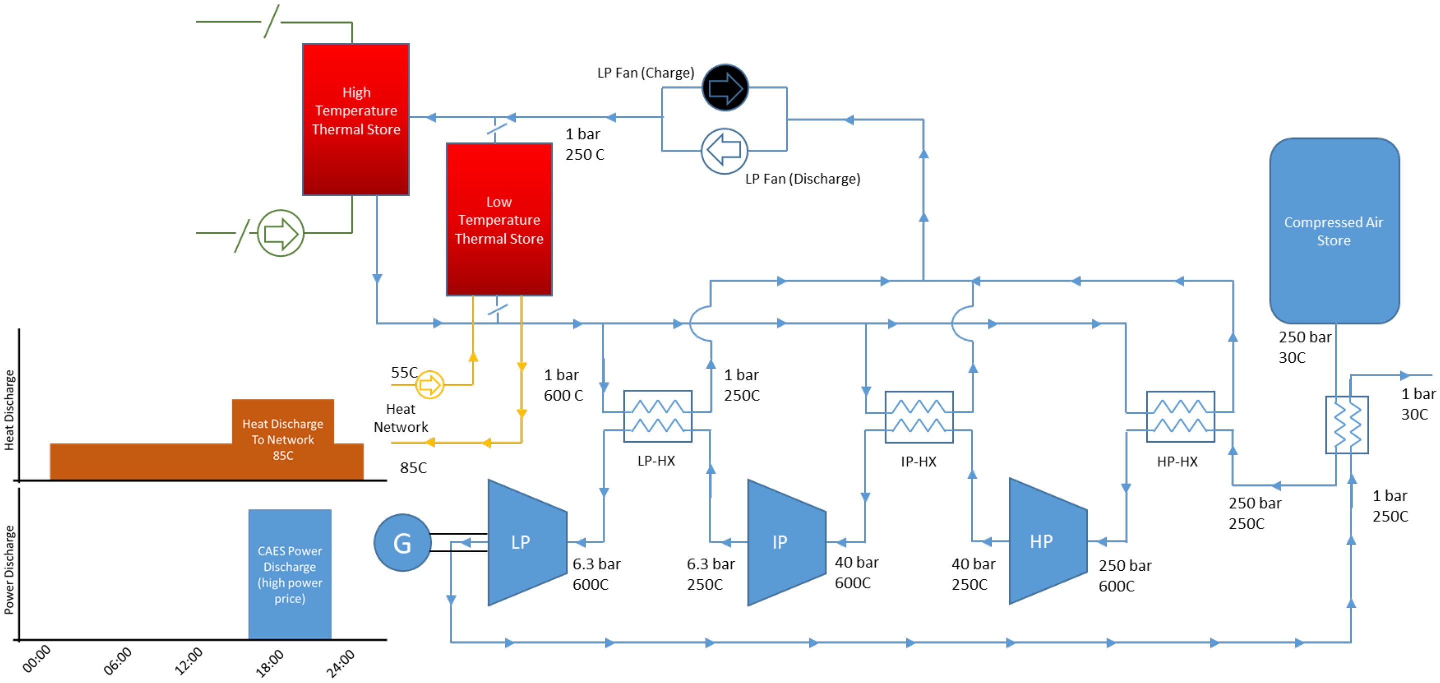
CAES: Charging - Utilising Baseload Waste Heat from Combustion



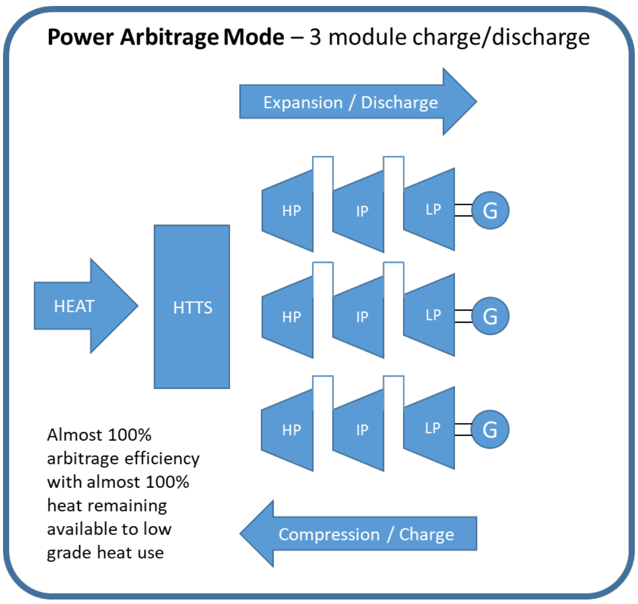
Discharge Cycle:

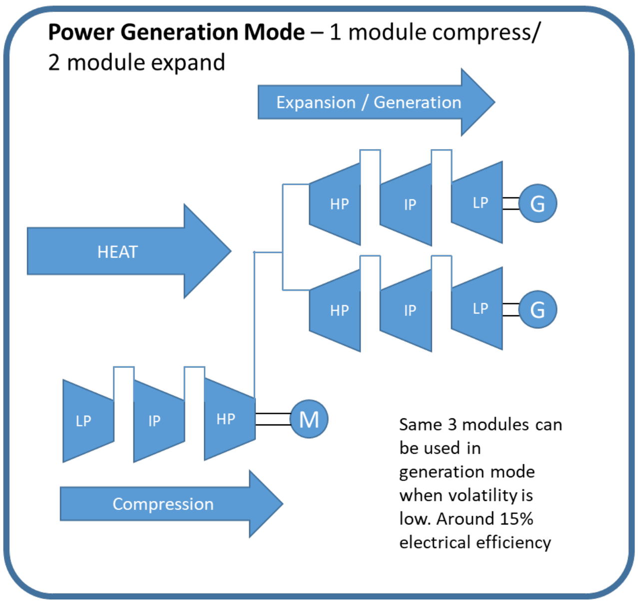
The dis-charging cycle occurs during high grid power price periods, when renewables are offline, power is exported to the grid. In the discharge cycle the CAES effectively reverses. The high pressure 250 bar compressed air leaves the store and is firstly recouperated to 250C and is then heated to 600C with heat from the HTTS. This 250 bar/600C air is then expanded in the HP machine, reducing to 40 bar and 250C. The air is then heated in the second heat exchanger to 600C again and expanded in the IP expander. A third heat exchanger heats again before entering the final LP expander. The completely expanded air is then passed through the recuperator before exhausting to air.

CAES: Dis-Charging - Peak Power / Local Heat Network Demand



System Flexibility: Power Arbitrage vs Power Generation Modes - The CAES system can also be operated in Power Generation Mode, generating baseload, as well as the Power Arbitrage Mode enabling peak load export. Baseload operation would be less preferable given the market prices for baseload would be much lower, however in the event that either the CAES system became fully charged or completely depleted, the system could switch to generate and bypass storage. In this configuration for a multi-module system, 1 x module would operate as a compressor while 2 x modules would act as expanders, with heat energy introduced in the interface.





5. CCUS Assessment

See Annex 1.4 CCUS Assessment for a detailed report on the feasibility of CCUS to the project's flue emissions.

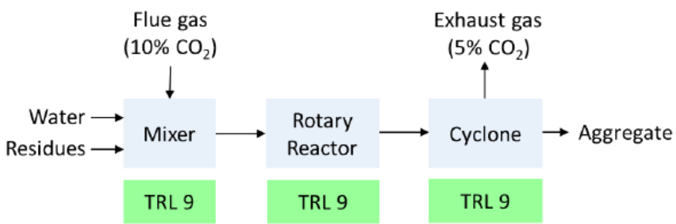
The main element of carbon removal the project is concerned with is the carbon content of the biochar. This content is discussed briefly here and in more detail in the section on Life Cycle Assessment and Biochar Use Cases. However, around 65% of the CO2 removal potential lies within the carbon capture of carbon in the flue gases (syngas or combusted flue gas) downstream of the pyrolysis unit.

The CO2 emissions from each pyrolysis unit in flue gas will be around 15 tonnes/day (5kt/year). This flow rate is around two orders of magnitude below what is traditionally discussed in carbon capture, and this scale challenge presents the single major problem to CCUS deployment on pyrolysis-CHP units of this kind. The challenge is two-fold;

1. Firstly, there is the scale challenge of carbon capture, at low flow rates the CAPEX cost of installations become disproportionately large, increasing the cost per tonne captured
2. Secondly, with only small amounts of CO2 captured the disposal routes available become more limited and those that remain are costlier.

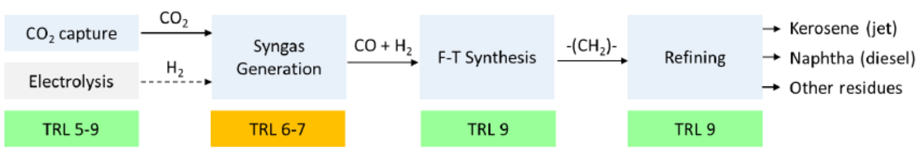
We studied 8 CCUS 'pathways', from 'do nothing' through various utilisation (circular carbon economy) options and capture for geological sequestration across the 4 likely geographical contexts. We down selected these options to 3 for detailed discussion and modelling, namely:

1) Mineralisation



Mineralisation uses alkaline residue in flue gas to mineralise CO2 into saleable aggregates. It is a form of permanent sequestration. CO2 can be captured directly from flue gas. Technology is proven at TRL9.

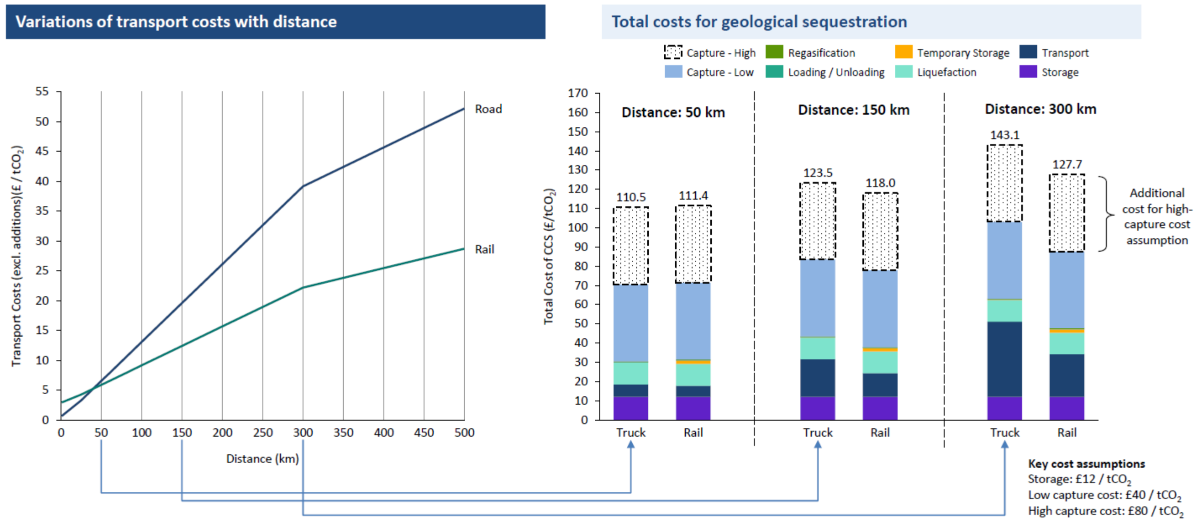
2) Synthetic Fuel Production (via FT Synthesis)



Synthetic fuels are a carbon neutral product (CCU). The process combines a series of chemical processes at various stages of technical advancement. The process is generally undertaken at scales several orders of magnitude larger than those that could be accomplished on a small biochar site. The viability of this option increases over time as we add additional sites. Additional sites will allow for more efficient aggregating of output, to sell as a raw product in to such a process.

3) Geological Sequestration

Capture for geological sequestration is a realistic possibility with capture, transport and storage costs from a flue gas projected as being within the tolerable range between £70-£100/tonne removed for vehicle based transportation where sites are within 50km of a CCUS cluster or other sequestration site interface (see below). Above this range, at this scale CO_2 transportation costs are prohibitive.



Conclusion

Our conclusion is that CCUS is not currently a feasible option for the community district heating model that we are proposing except in very limited geographical circumstances.

- CCS via mineralisation to generate aggregates is a viable option. However, limitations on the supply of residues and the mass of these materials mean that proximity to source and durability of source is highly important. The mineralisation technologies are generally proven (TRL9) and could be added relatively easily with low technological risk to future projects.

- CCU via synthetic fuels presents a huge potential market but is unlikely to be compatible with Mersey Biochar's community CHP approach until scale and number of sites increase. This provides the financial model with additional upside potential in the future.

- CCS via capture and geological sequestration is a feasible option for sites in relative proximity to storage sites (<150 km) via truck, at costs potentially below £100/tonne, with some projections suggesting £70/tonne possible. The ultimate viability will depend on the evolution of capture costs at small scales.

There are existing viable options for CCUS from small scale sites such as pyrolysis, but there remain some constraining factors until there is greater penetration of this approach. Nevertheless, there remains a significant opportunity for neutral and negative carbon capture from pyrolysis units.

Therefore, we will not be proposing the demonstration of CCUS on the pilot project as part of Phase 2. Our focussed aim will be the successful demonstration of the removal of GHGs via a biochar process, the utilisation of the resultant heat for space heating via a heat network, and the production of zero carbon energy and grid services. The routes more than meet the ability to scale to the removal of 50kt/yr at a price that is affordable.

6. Feedstock Strategy

A robust feedstock strategy is critical to bioresource based projects and so we engaged forestry and logistics partner Stobart Forestry and community woodland organisation Mersey Forest to develop a long-term strategy for feedstock supply for the pilot and future projects. For detail refer to *Feedstock Strategy Report Annex 1.6*, and also *Technology: Pyrolysis Plant Annex 1.1.2* as part of the pyrolysis technology report where the feedstock test run results are covered. Our approach is to develop a flexible feedstock strategy that considers:

1. **Feedstock Flexibility** – Our solution will be designed to be feedstock flexible across the range of identified sources. This ensures our procurement can fit into a range of contexts and encourage biodiversity where land use change occurs.
2. **Local Secure & Stable Procurement** – the key to success for any bioresource project is secure, stable and price certain feedstock supply. Without this, attracting investment in a project that depends on such an input is very difficult and operationally challenging. By partnering through long-term contract or acquisition this risk is effectively underwritten, and local economy is created.
3. **Maximising Local Benefit & Job Creation** – local procurement means local value retention, providing new revenue streams to local natural capital. The value of the project can be appropriately distributed between the plant and its resources.

We are proposing 2 feedstock source categories as follows:

Woodland Creation & Management Creation of new permanent woodland/ bringing existing forest cover into active management (not felling) and production, our primary source	**Energy Cropping** Land use change of vacant and marginal land to energy crop cultivation/ new established energy crop plantations where farming practices are un-economic or require diversification
• Maximises biodiversity gain • Improves natural capital, flood alleviation • Contributes to nature based sinks target • Species/Yield – broadleaf species yielding circa 3-10 t/ha/yr	• Maximises yield • Facilitates agricultural diversification • Species/Yield – Miscanthus, willow (SRC) and eucalyptus (SRF) yielding 8-30 t/ha/yr

There are around 600,000 hectares of unmanaged woodland in the UK and the Government is promoting planting that will also require management, this will be the primary source. This equates to around 800,000tpa that could be recovered and the Mersey Biochar process will be uniquely able to utilise this material and provide a key revenue stream to these operations creating hundreds of new jobs and improving the environment.

Each pyrolysis module would require around 4,000 tonnes/year of feedstock (assuming around 7,900 operation hours), equivalent to 275 to 550 hectares for the energy crop and woodland sources respectively.

We have considered 5 feedstock sources for the project, some of these have been tested at the Pyrocore demonstration facility. All feedstocks would be sourced local, never imported, the projected costs are given below:

- Virgin Woodchip - £75-£83 per dry tonne
- Whole tree chip/arb arising - £50-£65 per dry tonne
- Miscanthus - £65 per dry tonne
- Short Rotation Coppice (Willow) - £65-£70 per dry tonne
- Short Rotation Forestry (Eucalyptus) - £75-£83 per dry tonne

A central tenet of the project is the concept of working in collaboration with the supply of feedstock, this includes working with local woodland landowners to better manage and make more productive their undermanaged woodland, or working with agricultural landowners to explore diversification of parts of their land into energy crop production. A small community based biochar project with a flexible feedstock strategy is uniquely placed to utilise these sources and to avoid competition from large procurers like BECCS plants such as Drax. Market prices for biomass fluctuate significantly over time making financial modelling challenging. We have used the prices given above on the basis of these being sufficient to support a given operation for energy cropping or woodland extraction, we have provided example cropping economic models in the full report. These prices for tree chip, Miscanthus and willow are being seen today and should improve as technology advances and innovation work is underway by stakeholder partners Rickerby Estates (willow) and Terravesta (Miscanthus).

For the demonstration site we have estimated that there is an availability of 200,000 tonnes per annum of our target feedstock source from undermanaged woodlands. The feedstock is currently actively sourced by our project partner Stobart Forestry and they would simply be expanding their operations. We can also look to work with our host site partner United Utilities about the possibility of sourcing feedstock from existing woodland/new planting on their wider estate. We also estimate that there is a potential of up to 27,000 tonnes/year from new established biomass on just 1% of the land within a 50-mile radius of the pilot site.

7. Natural Capital, Social Value & Employment

See Annex 1.7 – Social Value, Employment & Natural Capital for a complete review of the non-financial and wider economic benefits of the project discussed here and the complete natural capital assessment.

Employment

Depending on the size of a given site, and therefore the feedstock requirement, we expect the creation of 2-3 FTE roles per site across roles from local feedstock supply, site O&M, and biochar export and use.

Job Description	Number FTE
Plant Operation - Site Operative	0.25
Plant Operation - Asset Management	0.25
Feedstock - Forestry Work	0.50
Feedstock - Logistics, processing, delivery	0.44
Biochar - delivery and use	1
TOTAL per single module site	2.43
TOTAL at 50 ktpa CO2 removal	35-40

For the scaled up operation to hit the 50,000 tonnes/year of CO_2 removal requiring around 16 sites we can project around 35-40 roles being created.

Alternative models of Ownership

As a project we are keen to promote community energy/cooperative energy (RESCoops) and alternative models of ownership for community biochar energy projects. Community ownership is ideally suited to these projects especially when it comes to forming links with local woodlands and landowners. The community ownership model is motivated to promote local benefit, environment and jobs above profit for owners. Other advantages include:

- Direct benefit to and prioritisation of local community (eg employment, environment)
- Take direct local energy action through energy efficiency/fuel poverty programmes
- Keep money in the local economy (local resources, local labour, local investment)
- Foster social acceptance for renewable energy
- Enable wider participation and investment in decarbonisation

A number of alternative ownership models exist including community benefit society (BenCom), cooperative, and Community Interest Company (CIC). Our preferred incorporation is to use CIC.

Natural Capital

The primary natural capital benefit of the project is through the provision of new revenue streams that can support the maintenance and management of un-managed woodland and the planting of new woodland through the procurement and use of otherwise un-utilised waste residue feedstock.

In terms of climate change mitigation, the development and maintenance of local woodland can sequester carbon, provide low carbon material, provide areas for recreation, improving health, and reducing car travel. In terms of adaptation woodland can support in cooling the local environment especially in urban areas, reduce flood risk, manage water resources and, reduce soil erosion and support bio-diversity.

A detailed natural capital assessment of the benefits of increased woodlands to the Warrington area has been completed by Liverpool JM university as part of the same Annex 1.5 report. This supports the objectives of the local woodland charity organisation, and our project partner Mersey Forest who have developed a long term plan to expand woodland cover and open up its benefits tot the local community.

8. Project Economics

Project economics and financial modelling are covered in detail in Annex 1.7.

The aim of the project is to develop a technology concept that can achieve a cost of carbon removal at below £200/tonne in 2030. The cost of removal is derived through discounted cash flow financial modelling over the period of a representative project's life. Modelling combines the capital costs, operational costs and finance costs with the revenues that the project will produce over life to derive a cash flow to service an investment. This cash flow needs to achieve an Internal Rate of Return (IRR %) that surpasses what is through to be a reasonable investment hurdle rate when considering the risk of the project.

The financial model will be performed on a representative future project at years 2025 and 2030, we test on different dates at the cots and market process are projected to differ over time. All other things being equal, the cost of removal is derived by altering the carbon price until the project IRR passes the hurdle rate. The hurdle rate we are targeting is 8-9% post tax IRR.

options.

		2025	2030s
Carbon Removal Price:	£/tonne	£170	£70
Total Revenue	£	£27,559,636	£23,004,419
Carbon Removal Revenue:	£	£9,705,950	£3,996,568
Heat Revenue	£	£7,062,365	£7,181,054
Power Export Revenue:	£	£27,895	£25,865
Peaking Power Revenue:	£	£261,555	£274,897
Char Revenue:	£	£3,480,147	£3,341,759
Arbitrage Revenue:	£	£7,283,278	£8,459,173
Inertia Revenue:	£	£0	£0
Total Revenue Annual avg	£/yr	£1,102,385	£920,177
Pre-Tax IRR:	%	10.11%	10.12%
Post-Tax IRR:	%	8.18%	8.14%

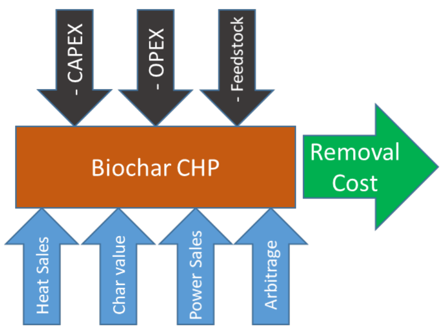


Table 2 - Project revenue stacking - Estimates in real terms – example small 1 module site char carbon removal only

The above table gives the modelling outputs for a simple, single pyrolysis module site with around 9 CAES energy storage systems. Our modelling shows that we should be able to achieve an investable project in 2025 and 2030 with carbon removal cost rates of £170/tonne and £70/tonne respectively. The improvement in the removal cost over time is attributable to two main factors; 1) the reduction in CAPEX costs of the project and 2) the improvement in income from other non-carbon revenue streams.

CAPEX Costs Reduction

We are forecasting a small fall in CAPEX costs for the core pyrolysis plant of around 15% between the FOAK pilot and the 2030 plant as procurement is optimised. We are not projecting any reduction in cost for the energy centre balance of plant and civils costs. The most significant cost saving will be realised in the CAES system where reductions in production costs of around 40% to 2025 and 70% to 2030 are forecast from the current FOAK plant. Overall the capital cost of this representative plant is forecast to fall from £5.5million in 2025 to £4.2million in 2030 (note this is not comparable to the pilot plant which has reduced number of CAES units).

Project Revenues

Our project economics depend on both carbon removal revenues and a number of energy related revenues as shown in the revenue stack in Table2. The market prices associated with these other revenues evolve over time as markets change and therefore influence the associated revenues. This is discussed in more detail in Annex 1.7. In particular base power markets become less valuable and peaking and arbitrage markets much more valuable and zero carbon heat is also much more valuable. On the other hand, some revenues such as char income are forecast to fall over time and the market value of char drops. We exclude inertia revenue for now, this should be very cheap to include.

9. Market Potential, Carbon Markets and Scaling to 2030

For detail see *Annex 1.9 Market Potential, Carbon Markets and Scaling to 2030*.

The GGR competition has 2 objectives, demonstrate a technology that can remove >1,000 tpa and outline path to technology reaching 50k tCO2e per annum by 2030.

Our solution is small-scale modular and the path to reaching 50ktpa is through multiple deployments. This will be facilitated through flexibility, but also standardisation, both technical and commercial.

Pyrolysis Modules	Feedstock		Zero Carbon Energy		CO2e Removal			Sites Required for 50 ktpa CO2	
No	tpa	hectares*	GWh/yr	Char Generation - tpa	Char only - tpa	in CCS - tpa**	Char + CCS - tpa	Char Only	Char + CCS
1	3,866	552 to 276	11.36	677	2,318	4,344	6,662	21.6	7.5
2	7,732	1105 to 552	22.72	1,353	4,636	8,688	13,324	10.8	3.8
3	11,597	1657 to 828	34.07	2,030	6,954	13,032	19,986	7.2	2.5
4	15,463	2209 to 1105	45.43	2,706	9,272	17,376	26,648	5.4	1.9
5	19,329	2761 to 1381	56.79	3,383	11,590	21,720	33,310	4.3	1.5

*@ 14t/ha/yr
** assumes 85% capture sequestration rate

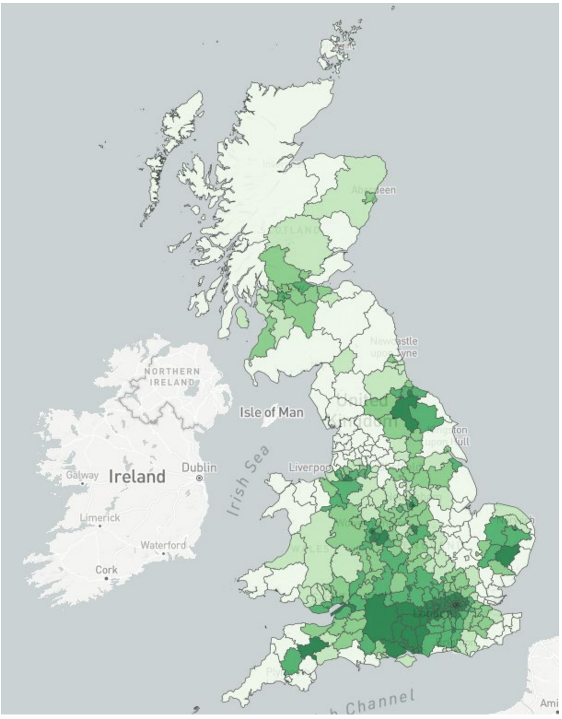
The demonstrator site will be a single module site, and will remove 2,318 tCO2e/year in the biochar. The modular and scaling nature of the solution means larger sites with more modules can be proposed where the heat offtake potential is present.

Small Sites 1-2 Modules ex CCUS

We believe our sites will generally be characterised by 1-2 module char only carbon removal (orange cells above) and therefore typically removing between 2ktpa-5ktpa per site. These sites will not have CCUS as this is deemed unfeasible (see CCUS Assessment). However importantly they will provide zero carbon dispatchable power and heat (for district heating c90°C) into the energy system. Reaching 50ktpa would therefore require 10-15 sites, but these projects are feasible today and not dependent on the development of 3rd party CCUS infrastructure.

Larger Sites 4-5 Modules inc CCUS

CCUS might be feasible for larger sites where 4-5 modules are proposed (green cells) but the geographic market potential is limited and highly dependent on CCUS infrastructure development. In this case there might only need to be 2-3 sites developed. We have not developed this larger concept in detail at this stage.



Opportunity Mapping – to understand where geographically the opportunities for future sites might occur we commissioned a Geographic Information System (GIS) mapping exercise. The technique overlays a series of data we consider important to deployment of future biochar community energy sites including the availability of bioresources both existing and potential for planting, with the existence of energy demand for the important decarbonised heat offtake.

The detailed set of individual metrics can be seen in the full annexed report. Critical data sets include energy crop and existing woodland data sets. Heat density (gas) and existing heat network and CHP site datasets.

The idea is that this tool will be developed through the Phase 2 period once there is a better understanding of the project's commercial needs.

Carbon Standards and Markets

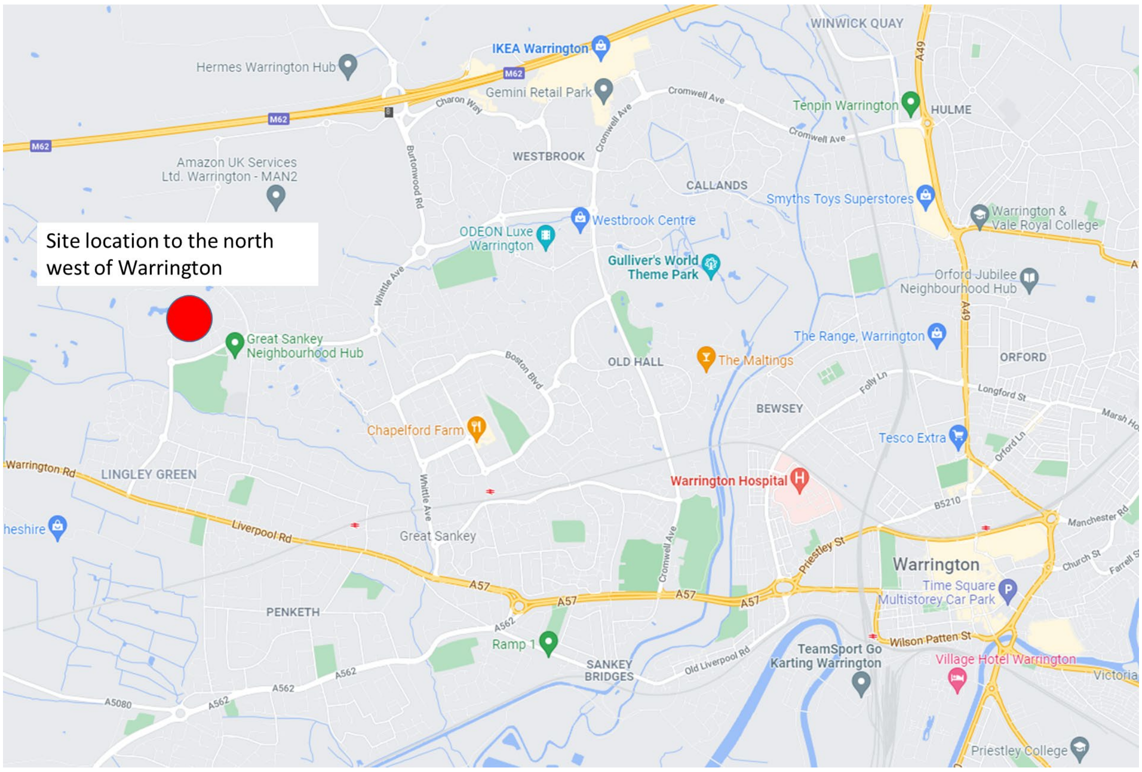
At present there are no compliance based requirements for carbon removal in the UK. The UK ETS is the closest analogue which requires emitter procure allowances of credits under a cap and trade scheme. For removals to reach the levels required by the 2030s (c5MtCO2e/yr) and 2050s (c63 MtCO2e/yr) a legislated compliance system that links charges/taxation to quality engineered removal infrastructure will be required. However, for the moment the market is reliant on a small but emerging voluntary market for removals.

These markets, whether voluntary or compliance need to be underpinned by robust standards that define the traded credits within them. In the paper we discuss in detail the standards and markets that exist today. While we have not selected a standard or market that we would work within, we have had conversations with Puro.earth, one of a few specialist carbon market operators that issue credits for biochar based carbon removal and are trading credits for similar biochar projects that operate in Europe and elsewhere. Our project would fully conform to the Puro.earth standard and we would likely utilise this in Phase 2.

10. Pilot Project Proposal, Planning & Delivery

Site Location

The proposed pilot site is the headquarters of United Utilities PLC, the water utility for the north west of the UK, located at Lingley Mere business park in Warrington. The consortium has had a relationship with UU for the past 18 months and UU are highly motivated to decarbonise their operations and would provide land to develop the demonstrator, and would act as offtaker for the heat output and possibly offtake biochar and carbon credits as part of a long term agreement. We have developed a Heads of Terms agreement for a commercial partnership that covers land lease for demonstrator phase and longer term commitment including offtake.



The team also has a well-established partnership with Warrington Council, the local planning authority, through collaboration on a wider borough decarbonisation project. Warrington are one of the leading UK councils for decarbonisation ambition, activity and progress. Warrington have supplied a letter of support annexed in the main report.

Site and Heat Network

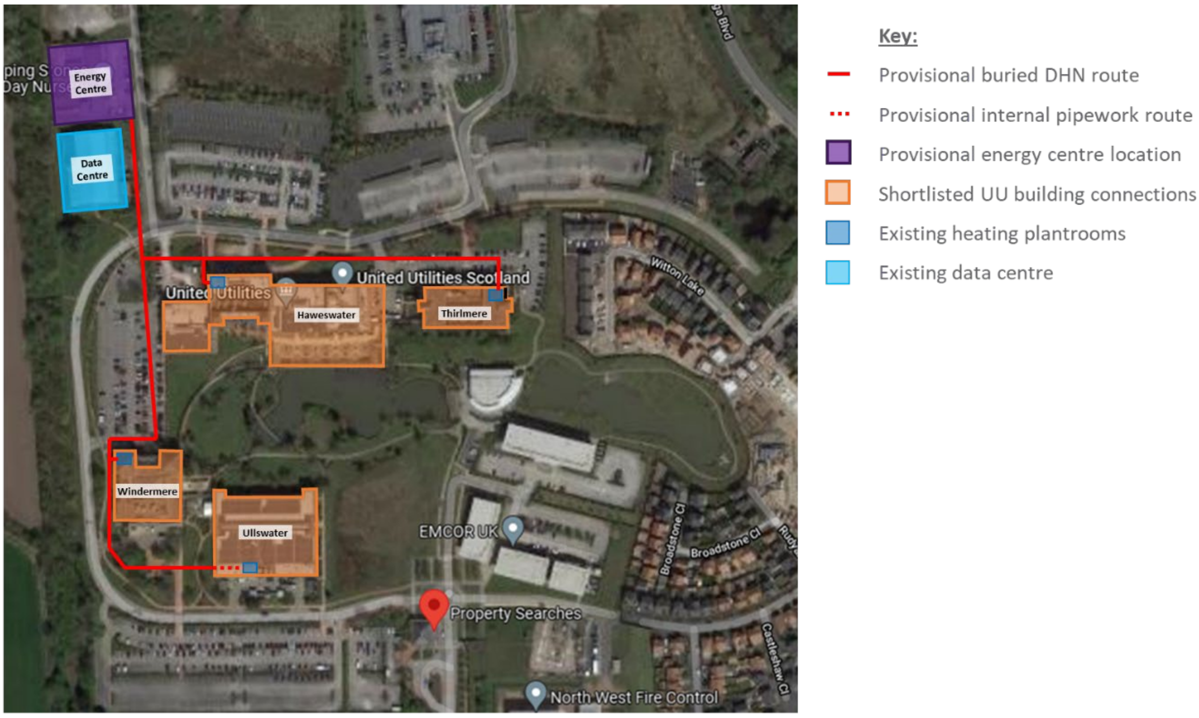
United Utilities HQ is an ideal site for this type of project. They are a single heat customer making the commercial negotiations much simpler. They are also highly motivated organisationally to target decarbonisation and Net-Zero. The lease plot that is available to us is located in the north west of the UU business park site (purple box below). It is here that we will install the energy centre. A detailed site plan and energy centre layout can be found in Annex 1.9. The energy centre will house the pyrolysis engine, the CAES systems and all the balance of plant.

There is a good amount of heat demand across the site, the intention would be to connect into the 4 main office buildings to supply space heating and also to the data centre next door to supply cooling (cooling being supplied from a heat powered absorption chiller).

The heat demand across the site from gas across the 4 main buildings:

- Haweswater (1,734,000kWh)
- Thirlmere (501,000kWh)
- Ullswater (2,428,000kWh)
- Windermere (1,100,000kWh)

Total annual gas demand = 5,763,000kWh (equates to 93% of UU Warrington gas demand). A detailed heat network study can be found in Annex 1.9. We should be able to replace around 70-80% of the gas consumption of the UU site with zero carbon heat.



11. Annexes

11.1. Annex 1.1 – Biochar Production & Use Cases (supplied later)

11.2. Annex 1.2 – Technology: Pyrolysis Plant

11.2.1. Annex 1.2.1 – Pyrolysis Testing Methodology

11.2.2. Annex 1.2.2 – Pyrolysis Feedstock Test Results

11.2.3. Annex 1.2.3 – Drawings & Diagrams

11.3. Annex 1.3 – Technology: Flexible Power & Heat

11.3.1. Annex 1.1.1 – CAES Drawings & Diagrams

11.4. Annex 1.4 – CCUS Assessment

11.5. Annex 1.5 – Feedstock Strategy

11.6. Annex 1.6 – Social Value, Employment & Natural Capital

11.7. Annex 1.7 – Project Economics & Financial Modelling (supplied later)

11.8. Annex 1.8 – Market Potential, Carbon Markets and Scaling to 2030

11.9. Annex 1.9 – Pilot Project Proposal: Scope, Delivery, Schedule, Planning & Permitting