Negative Emission Technologies

Opportunities for Greater Manchester

Prepared for: BEIS & AECOM; Under the DEEP City Decarbonisation Project

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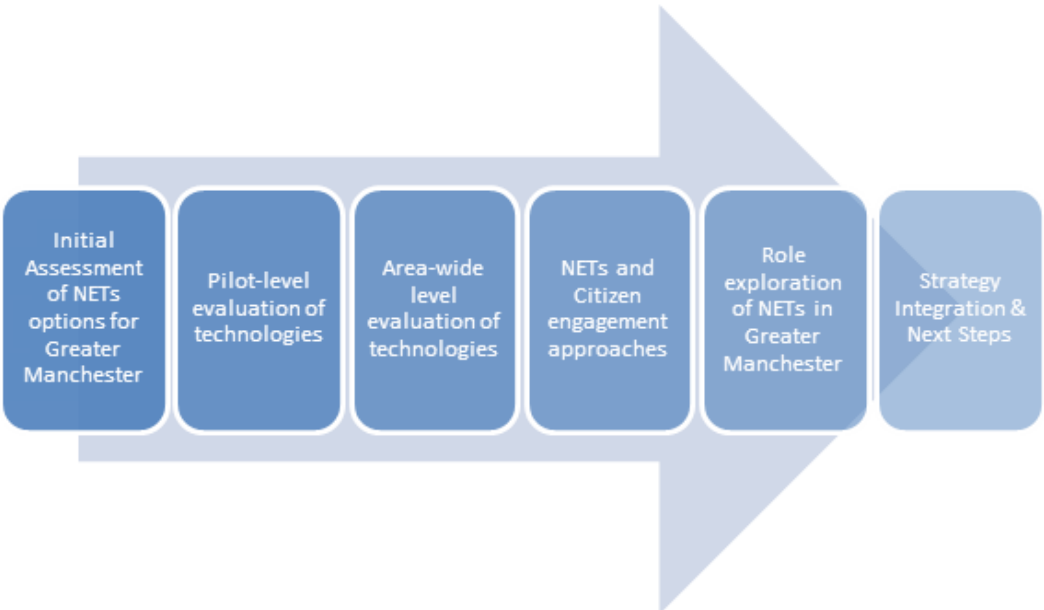
1. Executive Summary

Introduction and Background

Under the Paris Agreement, 189 countries ratified the need to take the necessary measures to stay well below 2°C increase by 2100. This includes varied and numerous plans that involve carbon neutrality in national, regional and local governments around the world.

Greater Manchester Combined Authority (GMCA) has established a net-zero target by 2038 (baseline year 1990). Hard to address residual emissions are those remaining after all behavioural change, grid decarbonisation and energy efficiency measures are implemented. More direct interventions such as negative emission technologies (NETs) are required to address these challenging to mitigate emissions residual emissions. NETs can also be referred to as carbon removal solutions. These technologies can provide support for the carbon neutrality pathway in Greater Manchester, although specific information needs to be explored.

The evaluation of potential technologies' deployment in Greater Manchester is needed, alongside an assessment of their barriers and co-benefits in the specific GMCA context. These components will be integrated into a strategy that will establish recommendations for the further development of NETs in the region. The present report will represent the outline of high-level approaches of potential technologies that could be explored through feasibility studies in Greater Manchester.



Schematic diagram that shows the process stages for the development of this report

Figure 1.

Technologies Assessment

The identification of potential negative emission technologies for Greater Manchester was developed through the initial assessment of 20 different negative emission technologies (nature-based, engineering-based, and hybrid solutions). These are the technologies that can remove carbon dioxide from the air via sequestration or utilisation. Some of the technologies were discounted due to the unsuitability of the configurations of resources and infrastructure in Greater Manchester. The list of 20 technologies was narrowed down to 9 through this initial assessment. The remaining technologies were assessed through the comparative analysis of costs, technology readiness, and other relevant metrics to negative emission technologies intrinsic characteristics. The descriptors regarding their potential implementation in Greater Manchester were evaluated through governance capacity, resource availability, and scalability & flexibility.

The technologies described in this strategy include the following:

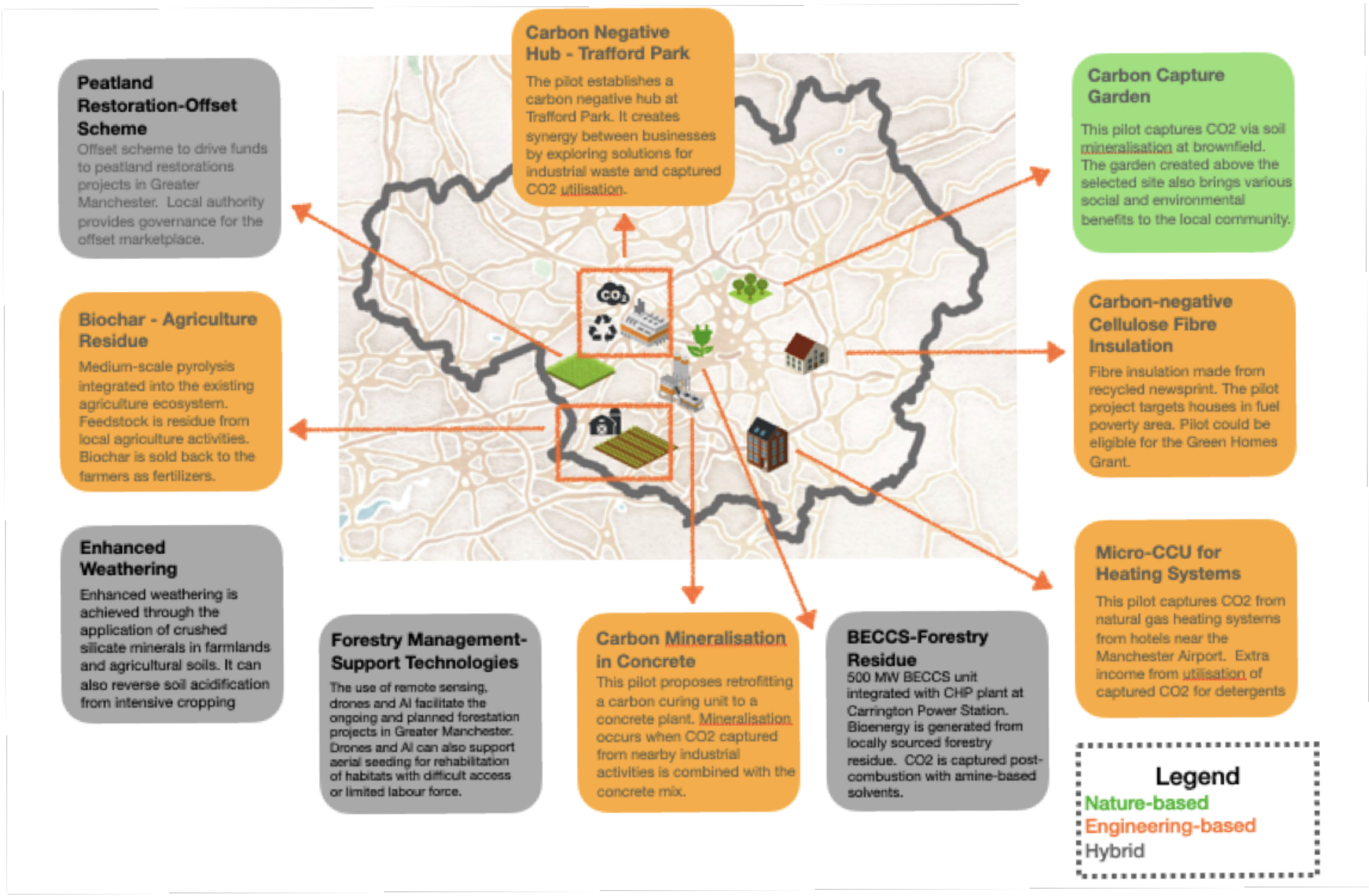
Table 1. Technologies selected from the initial assessment for Greater Manchester		
Technology No.	**Technology**	**Details**
1	Micro Carbon Capture and Utilisation (MCCU) Device for Heating Systems	• Device that captures carbon dioxide (CO2) from flue gas using potassium hydroxide (KOH) • Produces a commercial by-product (potassium carbonate) that can be integrated into supply chains of diverse industries • One unit integrated into commercial heating systems can capture up to 906 kg/CO2 per year
2	Forestry with Supporting Technologies for Planting, Monitoring and Verification	• The use of drones can support planting and monitoring efforts • Drones equipped with germinated seed pods can plant hundreds of thousands of trees per day
3	Urban Soil Management via Carbon Capture Gardens	• The use of mineralisation in urban areas can sequester up to 85 t/ha per year • Optimal technology for its use in brownfield areas • Can be developed with non-toxic construction waste
4	Carbon-Negative Cellulose Fibre Insulation	• Recycled newsprint is repurposed for insulation materials • Can be developed in areas with fuel poverty through the Green Homes Grant • Life-cycle analysis of the material: sequestration potential of 1.11 tonnes of CO2 per tonne of cellulose fibre insulation
5	Carbon-Market for Peatlands Restoration	• Peatland restoration main barrier is lack of funding • Use of carbon markets to support the development of peatlands restoration projects • If sections of peatlands are restored in Greater Manchester: carbon sequestration of up to 80,000 tCO2 per year
6	Biochar for Agriculture Ecosystem	• Medium-scale pyrolysis unit for biochar production suggested • Closed-loop of biomass and biochar production suggested in partnership with farmers • 16,000 tCO2/year of sequestration potential
7	Carbon Mineralisation in Concrete	• Sequestration of CO2 through carbonation or concrete curing • Can be implemented in Trafford Park • Up to 1020 kgCO_2 carbon mitigated per hour
8	Bio-Energy with Carbon Capture and Storage (BECCS)	• Retrofitting of Carrington Power station for co-firing • Post-combustion with amine-based solvent proposed as carbon capture process • BECCS (~500MW) with locally sourced biomass: Mitigation of up to 2.99 Mt CO2 per year
9	Enhanced Weathering	• Use of silicate-abundant crushed rocks in agricultural land • Potential sequestration if applied in Greater Manchester arable land: 5146 tCO2 and 41,173 tCO2 per year depending on application rate (10-30 t of material per ha)

Proposed Initiative for Business Engagement

Trafford Park: Carbon-Negative Hub

This initiative integrates the implementation of multiple negative emission technologies and CCUS technology options. This approach aims to explore industrial symbiosis for carbon mitigation, through the redefinition of waste and carbon dioxide as a resource to keep it in the material loop. Principles of circular economy are used as a basis for the development of this initiative.

Figure 2 below showcases a snapshot of the potential projects that could be developed in Greater Manchester as presented in this report.



NET strategy for Greater Manchester: a Snapshot

Figure 2.

Residual Emissions and Potential Impact

Greater Manchester Combined Authority reported in 2019-2020 a number of 12,766,352 tCO_2 emissions of Scope 1 & 2, and of 15,617,021.86 tCO_2 considering scope 1,2 & 3 (CDP, 2019). GMCA has the baseline year of 1990 for their net-zero targets, with consideration of base year emissions of 21,200,000 tCO_2 and a percentage reduction target of 97.3% by 2038. In their CDP report, it is mentioned that the pathways created by the Tyndall Centre are followed to ensure a fair share of carbon emissions following the carbon budget framework. This would account for a total of residual emissions of 75$ktCO_2$ according to the Tyndall Centre report. This value, even if not a projection, has been the guideline and background (as part of the emission pathways) for the development of climate policies and targets within the Greater Manchester context.

The technologies implemented could support in their maximum scale with the carbon removal of up to 3.1 $MtCO_2$ per year. Scenarios were created to demonstrate the potential impact of carbon removal in the Greater Manchester area and described the mixture of technologies that could mitigate a specific number of residual emissions.

1. Low-level of residual emissions with high importance on nature-based solutions (75ktCO2 as suggested by the Tyndall Centre)

2. Medium-level of residual emissions with a mixture of nature, hybrid and engineering-based solutions (250ktCO2)

3. High-level of residual emissions with a higher reliance on engineering-based methods (750ktCO2)

When compared with similar cities, medium or high-level of residual emissions has a higher likelihood for Greater Manchester. This leads to the conclusion that in a portfolio approach of NETs, nature-based solutions cannot be the dominant component used to compensate for Greater Manchester's higher residual emissions. The use of hybrid or engineering-based solutions will be required to be integrated into the strategy to meet the 2038 target.

Conclusions and Recommendations

This report highlights possibilities for the integration of negative emission technologies in the Greater Manchester region. For the further development of the ideas presented, feasibility studies will be required, as well as the involvement of different stakeholders in the area to facilitate the integration of individual efforts to contribute to climate change mitigation efforts. In addition, the following recommendations must be taken into consideration:

1. Importance of collaboration and networking between different stakeholders, industries and research institutions facilitated by GMCA

- Establish strategic partnerships, public-private partnerships, inter-intra sector network or platform for knowledge exchange and co-creation
- Centralised coordination of stakeholders collaboration, joint targets, and legally binding aims
- Develop community-based or business-led projects to aggregate knowledge sharing
- Carbon removal that engages with the citizens of Greater Manchester in raising the awareness of emission reduction and carbon capture

2. Collectively develop standardised NET terminology and criteria for best practices in NET projects considering suitability within the Greater Manchester context

- Universities and research institutions are crucial to providing the scientific foundation
- It is required the development of frameworks for quality control, to avoid arbitrary claims about net-zero/negative emissions
- Carbon removal good practices that implement principles of ethical carbon removal, with long permanence and negative on a lifecycle basis that complement known mitigation technologies/methods instead of replacing them

3. NET approach must be compatible with how GMCA defines net-zero

- Focusing on multiple benefits including societal and economics of carbon capture initiatives

4. Explore different sources of funding for NET projects, establish a carbon market that offers stakeholders financial incentives

- Opportunity to deliver upfront investment for delivery now against future-benefits
- Understand how private finance and beneficiaries can interact with public support to achieve an increase in delivery

5. NETs will be required to be deployed at a large scale in Greater Manchester

- The residual emissions and plausible scenarios demonstrate that it is unlikely that Greater Manchester will be able to solely rely on nature-based solutions to compensate for its residual emissions as set out in its net-zero strategy
- The use of hybrid or engineering-based solutions will be required to be integrated into the strategy

6. The current mitigation initiatives must be quantified on a joint platform

- The current mitigation initiatives will be decisive for the future emissions pathway of Greater Manchester
- Their characteristics and planned scale must be quantified on a collaborative platform to understand their real impact against their net-zero targets
- This platform will allow understanding of residual emissions trajectories and the concrete role of carbon removal in Greater Manchester

Recommendations for the NETs deployment in Greater Manchester

Table 2 outlines short-term, mid-term and long-term actions for NET implementation before Greater Manchester's 2038 target year.

TABLE 2. SPECIFIC ACTION PLAN	
SHORT-TERM ACTIONS (YEAR 1-2)	• Detailed assessment: mitigation capacity of the current and planned projects and initiatives • Define long-term vision: alignment of mitigation efforts with the net-zero strategy and trajectory • Clear quantification of mitigation strategies and trajectories • Feasibility studies: development of supporting information for future implementation of negative emission technologies in specific locations • Creation of business cases for individual negative emission technologies • Identify and establish strategic partnerships: between research institutions, businesses and local governments • Ensure collaboration within all the independent mitigation efforts and projects (traditional mitigation and negative emission technologies initiatives) • Identify sources of funding • Governance framework: development of a governance framework and local authority led steering group • Establishment of a monitoring and verification system for ongoing projects

Mid-term actions (Year 3-5)	• Creation of numerous demonstration projects with scalability potential to build legitimacy:
	  ○ Carbon Capture Gardens
	  ○ Biochar
	  ○ Enhanced weathering (medium-scale engagement with farmers)
	  ○ MCCU for heating systems (pilot-scale)
	• Scale-up of demonstration projects completed
	• Continue with projected started in years 1-2
	• Quantify waste biomass and its allocation in Greater Manchester
	• Establishment of feedstock procurement network for Biochar and BECCS
	• Trafford Park, Carbon-Negative Hub: establish detailed carbon material flow within industries

Long-term actions (Year 6+)	• Scale-up and continued delivery of NET projects depending on the target of residual emissions • Quantification of captured/ sequestered emissions • Assessment of results: Contribution to the net-zero pathway • Maintain habitats created i.e. sustained management of woodlands and peatland

2. Introduction & Background

The IPCC, along with other international bodies, have suggested that emissions reduction, mitigation and management should be prioritised. Many nations are working towards aligning their emissions with the 2016 Paris Agreement targets which aim to limit future temperature increase even further to 1.5 degrees. In order to reach such ambitious targets, negative emissions technologies and carbon removal solutions must be deployed. This international call to action has led to the adoption of carbon neutrality, or net-zero, commitments across the globe, with aspirations to employ innovative methods in order to effectively mitigate emissions and tackle the impacts of climate change.

Whilst emissions mitigation, reduction and behavioural change have a key role to play in achieving these net-zero targets, these strategies will be insufficient on their own. In 2017, the Royal Society and the Royal Academy of Engineering reported that after all feasible emissions reduction methods had been implemented, residual emissions will leave a significant carbon gap of 130 $MtCO_2$ per annum by 2050. Therefore, the need to deploy carbon removal solutions as part of emissions management activities is vital. Achieving carbon neutrality will be a challenging process and will require large-scale uptake and deployment of greenhouse gas removal methods in order to be realised.

In 2019, the UK was the first major economy to commit to having net zero greenhouse gas emissions by 2050. This target aims to reduce the UK's net emissions by 100%, using 1990 as the baseline, within the next thirty years. Progress has been made with emissions being drastically reduced. Governmental commitment has been shown through the development of financial mechanisms and policy tools; such as, the creation of schemes and funds for low-carbon and sustainable alternatives. The support of national ambition has been placed by some local authorities and regions through setting targets with a shorter timeline for completion. These regions, such as Greater Manchester with its goal for net carbon zero emissions by 2038, will lead societal change and sectors transformation through their decarbonisation process.

Greater Manchester's aspiration for 2038 will only be realised if a diverse range of stakeholders, funders, innovators and industries are involved with the decarbonisation transition. The Greater Manchester region was involved in the development of the SCATTER (Setting City Area Targets and Trajectories for Emission Reduction) guide which helps to identify actions needed in order to meet the carbon neutral target and had the potential to lead in the deployment of decarbonisation technologies at a regional level. Greater Manchester combined authority (GMCA) is part of the CDDP Decarbonisation project is running in six cities, including Greater Manchester and is supported by the Department for Business, Energy and Industrial Strategy (BEIS). This programme aims to develop pathways to achieving net zero heating and cooling in cities across the UK. This report outlines the role carbon removal solutions will have in addressing these challenging areas under the framework progressing further the development of the CDDP Decarbonisation Project delivery and contributing to net zero considering a wider perspective.

3. Aims & Methodology

This specific report aims to further develop Greater Manchester's existing strategy for decarbonisation by including potential carbon removal solutions which would help to tackle the area's remaining emissions. The residual emissions scenarios greater differ as the will alter depending on how much the Greater Manchester area is able to reduce its emissions and decarbonise key sectors before 2038. Whilst the region can take specific action, some of this is also reliant on national initiatives such as the decarbonisation of the grid and driving policy.

This report uses comparative assessment frameworks to uncover the most appropriate carbon removal solutions in the Greater Manchester context, taking into considerations factors such as funding, governance and resource availability. The resulting carbon removal solutions included nature-based, hybrid and engineering-based approaches. Finally, this report aims to support the creation of a strategy which integrates carbon removal methods into Greater Manchester's current climate change mitigation efforts. Considering most of the technologies discussed are at early development stage, technology details and data are collected from lifecycle assessments, case studies, literature review and discussions with industry professionals. As such, the claims made in this report could be based on context and locations different than Greater Manchester. The confidence on the estimates must be considered as peer reviewed but through the lens of an innovation project. Therefore, the estimates are as accurate as it is known to the authors, but are prone to be improved as more information is available of medium-scale deployment or as an increased number of relevant pilot studies are conducted.

4. National & Local Supporting Policy

The development and deployment of each of these of the suggested carbon removal methods is supported by policy, or funding, opportunities through the UK government. In 2019, the UK government committed to a Net Zero Target, as recommended by the Climate Change Committee (CCC), and has since been developing policy and pathways to support decarbonisation. Progress thus far is promising with emissions being 44% below 1990 levels in 2018, thanks to changes in electricity generation, waste treatment and across the industrial sectors. According to Carbon Brief, as of March 2021, the UK is 48% of the way to achieving the Net Zero goal. This emissions reduction can mainly be attributed to the COVID-19 pandemic, with national lockdowns drastically limiting both national and international travel. Whilst this is a symbolic success, emissions are set to rebound as the economy reopens.

Therefore, national supporting policy is vital to ensure decarbonisation continues to be successful. The Clean Growth Strategy published by the Department for Business, Energy & Industrial Strategy allocates £184 million to developing energy efficiency and supporting innovative low carbon heating technologies. Furthermore, the Department for Environment, Food and Rural Affairs' 25 Year Action Plan sets out clear targets for the creation of woodland and the maintenance of forestry in order to sequester carbon and support urban tree planting. The Action Plan also highlights the need to protect native species and improve biodiversity, both on land and in the seas. It builds upon the Biodiversity 2020 strategy published in 2010 and aims to raise the importance of natural capital to improve the lives of the public and work towards achieving the SDGs.

The recent Science and Innovation Strategy for Forestry in Great Britain highlights the importance of forestry protection, development and research due to its role in supporting ecosystems, climate change mitigation and tackling the biodiversity crisis. The 2020 CCC Land Use: policies for a Net Zero UK report indicates that forestry covers in the UK needs to increase to at least 17% by 2050, achievable by planting 30,000 hectares of woodland each year. Therefore, nature-based solutions have a significant role to play in the UK's low carbon, sustainable future and in adapting and becoming resilient to the impacts of climate change.

Further decarbonisation policy support can be found in the Ten Point Plan for a Green Industrial Revolution which explores a green recovery, the creation of green jobs and methods of accelerating the transition. More recently, the announcement which pledged a further £350 million to focus on cutting emissions in heavy industry and construction not only demonstrates national commitment to carbon neutral goals but specifically aligns with the goals of the CDDP City Decarbonisation project.

The Sixth Carbon Budget, published by the CCC in December 2020, includes policy suggestions which aim to strengthen and solidify the progress towards Net Zero. These include, a major national, Government led, investment programme which would support the creation of carbon markets, the galvanisation of communities to choose low-carbon options, and better climate policy in the recovery from the COVID-19 pandemic. It also advocates for the creation of low-carbon policy packages for all sectors which use a systems approach to remove barriers to investment, innovation and skill building.

One such industry focused approach is the Industrial Decarbonisation Strategy which focuses on manufacturing and construction and encouraging the emergence of new low carbon industries. It has allocated £171 million to nice green tech projects across the UK to undertake studies which support the upscale of infrastructure for carbon capture, usage and storage (CCUS) and hydrogen. A further £932 million has been provided to 429 projects across England which will aim to reduce emissions from public buildings. The new blueprint also commits to more secure carbon pricing, new product standards, support for skills transition and an expectation that industrial emissions will fall by two thirds by 2035.

Interest in achieving carbon-zero goals has also been demonstrated at regional and local levels. Greater Manchester has set the target of being a zero-carbon city by 2038. Strategies such as the Zero-Carbon Action Plan and the Manchester Five-Year Environment plan set out pathways to achieving this. The Five-Year Plan aims to address key challenges in the region, including climate change mitigation, air quality and protection of the natural environment. Research by the Tyndall Centre has also been considered in calculating the emissions pathways for GMCA, suggesting that emissions should be cut by 15% annually to move towards achieving the 2038 target.

The Greater Manchester Region has already demonstrated its commitment to action through the creation of Greater Manchester's Tree and Woodland Strategy and its contributions to the development of the Northern Forest and peatland restoration efforts in the region. A further example of GMCA's support is demonstrated in Manchester's Green and Blue infrastructure Strategy which establishes the importance for urban green infrastructure and spaces for regulating climatic changes and also commits to making such spaces more accessible within the city and beyond. Proposed projects such as Carbon Capture Gardens and Forestry endeavour to support and align with these Greater Manchester strategies.

5. Potential Options for Greater Manchester

NETs options available

The identification of potential negative emission technologies for Greater Manchester was developed through the initial assessment of 20 different negative emission technologies (nature-based, engineering-based, and hybrid solutions). These are the technologies that can remove carbon dioxide from the air via sequestration or utilisation.

Each of these technologies has to potential to make a significant impact on carbon removal potential but their success and ability to scale is highly context-specific. As a result, many of the NETs are not relevant for the Greater Manchester area due to limited access to certain resources, regional stakeholder perceptions and preferences and the existing infrastructure. Therefore, some technologies were discounted at an early stage. Examples of this include, direct air capture was eliminated due to the lack of accessibility to reservoirs and high costs, forestation efforts were also excluded from further analysis as Greater Manchester already has large scale efforts improving tree coverage, such as The Northern Forest. As a result, NETs were prioritised which could build upon existing initiatives in the region, have scalability potential with the creation of large emissions reduction or have a high readiness level. Other factors such as policy support, co-benefits and land availability were also considered. Table 3 outlines the 20 NETs which were first assessed.

Table 3. Comparative Assessment for NETs

No.	Negative Emission Technology
1	Soil Carbon Sequestration for Croplands
2	Micro Carbon Capture and Utilisation (MCCU) Device for Heating Systems
3	Soil Carbon Sequestration for Grasslands
4	Carbon Capture Bench
5	Forestation
6	Urban Soil Management via Carbon Capture Gardens
7	Carbon-Negative Cellulose Fibre Insulation

8	Enhanced Weathering
9	Direct Air Capture
10	Top Gas Recycling Blast Furnace with CCS Coupling
11	Forestry with Supporting Technologies for Planting, Monitoring and Verification
12	Bio-Energy with Carbon Capture and Storage (BECCS)
13	Biochar for Agriculture Ecosystem
14	Sewage Sludge Biochar
15	Carbon Mineralisation in Concrete
16	Aggregates from Industry Waste and Captured CO2
17	Peatlands Restoration
18	CCS-Hydrogen System
19	Microalgae CCUS
20	CCS Retrofit Energy-from-waste Plant (EfW)

Selection Criteria

The technologies assessed in the present report were evaluated through a comparative assessment of the following criteria:

Table 4. Criteria for comparative assessment of negative emission technologies		
Aspect	**Description**	**Scoring Scale**
Technology Readiness	Technology readiness levels (US Department of Defense, 2008)	1-9

Costs	Cost per tonne of carbon sequestered/captured	1-10
Governance capacity	Following framework (Bellamy, 2018): “Public principles for the good governance of NETs”. Refers to the level of control of assets and level of influence of relevant stakeholders	1-10
Mitigation potential	Based on evaluation done in review (Shepherd, 2009)	1-10
Timeliness	Based on (1) time to reach max. capture capacity and (2) other factors (flexibility, controllability, reversibility)	1-10
Permanence	Longevity; “Temporary” / “Permanent”, based on storage time	1-10
The criteria table was adapted from the methodology presented by Rueda, O. Et al. in the paper “Negative-emissions technology portfolios to meet the 1.5 ◦C target” (2021)		

These criteria can be used to evaluate different types of negative emission technologies and develop a comparative assessment of their most relevant characteristics. The details of each criterion are described in table 4.

In this table, the criteria related to the context of the city or local authority were added, including governance capacity, resource availability and scalability & flexibility. These additional criteria aim to evaluate the applicability of a specific technology under the Greater Manchester context. As some technologies can have promising scores in the assessment related to the technology itself, but their applicability could be limited when evaluating them in a local context.

Table 5. Description of the comparative approach for NETs										
Aspect	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
Mitigation potential (CO2 mitigated per tonne of product or unit per annum)	<200kgCO2		>200kgCO2		>500 kgCO2		>1tCO2		>2 tCO2	
Cost per tonne (GBP per tonne removed)	300		200-300		100-200		50-100		0-50	
Permanence	<10 years		10+ years		50+ years		100+ years		Geological time (hundreds of years)	
Technology readiness	Basic principles observed and reported	Technology concept or application formulated	Analytical and experimental critical function demonstrated	Component validation in laboratory environment	Component validation in relevant environment	System model or prototype demonstration in relevant environment	Prototype demonstration in operational environment	System verified and tested; commercial design has been developed	Actual system proven in deployment	
Governance capacity	Very low No access to the resources and assets		Low No direct control over resources and assets Some influence over stakeholders		Medium No direct control over resources and assets HIgh influence over stakeholders		High Some control over resources and assets		Very High High control over resources and assets	
Resource availability	Very Low No access to resources		Low to medium access to resources		Medium access to resources		Medium to high access to resources		High access to resources	
Scalability and Flexibility	System not scalable nor flexible (location)		Limitations to scalability or flexibility		Moderate scalability or flexibility		System is either highly scalable or highly flexible		Highly scalable and highly flexible	

Assessment results of NETs technologies for Greater Manchester

The results for the assessment corresponding to the technology independent from the context, are the following:

Table 6. Results from general comparative assessment of NETs				
Technology	**Mitigation Potential**	**Costs**	**Permanence**	**Technology Readiness**
BECCS-CCUS	10	6	4	6
Biochar	9	5	10	8
MCCU	6	3	4	7
Insulation	7	5	5	9
Carbon Capture Gardens	9	7	10	7
Concrete	10	6	8	8
Enhanced Weathering	9	7	10	7
Peatland Restoration	10	10	**5***	9
Peatland Restoration has a score of 5* in permanence as the longevity of the sequestered carbon is highly dependent on environmental factors, being highly variable.				

The results of this table showed high scores for land management solutions such as carbon capture gardens, peatlands or biochar.

The evaluation of the technologies under the GMCA context is shown in the following table:

Table 7. Results from comparative assessment of NETs under GMCA context			
Technology	**Governance Capacity**	**Resource Availability**	**Scalability and Flexibility**
BECCS	Low control over assets and medium influence over stakeholders	Low availability of resources	Low scalability due to resource constraint Low flexibility due to location specificity
Biochar	Low-medium control over assets and medium influence over stakeholders	Medium availability of resources	Medium scalability due to resources availability Medium flexibility on location

MCCU	Medium control over assets and high influence over stakeholders	Medium availability of resources	Medium scalability due to network complexity High flexibility on location
Insulation	Medium control over assets and high influence over stakeholders	Medium availability of resources	High scalability High flexibility on location
Carbon Capture Gardens	Medium control over assets and high influence over stakeholders	Medium availability of resources	Medium scalability due to land availability High flexibility on location
Concrete	Low control over assets and medium influence over stakeholders	Low availability of resources	Low scalability due to location specificity Low flexibility due to location specificity
Enhanced Weathering	Low-medium control over assets and medium influence over stakeholders	Medium availability of resources	Medium scalability due to network complexity High flexibility
Peatland Restoration	Low-medium control over assets and medium influence over stakeholders	High availability of resources	High scalability High flexibility

These results favoured the exploration of technologies where GCMA have higher control over assets and resources. This showcased as the carbon-negative insulation, carbon capture gardens, and peatland restoration as an opportunity for their development in Greater Manchester.

The individual analysis of the results of each technology is presented in upcoming sections of this report.

6. Key Opportunities: 2021-2038

The table below summarized the 8 proposed carbon removal solutions for the Greater Manchester. Further details of each solution can be found in the appendix.

Table 8. Summary of Proposed Technologies				
Proposed Technology	**Costs**	**Mitigation Pot**	**TRL**	**Key Stakeholders**
Carbon Capture Garden	If dolerite is used as soil substrate: 25 GBP per tonne (20t to 1600t required) Residual construction waste can be used instead to reduce the production or extraction of new materials The costs for landscaping and implementation of the rock substrate range between 2 to 7,000 GBP per ha	Up to 85tCO_{2e} /year Up to 15 years carbon capture efficiency	7	Local authority Third party verifier Academic Institutions Contractor Landscaper Construction Company
Biochar	GBP 295-445/tonne of biochar GBP 120-182 tCO_{2e} /tonne of biochar	1.25- 2.96 tCO_{2e} /tonne of biochar	8	Local Authority Farmers UKBRC Pyrolysis Manufacturer

				Biochar Provider Technical Consultants
Carbon-Negative Fibre Insulation	11 GBP per bulk of 12 kg of product	1.11 tonnes of CO_2 sequestered per tonne of carbon fibre insulation	9	Local authority Local community Insulation provider Contractor
Peatland Restoration	GBP 1009/ha	40,000-80,000 tCO_2e/year (GM site)	9	Academic Institutions Local Authority Farming Community Moors of the Future Lancashire Wildlife Trust
Enhanced Weathering	Dolerite/basalt: 25 GBP to 125GBP per tonne Olivines (10 to 30 µm): 100 to 180 GBP per tonne	0.1-1.25tCO_2 per tonne of material	7	Material providers Third-party verifiers National Farmers Union Local Authorities Nature Greater Manchester
Carbon Mineralisation in Concrete	USD 100/t CO_2	17$kgCO_2$ /m^3 of concrete produced 510 to 1020 $kgCO_2$ reduced/ hour (30-60 metric cubes/hour concrete)	8	Local Authority Technology Provider Industry Representatives Concrete Manufacturer
Micro Carbon Capture and Utilisation	GBP 12, 000 GBP/unit	700 $kgCO_{2e}$ - 906 $kgCO_2$ /unit/year	7	Social Housing Communities Local Authority Gas Supply Company

				Potassium Carbonate Buyer
Bio-Energy with Carbon Capture and Storage (BECCS)	Retrofitting: 1050-1120 GBP/kWe OPEX: 2-3 GBP per tCO_2	Up to 2.99 Mt CO_2 depending on feedstock	6	ESB Drax or other Academic Partners Skilled Labours MEA Suppliers Forestry Project Organisations Align CCUS Initiative CCUS Industry Partners

Technology #1: Carbon Capture Gardens

Potential Project for GMCA

Manchester Green and Blue Infrastructure Strategy (2015) highlights that integrated green infrastructure is important for managing climate change, highlighting the importance of soil in land management and biodiversity maintenance. The implementation of carbon capture gardens would support these endeavours.

Greater Manchester has multiple locations of brownfield areas that had been commissioned for the development of social housing. The potential project suggested is the integration of pilot cases of carbon capture gardens integrated into the pieces of green areas in the social housing developments. The cumulative suggested area from scattered green spaces is within the range of 10 to 12 ha. The use of area-wide GIS analysis and site-specific feasibility studies would be required. The implementation of the garden should consider the use of residual construction waste to reduce costs. The depth required for the substrate is of 100 mm to ensure a mitigation potential of up to 85tCO_2 per hectare. The mitigation potential of this project could be within the range of up to 850 to 1020tCO_2 depending on the area chosen for the project. The monitoring and verification processes are done through measurements for inorganic carbon content in soil. This data is obtained through academic and technical papers and corroborated by industry professionals.

The co-benefits of this technology applied to Greater Manchester include potential mitigation opportunities in already planned areas of construction, repurposing of construction waste, community engagement opportunities, increased water retention in soil and improved soil quality.

GMCA's role would need to be focused on enabling the project to be developed in suitable social housing areas. GMCA must appoint contractors/landscapers and third-party verifiers/academic institutions for the development of the project. GMCA should evaluate the potential scaling up of the pilot project to target other relevant areas in the region as appropriate.

Main Advantages

- It can be implemented as part of social integration initiatives, due to its high flexibility and multipurpose component of the garden itself
- Additional co-benefits for the soil health such as: increased water and nutrient retention in soils, improvement in soil fertility
- It is a highly scalable type of technology as the implementation method is simple in comparison to other carbon removal options and can be adapted to different areas
- It can be used for educational purposes if it is developed with a community focus

- It can help transforming brownfield areas if other land availability is limited, and it supports the repurposing of construction waste
- This technology does not have any visual impacts in the landscape; therefore, it enables higher social acceptance of the project

Barriers, Risks and Policy Considerations

- The mitigation potential depends on the amount of material used as a substrate. Therefore, the design of the garden needs to be developed to align the mitigation aims of the initiative.
- If construction waste is used instead of pure dolerite, the material will be heterogeneous, requiring constant monitoring and verification processes to ensure the mitigation efficiency.
- If allotments are chosen as part of the community garden, then pure dolerite needs to be used instead of construction waste, due to potential heavy metals in the material.
- If the garden is built on temporary brownfield areas that will be repurposed in the upcoming years, then strong policy developments need to accompany the implementation of these projects, to ensure the appropriate treatment of the substrate. The brownfield areas ideally should not be repurposed within 15 years to maximise the mitigation impact of the gardens.
- Social acceptance of this project is relevant for its success. The onboarding of the community could prove challenging if there is weak engagement between the local authority and the community groups.
- The development of funding or financial incentives related to urban development should incorporate measures that support the development of urban land management practices with carbon sequestration objectives.
- The mitigation potential will only have similar results every year, if the substrate is replaced every 10 to 20 years. The experimental results have shown that the mineralisation process declines drastically after approximately 20 years depending on the granule size and the biogeochemical processes of the soil. It must be noted that the CO_2 sequestered has been stabilised into inorganic carbon, in form of carbonates. Therefore, there is no risk of the carbon to be released into the atmosphere if the substrate is not replaced or if the area is converted into a different urban facility in the future.

Technology #2: Biochar

Potential Project for GMCA

This report proposes a small industrial scale pyrolysis plant for the Greater Manchester area using waste biomass as the main source of feedstock. The produced biochar will be prioritised for agricultural land application within GM and its surrounding regions. The AGMA decentralised energy study from 2010 found that there is potential for access to 10,217 tonnes of biomass per year within the GM boundary supplemented by access to a wider regional supply chain for up to an estimated 325,000 tonnes/annum could be contracted (URBED, AECOM and Quantum Strategy and Technology, 2010). Currently, there is no data on the estimated quantity of waste biomass accessible within the GM boundary. According to GM's Waste Management Plan, the majority of waste biomass produced in GM is planned for heat and energy production, waste allocations include the Runcorn Thermal Power Station, the In-vessel Composting and the Thermal Recovery Facility in Bolton. The remaining amount of waste biomass available for biochar production is subject for further evaluation. With regards to the available agricultural land for biochar application, Defra (2018) estimated the size of arable land in GM to be 9264 ha. The agricultural land in GM is indicated with the figure below (GMODIN, 2020).

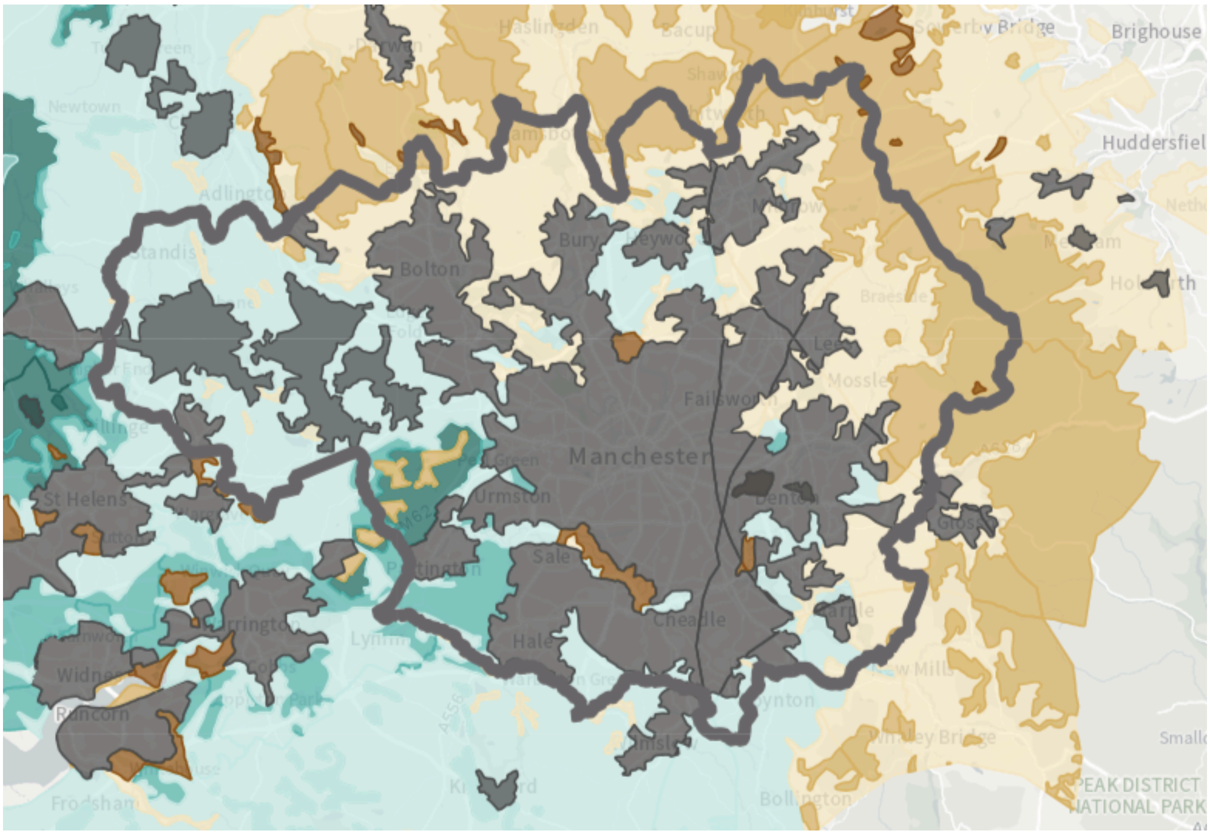


Figure 3. Agricultural land in GM represented in green shade

The proposed small-scale pyrolysis plant requires 2000 odt (oven-dried tonnes) of biomass annually and can produce up to 727 odt of biochar per year (Shackley et al., 2011. An optimal location for this plant is within the Trafford district. It is close to agricultural land, thus able to keep transportation costs at a minimum. Furthermore, it is close to Trafford Park, where waste from food manufacturing activities there could be readily available. The pilot seeks to establish a closed-loop system of biomass and biochar within GM boundary. This approach ensures the feedstock is sustainably and locally sourced which also reduces the emissions from feedstock transportation. It is vital to involve local farmers, farmers' association from the beginning of the pilot. GMCA could help facilitate this. In this system, farms are identified as "prosumers" in that they are both the producer of feedstock (crop residue) and consumer of biochar.

Main Advantages

- Biochar for soil application is found to increase crop yield, stabilise soil carbon, improve soil nutrient and increase soil water retention. Other agricultural benefits may come from decreased fertiliser needs by increased fertiliser efficiency and reduced drought stress in drought prone areas.
- Biochar can be used to sequester CO_2, other pyrolysis by-products bio-oil and syngas can be used for fuel and energy production
- Less fertiliser is required for agricultural use when applied together with biochar
- Additional revenue from the sale of biochar, building stronger business case for biochar as a viable solution for carbon removal

Barriers, Risks and Policy Considerations

- Most waste biomass are already allocated elsewhere in the UK such as electricity generation, anaerobic digestion and return to soils. The supply of waste biomass for biochar may need to compete with these more established methodologies.
- Purpose grown biomass such as willow or perennial grasses has net carbon footprint, the carbon required to process the crop is greater than the amount sequestered. Land-change emissions, land and biomass competition are other areas of concern of using purpose grown biomass.
- The effect of biochar on soil and crops varies with the type of biomass, the precise implication of these requires more in-depth analysis
- A localized biochar value chain requires the establishment of a biochar market. Currently, there is a lack of regulative and economic incentive for biochar, limiting its potential large-scale agricultural use.

- Waste-derived biochar is under strict regulations land application is subjective to Depends on the biomass used, the
- Biochar using waste biomass requires a permit under the Environmental Permitting Regulations (England and Wales) 2007 to ensure this method does not cause any harm to human health or the environment
- Additional protocols for biochar will need developing by the Environment Agency and the Waste and Resources Action Programme for biochar to be classified as non-waste product suitable for soil amendment

Technology #3: Carbon-Negative Fibre Insulation

Potential Project for GMCA

The Clean Growth Strategy (2017) highlights the Government commitment to prioritising households in fuel-poverty and rented homes to EPC C by 2030.

The potential project for GMCA consists in the small-scale deployment of the insulation as a pilot project that can be implemented in areas of fuel-poverty. An initial selection of a hundred social housing units for the retrofitting is proposed. According to Mapping GM, the southern central region of Greater Manchester shows higher incidence of fuel poverty, highlighted in red (see figure x). The data of average number of material used is extrapolated to show a potential of carbon sequestration of 200 to 800 tCO2, this range can vary depending on the type of houses chosen and the type of insulation that would be required. The development of building typology studies to choose eligible properties for the development of this project should be considered as a priority next step. The selection of other relevant/opportunity areas via metrics such as building stock analysis should be considered.

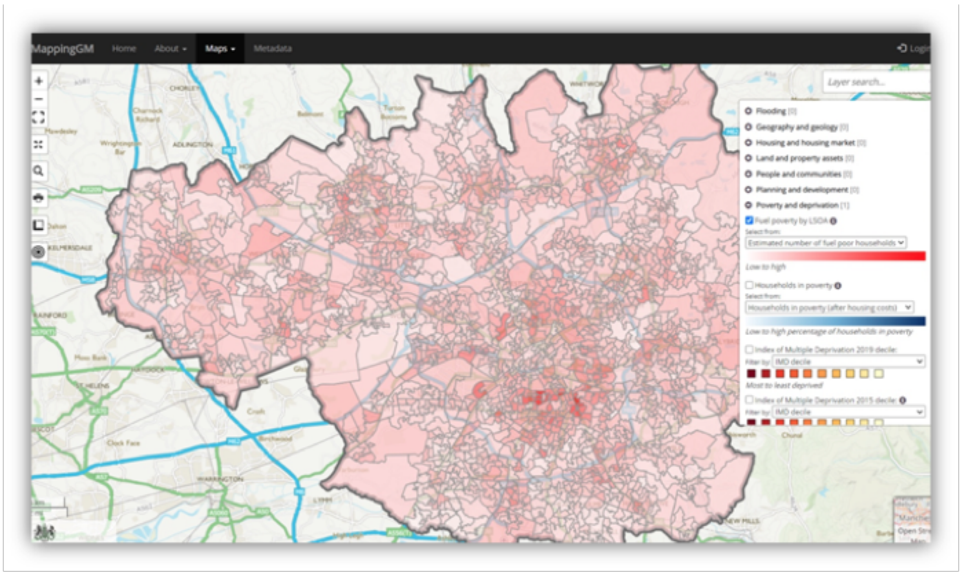


Figure 4. Map showing the fuel-poverty areas in Greater Manchester in dark red

The co-benefits of implementing this insulation material in fuel-poverty areas are supporting the sustainable transition in vulnerable communities, where the insulation can be the most beneficial. This project aligns to the aims of the Clean Growth strategy, as this project would increase the energy efficiency in fuel-poverty homes.

GMCA's role should focus on engaging with the communities, overviewing the development of the project, and ensuring the creation of clear signals regarding finance and through the development of robust policy frameworks to support the development of these technologies, supporting the enforcement of new standards of the use of these materials in new builds. GMCA in their role as Local Planning Authority, can promote the use of this material, and can use their leverage with local businesses and property owners to encourage uptake in the private sector. The local authority should evaluate the potential scaling-up of the pilot project to target other relevant areas in the region. As next steps, GMCA could identify planned or potential Council-led retrofitting initiatives that could incorporate cellulose insulation, evaluate the use of external verifiers with local providers to ensure carbon sequestration potential of the technology in the regional context. The development of safety regulations of the material must be undertaken.

Main Advantages

- This technology can be easily implemented, as it is a direct replacement of traditional insulation. Therefore, the barriers for adoption are more manageable by local authorities, as they are similar to processes already experienced by them when facing other transitions to more sustainable products and goods.

- It enables the opportunity of replacing polluting and carbon intensive insulation materials, such as polystyrene, and polyurethane foam, avoiding further emissions through the creation of these products
- The implementation of this material in communities with vulnerable fuel-poverty contexts could support the fair transition to wide scale sustainable practices in a region

Barriers, Risks and Policy Considerations

- The community engagement may be challenging, appropriate dissemination of information and social incentives must be presented prior to the implementation; a strong governance plan must accompany this technology.
- The development of in-depth studies of the properties is required to understand the type of insulation that is required. This will have a direct impact on the mitigation potential of the projects developed and may vary drastically from one region to another.
- There needs to be higher financial incentives or policy instruments to support the adoption of this material as with other low-carbon products.
- This material needs to have strong policy frameworks aligned to its deployment for its appropriate disposal, to ensure avoidance of increased emissions at the end of its lifecycle (e.g. to avoid its waste treatment through incineration practices).
- The carbon-negative insulation provider must ensure the sustainable and ethical source of their primary material, with verifications through life cycle analysis. Otherwise, the avoidance of emissions would be the main advantage of this material, but should not be considered as carbon-negative, hindering potentially higher climate impacts that a wide scale adoption of the material could have.

Technology #4: Peatland Restoration

Potential Project for GMCA

For the Greater Manchester context, peatland restoration is presented as one of the key recommended carbon removal solutions due to the reasons summarized below. Although the local authority has limited control over the assets, it can use its influence over the key stakeholders to support restoration efforts. Greater Manchester also has high resource availability, which imply highly scalable and flexible of pilot projects.

Greater Manchester's urban cities are close to both extensive lowland and upland peat, placing it in a unique position to fulfil that role while simultaneously capture the numerous social co-benefits of peatland restoration. SCATTER, a UK city-focused low carbon pathway model, suggests 50-75% peatland in the city region will need to be restored to meet Greater Manchester 2038 carbon neutrality target (Smart et al., 2020). Recent pilot at Greater Manchester has found the lowland peat with an area of 5,029 ha is associated with emissions of 129,730 t $CO_{2\text{-}e}$ /yr and upland peat of 12,480 ha, with associated emissions of between 49,633 and 51,709 t $CO_2\text{-}_e$ / yr. Furthermore, 90% of lowland emissions are derived from three-forms of intensive agriculture (turf production, cropland, intensive grassland). Thus, lowland peat restoration needs to be focused on shifting away from these high-emitting agriculture practices. For instance, a switch from intensive agricultural practices to paludiculture could produce GHG savings in the range of 50-80,000 t CO2-e yr-1 in Greater Manchester. The recently completed Greater Manchester Peat Pilot report analysed what 'restoration' could look like in a GM context, specifically across lowland peat assets.

Main Advantages

- Peatland restoration is vital to restoring the carbon sequester function of peats
- Biodiversity
- Water quality
- Flood prevention
- High mitigation potential and low costs and various co-benefits
- Proven technology: Rewetting and restoring damaged peatlands is a proven technology that has been well developed in projects across the UK and internationally

Barriers, Risks and Policy Considerations

- Lack of economic and policy incentive to switch from intensive farming practices to more sustainable ones (e.g. paludiculture) or other methods to include the natural capital benefits or ecosystem costs to the current business mode
- Misalignment between property ownership and peatland hydrological units, difficult to define project boundaries
- No verification process for the restoration efforts, this lack of clarity translates to uncertainty surrounding carbon pricing
- Lack of market infrastructure for to encourage transition to paludiculture from farmers, and unclear market signal for investors
- General lack of exposure and accessibility to the research, training, know-how, and good practices cases surrounding peatland restoration

- Permanence depends heavily on the continued monitoring and maintenance of restored peatlands.

Technology #5: Enhanced Weathering

Potential Project for GMCA

The Clean Growth Strategy (2017) identifies enhanced weathering as one of the technologies which could be required to achieve greenhouse gas removal. This technology or method can be implemented on a percentage of the arable land in Greater Manchester. According to Nature Greater Manchester, by the end of 2018, there was 9,264 ha of arable land in the region. To avoid further potential risks or barriers, the use of finely crushed volcanic rock is selected instead of olivines, this will allow soil safety regarding potentially high nickel concentrations. The application rate within the range of 10 to 30 tonnes per hectare per year is suggested by academic papers and corroborated by technology developers. This will depend on the types of crops used and the soil composition. The carbon sequestration potential assuming the total area of arable land in Greater Manchester and the aforementioned application rates, is between 5,146 tCO_2 and 41,173 tCO_2 per year. The monitoring of results can be done through inorganic carbon content in soil overtime. The measurements can be collected and developed in collaboration with the University of Manchester.

The co-benefits of implementing this method in Greater Manchester include an increased crop yield (which translates into higher revenue for farmers), higher water retention in soil, and improved soil health. It also supports efforts against increased soil acidity.

GMCA's role should focus on developing public financial mechanisms to support the development of this method in agricultural premises, or consider it to be included in the developing initiatives, such as the Greater Manchester Environment Fund. The creation of strong policy frameworks to incentivise low-carbon agricultural practices that include enhanced weathering as an option are required. The local authorities could overview the engagement with farmers thorough the creation of knowledge sharing workshops and campaigns.

Main Advantages

- Co-benefits for the soil when it is applied to crops: increase of crop yields, and improvement of soil health

- The adoption of this method has low technical barriers, as the practice of applying crushed granular limestone to reverse soil acidification from intensive cropping and the application of other granular fertilisers is already widely extended within the agricultural sector. Therefore, the application of other grainy materials can be done with existing farming and agricultural equipment.

Barriers, Risks and Policy Considerations

- For the olivines implementation, feasibility studies for evaluating the application rate are fundamental; as depending on the type of crops and characteristics of the soil, the amount of nickel released varies. Nickel can be easily mobilised during chemical weathering and can be adsorbed by organic matter. In some areas of the UK, the normal background concentrations of nickel must be preserved under 40mg/kg.
- The farmers and other community engagement and building trust for the adoption of this method, could be a definite barrier for the deployment of this method. Appropriate dissemination of information and social incentives must be presented prior to the implementation. This should include training, workshops and network development. The creation of a strong governance plan must accompany this technology to integrate multiple stakeholders.
- The development and enforcement of clear monitoring and verification frameworks for this method will be required to provide additional financial revenue to the farmers if the technology is supported through external investment (ethical carbon market trading or auctioning mechanisms). The financial support through local governments should be developed in the near-term for the initial adoption of this technology while the monitoring and verification framework is created.
- One of the main barriers for the adoption of this method is the financial context of farmers. The creation of financial incentives or policy instruments to support the adoption of this method should be developed to ensure the success of this method, which can include mechanisms through tax reduction or public funding for projects. Currently, studies are being undertaken by multiple institutions in the UK, such as ClimateXChange, to understand how to overcome the financial barriers to farmers for its successful deployment.
- The mitigation potential will only have similar results every year, if material is continuously added to the soil every year or every couple of years. The enhanced weathering of the material added can still be active in future years, but the reaction may be completed within 10 to 20 years depending on the granule size and the biogeochemical processes of the soil.
- This process is finite in the long-term (decades to centuries), as the soil reaches a saturation point.

Technology #5: Carbon Mineralisation in Concrete

Potential Project for GMCA

Trafford Park is selected to be the optimal location for the concrete-curing pilot. It is an Industrial Park of 1,330 businesses that encompass an array of different industries that could provide significant CO_2 emissions. Currently, one concrete manufacturer is identified at this location. Initial research also identified manufacturers at this location, but more studies are needed to determine the specification and capacity of these manufacturers. Additionally, Trafford Park has steel fabrication and manufacturing businesses, which can supply the slag needed for alternative carbon mineralisation technologies. For this pilot project, concrete curing is the selected carbon mineralisation process for captured CO_2 utilisation. The pilot is based around one concrete manufacturer at Trafford Park.

Potential technology provider could be a Canadian-based company CarbonCure that retrofit curing systems for concrete plants. It is one of the first companies with commercialised carbon curing technology. With captured CO_2 being the key component, the proximity to CO_2 source is vital. According to CarbonCure, the bulk of the cost would be the transportation and storage of captured CO_2. A system where the emission source is close to the concrete plant could lower the costs significantly. Furthermore, a strategic partnership between waste-CO_2 supplier and the concrete manufacturer needs to be established to ensure a steady supply of CO_2.

The future scale-up of the pilot could be rolled out in a phased approach. For example, retrofitting the concrete curing unit with other concrete manufactures at Trafford Park. Incentives could also be put in place to encourage decreasing embodied carbon in new construction in GM.

Main Advantages

- Advance the development of CCUS
- Turning captured emissions into a resource to create products can create additional revenue streams
- Deployment ready in North America
- Increased compressive strength for concrete product

Barriers, Risks and Policy Considerations

- Transportation of captured emissions accounts for the bulk of costs associated with this pilot, therefore it is necessary to establish an emission source close to the concrete plant
- Lack of an UK or regional carbon market to offer an economic incentive for the concrete manufacturer
- Regulation incentives are required to encourage the uptake of carbon-mineralised concrete
- A lack of business case of demonstrating this technology in the UK
- Lack of national or local policies to accelerate the adoption of such low carbon concrete in the construction sector
- Carbon storage sites such as geological storage can be difficult to access in an urban setting.

Technology #6: Micro Carbon Capture and Utilisation Technology

Potential Project for GMCA

According to the CDDP Stage 1 report for decarbonisation of heat in greater Manchester (2020), 86% of the buildings in Greater Manchester use natural gas; therefore, are eligible for this technology. Pilot projects with this technology have been done with at least ten devices at a time to ensure a considerable production of the byproduct to integrate into an external supply chain; eventually scaling-up in the area as the networks are created for faster deployment. The project proposed can take place in social housing buildings where local authorities have higher control and level of influence. This pilot would be implemented in ten buildings where the boilers have been recently updated, being not cost-effective its immediate or near-term replacement for other heating options. If the results obtained in the deployment in the US and Canada are extrapolated, then the potential carbon removal of this project would be of around $7tCO_{2e}$ per year. The results from the CDDP reports can be used as a guidance for the area selection. Trafford Park has multiple businesses that use potassium carbonate as raw material. These businesses (e.g. cosmetic companies) could be potential buyers of the byproduct.

The co-benefits of this technology applied to Greater Manchester include an alternative for decarbonising targeted heating systems that cannot be updated in the near-term, the potential return of investment, the impact to communities' carbon footprint and businesses awareness of carbon capture and utilisation opportunities.

GMCA's role would need to be focused on supervising the area chosen for the project development, engaging with the community, strengthening the network with the industrial businesses and overviewing the implementation of the project. GMCA should evaluate the potential scaling up of the pilot project to target other relevant areas in the region.

Main Advantages

- It can serve as a transitional technology for gas boilers that have been replaced in recent years
- It provides the possibility of selling the by-product (potassium carbonate) to companies that want to use it as part of their supply chain with carbon capture and utilisation benefits with potential slow Return of Investment

Barriers, Risks and Policy Considerations

- The technology has been developed and implemented in the US and Canada, this means that the calculations results, and carbon sequestration potential could differ when applied in the UK. This technology is starting to be deployed in Japan, and although currently it is being exported from Canada, it will have its own production line in Japan, the considerations of the carbon footprint from travel need to be raised and considered.
- This technology only provides CO_2 sequestration in boilers fueled with natural gas. Therefore, its main aim should be of serving the purpose of a transitional technology within this decade.
- The MCCU requires a buyer for the byproduct for it to have a Return of Investment. The buyer analysis needs to be ethically considered, to have longevity of the byproduct as the primary focus. The managing body of the technology needs to have a strong partnership with industrial business in the area to initiate the transaction; an appropriate business case creation is mandatory prior to its implementation.
- There needs to be social engagement and trust from the communities or businesses prior to the technology deployment to ensure a cooperative process.

Technology #6: Bio-Energy with Carbon Capture and Storage (BECCS)

Potential Project for GMCA

The Committee on Climate Change (CCC) has established that carbon capture and storage needs to be deployed by 2030 with a removal per annum of 10 $MtCO_2$. They have expressed the need for the removal of 67MtCO2 through BECCS by 2050. This can only be achieved if 22 plants of 500MW are deployed across the UK (Donnison et al., 2020). Carbon Capture Utilisation and Storage (CCUS) was highlighted in the 10 Point Plan released in November 2020. The plan commits to making the UK “a world-leader in technology to capture and store harmful emissions away from the atmosphere" with a target of removing 10 $MtCO_2$ by 2030.

The proposed location for the development of BECCS in Greater Manchester is at Carrington Power Station, which is a gas-fired Combined Cycle Gas Turbine power station. It has a capacity of 884 MW for electricity production at a 58% efficiency rate. This plant can be retrofitted with the integration of bioenergy and carbon capture facilities (500MW due to efficiency purposes demonstrated via case studies and pilot projects). Life Cycle Analysis of the plant needs to be commissioned through the planning specifications, to ensure that negative emissions occur; as the chosen biomass- feedstock and additional energy penalties could make the project not viable under specific conditions.

In this project, it is proposed the use of the captured carbon and store it through processes of mineralisation, or through low-carbon concrete and concrete aggregates. The rest of the captured carbon can be integrated into the supply chain of industries in the area (e.g. Trafford Park industries). Only locally sourced feedstock for bioenergy is considered in this proposal due to a lower carbon footprint and feedstock transportation costs. A 500 MW plant operating at 85% capacity factor requires around 2.33MT of feedstock (Donnison et al, 2020).

For a 500 MW plant using locally sourced bioenergy feedstock, the emissions captured annually is estimated to be an average of 2.99 Mt CO_2 with 3.72 TWh electricity (Donnison et al, 2020). This estimate considers the whole system, including the carbon uptake from feedstock. Therefore, the double counting of emissions needs to be evaluated and avoided. The estimate could change due to the conversion factors being modified as technology progresses, and the boundaries of calculation can also influence the final results of mitigation potential.

GMCA's role should focus on developing public financial mechanisms to support the development of this technology. The creation of strong policy frameworks to regulate the ethical feedstock procurement is required for the implementation of this method. The local authority should engage in potential discussions to evaluate feasibility of deployment within the next decade. The creation of campaigns or engagements with society and communities is relevant for the social acceptance of the project. The development of strong partnerships with AlignCCUS and industry stakeholders is relevant for the development of BECCS in areas with limited access to geological reservoirs, such as Greater Manchester. GMCA should align their current policies and initiatives to the 10 Points Plan for Green Recovery and the CCC recommendations. BECCS and CCUS need to be enabled as a deployment priority within the next decade.

Main Advantages

- It has a high mitigation potential
- The decarbonisation of energy sector while meeting energy needs

- It has low operational costs
- It has the potential of creation of green jobs
- BECCS enables the use of carbon as a good in supply chains for industries in the area (CCUS approach)

Main Barriers, Risks and Policy Considerations

- The barriers and risks associated with BECCS include appropriate carbon dioxide transportation, high investment costs, and funding required, social acceptance due to unfavourable social perceptions of CCS, and supply chain creation across sectors that could favour the feedstock supply or could be favoured by the integration into their own supply chain of the carbon dioxide that has been captured. This is key to ensure the scaling up of projects and the support of external stakeholders.
- One of the main barriers to effective storage of carbon relies on the lack of infrastructure to geological reservoirs nearby the project development area. Therefore, the integration of the system when the infrastructure to offshore geological reservoirs occurs, or CCUS needs to be taken into consideration. Other storage options can be through mineral carbonation or low-carbon concrete options.
- The biomass/feedstock chosen must be supplied by nearby regions to ensure low emissions due to transportation. It must be carefully selected to ensure carbon negativity in the overall process, as intensive energy requirements can come from biomass with high water content. The biomass must be sustainably supplied, to avoid land-use changes and food competition by using crops as feedstock. The development of robust policy frameworks and procedures for the feedstock procurement are required to be in place prior to the implementation of the plant.
- The skilled labor required to undertake the development of this project needs to be assessed carefully, as a wide range of experts will be required to install and keep the plant ongoing with risk minimisation objectives.
- Considerations of land availability, profitability, flue gas properties, the technology used for retrofitting, energy conversion processes, and solvent degradation, need to be acknowledged for the development of the project.
- The development of funding sources is determinant for the deployment of this technology at the scale that is required.

7. Other Potential Solutions

This section highlights the technologies or schemes that could help support and enable the ongoing and proposed carbon removal solutions by suggesting a framework or the adoption of ancillary technologies. These solutions can contribute to an enabling environment that can help mitigate the barriers and maximise the potential of current and proposed carbon removal efforts.

Forestry with Supporting Technologies for Planting, Monitoring and Verification

Technology Details and Relevance for Greater Manchester

Forestation is a carbon removal method that includes reforestation and afforestation strategies. Trees are natural carbon sinks. They are vital for climate system regulation with a direct impact on atmospheric factors.

The main challenges for forestry projects are the human capital required for plantation and the intricacies of monitoring due to the complexities of the ecosystem. Therefore, technologies could be considered to support these efforts.

These include drones that plant biodegradable capsules with germinated seeds at one seed per second or per two-seconds (depending on the company). This technology makes planting more cost-efficient and faster. In addition, it supports the adequate development of the seedlings by constant monitoring with the use of the drones. Drones and remote sensing can also be used during the monitoring part. Through the analysis of imageries or the integration of sensors, a diverse number of characteristics can be analysed to understand the changes in carbon stock, humidity, tree cover, biodiversity, etc.

Greater Manchester region has developed a forestation strategy called “All our Trees”. It establishes ambitious goals of planting at least 1 million trees by 2024 and further 2 million by 2050. This strategy has been developed in order to help Greater Manchester to contribute to the achievement of its climate targets. This implies, that monitoring and verification processes and high investment of time and funding for planting will be required to integrate millions of trees within the upcoming decades. The technologies could support this forestry initiative or other relevant initiatives, such as the Northern Forest, the Trees for Climate project, among other forestry efforts.

The UK Forestry Commission released a report in January 2019, stating afforestation costs for different regions in the UK. It was estimated that in England, the planting and fencing would require a total of

5095 GBP per ha, with a government administration of 637 GBP per ha. This is considering normal planting methods.

The use of drones for the planting phase has a cost of 0.58 GBP per tree, or cheaper depending on the scale of the project. Considering the recommendations by British Hardwood Tree Nursery, where there could be planted up to 4,444 trees in the hectare of the pilot study. This resulted in an estimated cost within the range of 2500 to 3000 GBP. The following barriers and risks need to be acknowledged and managed appropriately:

- Land ownership can be a constraint if the project is not developed within an area owned by the local authority
- The integration of this project under the framework of another initiative could be challenging by dealing with multiple stakeholders; a close collaboration with partners will be required
- The monitoring must continue for several years to ensure the optimal carbon sequestration and the continuous support to biodiversity opportunities; while optimal policy frameworks to ensure long-term management must be considered
- The integration of these methods could be disruptive to forestry organisations that have developed fixed schemes with human capital-based plantations; their engagement and acceptance of this initiative is key for its success

Relevant Case Study

CASE STUDY - FORESTRY MANAGEMENT SUPPORTING TECHNOLOGIES

TECHNOLOGY ENABLED LAND REHABILITATION IN GLENCORE

Figure 5. Glencore restoration project with aerial seeding

Dendra system is a UK-based company that seeks to drive faster restoration for environment and community at scale with enabling technologies. Their project with Glencore managed to restore 850 ha of land managed by mining operations.

Dendra system incorporated automated aerial seeding and mapping technologies to Glencore's ongoing rehabilitation program to address 3 primary needs: 1) enable access across challenging terrains; 2) improve ground-level site safety; 3) reduce erosion risk. Dendra System deployed drones for aerial reseeding of woodland seed mixes and pasture mixes. Project also included pre-seeding mapping and germination monitoring. In addition to increased seeding efficiency, there are added benefits of decreased soil compaction and disturbance (Dendra, 2020).

Figure 5. Glencore Case study

Carbon Market for Greater Manchester

Technology Details and Relevance for Greater Manchester

This report proposes the Greater Manchester Carbon Market Scheme to drive resources and funding towards peatland restoration projects. This initiative can be designed as a natural continuation of the Greater Manchester Peat Pilot. Furthermore, it can help address the funding and engagement barriers typically associated with large scale peat restoration efforts. The funding scheme could also be scaled up to include other nature-based carbon removal projects taking place in Greater Manchester. Blockchain technology can be used to accelerate the transactions and lower transactions costs, and ensure transparency. This scheme also encourages citizen engagement, more exposure on peatland and establish close collaborative relationship with farmers. Figure 5 below illustrates the basic set-up of a carbon-market scheme.

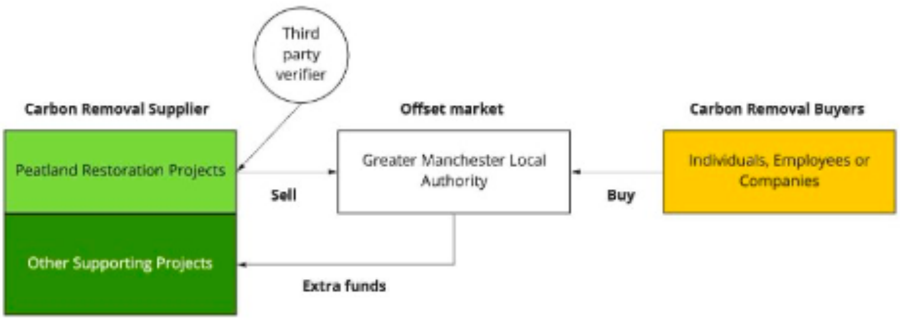


Figure 6. Example Carbon-market setup

Greater Manchester local authority can act as a marketplace for carbon removal certificates; this can be done alternatively through the partnership of a third-party organisation (eg. Nori, Puro.earth). In this case, the local authority of Greater Manchester buys certificates from peatland projects and sells it to individuals, employees or businesses. Peatland restoration projects need to be verified by a third-party verifier to give transparency and credibility of the projects. Those supporting projects which do not qualify for certificates can be supported financially by the extra income from the offset market. At the other end of the model, individuals and employees can purchase to offset transportation while businesses can offset scope emissions.

Peatland restoration costs on average £1009 / ha. The costs vary significantly due to the wide array of restoration strategies in use. Carbon price also varies with different offset projects. For this pilot, the carbon removal certificate is set at £15/tCO_2 removed.

Table 8 lists a portfolio of potential peat projects aiming to addresses challenges of peat restoration from all angles. Farm-level projects at lowland offers restoration solutions unique to the characteristics of the targeted peat area. Innovative solutions are also encouraged and supported with this scheme. For example, demonstration pilots with Manchester University or UK Biochar Centre can explore the application of biochar on peatland.

TABLE 8. EXAMPLE PORTFOLIO OF PEATLAND PROJECTS

PROJECTS	**DETAILS**
Peatland restoration projects	• Qualified for carbon removal certificates • Farm-level project (lowland) • Biodiversity restoration (highland) • Demonstration pilots with universities
Supporting projects	• Not qualified for carbon removal certificates • Farmer training programs on paludiculture • Citizen engagement campaigns • Peatland modelling and mapping initiatives • Emission quantification initiatives

Relevant Pilot

CASE STUDY - CARBON REMOVAL MARKETPLACE FOR PROJECTS IN USA
TO FOSTER CO-CREATION FOR LOCAL CARBON REMOVAL PROJECTS

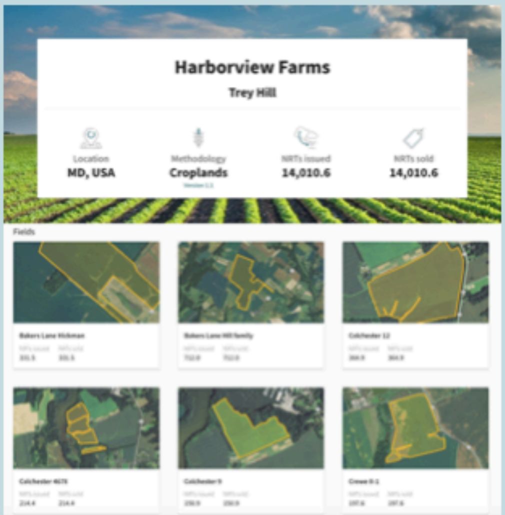


Figure 23. Example carbon removal project (Nori 2020)

Nori is an US-based carbon removal marketplace backed by blockchain technology. It seeks to galvanise farmers in USA to adopt more soil management and crop production practices that can draw carbon from the air and store it in the soil. The carbon removal marketplace provides social integration that enables farmers to manage their land sustainably while providing them an additional source of income through carbon certificates. The collaboration within the organisation and the farmers is close, as the verification of the projects is done periodically and through blockchain technologies to ensure transparency in their process. Currently, they have developed a standardised methodology for croplands, which included provisions for eligibility, monitoring, verification, report etc. The carbon removal suppliers can extend to world's food producers, pasture and forest land managers, developers of direct air capture technologies, and many more. It engages with farmers to provide training about land management (Nori, 2020).

Figure 7

Trafford Park: Carbon-Negative Hub

Technology Details and Relevance for Greater Manchester

The recently announced Ten Point Plan for a Green Industrial Revolution shined a spotlight on CCUS (clusters) and its role in industrial decarbonisation. Several larger industrial parks in the UK, such as Humber has received funding from the government to test the viability of CCUS innovations. These recent developments sent a clear signal to the market and opens windows of opportunity for bottomup approaches to reginal CCUS deployment. Greater Manchester can seize this opportunity take the lead in CCUS and low-carbon innovations.

Trafford Park is an industrial park that has favourable characteristics for its development into a carbon-neutral or Carbon-Negative hub. It has 1,330 businesses that encompass an array of different industries. The basic set-up of a carbon-negative hub is based on the concept of industrial symbiosis where loops of technical or biological materials are created while the leakage and waste in the loops are minimised. Carbon emissions captured from industrial processes can be introduced into the loop and be used as a resource to create new products. The carbon source in Trafford Park can come from manufacturing processes, such as food and cement manufacturing. Other carbon sources could potentially come from a BECCS plant, from the Micro Carbon Capture and Utilisation device integrated into heating systems or from the already existent power station in Carrington. The utilisation of the carbon captured can have applicability in a diverse range of industries. These include glass and steel production (with the use of technologies, such as C-Carbon), the use in the built environment industry with concrete or aggregates, its use in agricultural products in the manufacture of fertilisers, its use in the polymer industry, with the manufacture of plastics and plastic packaging, or in the use of the cosmetic industry as part of soap, shampoos or detergents. Also, the waste obtained through steel production can be used to develop aggregates used in concrete manufacturing. In Trafford Park, there are industries that cover each of those options and could be included in the development of the project. The inclusion of offsetting scheme options for employees and businesses is proposed for the development and support of nature-based solutions in Greater Manchester.

This pilot project aims for the development of synergies and collaboration within the companies in Trafford Park that could be expanded to have partnerships with other key stakeholders in the Greater Manchester region.

Some financial opportunities could make this initiative attractive for the companies involved and give them an incentive to promote the project development. The uptake of Carbon Capture and Utilisation (CCUS) technology options becomes more lucrative through additional revenue streams, which would imply less dependence on government funding. Another benefit this project could bring to the companies involved is the increased visibility as change makers and innovators in the carbon neutrality space. The Greater Manchester area could also benefit from this increased exposure with its strong commitment to net-zero targets through creative solutions.

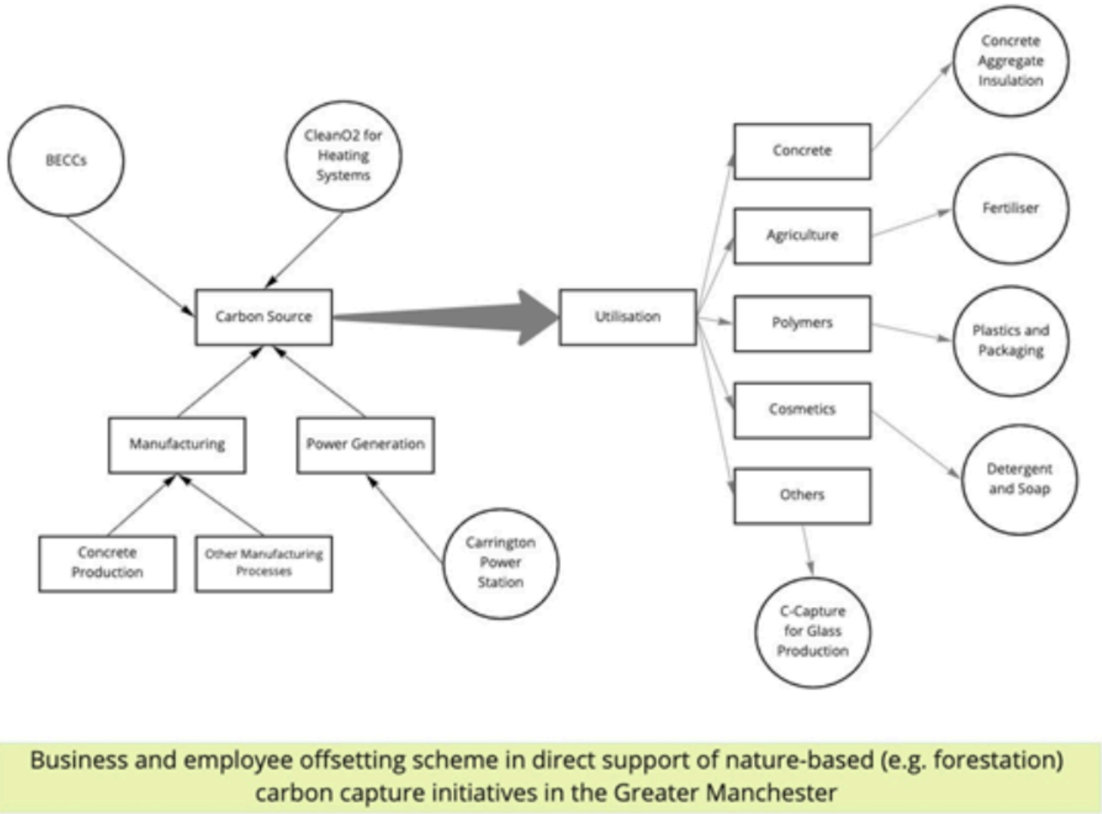


Figure 8. Offsetting schemes for NETs in Greater Manchester

The potential list of technologies appropriate for the Trafford context are:

- Concrete and carbon aggregates
- C-Capture technology for glass and steel companies
- CleanO2: Micro Carbon Capture and Utilisation technology for heating systems
- Polymers production and carbon-based catalysers

Key Considerations

A key consideration for a Carbon-Negative Hub is the need for an independent governance structure with key industry representatives and CCUS specialists for monitoring and implementation purposes. Active engagement with actors open to CCUS should be promoted through workshops and consultations. Another method to promote active engagement is to highlight the social and financial incentives of CCUS. Only with a good governance structure and close relationship with a broad set of stakeholders the hub may establish a circular ecosystem that can reuse captured carbon as a resource.

Cost reduction is another important factor for the success of the hub. That can be achieved by minimising transportation and storage costs for captured carbon and the reuse of existing infrastructure. Finally, carbon capture technologies need to be carefully selected to ensure the captured carbon is in a chemical form that is readily compatible with other processes for its further utilisation.

CCUS is considered within the negative emission technologies framework as some options of utilisation provide opportunities for long-term sequestration. In addition, when evaluating the life cycle analysis of the products created through CCUS systems, the carbon accounting can provide insights of negative emissions as shown by products developed through these methods.

Environmental Benefits

- Carbon emissions reduction from the manufacturing process and energy production
- The carbon from the emission source tends to undergo chemical processes to create more stable forms of carbon that will be preserved in solid and liquid states. Mitigating the possibilities of its release into the atmosphere.
- Another benefit comes from the use of a specific technology where waste is involved. By using sewage sludge as new energy sources or valuable chemical forms, the reduction of the waste going into landfills is decreased.
- Accelerated pathway to net-zero targets. The inclusion of carbon-negative elements into the supply chain of a company, allows them to increase mitigation efforts within their scope 3 emissions, which tend to be the most challenging one for businesses.
- Reduction of emissions through the local transportation of carbon-based resources for the manufacturing process.

Business and Economic Benefits

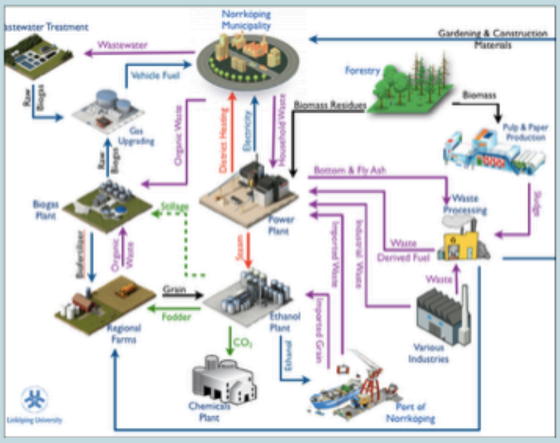
- Provide additional revenue streams from captured carbon utilisation into high-value products. An example of this is the use of the potassium carbonate created by the use of the Micro Carbon Capture and Utilisation and its further integration in the supply chain of cosmetic companies.
- Projects generated by the partnership and collaboration of relevant industry stakeholders, without it being fully reliant on government funding.
- This initiative could get high visibility, social engagement, and investment opportunities as the first carbon-neutral or carbon-negative hub in Europe with a carbon circularity approach.

- The cooperation within different industries can contribute to having a reduction in energy usage. And the local generation of resources can also contribute to a cost reduction in transportation.
- Some of the carbon elements that result as by-products of manufacturing processes can be utilised rather than being considered waste. This will avoid some gate fees of the waste disposal.
- With the development of this initiative, multiple pilot projects could be implemented with time alignment. Therefore, the management of multiple carbon-negative projects could be done as a whole, decreasing labour costs.

Relevant Pilot

CASE STUDY - NORRKÖPING INDUSTRIAL SYMBIOSIS, SWEDEN

BEST PRACTICE OF MUNICIPALITY AND INDUSTRY CO-CREATION



Norrköping Industrial Symbiosis Network

The Norrköping Industrial Symbiosis was set up in Norrköping, a historically industrial centre known for its textile industries. The city is located at the inlet from the Baltic Sea and is home to important logistic services and has expended in recent decades to include other industries. The main goal of this symbiosis is to explore the synergy between the existing industries, and encourage resources recycle and reutilisation. The close proximity to Linköping University allows collaboration with local industries for R&D. This symbiosis system was started through self-organisation rather than a planned development. With the symbiosis research unit and the municipality as the main facilitators, the initial industrial network was established with three dominant companies E.ON (CHP plant), Agroetanol (bioethanol production) and Svensk Biogas. This symbiosis system plans to capture CO2 exhaust from agroethanol manufacturing to be used in other industries.

Figure 9. Industrial Symbiosis Case Study

8. Innovation

The following table showcases a range of projects that are in development in the UK. They explore CCUS technologies with viable products or supporting technologies for carbon removal efforts. Such products could be applicable for use in industry clusters.

TABLE 9. OPPORTUNITIES FOR CCUS

NAME	CITY	PRODUCT
Carbon Capture Machine	Aberdeen	• Producing solid carbonate feedstocks and products
Econic Technologies	Macclesfield	• Developing catalytic technology for manufacturing polymers from waste carbon dioxide
Cambridge Carbon Capture	Cambridge	• Patented CO2LOC technology: The mineralization process permanently locks the sequestered CO2 in rock form and due to its flexibility, can be utilized across a range of industries.
Carbon8 Systems	Suffolk	• Chemical processes which treats industrial residues using captured CO2 to create low-carbon products
Dendra Systems	Oxford	• Industrial-scale reforestation using drones and air-fired planting systems
CCm Technologies	Swindon	• Technology to efficiently use industrially segmented CO2 and to safely convert it into materials with a commercial value including fertiliser and plastics
Carbon Clean Solutions	London	• Custom carbon capture solutions for industrial plants. Modular systems and solvents which significantly reduces the costs and environmental impacts of existing CO2 capture techniques.
Calcium Solutions	London	Purifies calcium-based products, including gypsum, phosophogypsum and calcium carbonates.
C-Capture	Leeds	• Capture CO2 from power station flue gas, applicable to power stations, cement plants, hydrogen production facilities, steel or glass making factories, or natural gas upgrading plants.

Oxford University Research Group	Oxford	• Creation of jet fuel from captured CO2 which is then processed chemically. Highly efficient with lower costs of traditional fuels. In research stages.
HyNet North West	Liverpool	• Re-use of Liverpool Bay oil and gas fields and related infrastructure to deploy CCUS at scale. Estimated CO2 storage capacity of 130 million tonnes.
University of Sheffield, PACT and Align CCUS	Partnership, multiple locations	• Industrial and academic research and development support to promote and accelerate the commercialisation of carbon capture technologies. PACT facilities to be used for research into solvents for CO2 capture from natural gas.

9. Scale of Impact of the Proposed Measures

Scope and Background

Greater Manchester Combined Authority reported in 2019-2020 a number of 12,766,352 tCO_2 emissions of Scope 1 & 2, and of 15,617,021.86 tCO_2 considering scope 1,2 & 3 (CDP, 2019). GMCA has as baseline year of 1990 for their net-zero targets, with a consideration of base year emissions of 21,200,000 tCO_2 and a percentage reduction target of 97.3% by 2038. In their CDP report, it is mentioned that the pathways created by the Tyndall Centre are followed to ensure a fair share of carbon emissions following the carbon budget framework. This would account for a total of residual emissions of 75ktCO_2 according to the Tyndall Centre report. This value, even if not a projection, has been the guideline and background (as part of the emission pathways) for the development of climate policies and targets within the Greater Manchester context.

The scope of this strategy is to support the management of the potential array of residual emissions that could remain after traditional mitigation efforts and societal change have been implemented. The use of the carbon markets and negative emission technologies is commonly developed to target the residual emissions or the carbon gap, as the last compound for the integral strategy. Residual emissions could be especially challenging if not mitigated through alternative methods, such as through offsetting schemes or in situ carbon removal approaches. These alternative methods are not intended to substitute traditional mitigation strategies that lead to societal change; on the contrary, they are required and expected to complement these social transitions. Therefore, the understanding of the potential role that negative emission technologies could have in the overall strategy for a net-zero Greater Manchester to mitigate its residual emissions is vital for the achievement of regional carbon neutrality.

It is common practice that cities around the world evaluate their potential residual emissions within the range of 10% to 20% of their baseline year emissions (see table below).

Table 10. Residual emissions comparison across different cities

City/Region	Residual Emissions (unit of CO_2 per year)	Percentage of emissions (of their baseline year)	Target year for carbon neutrality
Greater Manchester [a]	75 kt	<5%[a]	2038[a]
Bristol [b]	750 kt	10%[i]	2030[i]
Paris (outer region) [c,d]	>4Mt	20%[c,i]	2050[c,i]

Copenhagen [e]	500 kt	20%[i]	2025[i]
New York [f]	8.9 Mt	15%[i]	2050[i]
Seattle [g,h]	677 kt	10%[i]	2050[i]
[a]Tyndall Centre, 2018; [b]City of Bristol, 2020; [c]City of Paris , 2020; [d]Ibrahim, N., 2012; [e]European Green Capital, 2012; [f]City of New York, 2014; [g]Government of Seattle, 2008; [h]Seattle City Council, 2013; [i]Balouktsi, M., 2020.			

Therefore, the scenarios proposed will encompass the ranges between 75ktCO_2 up to 2.1MtCO_2 (10% of baseline year emissions).

Scenarios

Three scenarios will be developed under the integration of a portfolio of relevant technologies that would be required for achieving mitigation of a specific number of residual emissions. The first scenario will encompass a low-emissions panorama with 75ktCO_2, the second scenario will portray a mid-emissions scenario with 250ktCO_2, and the third scenario will showcase the options for a high-emissions panorama of over 750ktCO_2 (including 2.1MtCO_2).

Scenario 1

The first scenario considers the residual emissions proposed for Greater Manchester by the Tyndall Centre. It includes the continuation of the forestry efforts already being undertaken by Greater Manchester through the Trees for Climate initiative, and the target of planting 500 ha in the upcoming year; using the figure of 10 tCO_2 per ha per year suggested by the UK Forestry Commission for carbon uptake of temperate forests (it is important to note that this carbon uptake may vary across the lifetime of the trees, but it is used as an average number). The percentage is low as the emissions and sequestration are developed assuming yearly numbers. While forests can sequester significant amount of carbon dioxide but throughout a long period of time and depending on their growth phase and management. Projections from the peatlands restoration is considered with its lowest value in the potential range (from the figures provided by Great Manchester Wetlands Nature Improvement Area Partnership and the Wildlife Trust); which will follow the same considerations as enhanced weathering of lowest potential numbers consideration, with the lowest application ratio. Two medium-sized biochar plants are proposed, the biochar will have to be employed as part of more varied initiatives rather than just playing a key role in soil (e.g. use for water remediation, etc.); under this scenario, potential feedstock requirements of green city waste could be required for the second biochar plant. The integration of carbon capture gardens through mineralisation processes (10 ha) and the implementation of carbon sequestration methods in concrete will be essential for the target achievement. The use of nature-based solutions and soil-based methods will be enough to manage residual emissions under this scenario.

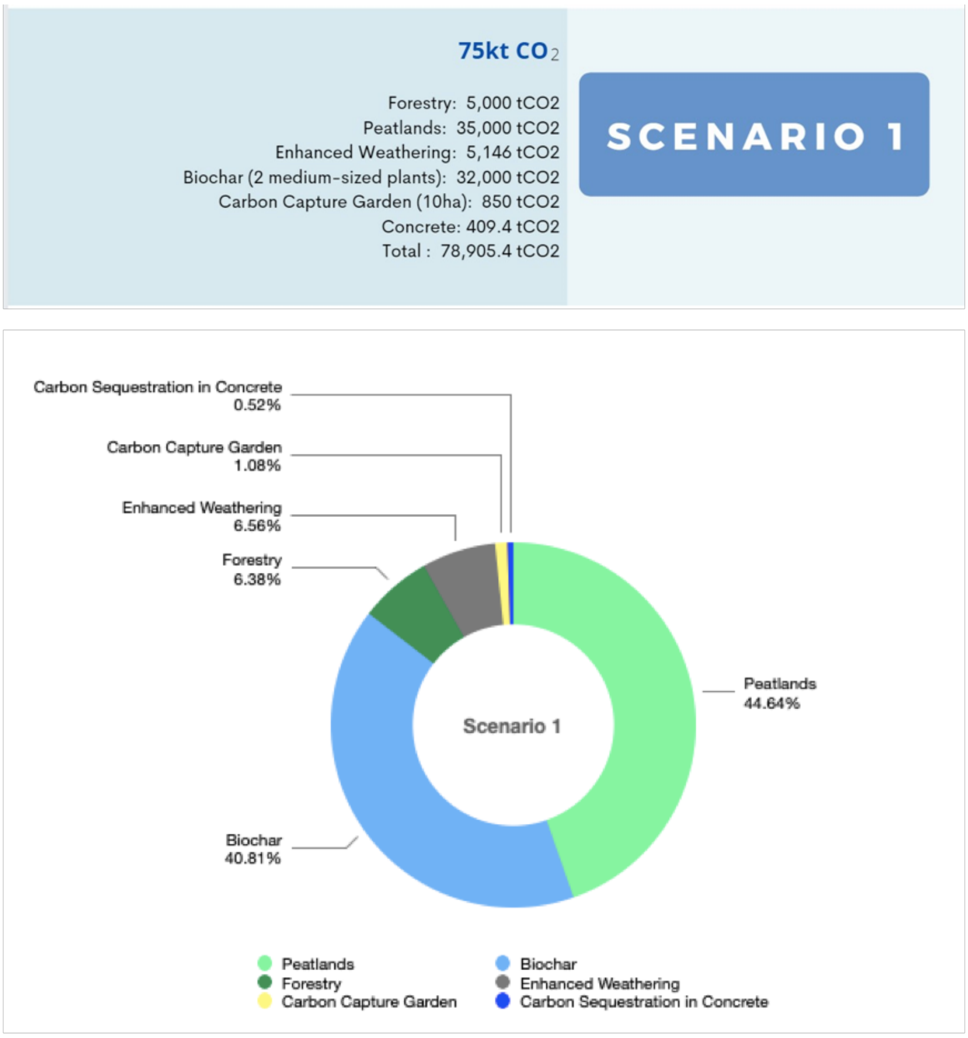


Figure 10. Scenario 1

Scenario 2

The second scenario considers a target of 250ktCO_2 as residual emissions. This scenario includes an assumption of double the efforts of the Trees for Climate initiative portrayed in scenario 1, this could theoretically be achieved with either planting double the area, or choosing tree species with higher carbon sequestration potential. The peatlands restoration will be considered as reaching almost its highest value in the potential carbon sequestration range. Enhanced weathering will be expected to be implemented with higher application rates of silicate-material. For biochar, the characteristics remain the same as under scenario 1. The integration of carbon capture gardens through mineralisation processes will require a higher amount of land (50 ha). The carbon sequestration methods in concrete will remain the same as under scenario 1, and the use of 20 units of Micro Carbon Capture and

Utilisation (MCCU) devices is considered. The increased ambitions of expanding nature-based solutions are expected as part of the societal change required to achieve this target, to avoid over reliance on engineering-methods. The integration of a BECCS plant (working at low capacity) with the integration of CCUS in Trafford Park is proposed to be implemented under this scenario. The use of engineering-based solutions is required to manage a fraction of the residual emissions.

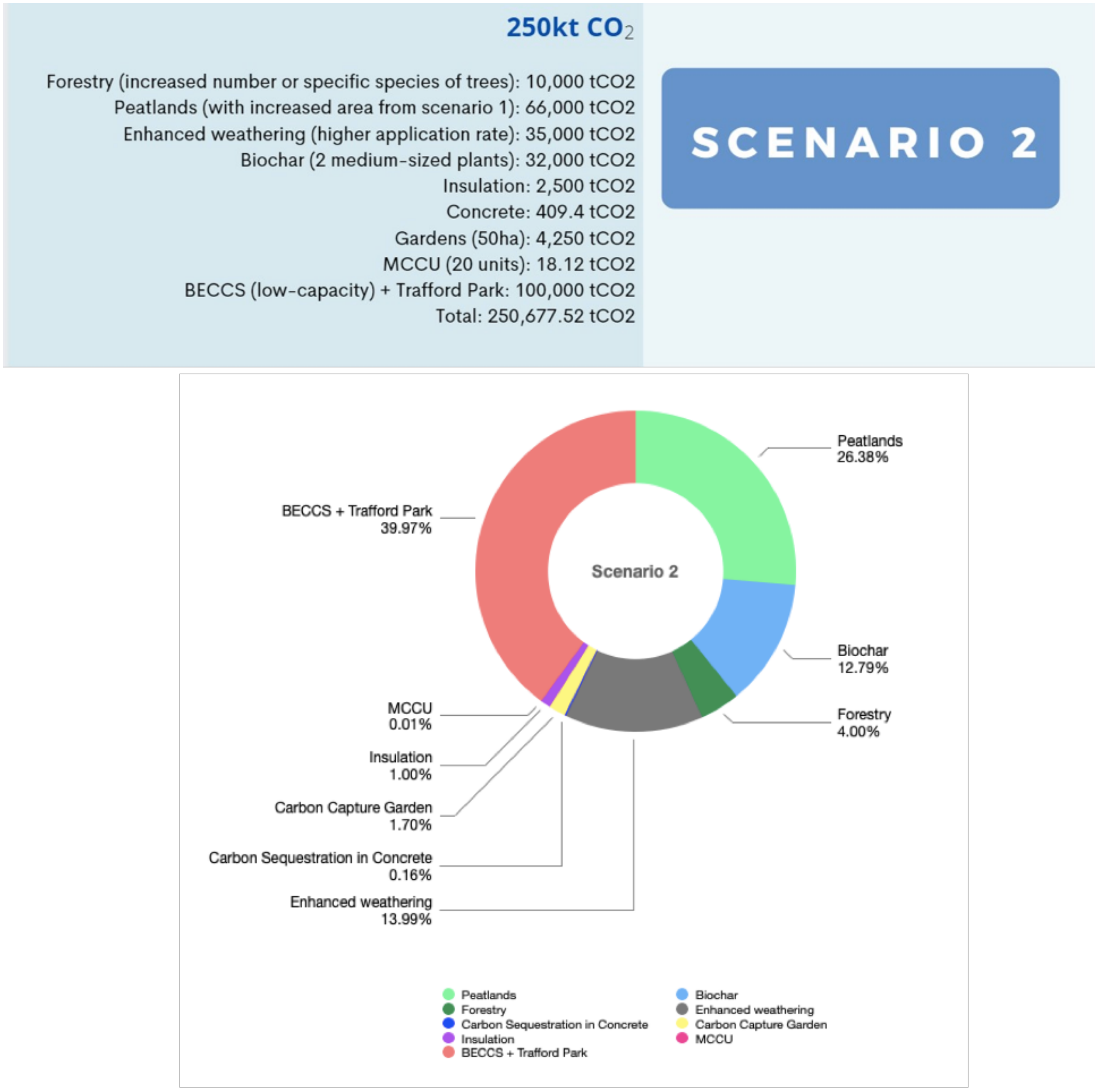
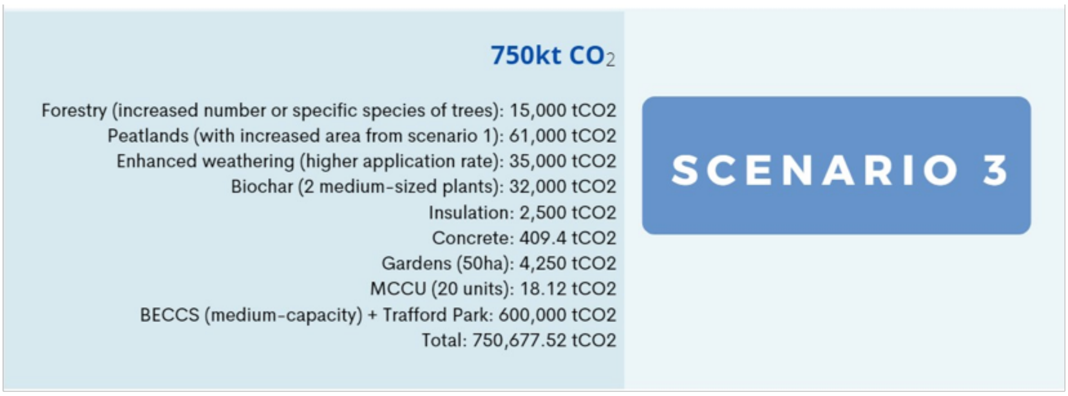


Figure 11.. Scenario 2

Scenario 3

The third scenario considers a target of 750ktCO_2 but can be extrapolated to cases where residual emissions are higher up to over 3MtCO_2 (including the 10% consideration of residual emissions of 2.1MtCO_2). This scenario includes an assumption of triple the efforts of the Trees for Climate initiative portrayed in scenario 1, It describes the development of the other technologies as under scenario 2, only adjusting the capacity of the BECCS plant as required, relying heavily on engineering-based solutions. Under more ambitious requirements of higher residual emissions, in addition to the increase of BECCS capacity, increased forestry can be explored (considering land availability as a potential limitation), a wider adoption of carbon-negative insulation materials could be implemented, and increased areas for carbon capture gardens.



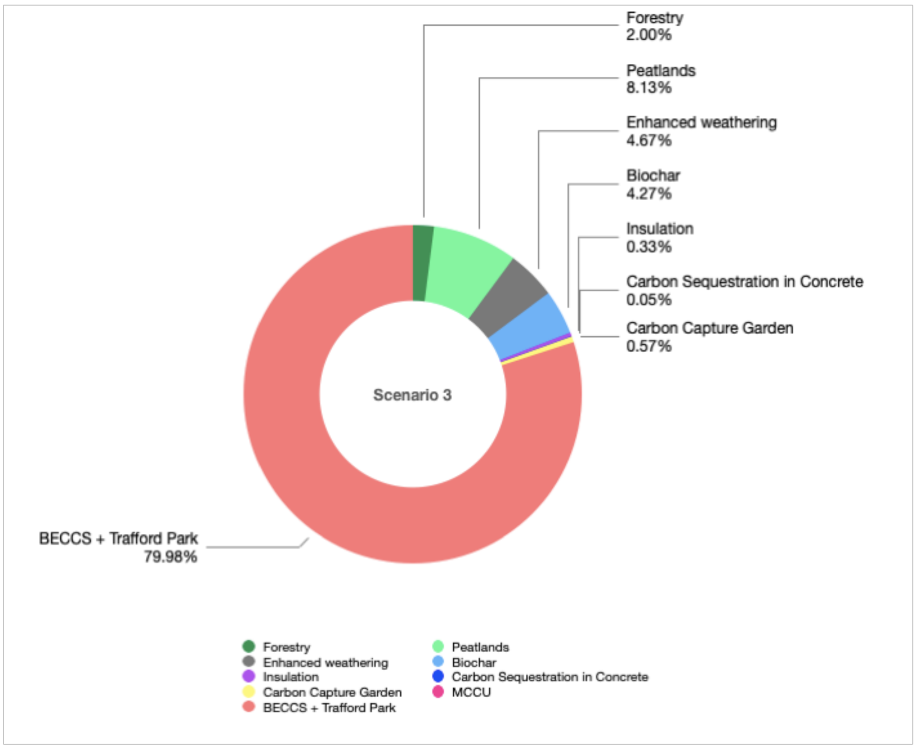


Figure 12.. Scenario 3

Key Findings from the Scenarios

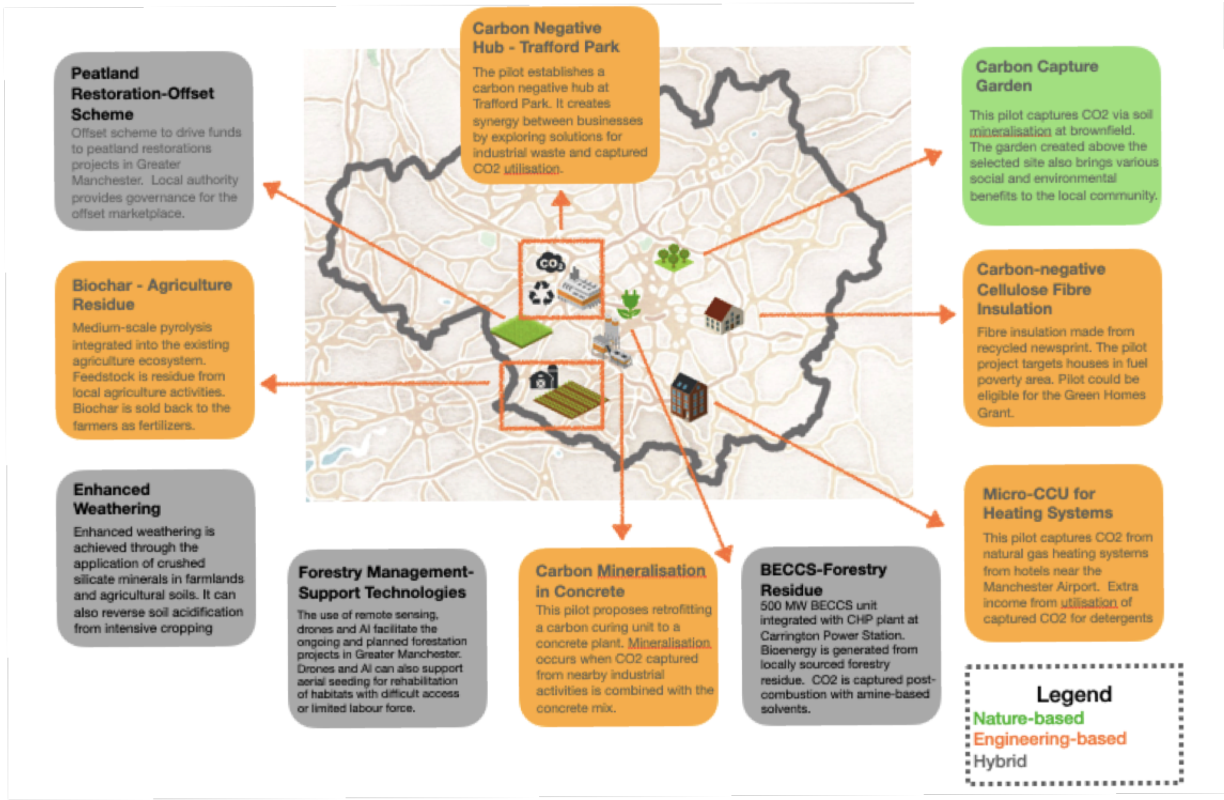
- For scenarios of and over 250ktCO_2 emissions the reliance of engineering-based solutions will be required due to the limitations of natured-based solutions, highlighting land availability as the main constraint factor. This includes forestry efforts, biochar, peatlands restoration and enhanced weathering.
- Nature-based solutions will be relevant only if societal change and energy transition has impactful enough results in the trajectory of mitigation of emissions; therefore, minimising the role of residual emissions to under 250ktCO_2
- Main opportunities to currently expand for carbon capture and sequestration are:
    - Forestry
    - Ensure peatlands restoration to its maximum capacity
    - Biochar application
    - Carbon-negative insulation
    - Carbon capture gardens
    - Integration of carbon sequestration in concrete production
- Through the integration of the pilot studies and area-wide solutions methods and technologies as presented in the present report, considering the upper range of potential of the proposed projects, the mitigation potential is of up to: 3.13Mt CO_2.

Details of the data and level of confidence

The carbon capture and sequestration values used throughout the report were obtained in their majority through lifecycle analysis and revised by industry experts. When the information was not available through life cycle analysis, case studies were used to compare against academic or technical papers to provide a wider vision of the information (e.g. BECCS). The confidence on the estimates must be considered as peer reviewed but through the lens of an innovation project. Therefore, the estimates are as accurate as it is known to the authors but are prone to be improved as more information is available of medium-scale deployment or as an increased number of relevant pilot studies are conducted.

NET Strategy for Greater Manchester - A Snapshot

The summary of the suggested projects, details and their potential/suggested location are shown in the scheme below. The projects are colour-coded depending on the type of technology they represent (nature-based, engineering-based or hybrid).



NET strategy for Greater Manchester: a Snapshot

Figure 13


Roadmap to Net-Zero 2038
- Strategies for Negative Emission Technologies
2038
MEDIUM-TERM ACTIONS
Demonstration Projects
Project scale-up
Monitoring and Verification
Procurement Network
LONG-TERM ACTIONS
Scale-up
Quantification
Assessment
SHORT-TERM ACTIONS
Assessment
Long-term Vision
Strategic Partnerships
Governance Framework
Demonstration Projects

Figure 14

Table 12. Specific Action Plan	
Short-term actions (year 1-2)	• Detailed assessment: mitigation capacity of the current and planned projects and initiatives • Define long-term vision: alignment of mitigation efforts with the net-zero strategy and trajectory • Clear quantification of mitigation strategies and trajectories • Feasibility studies: development of supporting information for future implementation of negative emission technologies in specific locations • Creation of business cases for individual negative emission technologies • Identify and establish strategic partnerships: between research institutions, businesses and local governments • Ensure collaboration within all the independent mitigation efforts and projects (traditional mitigation and negative emission technologies initiatives) • Identify sources of funding • Governance framework: development of a governance framework and local authority led steering group • Establishment of a monitoring and verification system for ongoing projects

Mid-term actions (year 3-5)	• Creation of numerous demonstration projects with scalability potential to build legitimacy:
	    ○ Carbon Capture Gardens
	    ○ Biochar
	    ○ Enhanced weathering (medium-scale engagement with farmers)
	    ○ MCCU for heating systems (pilot-scale)
	• Scale-up of demonstration projects completed
	• Continue with projected started in years 1-2
	• Quantify waste biomass and its allocation in Greater Manchester
	• Establishment of feedstock procurement network for Biochar and BECCS
	• Trafford Park, Carbon-Negative Hub: establish detailed carbon material flow within industries

Long-term actions (year 6+)	• Scale-up and continued delivery of NET projects depending on target of residual emissions • Quantification of captured/ sequestered emissions • Assessment of results: Contribution to the net-zero pathway • Maintain habitats created i.e. sustained management of woodlands and peatland

11. Recommendations and Next Steps

Key Recommendations and Actions for Stakeholders

The following recommendations and next steps were created through the analysis of the present report and the integration of the perspectives collected from a stakeholder engagement workshop held with local authorities, environmental not-for-profits, academic and research representatives, among other relevant stakeholders.

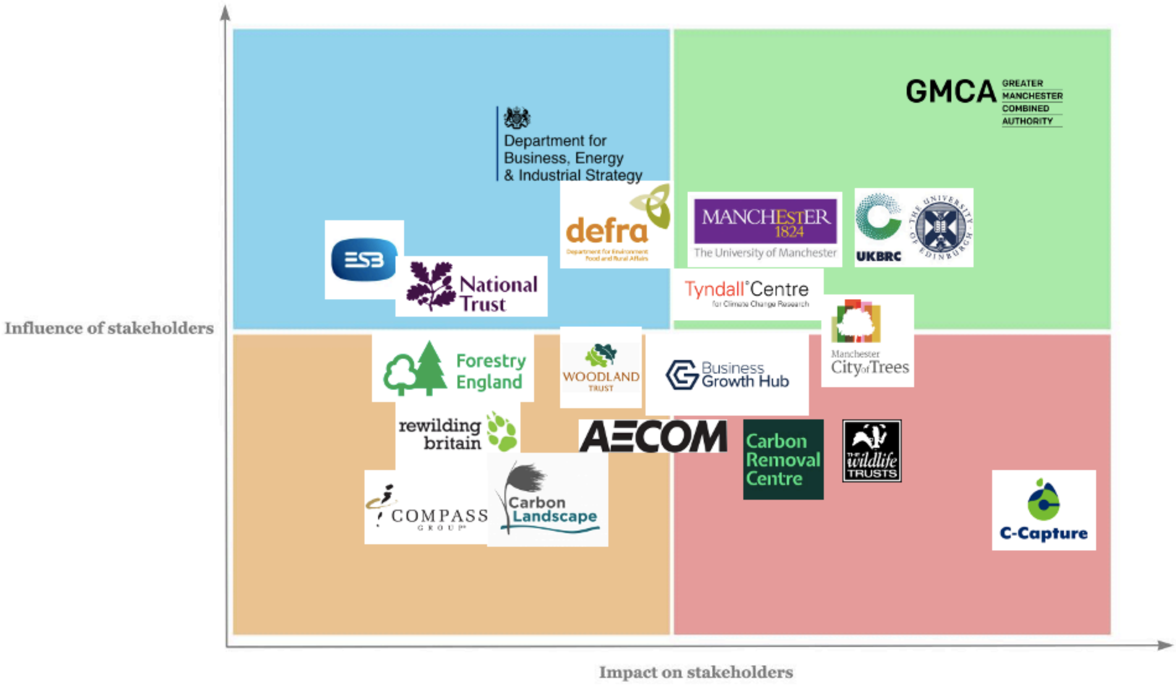


Figure 15. Stakeholder map (based on stakeholder workshop)

The figure above represents stakeholders that will be key for the development and implementation of negative emission technologies in Greater Manchester. The X axis represents the impact that the success of the NET projects will have on stakeholders; while the Y axis represents the level of influence that different stakeholders have on the development of the projects.

1. Importance of collaboration and networking of different stakeholders, industries and research facilitated by GMCA

- Establish strategic partnerships, public-private partnerships inter-intra sector network or platform for knowledge exchange and co-creation
  explore established partnerships
- GMCA helps with the coordination on collaboration, joint targets and legally binding aims
- Develop community-based or business-led projects to aggregate knowledge sharing; pilots to show how wetter farming/peatland restoration can be done successfully
- Carbon removal that engages with the citizens of Greater Manchester in raising the awareness of emission reduction and carbon capture

2. Collectively develop standardised NET terminology and criteria for best practice NET projects considering suitability within Greater Manchester context

- Universities and research institutions are crucial to provide the scientific foundation
- Need frameworks for quality control, to avoid arbitrary claims about net-zero/negative emissions
- Need a clear understanding of what 'success' means is in terms of NETs
- Carbon removal good practices that implement principles of good carbon removal, with long permanence and negative on a lifecycle basis that complement known mitigation technologies instead of replacing them

3. NET approach must be compatible with how GM defines net-zero

- E.g. geographical boundaries, which scopes and which sectors are included
- Focus on multiple benefits including societal and economics of carbon capture initiatives

4. Explore different sources of funding for NET projects, establish a carbon market that offers stakeholders financial incentives

- Ensuring funding is available for those businesses affected by any increased costs required by implementing low carbon solutions
- Major investing looking at opportunity to deliver upfront investment for delivery now against future benefits
- Understand how private finance and beneficiaries can interact with public support to achieve an increase in delivery

5. NETs will be required to be deployed in a large-scale in Greater Manchester

- The residual emissions and plausible scenarios demonstrate that it is unlikely that Greater Manchester will be able to solely rely on nature-based solutions to compensate for its residual emissions as set out in its net-zero strategy
- The use of hybrid or engineering-based solutions will be required to be integrated into the strategy

6. The current mitigation initiatives must be quantified on a joint platform

- The current mitigation initiatives will be decisive for the future emissions pathway of Greater Manchester
- Their characteristics and planned scale must be quantified on a collaborative platform managed by GMCA to understand their real impact against their net-zero targets
- This platform could be similar to the one developed by Newcastle City Council
- This platform will allow understanding of residual emissions trajectories and the concrete role of carbon removal in Greater Manchester

TABLE 13. SUGGESTED NEXT STEPS (ACTIONS) PER STAKEHOLDER

STAKEHOLDERS	ACTIONS
GMCA	• Evaluate current and planned projects, understand GM capacity, explore integration of suitable carbon removal technology into existing structures, • Establish a NET steering group and facilitate network engagement through workshops • Set clear visions and define the roles of NETs in a GM's net-zero pathway, clarifying how each initiative should be utilised and prioritised compared to other mitigation options, explore alignment with current and planned projects • Identify key partners and establish strategic partnerships • Develop governance structure, bringing people from different stakeholder groups and different industries • Provide feedback on the proposed NET project locations • Implement demonstration programmes with universities and businesses • Establish a carbon market in Greater Manchester to drive funding and resources to nature-based NET projects (e.g. peatland restoration)

Governments	• Review national opportunities and regional for industrial CCS and ensure that it is given the necessary prominence. • Develop and disseminate best practices for NET projects in industry to enable faster learning about the application of the relevant technologies. • Design and implement enabling policies and legal and regulatory frameworks, and provide incentives that accelerate commercial-scale NET deployment in industry beyond the demonstration phase. • Form public-private partnerships between government and investors to enable these products. • Explore sector-based approaches for NET policies in appropriate specific sectors
Businesses	• Companies engage directly with their value chains and all relevant stakeholders to identity NET opportunities • Compile an inventory of the materials in use, industrials processes and capacity in the industry to determine whether such processes can be combined with CCS • GM industry leaders should raise awareness and interest with branch organisations and authorities in existing industrial agglomerations and create a dialogue on possible co-operative actions • Businesses within an industry cluster should explore opportunities for synergy and co-creation, collaboratively identify CCUS opportunities
Universities and Research Institutions	• Clearly define standardised NET-related terminology • Work closely with GMCA to understand the residual emissions, carbon budget and different scenarios to net-zero • Establish NET project verification and monitoring processes and protocols by working closely with governments and businesses • Develop capacity building and education programmes at universities with public-private partnerships • Develop demonstration projects with other stakeholders that aligns with the strategic vision of Greater Manchester (e.g. biochar and peatland restoration)
NET Suppliers	• Work closely with GMCA, universities and local businesses to develop demonstration projects • Partner with GMCA in delivering theme-based NET workshops that creates dialogue with businesses and investors, also raise public awareness in NET's role in GM's net-zero pathway
Community Groups	• Develop awareness campaigns, workshops and educational programmes with universities and GMCA • Work closely with GMCA on the proposed offset scheme (e.g. supporting programmes such as workshops and skills development sessions with farmers) • Engage with NET providers on the alignment between current nature-based solutions with the proposed NET projects, exploring synergy and opportunities for co-creation (e.g. planned forestation projects with BECCS)
Citizens	• Explore peatland projects in the proposed GM offset market space • Actively participate and engage in workshops and seminars accessible to the public

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