OPPORTUNITIES FOR ATMOSPHERIC CO_2 REMOVAL IN NORTHERN IRELAND USING BIOCHAR

A Report by the Bryden Centre and CASE, Queen's University Belfast, and Renewables United, grant funded by the Department for the Economy, Northern Ireland

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EXECUTIVE SUMMARY

Northern Ireland needs to decarbonise and has set a target for achieving net zero carbon emissions by 2050[1] to restrict the impacts of climate change. Switching away from fossil fuels will give greater security to energy supply but a switch to low carbon energy generation is not enough on its own to meet carbon net zero targets. Carbon Dioxide Removal (CDR) could be an important process to incorporate into decarbonisation pathways, to help Northern Ireland achieve such targets. This view is supported by the latest IPCC Climate Change report (2022)[2] which states that CDR is necessary to achieve net zero CO_2 and greenhouse gas (GHG) emission reductions both globally and nationally, counterbalancing 'hard-to-abate' residual emissions.

As part of work to underpin future action plans to fulfil Northern Ireland's Energy Strategy, the Department for the Economy (DfE) commissioned CASE and the Bryden Centre at Queen's University in partnership with the consultants Renewables United to investigate the potential of biochar-based CDR in Northern Ireland. Biochar is one of a number of ways to capture carbon from the atmosphere, but given Northern Ireland's relatively large agricultural sector, offers both a route to reliable and inexpensive CDR and a potential new revenue stream for the country's farmers. The investigation included discussions with a range of different stakeholders to inform:

- A techno-economic feasibility assessment of local and centralised operational models including a desk study to determine the likely qualities of biochar that could be produced using current Northern Ireland feedstocks and a discussion on the potential biochar uses/long-term sequestration in Northern Ireland (Chapter 7)
- A review to establish current and future policy, regulation and legislation in this area and the impact on use of biochar for carbon credits (Chapter 8)

Over 70 organisations (see Annex A) were consulted during the creation of this report. While the concepts of bioenergy and Anaerobic Digestion (AD) for biogas production were generally understood, awareness of the potential of further energy and biochar production from digestate was much more limited. While stakeholder knowledge of the area was not broad, insight into attitudes was gained and the project as a whole was useful as the discussions held served to socialise the potential of biochar, including the opportunities for additional farm incomes and carbon offsetting.

Agriculture has a significant role to play in both low carbon energy generation and CDR in Northern Ireland. Although agriculture contributes significantly to GHG emissions, the sector has potential to be a key part of the decarbonisation solution. If a 'whole system approach' can be introduced through low carbon farming cooperatives, the biogenic carbon captured in agricultural biomass could be removed and stored in biochar for longer term carbon storage and removal. Biochar is a product of gasification of biomass and can be incorporated into soil or added to products such as concrete for carbon storage. This process could integrate into low carbon energy production and contribute to significant decarbonisation in Northern Ireland.

Against this backdrop, this report summarises and evaluates the potential value of CDR in Northern Ireland, through the production of biochar from different biomass sources including grass silage digestate, miscanthus and short rotation coppice (SRC) willow. Biochar quantities, carbon reduction potential and economic return for each of the three biomass to biochar scenarios were modelled and compared to identify what each pathway could deliver for Northern Ireland. The report also details what a low carbon farming co-operative could look like in Northern Ireland, as well as summarising the policy and economic levers and barriers for carbon farming.

One of the potential uses of biochar is as a gold standard carbon offset as carbon stored is easily audited and, if stored appropriately, will sequester carbon for hundreds or thousands of years. Currently, carbon offsetting has a dubious reputation although many organisations are striving to improve standards. Many schemes are impossible to verify, and some are demonstrably based on false assumptions and do little to remove carbon from the atmosphere. Establishing an audited, biochar based, gold standard carbon offset industry in NI to address this global market is an option but will offshore the benefits of NI biochar CDR when there are practical uses within NI.

A number of conclusions were drawn from the reviews of academic papers and reports, modelling of Northern Ireland's agriculture sector and discussions with stakeholders. Consideration of the goals of DfE's Energy Strategy, and Northern Ireland's climate act were important as was the financial consequences and opportunities for the region. Key findings included:

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[1] *Climate Change Act (Northern Ireland) 2022, Acts of the Northern Ireland Assembly* [Climate Change Act (Northern Ireland) 2022 (legislation.gov.uk)]

[2] *IPCC (2022) Climate Change 2022, Mitigation of Climate Change, Working Group III contribution to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change* IPCC_AR6_WGIII_Full_Report.pdf

1. CDR is necessary to meeting carbon targets, as emphasised by multiple reports, including the IPCC.
2. The digestate output from existing anaerobic digestion plants in Northern Ireland is around 110kt of dry matter, equating to 32kt of biochar with a CDR potential of 118 ktCO_2e (around 2% of the current emissions from the agricultural sector in Northern Ireland).
3. 200 kt of biochar could be produced per year if all housed livestock manure and underutilised silage in Northern Ireland was used to produce digestate via anaerobic digestion (c. 400 ktCO_2e per year of CDR)[3]. This is equivalent to 7.1% of the current GHG emissions for the agricultural sector in Northern Ireland (5.6 MtCO_2e per year).
4. Given Northern Ireland's current low level of forestry and the current usage patterns for amenity, nature or existing timber industries including bioenergy via wood chip, forestry was not found to be a realistic route to large scale biochar production. Even if substantial reafforestation occurred this would not have significant consequence based on growth achieved by 2050.
5. The Climate Change Committee (CCC) model in Northern Ireland has a target of 36 kha of bioenergy crops by 2050 for decarbonisation. If all the new bioenergy area was taken up by:

   i. Miscanthus, biochar potential per annum by 2050 is around 123 kt, with a total CO_2 removal potential of 365 ktCO_2e.
   ii. SRC willow, biochar potential per annum by 2050 is around 145 kt tonnes, with a total CO_2 removal potential of 420 ktCO_2e.
   iii. Grass silage, biochar potential per annum by 2050 is around 121 kt tonnes, with a total CO_2 removal potential of 246 ktCO_2e. With this scenario other benefits were noted relating to the lower extent of land use transition needed in Northern Ireland and the ability to execute without reducing land for grazing.

6. Biochar produced in Northern Ireland could be a valuable income stream for farming cooperatives and could be directly used by NI's concrete industry to help reduce the carbon footprint of their products.
7. An additional 700 to 800 new jobs could be created in rural communities across Northern Ireland through creation of a CDR industry based on biochar. If this is linked into the production of biomethane via AD then around 2000 jobs could be secured by 2030.
8. Additional revenues of up to £300m are forecast based on biochar-based CDR with syngas and biomethane production. This figure is heavily dependent on price for CO_2 removal certificates and gas prices.

This report covers the current technical and UK/NI policy and regulatory frameworks for biochar. While there has been a rapid increase in interest in biochar as a CDR tool and a growing body of research and demonstration projects world-wide, regulatory frameworks and government policy developments are still to embrace biochar as part of the decarbonisation solution. To put biochar-based CDR on a firm basis in NI a number of steps are recommended. These include:

1. Cross departmental (DfE and DAERA) support for CDR is needed. This should consider both agricultural and carbon balance unintended consequences.
2. Engagement with DESNZ is needed to align new policy with the upcoming UK wide policy.
3. Further research is required:

   i. To understand implications of GHG removal solutions, including holistic assessments of their feasibility and acceptability.
   ii. To deliver innovative monitoring, reporting and verification (MRV) tools, technologies and techniques that assess the effectiveness, integrity and longevity of land-based carbon dioxide removal.
   iii. To work with industrial manufacturers, such as the concrete industry, to determine the best utilisation of CDR products to decarbonise manufactured products whilst also ensuring the long term permeance of the carbon dioxide removal.
   iv. An investigation of land utilisation to maximise the sustainable biomass output of our land for food, animal feed, bioenergy, bioproducts, timber products and carbon dioxide removal needs.

4. Community and stakeholder engagement is needed to communicate the concept of whole system carbon farming co-operatives. This is due to the general low-level of awareness noted during discussions with stakeholders. If biochar production at scale is to be achieved, then farmers will need to be bought into the concept as they are the main source for feedstock. Communities will also need to accept local bioenergy facilities at a scale larger than current AD plants.

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[3] https://doi.org/10.1016/j.renene.2022.06.115

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LIST OF ABBREVIATIONS

AD	Anaerobic Digestion
AFLU	Agriculture, Forestry or Land Use (AFLU)
BECCS	BioEnergy Carbon Capture and Storage
BECCUS	BioEnergy Carbon Capture, Utilisation and Storage
BEIS	Departmwent for Business, Energy and Industrial Strategy
BEV	Battery Electric Vehicle
bioSNG	Biogenic Synthetic Natural Gas
CC	Carbon Capture
CCC	Climate Change Committee
CCGT	Combined Cycle Gas Turbine
CCS	Carbon Capture and Storage
CCUS	Carbon Capture Utilisation and Storage
CDR	Carbon Dioxide Removal
CHP	Combined Heat and Power
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalents
COP	Coefficient of Performance
CORC	CO_2 Removal Certificates
DACCS	Direct Air Carbon Capture and Storage
DAERA	Department of Agriculture, Environment and Rural Affairs
DESNZ	Department for Energy Security and Net Zero
DfE	Department for the Economy
EBC	European Biochar Certificate
ETS	European Trading Scheme
EU	European Union
GHG	Greenhouse Gas
GS	Grass Silage
GSD	Grass Silage Digestate
HTC	HydroThermal carbonization
$ktCO_2$	Kilo tonnes CO_2
kha	Kilo Hectares
LCOE	Levelized Cost Of Energy
Misc	Miscanthus
MC	Moisture Content

MRV	Monitoring, Reporting and Verification
$MtCO_2$	Mega tonnes CO_2
NAEI	National Atmospheric Emissions Inventory
NI	Northern Ireland
NPP	Net Primary Productivity
ODT	Oven Dried Tonne
RHI	Renewable Heat Incentive
ROCs	Renewables Obligation Certificates
SRC	Short Rotation Coppice
tCO_2	Tonnes CO_2
WIC	Wood In Construction

AD

AFLU

BECCS

BECCUS

BEIS

BEV

CC

CCC

1. INTRODUCTION

Northern Ireland has now fallen behind the rest of the UK on several key metrics for greenhouse gas (GHG) emission reductions, such as GHG reduction since 1990 (23.9% reduction compared to 52.6% for England, 51% for Scotland and 40% for Wales) and emissions per capita (5.2% of total UK GHG emissions, whilst accounting for only 2.8% of the UK's population in 2020).

The IPCC (2022)[2] state that it is 'now or never' if we want to limit global warming to 1.5°C. UK Climate Change Projections for Northern Ireland show a greater chance of hotter, drier summers and warmer, wetter winters with more extreme weather and rising sea levels. The high emission scenario for Northern Ireland shows that by 2070 winters could be up to 3.9°C warmer and 25% wetter, while summers could be 4.9°C warmer and 38% drier (DAERA, 2018)[4]. This reflects the real and imminent threat posed by climate change and supports the decarbonisation agenda in Northern Ireland.

The importance of reducing GHG emissions from sectors like energy, transport and agriculture is widely accepted as a necessary step on our pathway to decarbonisation. However, it is becoming increasingly clear that reducing emissions will not be enough to meet the targets set. GHGs from the atmosphere must be actively removed through pathways of carbon dioxide removal (CDR) to mitigate the impact of climate change.

The new energy strategy for Northern Ireland, "The Path to Net Zero Energy" (2021)[5] has a primary aim to achieve net zero carbon, however CDR is not mentioned within the strategy. Given that Northern Ireland is underperforming in the reduction of GHG emissions compared to other regions in the UK and the focus placed on CDR by the UK, EU, and IPCC, it is time for CDR to be prioritised in Northern Ireland and for CDR pathways to be developed specific to the region.

Carbon Dioxide Removal processes draw CO_2 directly from the atmosphere via engineered, biogenic or geological processes and stores the Carbon in the CO_2 molecule in a stable form for long periods of time. This reduces the amount of CO_2 in the atmosphere and offsets continuing anthropogenic emissions of greenhouse gases. CDR is different from Carbon, Capture and Storage (CCS) where CO_2 is captured typically from concentrated CO_2 streams from combustion or industrial processes and stored geologically. Captured CO_2 can also be utilised as a feedstock for new products – this variant is Carbon Capture Utilisation and Storage (CCUS). Where the fuel or feedstock is biogenic in origin then this known as Bio Energy, Carbon Capture and Storage (BECCS) or Bio Energy, Carbon Capture Utilisation and Storage (BECCUS) where the captured CO_2 is used to create new products. Both BECCS and BECCUS can be regarded as a form of CDR as they extract CO_2 from the atmosphere in the form of biomass. However, they are only CDR processes if the biomass comes from sustainable forestry or agricultural sources that are replenished – biomass from clearing old growth forests does not contribute to a net reduction in atmospheric CO_2.

Carbon, Capture, Utilisation and Storage will play an important role in driving down CO_2 emissions globally, but additional CDR will be required to get to net zero by 2050. At present CCUS is most economic for large emitters that are geographically clustered and located close to geological storage sites. Even in these cases, carbon capture technology will only capture c.90% of emissions. Outside of CCUS cluster sites industry has to balance the price of carbon emissions (or offsetting costs) compared with carbon capture and the expense of transportation by road or sea to a suitable storage site. Equally problematic are the emissions from aviation and shipping which currently cannot be captured for later storage. A recent report[6] reviewed the options for CCUS in Northern Ireland (NI) and concluded that due to the scale of CO_2 emissions, lack of clustering of sources and need to collect and ship CO_2 to an offshore geological site that conventional CCUS was not an economically sensible choice. Looking at biogenic methods of carbon capture was thought to be an alternative option.

Biochar is produced when biomass is heated in the total or partial absence of oxygen and is a thermochemical process that drives off the more volatile compounds to leave a residual char. Given the existing biogenic waste streams and productive agriculture sector in NI, biochar is an attractive option for CDR in the region. This offers many routes to both offsetting emissions and as a useful product such as a soil enhancer, animal feed additive, concrete filler or simply storing in old mines and quarries if just using for offsetting. There are already voluntary schemes which offer offsetting using biochar (and other sequestration routes). However, these are currently not regulated and suffer from a lack of transparency and universal acceptance. Recent moves by the European Commission[7] and potential initiatives in the UK under the new UK ETS scheme would see regulated markets

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[4] https://www.daera-ni.gov.uk/articles/uk-climate-change-projections
[5] https://www.economy-ni.gov.uk/publications/energy-strategy-path-net-zero-energy

[6] Carbon Capture, Utilisation and Storage Potential in Northern Ireland, The Bryden Centre, April 2021: https://www.brydencentre.com/ccus
[7] Sustainable Carbon Cycles COM (2021) 800

for carbon offsets such as those based on biochar. These steps would create confidence and substantially increase the size of trade in carbon offset credits giving significant economic opportunities to a region like NI that is rich in biogenic carbon.

Regulation and validation of carbon markets are essential for governments and the public to have confidence in the trading of carbon offsets. A recent example of the problems that besets current offsets is the selling of carbon credits for forestry conservation areas in California based on the very unlikely premise that these would be logged if carbon credits were not paid. Many schemes are based on growing and maintaining forestry. However, measuring the rate of carbon sequestration with accuracy is not possible and is highly dependent on location and environmental conditions in any one year. Also, the carbon absorbed by newly planted trees is small and plantations of mature trees can plateau in terms of carbon absorption. Harvesting of trees can lead to substantial loss of carbon due to burning of waste even if harvested wood is used for long-lived products. Of little value for carbon sequestration is the situation where trees are eventually used for the paper industry or biomass burning, then captured CO_2 rapidly returns to the atmosphere. Carbon offsetting is only effective in a national or global context if it genuinely would not have happened without the payment to offset. This is why many schemes are not justifiable as they would have occurred in a 'business as usual' scenario. Equally, any offset scheme must be able to provide an auditable and accredited account of sequestered carbon.

Biochar is attracting a substantial amount of attention worldwide as a robust method for locking up atmospheric CO_2 biogenically captured. Carbon sequestered as biochar can have a lifetime in excess of 10,000 years before it is broken down. Production of biochar is primarily by pyrolysis where biogenic feedstock is heated under an oxygen free atmosphere at temperatures lower than 500°C to drive off water and volatile compounds to form syngas (typically a mix of CO_2, CO, H_2, methane and other gaseous compounds), oils and tars. Syngas is a fuel and as such the production of biochar can be viewed as a form of BECCUS with a significant proportion of the carbon in the biomass feedstock converted to biochar. Combined with Anaerobic Digestion, for feedstocks suitable for biogas production, followed by pyrolyzing the remaining solids, additional bioenergy production can be achieved.

In the short-term, maximising the biogenic carbon capture potential from land is the easiest and most inexpensive proposition for any CDR process. Medium-term, there are major opportunities from exploring the blue economy and associated carbon sequestration. The relevant, blue economy prospect for this work is aquaculture where farming of macroalgae[8] such as sugar kelp has high carbon sequestration potential. Conversion of macroalgae to biochar is of growing interest internationally[9], particularly when the availability of land for growing biomass is limited.

1.1 Report Overview

Chapter 2 is a review of the current scientific literature on the production and uses of biochar. As an introduction to biochar and the technology of biochar production, section 2.1 reviews the main process options for the production of biochar. The chosen technology will depend on the feedstock being used and the quality of the biochar or co-products produced. The following section looks at some of the main applications of biochar both current markets and potential future uses.

Chapter 3 onwards looks at the unique Northern Ireland situation in relation to decarbonisation and agricultural production and summarises the benefits that biochar production could provide as a CDR technology.

Feedstock for biochar production such as anaerobic digestion digestate and woody biochar are evaluated, and resource assessment results are presented in relation to the likely quantities of biochar that could be produced from miscanthus, SRC willow and grass silage. Estimates have been made on the CDR potential, financial return and market value associated with these three biochar scenarios. The report also details what a low carbon farming co-operative could look like in Northern Ireland, as well as summarising in Chapter 7 the policy and economic levers and barriers for biochar production in Northern Ireland.

[8] *Dorte Krause-Jensen and Carlos M. Duarte, DOI: 10.1038/NGEO2790*

[9] *https://doi.org/10.1016/j.biombioe.2022.106650*

2. BIOCHAR

2.1 Production of Biochar

Compared to other carbon removal strategies discussed in the scientific literature, biochar has shown considerable potential in multiple areas. These include technological viability, scalability options, carbon removal costs, carbon stability and permanence, verification and monitoring, as well as the advantages connected with the many potential applications [1]. In light of the current condition of the carbon sink economy, carbon capture and storage through biochar synthesis is technologically feasible and potentially commercially profitable. The principle of carbon sequestration through biochar synthesis is straightforward. During plant growth, plants absorb carbon from the atmosphere through photosynthesis, which is retained inside the plant structure for as long as the plant persists. However, natural decay returns the carbon to the atmosphere as the plant dies, completing the natural carbon cycle. Biochar production breaks the carbon cycle by converting carbon to a form resistant to decomposition, preventing the emission of greenhouse gases back into the atmosphere [2, 3].

Combining photosynthesis with thermochemical conversion to produce biochar permits the development of a carbon removal system that is very efficient. Large-scale biochar production should eventually have an effect on the atmospheric carbon balance by reducing CO_2 concentrations. To produce biochar that is resistant to degradation and can remain stable in potential reservoirs for hundreds or thousands of years, it is necessary to carefully select feedstocks and optimize processing conditions to meet reservoir-specific requirements while achieving the highest achievable stability [4]. Moreover, this must be accomplished in the most environmentally responsible manner feasible. The value and effect of fast-growing speciality crops should not be underestimated if they are cultivated responsibly, despite the fact that biodegradable waste is a primary focus for decreasing potential emissions and increasing the circular economy. The land, water, and nutrient resources necessary to develop specialized feedstocks should not directly compete with food production systems. In general, feedstock eligibility must be assessed for certification reasons. In addition, the thermochemical conversion process should be energy efficient, and any conversion process gases or waste heat generated should be recycled to reduce emissions [5]. Fossil-based energy should not be used in the production process and should only be used sparingly in agriculture and transportation.

In addition, the ultimate application of biochar is crucial to its viability as a carbon sink and should be carried out as sustainably as possible following legislative and technical standards. Biochar can be utilized as a carbon sink in applications that do not include energy generation. Moreover, biochar must not be exposed to heat deterioration or oxidation during its service life or at the end of its service life [6]. This report discusses the various biochar production technologies available in the market as well as explores the numerous biochar-based carbon sink applications, including agronomy, livestock farming, stimulation of biological processes such as anaerobic digestion and composting, environmental remediation, civil infrastructure, and energy storage. The primary objective is to promote atmospheric CO_2 removal while facilitating enhanced utilization opportunities and secure carbon storage. Although biochar may be employed in several applications and value chains, its ultimate storage reservoirs include soils, civil infrastructure, and landfills. However, while optimizing biochar production to meet application-specific needs, carbon stability should continue to be the most important characteristic for biochar to fulfil its sequestration function when applied to such reservoirs for lengthy durations.

Several thermochemical conversion technologies, including pyrolysis, gasification, flash carbonization, and hydrothermal carbonization, are utilized to produce biochar [7, 8]. Selection of conversion technology depends both on the feedstock, desired secondary products, and biochar characteristics. The main techniques are covered in the following sections.

2.1.1 Pyrolysis

Pyrolysis is a thermal process involving the decomposition of biomass at temperatures between 300 and 900°C in an oxygen-free atmosphere. Biomass pyrolysis typically produces three separate products: solid, liquid and gaseous fractions. The process behind the pyrolytic breakdown of lignocellulosic material is intricate and has been thoroughly explored in the literature[9, 10]. Generally, numerous reactions occur in parallel and series. Among them are dehydration, devolatilization, depolymerization, charring, aromatization, decarboxylation, cracking, repolymerization, and condensation [11]. Literature reveals an agreement that biomass pyrolysis consists of three fundamental stages: (i) dehydration, (ii) primary degradation, and (iii) secondary reactions. At temperatures between 200 and 400°C, biomass undergoes most of the thermal degradation, producing solid char. This is followed by secondary reactions as the temperature rises, promoting additional devolatilization. Degradation mechanisms of lignocellulosic components have been widely researched in the literature. Between 250 and 350°C, hemicellulose decomposes, followed by cellulose, which decomposes between 325 and 400°C. On the other hand, Lignin is more stable and often decomposes between 300 and 550°C [11].

The yield distribution and attributes of the pyrolytic products depend on the features of the feedstock and the process parameters, such as temperature, heating rate, residence time, particle size, and reactor type. Given the sensitivities to varying process parameters, production ratios between biochar, Syngas and bio-oil can be tuned by operators to favour the production of the required product. In continuous flow systems, process parameters may be adjusted in real time to reflect changes in feedstock (for example).

Depending on the rate of heat transfer, the pyrolytic process can be classed as slow, intermediate, fast, or flash pyrolysis. Slow pyrolysis is an established and reliable method for producing biochar. It has a slow heating rate, with a typical processing temperature between 400 and 600°C, although temperatures higher than this range have been observed in the literature and a residence time between hours and days.

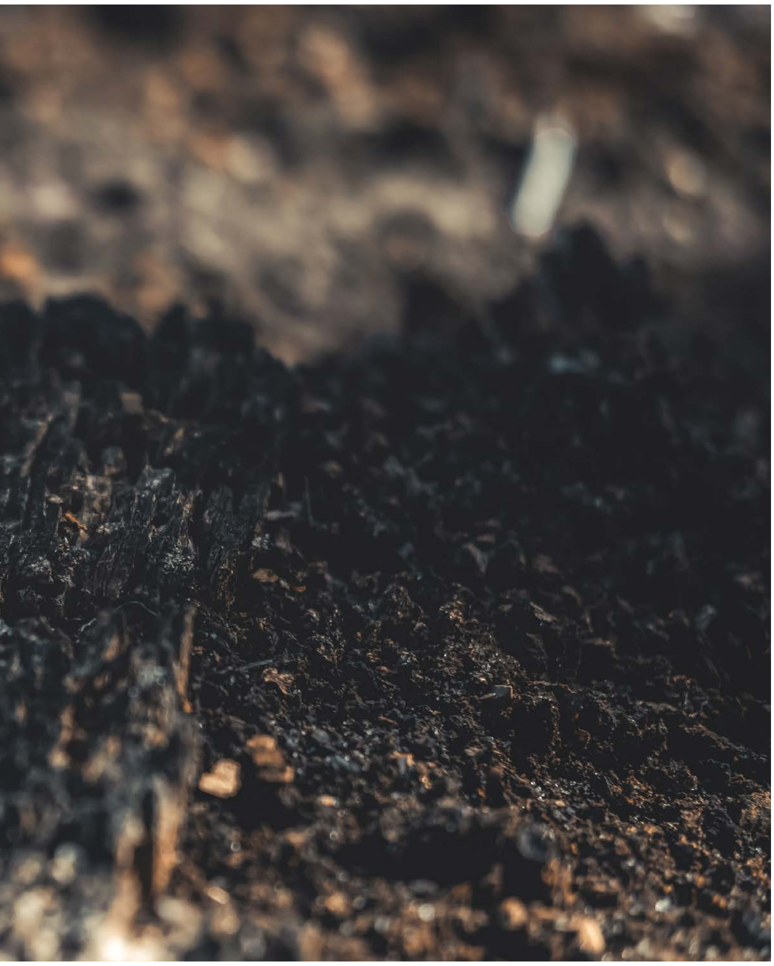
Slow pyrolysis is known to provide high biochar yields, and the literature indicates a range from 20% to 50%, which is mostly dependent on the feedstock and processing conditions [7, 12-15]. Typically, batch process fixed bed reactors, retorts, or converters are utilized for slow pyrolysis [16, 17]. Intermediate pyrolysis is conducted at a comparable processing temperature range but at slow to moderate heating rates, resulting in biochar yields of 20 to 40%. In addition, the processing is continuous and often lasts up to 30 minutes. Typical reactors include externally and internally heated rotary kilns and screw-based kilns [16-19]. Many commercially available reactors are based on these designs. In certain instances, the literature characterizes intermediate pyrolysis as slow pyrolysis. While fast and flash pyrolysis work in a similar temperature range, the heating rate is significantly faster, and the residence time is typically in the range of seconds, which favours bio-oil formation and provides a typical biochar output of 5 to 20 % [7, 12-15]. Reactors such as bubbling fluidized bed reactors and circulating fluidized bed reactors are typical of fast and flash pyrolysis. Other designs include ablative and cone reactors, in addition to the twin-screw reactor, which is based on the mechanical fluidized bed concept [16, 17]. In addition, several pyrolysis forms, such as microwave-assisted pyrolysis, vacuum pyrolysis, and hydro-pyrolysis, are discussed in the literature [12]. Slow and intermediate pyrolysis-based reactors are optimal for biochar production. Continuous rotary kilns and screw-based kilns are both mature and robust technologies.

2.1.2 Gasification

Gasification is a thermochemical process that generates biochar as a by-product. Typically, biomass gasification is conducted between 700 and 1000°C. in a slightly oxidizing atmosphere utilizing air, steam, or oxygen. Even though the primary products of gasification are comparable to those of pyrolysis, this process favours syngas generation. Literature indicates average yields of 5%, 10%, and 85% for biochar, oil, and syngas, respectively [7, 13, 15]. This technology is inefficient for biochar production due to the low char output produced with this method. Gasification is ideally suited for the generation of energy and numerous chemicals synthesized from syngas.

2.1.3 Flash carbonization

Another thermochemical technology discussed in the literature is flash carbonization, which requires the ignition and control of a flash fire in a packed bed of biomass at elevated pressure. The mechanism involves upward movement of fire and downward movement of air, which causes the conversion of lignocellulosic material primarily into gaseous and solid fractions. This technique typically requires less than 30 minutes residence time while maintaining a temperature range of 330 - 650°C [7, 20-23]. According to the scientific literature, biochar yields from flash carbonization (28-32%) are equivalent to those from slow and intermediate pyrolysis; yet, some producers claim higher biochar yields. However, the greatest disadvantage is the requirement for high pressure [7, 14]. Another possible approach for the effective manufacture of biochar is flash carbonization. This method is now utilized by biochar manufacturers.



2.1.4 Hydrothermal carbonization

Hydrothermal carbonization (HTC) is a thermochemical process that converts biomass in an aqueous, inert environment at high pressure, with a residence time of hours to days [24-26]. HTC may be divided into two types: low-temperature HTC (<300°C) and high-temperature HTC (300-800°C). HTC has significant conversion yields in relation to char, with low-temperature HTC yielding 65% and high-temperature HTC yielding 30 to 60% [7]. Because there is no need for pre-drying of the feedstock, this technology is suitable for processing wet biomass. Although this approach produces high biochar yields similar to slow pyrolysis, the physicochemical characteristics of the biochar generated may differ from those produced by slow pyrolysis. Malghani et al.[25] generated biochar via slow pyrolysis and HTC using corn silage; but the resultant biochar had different chemical characteristics, physical appearance and, when applied to soil, had different breakdown behaviour. The researchers found that HTC biochar degraded faster in all types of soils studied than slow pyrolysis biochar and explored its potential to drive additional GHG emissions such as CH_4 and CO_2 caused by organic matter priming. Slow pyrolysis biochar, on the other hand, demonstrated carbon stability and is thought to be more appropriate for climate change mitigation [25]. Furthermore, chars generated by HTC are not classed as biochar by the European Biochar Certificate (EBC) foundation [5]. HTC chars may be more suited for manufacturing biocarbon for energy generation since they have superior properties such as high calorific value and low ash content [24].

2.2 Biochar-based carbon sink applications

Biochar can be used in various applications including for carbon sinks, such as agriculture, energy storage, environmental remediation (soil and water), anaerobic digestion, building materials, composting and animal farming applications, as shown in Figure 2.1

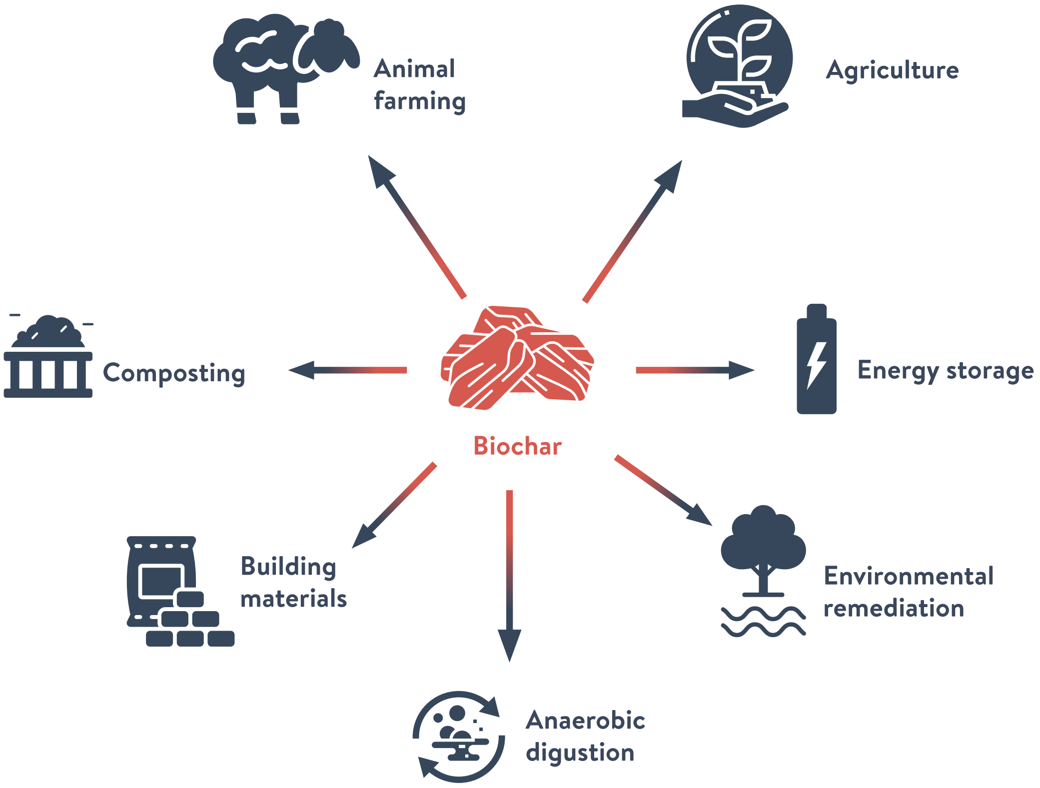


Figure 2.1 Biochar-based carbon sink applications, including agriculture, energy storage, environmental remediation (soil and water), anaerobic digestion, building materials, composting and animal farming

2.2.1 Biochar in agriculture

There is significant evidence in the scientific literature regarding the long-term storage of biochar in the terrestrial carbon pool through agricultural and forest soils. Soil is the greatest terrestrial carbon sink, and the influence of biochar application on soils has garnered significant scholarly and commercial interest over the past three decades. According to reports, biochar may be securely kept in soils for millennia, provided it is generated under the correct circumstances to establish carbon stability.

Numerous investigations have indicated that carbon persists in soil. Wang et al. [27] did a meta-analysis of 24 soil biochar stability investigations. Using 128 datasets, the researchers conducted a meta-analysis of biochar degradation and computed its mean residence duration. Degradation rates varied substantially based on feedstock type, processing parameters, experiment duration, and soil clay concentration. The results indicate that the labile carbon pool has a mean residence time of 108 days, while the stable carbon pool has a mean residence time of 556 years, with each pool comprising 3% and 97% of the total carbon, respectively. This clearly demonstrates that just a tiny fraction of biochar is bioavailable, whereas a significant portion contributes to long-term carbon sequestration. When biochar is applied to soils, it is susceptible to biotic, abiotic, and indirect stressors, which all influence the rate of mineralization. As previously noted, stable carbon should tolerate such stresses, but this relies on the feedstock and processing conditions. In addition to its potential for carbon sequestration, biochar offers other agronomic benefits.

It is believed that biochar application greatly impacts soil quality and fertility. In addition, improvements in nutrient cycling and an increase in water and nutrient retention have been noted. Theoretically, biochar application can considerably influence crop yield, water and nutrient efficiency, and soil health. In addition, biochar application has been found to help decrease greenhouse gas emissions from soils, such as carbon dioxide, methane, and nitrous oxide [1], despite the inconsistent outcomes reported [28, 29]. Due to biochar's influence on soil physical, chemical, and biological properties such as porosity and bulk density, soil water dynamics, acidification, interaction with soil organic matter and inhibition of priming effect, and stimulation of soil microbial activity and dynamics, the benefits as mentioned earlier are realized [30-32]. In general, the research results from adding biochar to soil suggest beneficial impacts; nonetheless, there have been occasions in which biochar treatment led to negative consequences. In general, the results described in the literature rely on the kind of biochar utilized, the feedstock utilized, and the production circumstances, the amount of biochar applied, the type of soil utilized, the specific cropping system, and the cultivation management practices employed [1, 4, 33, 34].

Literature is divided on the use of biochar as a fertilizer, with some authors pushing for its usage [35], while others minimize its value for this purpose [36, 37]. As previously mentioned, the discrepancy could be explained by the difference in soil and climate conditions, the processing conditions employed, or the feedstock types used for biochar production, as it is well known that the nutrient content of biochar is dependent on the raw materials used and the conditions of heat treatment [38].

Biochar, in general, contains a tiny quantity of essential nutrients elements [37]. This would necessitate the addition of 10–50 t/ha of biochar to the soil, depending on the soil and biochar properties. This places a financial burden on the farmer, hence restricting its application [39, 40]. Besides, biochar inputs over 50 t/ha have a negative impact on the soil microbial population, hence diminishing its fertility. Additionally, when administered at such high rates, it hinders plant germination and early development in the soil [41]. Furthermore, nutrients are released into the soil during the initial days following the addition of biochar [42], which reduces the plant's efficiency in utilizing these nutrients, thereby affecting the crop's productivity and quality.

Thus, biochar is typically employed as a soil amendment rather than a fertilizer to improve the physical and chemical qualities of the soil, although modest addition rates (1 t/ha) have been utilized as a nutrient transporter to improve the efficiency of fertilizer usage and minimize nutrient losses [41]. If, on the other hand, biochar is used as a fertilizer, its nutritional content is often augmented by chemical or organic fertilizers. In addition, as explained in the subsequent section, biochar can be coated with a variety of substances to aid the delayed release of these nutrients.

Chemical fertilizers are indispensable to contemporary agriculture, and their significance increases as the global population expand. However, the plant's utilization efficiency is poor, often between 30 and 35 percent, resulting in economic and environmental effects [43, 44]. Therefore, experts are developing innovative methods to maximize the advantages of chemical fertilizers while minimizing their negative impacts on the environment and costs to farms. In this context, biochar-based fertilizers, a technique that mixes conventional fertilizers with biochar as a carrier, have emerged as a significant area of agricultural study [43, 45].

This section illustrated the potential agricultural applications of biochar. In addition to functioning as a long-term carbon reservoir, agriculture is the most prevalent biochar-based carbon sink use described in the literature, where several advantages may be gained. However, the influence on soil and crops is variable and largely depends on the kind of feedstock utilized, and the processing parameters adopted for biochar synthesis, as well as the cropping system and management, approaches. Although biochar is not a nutritional source in and of itself, its usage as a nutrient transporter has received considerable attention in the scientific literature. Biochar-based fertilizers, a technique that mixes conventional fertilizers with biochar as a nutrient carrier, have been intensively investigated with encouraging results. Several preparation procedures were investigated, and various modification treatments were recommended to improve the performance of biochar. It is essential to comprehend the effect of such treatments on the carbon stability of biochar as well as the biochar's total environmental footprint; hence, full life cycle analyses must be conducted to establish biochar's carbon removal capacity. In general, using biochar as a nutrient carrier is a well-acknowledged method that can support several agronomic benefits while allowing for the long-term storage of nutrients in soils. However, biochar preparation skills are required to properly synthesize a usable product.

2.2.2 Biochar in animal farming

Utilizing biochar in livestock farming prior to its long-term preservation in soils can maximize its utility. This section will examine the numerous places where biochar may be utilized in the animal agriculture business and critically evaluate the literature-highlighted benefits and obstacles. In addition, the exact technological requirements for this application will be provided.

Recently, several researchers have examined the impacts of co-feeding biochar to pigs, cattle, fish and poultry [46-50]. Co-feeding Australian dairy cattle with biochar boosted milk output by 3.43 percent, protein-fat content by 2.63–6.32 percent, and decreased intestinal methanogens by 30 percent [47]. Similarly, co-feeding laying hens with biochar at a concentration of 2.5% boosted daily feed intake, improved laying performance by 6%, and raised shell firmness and thickness by 10% and 6%, respectively [50]. Goiri et al. found that co-feeding broilers with biochar at a concentration of 30 g/kg boosted daily weight growth, average body weight, and decreased feed conversion ratios compared to non-co-fed animals [49]. Notwithstanding, it has been demonstrated to improve the survival and development of aquatic fish [51]. Due to biochar's intrinsic adsorption capabilities, co-feeding with biochar decreased Gallibacterium anatis and Campylobacter hepaticus infections in fowl. Therefore, biochar may be a feasible substitute for antibiotics in animal husbandry [52]. Biochar's unique features may aid in maintaining gut bacteria (methanogens) inside its porous structure, hence lowering ruminant greenhouse gas emissions [47, 53, 54], which are the largest source of agricultural greenhouse gas emissions and hence have a beneficial effect on global climate change. Additionally, farm productivity may increase as a consequence of a reduction in the usage of artificial fertilizers as a result of enhanced animal excreta that maximizes soil fertilization quality [55, 56]. The impact of biochar on NI's agriculture industry in terms of reduction in methane emissions from cattle, impact on poultry and reduction in fertiliser use is outside the scope this report but would be an informative piece of research.

Co-feeding (combining biochar with animal feed) is a potential integration technique. This section highlighted the most crucial features of employing biochar as a co-feeding material for livestock, poultry, swine, and fish. Thorough research was conducted on the effects of co-feeding with biochar on growth, gut microbiota, enteric methane generation, egg output, and endo-toxicant mitigations, as well as biochar's potential application as a litter amendment and for aquatic wastewater treatment. This section illustrated the enormous value that can be retrieved through biochar in animal farming applications, where the biochar may be applied to soils for long-term storage while extracting additional agronomic value. However, there are major questions which should be addressed before widespread use. An immediate investigation into the long-term toxicity of biochar to animals is required while Biochar co-feed needs further study into the mechanisms of health improvement and toxin/pathogen removal. Other areas that need to be researched include the reduction of greenhouse gas emissions when storing liquid manure with biochar; using biochar as a litter and bedding; and when biochar is released into the environment. To have confidence in the use of Biochar on animal farms further comprehensive meta-analysis research is essential.

2.2.3 Biochar in anaerobic digestion (AD)

Utilizing biochar in the AD process prior to long-term storage, conceivably in soils, is an additional technique for enhancing value from which several technical benefits might be acquired. Biogas is routinely produced via AD which is the standard bioprocess for turning organic feedstocks into biomethane-rich gas [57]. However, several obstacles have prevented the broad implementation of this technique. Low methane efficiency, contaminants such as hydrogen sulfide, excessive CO_2 emission, operational instability, and inadequate substrate degradation, for instance, negatively impact biogas recovery potential Consequently, biogas output must be upgraded and maximized, and operational efficiency must be enhanced.

The addition of Biochar has been suggested as a successful and promising technique for enhancing the AD process's effectiveness and operational stability [58]. Biochar supplementation has been shown to reduce inhibitors, boost microbial activity, minimize the operational lag period, and accelerate electron transfer between acetogens and methanogens [58, 59]. Particularly, biochar additions increased biogas production by 22 to 40 percent and decreased lag time by 28 to 64 percent. Additionally, the number of methanogens and electro-trophic bacteria grew by between 24.6 and 43.8 percent [60]. Compared to graphene, carbon nanotubes with a single wall, and other carbon-based compounds, biochar is the most economically feasible substance since it can be produced from waste feedstocks [61].

Similar to other substances, biochar has an advantage in terms of aiding the AD process due to its improved porosity, high specific surface area, abundance of functional groups, and remarkable electron transfer capability [62]. Biochar's physicochemical qualities might be easily optimized during its synthesis by selecting the best feedstock and processing parameters, such as pyrolysis temperature and residence time [62].

Biochar synthesis and subsequent usage in AD may offer substantial environmental advantages [63]. In addition, the direct addition of biochar to AD systems without the requirement for infrastructure changes increases biochar's appeal and potential in AD applications [64]. Using the pyrolysis product (biochar) as an input to an AD system would achieve zero-waste objectives by assuring circular economy, material flow, gaseous emission reduction, soil preservation and energy conversion and recovery [65].

Biochar has been investigated extensively to improve AD operations, primarily for biogas generation and upgrading, operation performance and sustainability, and the mitigation of inhibitory impurities such as antibiotics, gaseous impurities, residues, microplastics, heavy metals and furan-by-products. This improvement is a result of the biochar's fundamental features, such as its high surface area, porosity, and surface functional groups, as well as its interaction with an anaerobic microbial consortium that facilitates sophisticated electron transport. Nonetheless, the following obstacles and prospects remain substantial causes for concern. Emerging environmental dangers, such as furan derivatives, antibiotic resistance genes, and nano-plastics, necessitate more studies to clarify biochar's underlying role in enhancing pollutants' absorption. Biochar efficiently eliminates pollutants from AD systems while enhancing the value of the resulting digestate. This strategy would improve the removal of contaminants while preserving the quality of digestate biofertilizer for agricultural applications. Under AD conditions, several batch experiments with diverse feedstocks and the addition of biochar have been performed. However, few large-scale AD systems testing trials have been undertaken to determine the appropriate dose, substrate-to-inoculum ratio, particle size, and re-use rates. Consequently, future research should focus on the field-scale application of biochar to treat AD. In addition, new research should concentrate on developing creative techniques and biochar composites, such as metal biochar frameworks and biochar-loaded nanomaterials, to boost biochar's sorption ability. Even though the vast majority of past research indicated that adding biochar to AD operations would significantly boost methanogenesis, a few studies have shown that adding biochar to AD operations had negative or even inhibitory effects. The unknown is the specific method by which this inhibition occurs. Therefore, optimizing the condition of biochar in fermentation systems necessitates a deeper understanding of the optimal inhibitory mechanism.

2.2.4 Biochar in composting

In aerobic composting, biochar co-composting combines biochar with compostable substrates such as manure, plant wastes, and sewage sludge [66]. Since co-composted biochar preserves all of the capabilities of compost and biochar, it is largely utilized to enhance soil conditions and attenuate harmful elements [67]. Applying biochar to soils is crucial for assessing its predicted effects. Generally, two procedures are used to mix biochar with compost: pyrolysis and composting. The first is to include biochar into composted substrates following the completion of the composting process and before soil application. This strategy might enhance soil nutrient availability and plant development [68-70]. Co-composting, the second method, involves the addition of biochar to substrates at the beginning of the composting process. The composted biochar would subsequently be used to amend soils. Co-composting is substantially less expensive than combining biochar with compost post-composting, which needs two independent steps: ordinary composting and biochar addition [67].

Biochar includes macro-and micronutrients that plants may utilize, such as N-P-K along with Calcium [71]. Co-composted biochar enhances soil nutritional conditions by boosting the soil's N-P-K, Ca concentrations and cation exchange capacity. [68, 72]. Consequently, soils retain more nutrients and cations for plant absorption [73]. Co-composted biochar can enhance the bioavailability of P in soils and decrease the demand for additional P-fertilisers in soils that have been supplemented [74].

The application of biochar that has been co-composed to soils can improve the soil's organic carbon content and soil moisture. When biochar was introduced to fertilizer-amended soils, the carbon content rose from 0.93 to 1.25 percent, while the moisture content rose from 18 to 23 percent [75]. However, not all research found biochar-amended soils to increase crop production or growth. Borchard et al. found no effect, either positive or negative, of biochar addition on maize yield [76]. Moreover, Xu et al. noticed a decrease in Suaeda salsa biomass after biochar application compared to the non-applied crop, as well as a small improvement in sodic saline soils after biochar amendment [77]. Using biochar decreased banana yield by 18 percent but did not influence papaya yield [78]. Other researchers determined that improved plant growth or yield is mostly attributable to the use of inorganic fertilizers, not charcoal addition and that adding biochar to soils may have had little or a negative effect on plant growth or yield [79, 80].

In conclusion, adding biochar to composted substrates following the completion of the composting process and before to soil application may improve soil characteristics and plant development [68-70]. Adding biochar at the beginning of the composting process (co-composting) offers several benefits. Glab et al. examined the increased water-holding capacity of sandy soils modified with co-composted biochar [81].

The biochar composting process and subsequent long-term storage in soils is a powerful demonstration of biochar as a carbon sink. However, the following points should be addressed moving forward. Numerous studies have shown the positive impacts of biochar-amended soils on crop health and yields; however, this effect varies according to soil type, biochar application technique, and plant variety. Therefore, additional research is required to determine the particular pathways through which biochar exerts its varied impacts. The subsequent immobilization of heavy metals in soils is a significant barrier to extending the use of co-composted biochar in soils, resulting in a lack of metals in plants. Optimizing the level of immobilization of heavy metals in order to prevent a heavy metal shortage in plants is, therefore, a crucial topic for future study. Long-term field applications of co-composted biochar in soils are required to examine the possible impact on soils, plants, and long-term strategies for mitigating pollutants. In addition, periodic use of co-composted biochar calls for more investigation. Other high-value feedstocks, including seaweeds and fish shells, have yet to be fully utilized, even though biochar made from plants has garnered substantial attention. Comparing co-composted biochar to other organic and inorganic fertilizers in terms of efficiency, drawbacks, and environmental effect requires more study. Continuous addition of co-composted biochar to the soil can result in an overabundance of nutrients, mainly nitrogen and phosphorus, leading to water contamination (groundwater eutrophication). Consequently, optimizing the application rate relative to the plant's consumption rate is essential and will continue to be the subject of future study. Urgently required are life cycle assessments of the greenhouse gas potential of soil amended with co-composted biochar to determine the degree of environmental impact associated with the use of such co-compost in comparison to standard compost without the addition of biochar and inorganic fertilizers.

2.2.5 Biochar in Environmental remediation

The use of biochar in applications for environmental remediation has emerged as a highly promising technology. This method promotes value maximization, as biochar may perform soil and water remediation in addition to its carbon sequestration function. Concerns about water pollution on a global scale and the concomitant difficulties involved with the production and disposal of huge quantities of industrial effluents and stormwater have led the scientific community to investigate efficient and cost-effective solutions [82]. As a result, biochar has been pushed as a feasible treatment solution for water polluted with a variety of emerging contaminants [83]. In general, the technical performance of biochar-assisted water treatment routes is significantly impacted by operational characteristics such as application simplicity, treatment efficacy, process resilience, scalability, and compatibility with other water treatment systems [84]. Biochar's unique physicochemical features, including specific surface area, ion exchange capacity, microporosity, and loading capacity, are responsible for its sorption potential. The particular features of the as-prepared biochar samples define the methods by which various pollutants interact with them [85, 86]. Utilizing biochar as an adsorbent in water clean-up prior to long-term storage is a technically feasible and economically advantageous value maximization technique.

Research suggests that biochar additions may be a promising technique for mitigating soil pollution by immobilizing organic and inorganic toxins [87]. Depending on the feedstock sources and pyrolytic conversion conditions applied, biochar's qualitative properties as a soil supplement vary greatly. Varying biochar materials generated from various sources have demonstrated diverse stabilization capacities and efficacy for soil contaminants. Soil organic pollutant remediation is typically achieved by sorption and degradation processes, whereas inorganic pollutant remediation is achieved via sorption and chemical precipitation [88]. For the quick fixation and adsorption of organic/inorganic pollutants in soil, biochar generated at a high temperature and with a high sorption capacity is preferable. However, soil microorganisms prefer low-temperature biochar with an optimal nutrient content because it speeds up biodegradation [89, 90].

In conclusion, the efficacy of biochar in removing soil pollutants has been demonstrated in most laboratory and field testing and studies. It is necessary to undertake both short- and long-term field experiments to acquire a deeper understanding. Models should be developed to predict field environmental conditions that vary based on soil type, soil texture, pH, salinity, and regional climate, among other factors. Increasing the performance of biochar in terms of sorption, surface area, and nutrient content by optimizing processing conditions and combining it with other highly reactive materials, such as nanoscale compounds, could be a viable strategy for making it more efficient cost-effective, and environmentally friendly. There is still much to investigate, and greater study is required, especially when using biochar as a soil amendment for polluted soils.

2.2.6 Biochar in building materials and construction

In response to the construction industry's expanding carbon footprint, there is an increase in demand for CO_2 emission control and reduction solutions. The construction industry's CO_2 emissions are affected by a number of elements, including the processing of raw materials, the production of cement, and, most significantly, construction. Three key characteristics have been identified as markers of the material's suitability for use in construction: chemical stability, thermal conductivity, and combustibility.

Chemical stability is essential to ensure no harmful chemical reactions occur when combining biochar with asphalt or concrete components. In general, it is known that concrete is susceptible to chemical assault, which reduces its durability. Moreover, asphalt deteriorates due to oxidation, which substantially influences the durability and stability of roads and pavements. The chemical stability of biochar, when coupled with concrete or asphalt, reduces the possibility of such destructive chemical reactions and ensures long-term durability. In addition, the low thermal conductivity enhances the insulating properties of buildings and structures. The key factor influencing this characteristic is porosity, especially the distribution of pore sizes. Reduced combustibility is a crucial safety criterion [4].

In addition, it has been established that biochar's water-holding ability provides enough hydration in cementitious admixtures, hence facilitating enhanced internal curing. This improves the durability, shrinkage resistance, fracture resistance, and mechanical properties. In addition, the research usually suggests structural advantages related to incorporating biochar into cement-based composites, such as increases in mechanical parameters, including compressive and flexural strength, ductility, and toughness. Biochar has demonstrated considerable promise for usage in building, providing several structural and functional benefits. Embedding biochar into the built environment for long-term carbon storage strengthens the proposition that civil infrastructure could also function as a solid carbon reservoir.

In conclusion, our investigation revealed that biochar might be utilized as a cementitious ingredient, imparting several structural and functional benefits. Incorporating biochar into asphalt and producing sustainable bricks also demonstrated several advantages. The scientific literature has many examples where biochar has been shown to have the potential to be included into bio-composites for enhanced insulation, electromagnetic radiation protection, and moisture management, all of which have shown excellent outcomes.

Biochar's ability for long-term carbon storage in infrastructure makes it a viable carbon reservoir. However, it is essential to remember that the service life of civil constructions varies considerably. When such constructions approach the end of their useful life, the materials can be recycled further or disposed of sustainably in landfills for long-term storage. In general, civil infrastructure is a resilient carbon reservoir, and further study is required to optimize and increase the potential use of biochar in the construction industry.

> "BIOCHAR HAS DEMONSTRATED CONSIDERABLE PROMISE FOR USAGE IN BUILDING, PROVIDING SEVERAL STRUCTURAL AND FUNCTIONAL BENEFITS"

2.2.7 Biochar in energy storage applications

Schmidt et al. have argued that the long-term storage of pyrogenic carbon inside advanced bio-based materials is a viable technique, so long as the material is not exposed to thermal breakdown or oxidation throughout its lifetime, once recycled, or upon termination [6]. Utilizing biochar in energy storage applications can be a very interesting means of generating substantial value while achieving the ultimate goal of long-term carbon sequestration. However, synthesizing biochar-based materials suitable for energy storage requires specialized understanding and engineering. In order to increase the carbon removal capability of this application, it is necessary to examine each biochar functionalization methodology in detail to guarantee that the requisite material properties and carbon stability are obtained while minimizing the environmental effect of the process.

Due to their high operating voltage, high energy density, and small size, lithium-ion batteries are the most popular kind of energy storage. Significant efforts have been undertaken to synthesize carbonaceous materials that are inexpensive, ecologically benign, and have a higher charge storage capacity. Biochar formed from biomass has garnered significant interest as anodes for lithium-ion batteries due to its huge surface area, porous nature, and potential for lithium-ion storage. Several researchers have suggested biomass-derived carbon as an electrode material for lithium-ion batteries due to its easy ion movement, high conductivity, and capacity to buffer volume fluctuations throughout the electrochemical process. Meanwhile, a greater comprehension of biochar’s’ physical properties and electrochemical activity is required to improve their performance in lithium-ion battery applications [91].

A precise functionalization method is required to produce such materials as batteries or supercapacitors with the requisite properties. In nearly all of the published experiments, biochar served as a prelude to future functionalization. Pyrolysis was frequently employed as the initial step in biochar synthesis. Typically, this was followed by a stage of activation or modification performed in the presence of several chemicals.

The primary obstacle encountered along this approach is the use of high temperatures to achieve the appropriate physical and chemical qualities when considering its application in the climate change mitigation route. In most experiments, the synthesized material displayed remarkable performance, yet, the fabrication procedure needed temperatures of 700°C or higher, occasionally exceeding 1200-1300°C. Operating at such high temperatures reduces the proportion of carbon in biomass converted to biochar, although temperatures over 700°C promote greater carbon stability. Therefore, it is essential to evaluate the process’s carbon yield. In addition, using numerous chemical reagents during the functionalization phase imposes an environmental impact that must be carefully assessed. Life cycle assessments must be employed to further comprehend the carbon sequestration potential of improved biochar-based materials employed in energy storage applications.

Another factor to consider is the disposition of this material once its useful life expires. As noted earlier, thermal regeneration is inapplicable from a carbon removal standpoint. Therefore, the final destination for these items is disposal in landfills for long-term storage.

Despite the high energy needs, chemical use, and poor carbon yield involved with synthesizing advanced biochar-based materials, the direct substitution of carbon materials derived from fossil fuels is a perceived benefit. In order to maximize the carbon removal potential of this application and to provide an economically viable product that can be applied on a large scale, it is recommended that future research concentrate on the development of production processes that employ lower temperatures and use low-cost and environmentally friendly functionalization techniques. Additionally, research should investigate sources of biomass that are readily available for large-scale deployment.

2.3 Biochar literature review references

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3. NORTHERN IRELAND AGRICULTURE

Agriculture is a significant part of the economy in Northern Ireland compared to the rest of the UK, with just over half of all registered businesses in Northern Ireland within agriculture (23%), construction (14%), retail (8%), and professional, scientific, and technical (8%) sectors. By comparison the agriculture sector accounted for only 5% of all UK registered business.

The agricultural sector employs nearly 25,000 people in Northern Ireland, contributing £640 million in wages and salaries to the Northern Ireland economy in 2019. The sector is responsible for 37% of the total sales in the NI Manufacturing Industry Sector.

The total value of annual Northern Ireland food production is £5.4 billion, feeding a population of 10 million, in relation to their dietary protein requirements, from a Northern Irish population of just 1.8 million people. Over £4.1 billion of the sector's sales were external to Northern Ireland (76% of total sales) in 2019, with nearly half going to Great Britain. Therefore, Northern Ireland is a key region for producing food for domestic consumption in the UK.

In Northern Ireland, most of the agricultural land use is dedicated to grazing. Rough grazing, mainly for sheep, accounts for 14% of the land use and 80% is for more intensive grazing, mainly for dairy and beef cattle. The intensity of the livestock sector in Northern Ireland is clearly reflected in the current land use with 94% of agricultural land in grassland, as either permanent, temporary, or rough grazing for livestock (Figure 3.1).

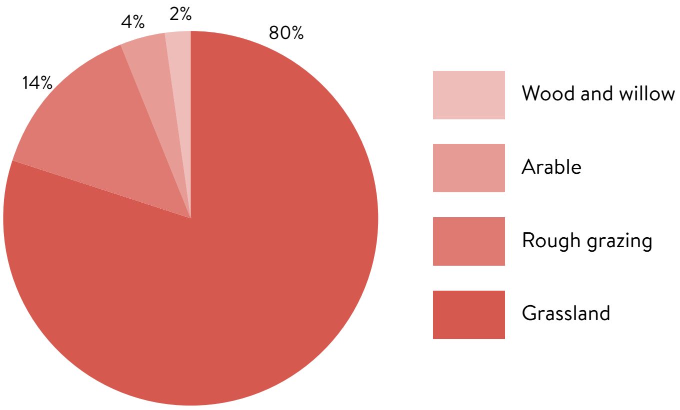

Figure 3.1 Agricultural land use in Northern Ireland from the Agricultural Census Data 2019

The agricultural land use reflects the intensity of the livestock sector in Northern Ireland, where the cattle population is as large as the human population. Figure 3.2 (top) shows the spatial distribution of livestock in Europe, illustrating the relatively high stocking density in Northern Ireland[10]. The bottom of Figure 3.2 shows manure production levels across Europe per km, and again the relatively high intensity of livestock farming is evident in Northern Ireland with a large proportion of the area showing production levels over 1500 tonnes/km^2.

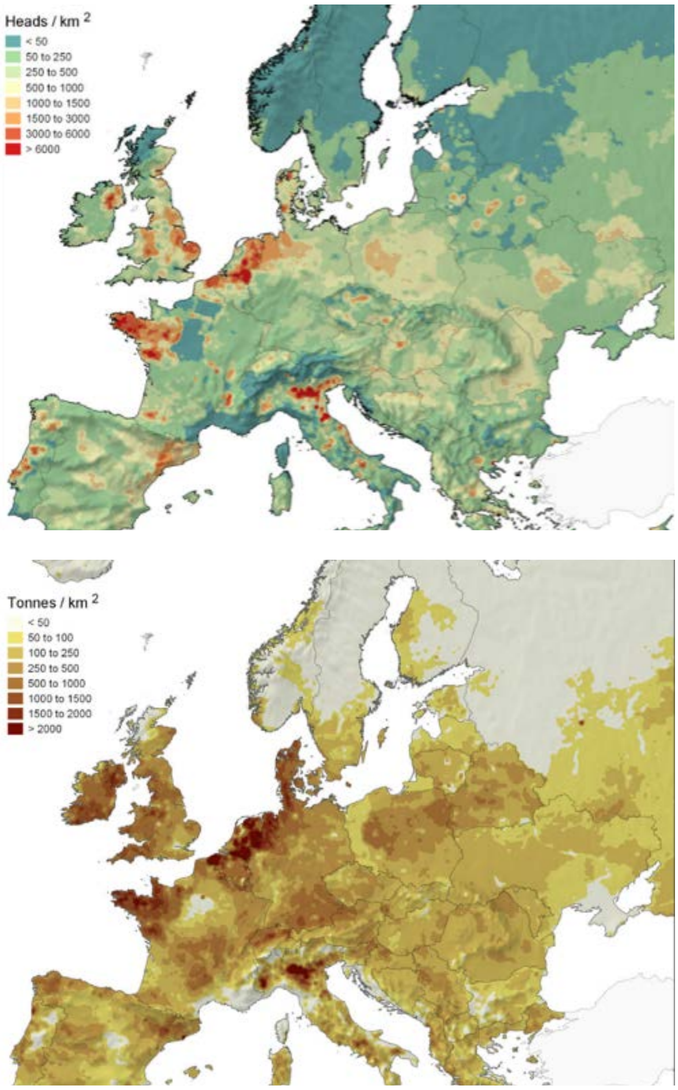

Figure 3.2 (Top) Spatial Distribution of livestock in Europe (Bottom) Farm manure production distribution in Europe. Adapted from Scarlat et al (2018)[10]

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[10] *Scarlat, N, Fahl, F., Dallemand, J., Monforti, F and Motola, V (2018) A spatial analysis of biogas potential from manure in Europe, Renewable and Sustainable Energy Reviews, Volume 94, Pages 915-930,* https://doi.org/10.1016/j.rser.2018.06.035

The intensity of the livestock sector in Northern Ireland is reflected in the GHG emissions for the region. The agricultural sector accounts for 27% of the GHG emissions from Northern Ireland in 2020, which is a significantly higher contribution from agriculture compared to the rest of the UK. GHG emissions in the agricultural sector have increased by 6% in Northern Ireland since 1990, the only sector which has not seen a reduction in its GHG emissions from this time (Figure 3.3)[11]

Agriculture	↑
Business	↓
Energy Supply	↓
Land use, land use change and forestry	↓
Residential	↓
Transport	↓
Waste Management	↓
Other	↓

Despite the disproportionately high productivity and output from Northern Ireland agriculture, there is no doubt that GHG emissions within the agricultural sector must decrease to avoid the consequences of climate change. This was reflected in the 2022 Climate Bill for Northern Ireland, including a net zero carbon target across all sectors of the Northern Ireland by 2050. Pressure is on the agricultural sector in Northern Ireland to decarbonise and reduce GHG emissions, therefore it is an important time so assess methods of doing so, such as biochar as a form of CO_2 sequestration.

Figure 3.3 Changes in GHG emissions in Northern Ireland since 1990. From DAERA, NI Greenhouse Gas Statistics 1990-2020 Report[11]

The increase in GHG emissions in Northern Ireland has coincided with a significant increase in gross turnover from the sector. Total gross turnover has over doubled in the past 20 years, from under £2 billion in 1990 to £5.4 billion in 2019[12] (Figure 3.4).

The significant increase in turnover from animal products has not led to a reflective increase rate in GHG emissions. Instead, total GHG emissions from the sector increased from 5,428 $ktCO_2e$ in 2006 to 5,567 $ktCO_2e$ in 2020, an increase of around 2.5%.

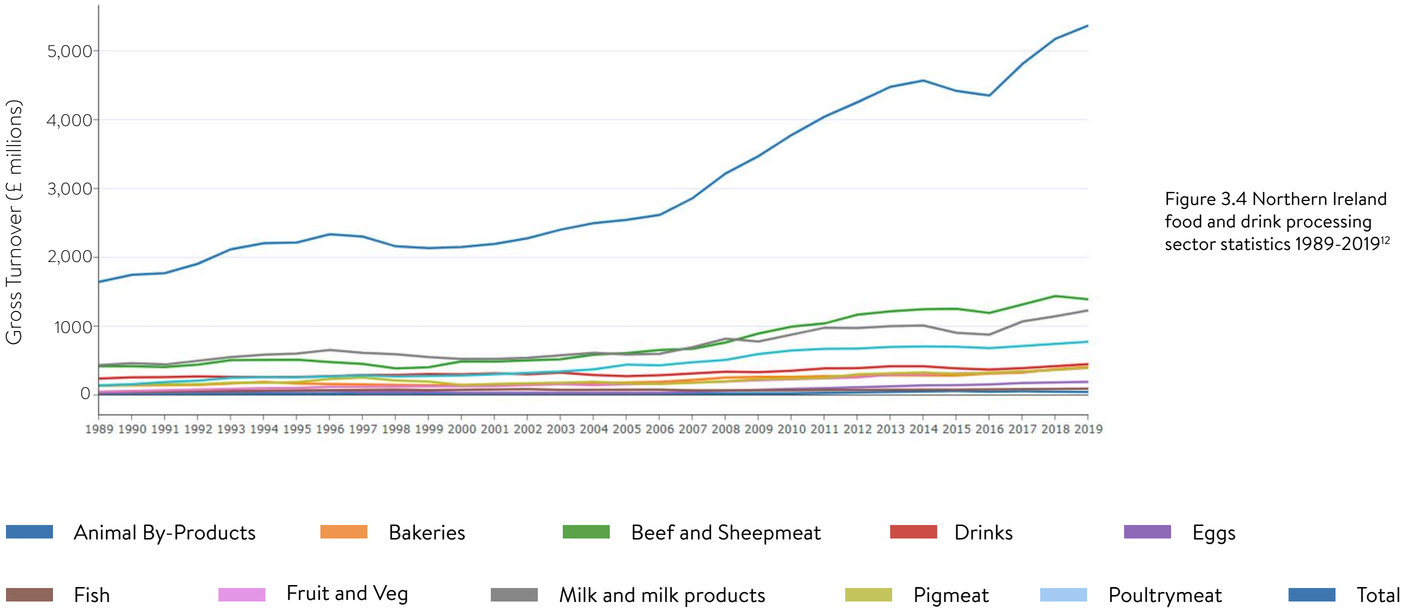

Figure 3.4 Northern Ireland food and drink processing sector statistics 1989-2019[12]

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[11] https://www.daera-ni.gov.uk/sites/default/files/publications/daera/NI Greenhouse Gas Statistics 1990-2020 Report FINAL.PDF

[12] https://datavis.nisra.gov.uk/daera/food-drink-processing-sector.html#charts

4. THE CHALLENGE OF REDUCING GREENHOUSE GAS EMISSIONS IN AGRICULTURE

It is predicted that at a global scale, agricultural productivity needs to double by 2050 to feed growing populations. Given the increasing rate of loss of productive farmland due to climate change, more pressure will be put on temperate climate regions, such as Northern Ireland, to increase food output to meet increased food demands. With the additional significant pressure to decrease greenhouse gas emissions from the agricultural sector, the question is, is it possible to fulfil these two goals at the same time?

An impact assessment by KPMG predicted an 86% reduction in cattle and sheep numbers would be needed to hit the target of net zero by 2045 in Northern Ireland, leading to on-farm job loss of 13,000 and a reduction of £11 billion in economic output[13]. Whilst reducing livestock numbers would reduce GHG emissions, as shown in the impact assessment, there are multiple factors to consider including the negative impact on gross turnover and the economy, as well as the movement of intensive agriculture to other locations in the UK, Ireland, and other international countries. There is a risk that the reductions in Northern Ireland GHG emissions could be offshored to other global livestock regions with no reduction in global GHG emissions.

A reduction in livestock numbers in Northern Ireland will also not come without a direct cost. Initial analysis by the Department of Agriculture in Ireland has suggested a compensation to farmers of €4,300 per “retired” dairy cow to reduce GHG emissions from the agriculture sector to meet EU Net Zero targets. With 1.55 million dairy cows, a 10% reduction in the herd would cost the Irish government over €660 million in compensation payments to dairy farmers[14]. The Dutch Government are also considering a radical cut in the livestock herd in Holland to tackle nitrogen emissions in the agricultural sector and have allocated a €25 billion budget to do so[15]. Both case studies highlight the significant cost that would come with livestock reduction in Northern Ireland.

Livestock reduction strategies, albeit contributing to a reduction in GHG emission, will decrease productivity and economic growth in the agricultural sector. Other solutions however have been identified as pathways to reduce GHG emissions via the agricultural sector while at the same time supporting economic stability. Such strategies include pathways carbon farming and carbon sequestration.

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[13] *Sandercock (2021): Northern Ireland net zero by 2025 bill would ‘devastate agri-food sector’, The Grocer* *Northern Ireland net zero by 2045 bill would ‘devastate agri-food sector’ | News | The Grocer*

[14] *Kennedy (2022): Dairy cow compensation could exceed €5000 per cow, Irish Farmers Journal* *Dairy cow compensation could exceed €5,000 per cow 24 July 2022 Free (farmersjournal.ie)*

[15] *BBC (2022): Why Dutch farmers are protesting over emissions cuts, Anna Holligan* *Why Dutch farmers are protesting over emissions cuts - BBC News*

5. CARBON DIOXIDE REMOVAL (CDR)

Carbon dioxide removal (CDR) refers to anthropogenic activities removing CO_2 from the atmosphere and durably storing it in geological, terrestrial, ocean reservoirs, or in products. It includes existing and potential anthropogenic enhancement of biological, geochemical or chemical CO_2 sinks, but excludes natural CO_2 uptake not directly caused by human activities[2]. The process of CDR removes CO_2 from the undesired location of the atmosphere, where it contributes to climate change, and puts it somewhere else, where it will not affect the climate for long periods of time.

The important role of CDR in global efforts to tackle climate change has been recognised by the Intergovernmental Panel on Climate Change (IPCC). IPCC (2018)[16] stated that all pathways that limit global warming to 1.5°C project the increased use of CDR over the 21st century. Different models suggest that limiting warming to 1.5°C will require CDR of between 5-15 Gt CO_2 per year by 2050.

Most stakeholders in Northern Ireland that were consulted, (see Annex A for list) did not fully understand the meaning of CDR and the associated pathways and technologies involved. Much of the confusion was due to the limited knowledge of the requirement for CDR and the difference between carbon offsets and carbon dioxide removals. Awareness of carbon offsets was wider than CDR, generally in relation to organisational plans to decarbonise either as the least expensive route or because there were no other economically feasible options. There was also little distinction among stakeholders between fossil carbon and biogenic carbon, with all carbon often considered to be "bad" in our journey to decarbonisation and Net Zero.

Farmers and their representatives were initially suspicious of the purpose of energy crops and biochar production, "My carbon stays on my farm" was one quote from a beef farmer. However, a greater familiarity with AD, existing farming cooperatives and explanation of the purpose and benefits did greatly ameliorate fears from the agricultural community although concerns did remain about slow adoption due to the conservative and cautious approach taken by many in the sector.

The latest IPCC report clearly sets out that, Carbon Capture and Storage (CCS) and Carbon Capture and Utilisation (CCU) applied to fossil CO_2 does not count as CDR. CCS and CCU can only be part of CDR methods if the CO_2 is biogenic or directly captured from ambient air and stored durably in geological locations/products.

Tanzer & Ramírez (2019)[17] present important characteristics of CDR:

- CO_2 is physically removed from the atmosphere.
- The removed CO_2 is stored out of the atmosphere in a manner intended to be permanent.
- Upstream and downstream GHG emissions, associated with the removal and storage process, are to be comprehensively estimated and included in the emission balance.
- The total quantity of atmospheric carbon dioxide removed and permanently stored is greater than the total quantity of carbon dioxide emitted to the atmosphere.

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[16] *IPCC (2018) Summary for Policymakers of IPCC Special Report on Global Warming of 1.5 degrees approved by governments SPM_version_report_LR.pdf (ipcc.ch)*

[17] *DOI: https://doi.org/10.1039/C8EE03338B-*

As illustrated in the Figure 5.1 below, CDR is part of a portfolio of response options to anthropogenic climate change[18]. Importantly, CDR is not a substitute for decisive action across the economy to cut emissions. The priority is to tackle the root cause of climate change by reducing emissions of GHGs from human activities whilst adapting to those emissions that are unavoidable or hard to abate.

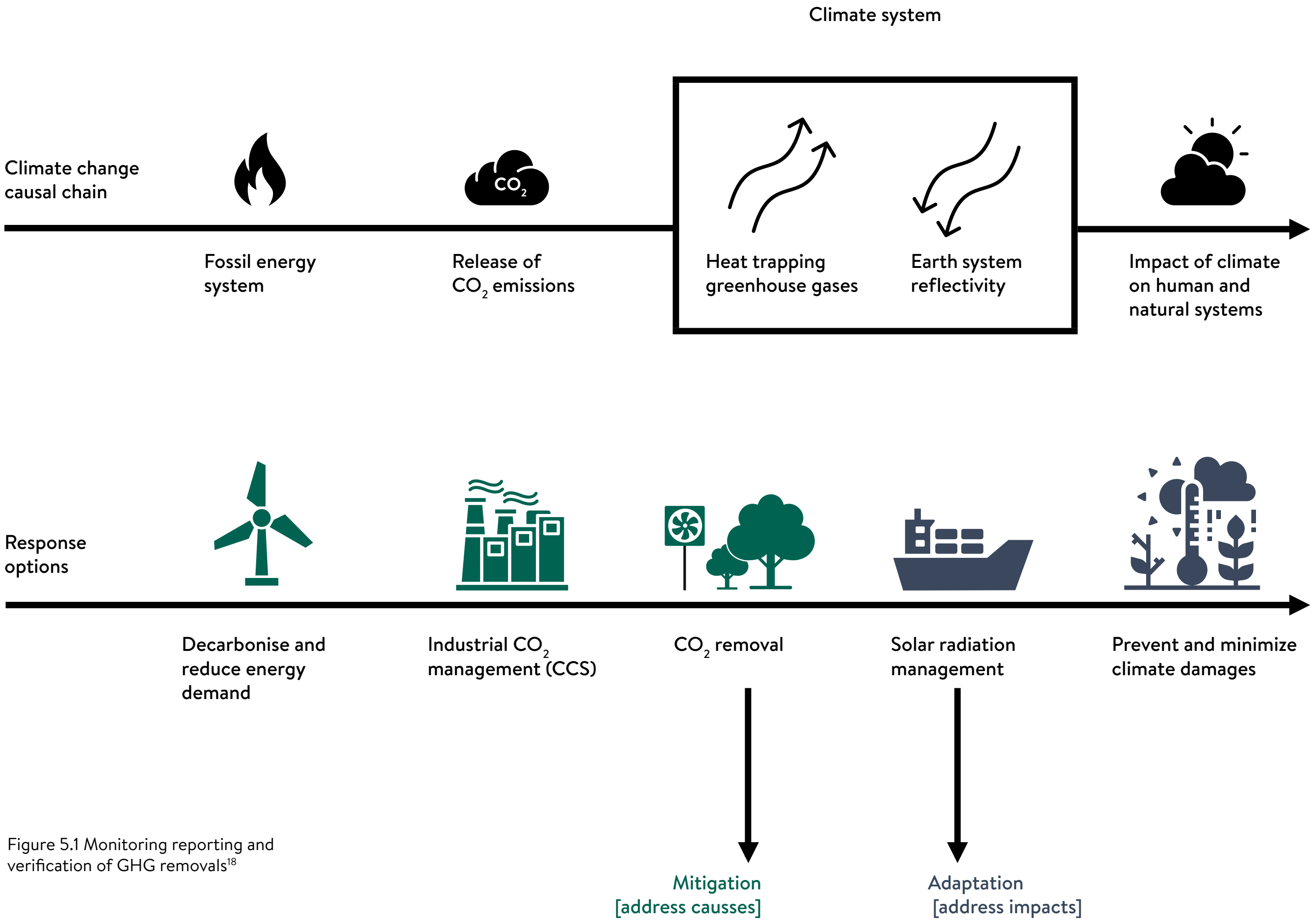

Figure 5.1 Monitoring reporting and verification of GHG removals[18]

CDR techniques includes bioenergy carbon capture and storage, biochar, soil carbon sequestration, forestation, wetland restoration and construction, direct air carbon capture and storage and enhanced terrestrial weathering. For CDR, the optimal conversion process is heavily influenced by deployment context and the market demand for outputs. The range of CDR approaches fall broadly into two categories:

- **Nature-based approaches:** such as afforestation, forest management, and soil carbon sequestration.
- **Engineering-based approaches:** such as Direct Air Carbon Capture and Storage (DACCS), Bioenergy with Carbon Capture and Storage (BECCS), wood in construction (WIC), biochar, and enhanced weathering

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[18] https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1026994/mrv-ggrs-task-report.pdf

Höglund (2022)[19] highlights the complexity of CDR, owing to a combination of inherent characteristics and regional variations, e.g., climates, biomass yields, local energy systems, and carbon storage method. Each CDR pathway is characterized by a distinctive CO$_2$ removal efficiency, timing required for any pathway to effectively remove the CO$_2$ from the atmosphere, and permanence. Figure 5.2 illustrates the different CDR methods and what implementation options are associated with each approach[20]. Biochar is highlighted as this route of CDR is the focus of this report.

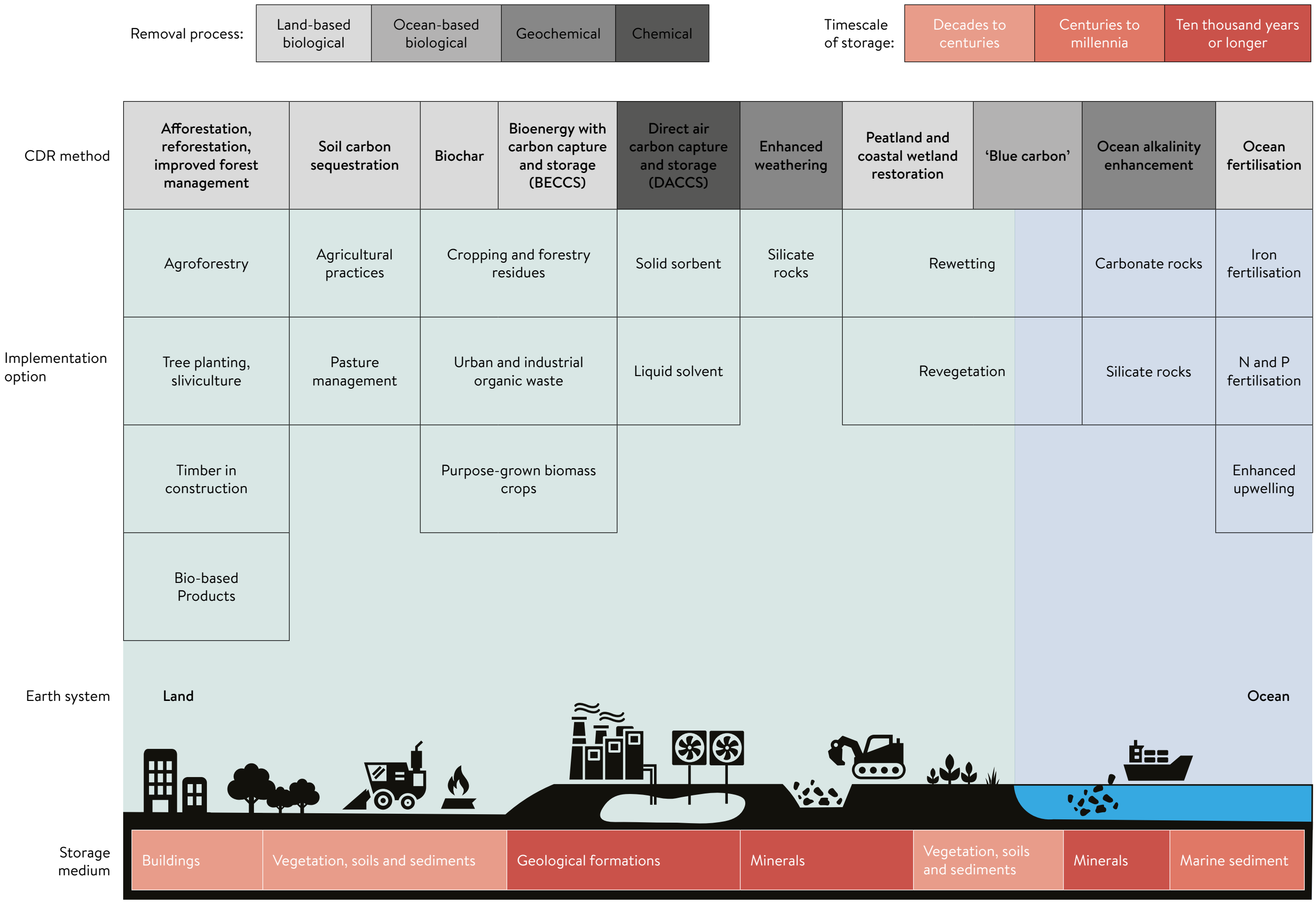

Figure 5.2 Carbon removal ecosystem according to the latest IPCC AR6 WGIII, adapted from Figure 2 in (Minx et al. 2018)[16]

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[19] *Höglund (2022) Rethinking CO$_2$ capture and storage, [Rethinking CO2 capture and storage - Høglund (en-US) (hoglund.no)]*

[20] *Minx, Jan C.; Lamb, William F.; Callaghan, Max W.; Fuss, Sabine; Hilaire, Jérôme; Creutzig, Felix et al. (2018) Negative emissions—Part 1. Research landscape and synthesis. In Environ. Res. Lett. 13 (6), DOI:10.1088/1748-9326/aabf9b*

The value of CDR's have been determined by voluntary markets through Carbon Dioxide Removal Certificates (CORC). CORCs are traded through indexes such as puro.earth[21] and are backed by large corporates such as Microsoft and Shopify.

These markets are voluntary, which has made the value of CORC's difficult to assess in terms of securing investment for projects. However, both the UK and the EU are developing regulated Emissions Trading Schemes (ETS) with underwritten values for CDR to assist in securing investment in projects to capture emissions from the atmosphere in the future. A BEIS consultation, which closed in September 2022, was on the design of a business model to attract private investment and enable CDR projects to deploy at scale from the mid-to-late 2020s.

In terms of the value of CDR's required for investors to fund projects, on puro.earth, £200 per CORC is an average value for a CORC, depending on the technology path funded for the engineered GHG removal. £200 per CORC is the value used in this report.

CDR through Bioenergy with carbon capture and storage (BECCS) has been identified as a key strategy in meeting Net Zero targets, with the UK's Climate Change Committee (CCC) indicating its potential to remove 20 to 70 $MtCO_2e$ each year by 2050. Recent studies[3] in Northern Ireland have also shown the high potential to incorporate biochar production into BECCS strategies to increase the CDR and decarbonisation potential. Biochar is one route of CDR (highlighted in the figure above) made from the heating of biomass in the absence of oxygen. The material can be added to soil, put through enhanced weathering, or incorporated into concrete. The latter two end locations represent longer scale carbon storage. The next section details the CDR approach of biochar production further.

> “CDR IS NOT A SUBSTITUTE FOR DECISIVE ACTION ACROSS THE ECONOMY TO CUT EMISSIONS. THE PRIORITY IS TO TACKLE THE ROOT CAUSE OF CLIMATE CHANGE BY REDUCING EMISSIONS OF GHGS FROM HUMAN ACTIVITIES”

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[21] *Puro.earth (2022) CORC Carbon Removal Indexes, CO_2 Removal Certificate Weighted Index Family (CORCX)* Carbon price (puro.earth)

5.1 Biochar

Biochar is a product of the gasification or pyrolysis of biomass. It is a solid carbonaceous material which represents a stable form of carbon which can resist thermal and biological degradation for extended periods, from centuries to millennia. Biochar can then be applied and safely stored in soils, building structures and various carbon sinks[22].

High temperature pyrolysis is the irreversible thermochemical decomposition of organic material at elevated temperatures in the absence of oxygen. The pyrolysis process converts organic material to gas, heat, and biochar. The syngas product is a mixture of hydrogen, carbon monoxide, steam, carbon dioxide and light hydrocarbon species, which is further processed in a gas cleaning and upgrading sequence to produce useable bio Synthetic Natural Gas (bioSNG). The fixed carbon component of the biomass produces biochar.

Biogenic carbon, absorbed from the atmosphere by vegetation biomass, moves through the pyrolysis process ending up in the biochar product. As grass/crops are readily consumed by animals, the carbon absorbed from the atmosphere is not removed or stored for a long period of time. Instead, the carbon is often released back into the atmosphere again through the respiration process.

If a biochar is produced from the crop/grass material, this represents a longer-term store of biogenic carbon and a means of carbon removal when followed with steps of incorporation into soil, building supplies or put through processes of enhanced weathering. The IPCC (2022) underlines the multiple co-benefits of biochar as a CDR technique stating that biochar production and use gives greater mitigation than bioenergy alone in relation to atmospheric carbon reductions.

There is currently zero commercial production of biochar in Northern Ireland. Previous studies carried out by AFBI and QUB have identified the high potential for digestate solids to be used as a feedstock for biochar production. Amongst all stakeholders consulted for this report there was little awareness of biochar as a form of CDR, even with stakeholders in the agriculture sector, the sector which would benefit the most from the adaptation of biochar as form of CDR. However, the ongoing research work in Northern Ireland is starting to inform stakeholders of the potential in Northern Ireland of biochar for CDR. More widely, in terms of CDR techniques, when asked, people consulted thought of afforestation as a means of pulling carbon out of the atmosphere although most were unaware of the limitations of this approach compared to biochar. Where land-owning stakeholders had considered reducing their carbon footprint then planting trees was the default option followed by increasing soil carbon.

Biochar has a commercial value for CO_2 Removal Certificates (CORC's) which can be traded on various Carbon Dioxide Removal (CDR) Exchanges, such as puro.earth (see Table 5.1 below).

	August 2022	1-Month Change		6-Month Change		YTD Change	
	EUR	EUR	%	EUR	%	EUR	%
CORC Biochar Price Index CORCCHAR	117.99	(22.17)	-15.82%	9.18	8.44%	2.36	2.04%

Table 5.1 CORC Carbon Removal Indexes and CO_2 removal certificate index for biochar from puro.earth 2022[18]

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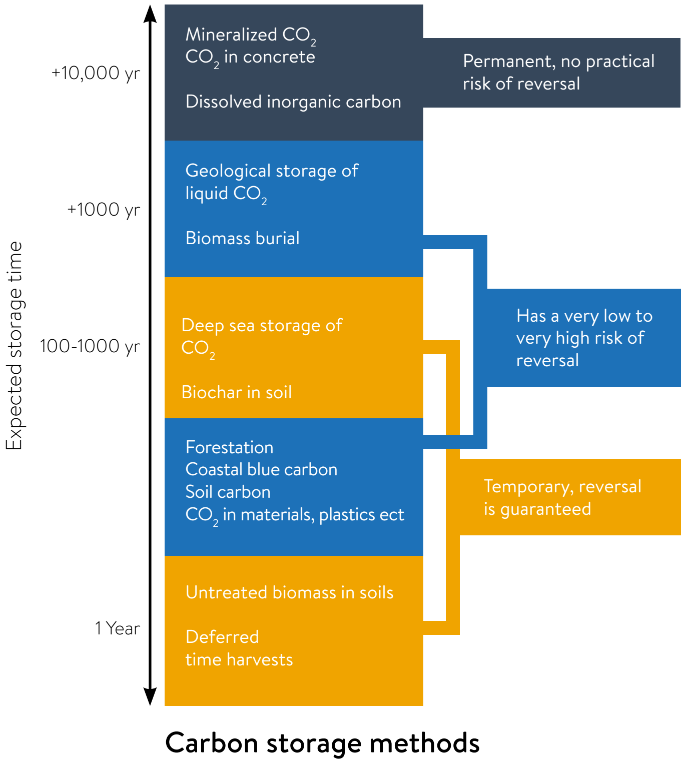
[22] *Fawzy, S., Osman, A.I., Yang, H. et al. (2021) Industrial biochar systems for atmospheric carbon removal: a review. Environ Chem Lett 19, 3023–3055. https://doi.org/10.1007/s10311-021-01210-1*

In relation to permeance, Figure 5.3 below[23] shows the different important distinctions for CO_2 storage methods based on expected storage time. The longevity of the CO_2 stored in certain end locations is very dependent upon how the biomass is used.

When biochar is incorporated in soil it can provide an important source of organic carbon to the soil ecosystems, storing around 2.7 times more carbon than traditional soils. However, as highlighted in Höglund (2022)[19], biochar degrades over time and the CO_2 stored is eventually re-released into the atmosphere, although there is considerable debate over the time of this reversal as the biochar decays in the soil. This is represented by the 'Biochar in soil' storage method in Figure 5.3. Regular monitoring, reporting and verification (MRV) is required to establish the quantity of CO_2 storage remaining in the biochar in the soil. Novel approaches are developing in the MRV of the permanence of CO_2 storage in biochar incorporated in soil.

The cost of MRV and the fact that biochar will decay with time and re-release CO_2 back into atmosphere has curtailed investment in biochar as a CDR pathway. If biochar was instead produced and stored in building materials like concrete, this would increase the expected storage time for carbon and would be classified as 'carbon stored permanently'. Represented in Figure 5.3 as 'CO_2 in concrete'.

Figure 5.3 Permeance chart for the expected storage time for different biomass carbon storage methods[23]



The storage of captured CO_2 in concrete has a very high level of permanence and is therefore easily monitored, reported, and verified. The incorporation of biochar into concrete is starting to attract significant interest, not only because of the CO_2 storage potential but also because biochar has been shown to enhance the physical properties of the concrete and reduce the embodied carbon content of the concrete by replacing other constituents such as aggregate.

Concrete is the most used material on the planet, but the manufacture of the Portland cement used in concrete is one of the highest emitting industrial processes in the world, responsible for 4%-5% of global GHG emissions. The process of heating and decomposing the limestone to make cement releases about 0.86 tCO_2e for every 1 tonne of cement produced. The replacement of aggregate in concrete with biochar not only significantly reduces the total CO_2 emissions of concrete but has also been shown to increase the compressive strength and the curing of the biochar augmented concrete.

There is approximately 1.5Mt of concrete produced in Northern Ireland per year, with the three largest precast concrete production plants in the UK, in terms of output, located in Northern Ireland. Therefore, there is a strong demand for Northern Ireland concrete products in the Great Britain construction sector.

In Northern Ireland, the production of cement is responsible for around 9.4% of all the industrial process and power emissions reported as part of the European ETS scheme in 2019. Like many sectors across the UK and Northern Ireland, the construction sector needs to decarbonise. The high level of emissions associated with the production of concrete must be dramatically reduced to avoid the consequences of climate change and incorporating biochar into this process could reduce the carbon footprint of concrete production while at the same time representing a permanent carbon storage method.

[23] *From: https://roberthoglund.medium.com/carbon-can-be-temporarily-stored-for-a-long-time-4bd7f94e3156*

6 POTENTIAL BIOMASS FEEDSTOCK FOR BIOCHAR PRODUCTION IN NORTHERN IRELAND

6.1 Digestate

A current potential underutilised feedstock for biochar production in Northern Ireland is digestate from anaerobic digestion (AD). In Northern Ireland there are around 90 operational AD plants. The majority of the digestate produced as a co-product from the AD process is currently spread to land as a bio-fertiliser. However, due to the intensity of the livestock sector in the region, and the current issue of nutrient overapplication in the area, there is environmental incentive to change the way digestate is managed in Northern Ireland.

OFGEM (2022)[24] states that 41.8% of the biogas produced from AD plants in Northern Ireland is from grass silage and 12.3% is from manures and slurries. This equates to around 225kt of grass silage and 440kt of cattle slurries and manure feedstock producing biogas to fuel the generation of 213 GWh of renewable electricity from CHP plants[25] (NISRA, 2022). The location of biogas fuelled CHP plants are presented in Figure 6.1. The digestate output from the existing AD plants is estimated to be 112kt of dry matter and equates to 32kt of biochar with a CDR of 118 ktCO_2e (around 2% of the current emissions from the agricultural sector in Northern Ireland).

118 ktCO_2e of biochar from current digestate produced in Northern Ireland equates to a CDR value of €14 million per year (puro.earth CORC Biochar price (Table 5.1)). This is in addition to the product value of the biochar, which is in the range of £100 to £200 per tonne depending upon the end use.

The grass silage feedstock for current AD plants represents 6,750 ha of bioenergy crops being grown in the region, exceeding the target of 5,000 ha for bioenergy crop production in NI set by the Committee on Climate Change (CCC) for 2030, to meet the Net Zero Pathway for 2050 (see Table 6.1 below). Also, significantly this energy crop production has not impacted on the region's food production as detailed in the KPMG report[26], 'Supporting a Renewable Gas Sector in Northern Ireland' and has contributed ~£7M of additional income to NI farmers for bioenergy crop production.

Figure 6.1 Location of biogas fuelled CHP plants across Northern Ireland

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[24] *OFGEM 2022a. Biomass sustainability dataset.* https://www.ofgem.gov.uk/publications/biomass-sustainability-dataset-2020-21

[25] *NISRA 2022. Electricity Consumption and Renewable Generation in Northern Ireland: Year Ending December 2022.* Electricity Consumption and Renewable Generation in Northern Ireland (economy-ni.gov.uk)

The KPMG report[26] noted, "*While there have been some examples of very localised competitive disruption, overall silage pricing doesn't appear to have been impacted by the development of the AD sector. We do note that average conacre prices have risen over the period, although this appears to have been driven primarily by an increase in demand for grazing land (presumably for the increased cattle numbers), since overall land utilised for grass silage production did not increase over the period. This indicates and validates the hypothesis that increased grass silage yields can be obtained as part of a well-ran grassland system.*"

Mehta et al (2022)[3] found that 200 kt of biochar could be produced per year from the digestate of all housed livestock manure and underutilised silage in Northern Ireland (c. 400 ktCO_2e per year of CDR).

The KPMG report[26], 'Supporting a Renewable Gas Sector in Northern Ireland', suggests a target of 1.4TWh of biomethane by 2030. This level of biomethane production would produce nearly 120 kt of biochar with a CDR of over 240 ktCO_2e.

Current and future digestate streams therefore represent a potential feedstock for biochar production which should be considered in new biochar CDR strategies.

> "CURRENT AND FUTURE DIGESTATE STREAMS REPRESENT A POTENTIAL FEEDSTOCK FOR BIOCHAR PRODUCTION WHICH SHOULD BE CONSIDERED IN NEW BIOCHAR CDR STRATEGIES"

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[26] *KPMG report, 'Supporting a Renewable Gas Sector in Northern Ireland' available from Action Renewables on request - https://actionrenewables.co.uk/*

6.2 Woody biomass

Biochar production is typically from woody biomass, however in Northern Ireland the availability of woody biomass currently is very restricted. Of the agricultural land only around 500 ha (0.05%) is willow grown as a bioenergy crop and around 17,000 ha (1.7%) is woodland, mostly planted for habitat diversity, see Figure 6.2.

A further 116 kha of forest land exists in Northern Ireland but this is predominantly utilised within existing markets for timber products with a large proportion of the residual material used for pellet production. The opportunity around using existing woody biomass in Northern Ireland for biochar production is therefore minimal.

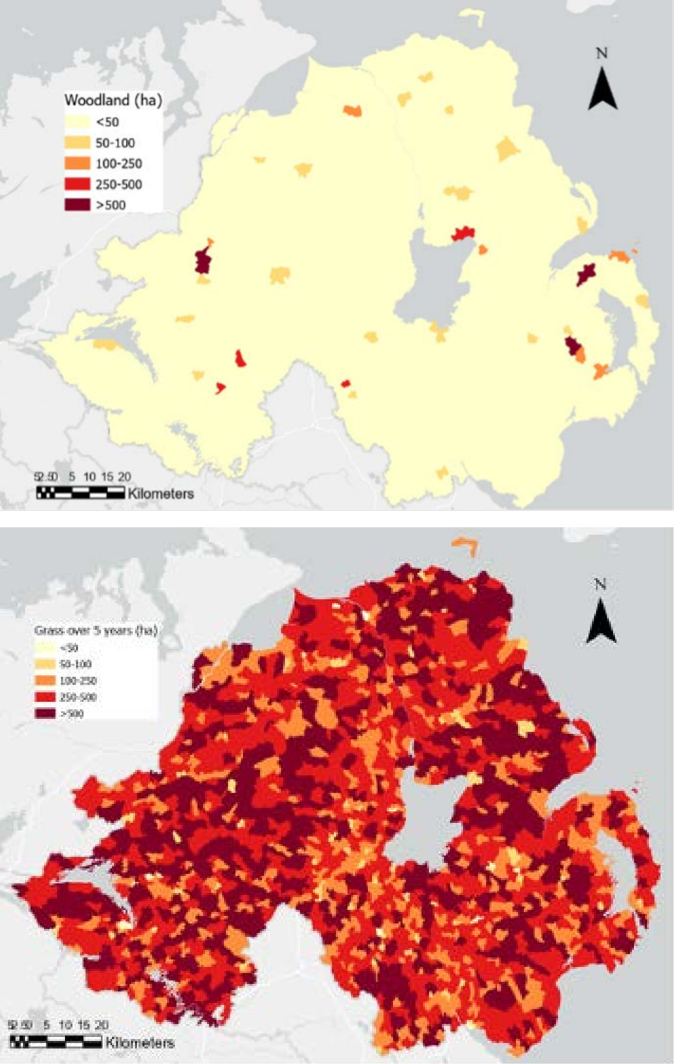


Figure 6.2 Townland map of area of grassland over five years old (left) compared to woodland (right) in Northern Ireland. (Based on the DAERA Census 2021)

Future land use change has been deemed crucial for mitigating climate change and reducing carbon emissions. The extent of land use change needed to meet the Net Zero Pathway by 2050 in Northern Ireland, as modelled by the CCC, is presented in Table 6.1 below. For the purpose of this report, to examine the role of biochar as means of CDR in NI, the target of 36kha of bioenergy crops by 2050, set by the CCC, for the production of bioenergy with carbon capture and storage (BECCS) is the primary land use change modelled in this report. Gasification/pyrolysis is one of the main bioenergy technology pathways specified by the CCC and biochar is a co-product of that pathway.

The areas designated for afforestation, forest land, bioenergy, and hedges and agroforestry must expand to reach net zero emissions. This is because these land use changes offer opportunities for increased bioenergy with carbon capture and storage (BECCS) technology, which transforms biomass into different forms of energy (such as power, heat, hydrogen, fuels, or methane), and an increase in the use of wood in construction (WIC). Both pathways decrease emissions by displacing the use of their higher carbon equivalents and remove carbon dioxide from the atmosphere.

Although the area for tree growth needs to increase in Northern Ireland by 2050, it is assumed, by the CCC, that new biomass from forests and afforestation transitions will primarily be used either as a temporary carbon storage or will be harvested as WIC. Considering the 25-30 year establishment period for new forestry prior to biomass harvesting, if forestry biomass is utilised for BECCS, it will not significantly contribute to CO_2 reduction prior to 2050, in light of the 2050 Net Zero Targets.

In terms of the changes identified by the CCC to release land for climate mitigation while maintaining a strong food production sector, the most relevant to Northern Ireland are:

- *Productivity improvements. There is scope for further abatement from measures to increase agricultural productivity, which in our Balanced Pathway could reduce emissions by 1 MtCO$_2$e in 2035 and 2050. These cover crops and livestock:*

    i. *Improving crop yields without the need for additional inputs such as fertiliser and pesticides can be achieved through improved agronomic practices, technology and innovation while taking account of climate impacts. Our Balanced Pathway assumes that wheat yields increase from an average of 8 tonnes/hectare currently to 11 tonnes/hectare by 2050 (with equivalent increases for other crops).*

    ii. *Stocking rates for livestock can be increased through improving productivity of grasslands and management practices such as rotational grazing. Evidence suggests there is scope to sustainably increase stocking rates in the UK.*

Categories	2020	2030	2035	2040	2050
Required land areas					
Cropland	45	27	24	23	23
Forest Land	166	129	138	151	178
Permanent Grassland	664	512	495	477	426
Rough Grassland	180	117	95	73	27
Settlement	66	71	72	73	76
Temporary Grassland	150	115	111	107	96
Afforestation	1	17	26	41	69
Hedges and Agroforestry	0	8	12	17	26
Bioenergy	0	5	13	21	36
Peatland restoration	5	82	121	134	152

Table 6.1 The extent of land use change needed to meet the modelled balanced Net Zero Pathway by 2050 in Northern Ireland, Climate Change Committee (Figures in kha)

These land use changes allowed for by the increase in agricultural productivity see a decrease of 45% in the land use categories of rough grassland, permanent grassland, temporary grassland, and cropland to be freed up for climate mitigation.

Referring to the land use changes in Table 6.1, the main remaining land use change, that is needed in Northern Ireland for decarbonisation which also supplies a new volume of biomass, is land for bioenergy. This would result in increased volumes of energy crops i.e., available biomass that could be used as a feedstock for BECCS and the production of biochar.

> “LAND USE CHANGES OFFER OPPORTUNITIES FOR INCREASED BIOENERGY WITH CARBON CAPTURE AND STORAGE (BECCS) TECHNOLOGY”

6.3 Energy crops

As the CCC modelling shows, an increase in the land available for bioenergy crops in Northern Ireland is needed to meet net zero targets by 2050. For Northern Ireland, based on work carried out by the UK Centre for Ecology & Hydrology, the target for energy crops planted by 2050 is estimated to be 36 kha. This increases the opportunity for using bioenergy crops for BECCS and the production of biochar as a CDR technology in Northern Ireland.

Miscanthus and Short Rotation Coppice (SRC) willow are the only two bioenergy crops considered in the CCC 6th Carbon budget, however the term energy crop can be applied to any vegetation grown for the purpose of generating energy.

Energy crops, through gasification, can produce both bio syngas and biochar. Such crops can be used for BECCS hydrogen, which relates to the gasification of biomass to syngas, then catalysis of this gas to hydrogen with the capture of CO_2, BECCS biofuels which is the gasification of biomass to syngas, then catalysis to other fuels, such as bioSNG, with the capture of CO_2 and BECCS biomethane which is the fermentation of biomass, as well the capture of CO_2 from biogas in the upgrading of biogas to biomethane for injection into the gas network. Table 6.2 below summarises CO_2 removal figures.

As previously stated, the two co-products from gasification of biomass are syngas and biochar. The CCC 6th CB Methodology only focused on CO_2 removal and did not model for the CDR from biochar

*"There are a wide variety of technology options proposed for removal of greenhouse gases from the atmosphere. The vast majority of these focus on CO_2 removal (as opposed to other GHGs), **and our analysis also focuses only on CO_2.**"*

Gasification parameters can be altered to favour the production of one co-product over the other. The emphasis in the 6th CB Methodology is the production of bioSNG. To align with the 6th CB Methodology, in this report, the biomass conversion factor is 67% syngas and 33% biochar.

The next chapter compares three scenarios of biochar production from 3 different energy crops, miscanthus, SRC willow, as well as grass silage at a centralised and a decentralised scale.

Biomass Conversion Technology	£/MWh 2020	£/MWh 2050	Effciency 2020	Effciency 2050	gCO_2e/kWh 2020	gCO_2e/kWh 2020
Biogas to biomethane	38	35	92%	94%	43	4
Biogas to biomethane with CCS	49	46	88%	90%	-49	-118
Biomass gasification to FT biodesel with CCS	127	86	34%	42%	-457	-485
Biomass gasification to FT biojet with CCS	132	89	34%	42%	-457	-485
Biomass gasification to heating fuel	72	70	52%	54%	28	-400
Biomass gasification to bioSNG with CCS	61	52	60%	66%	-229	-286
UK biomass gasification to H2 with CCS	86	71	51%	55%	-508	-571

Table 6.2 Biomass conversion technology and carbon dioxide removal figures (Adapted from CCC)

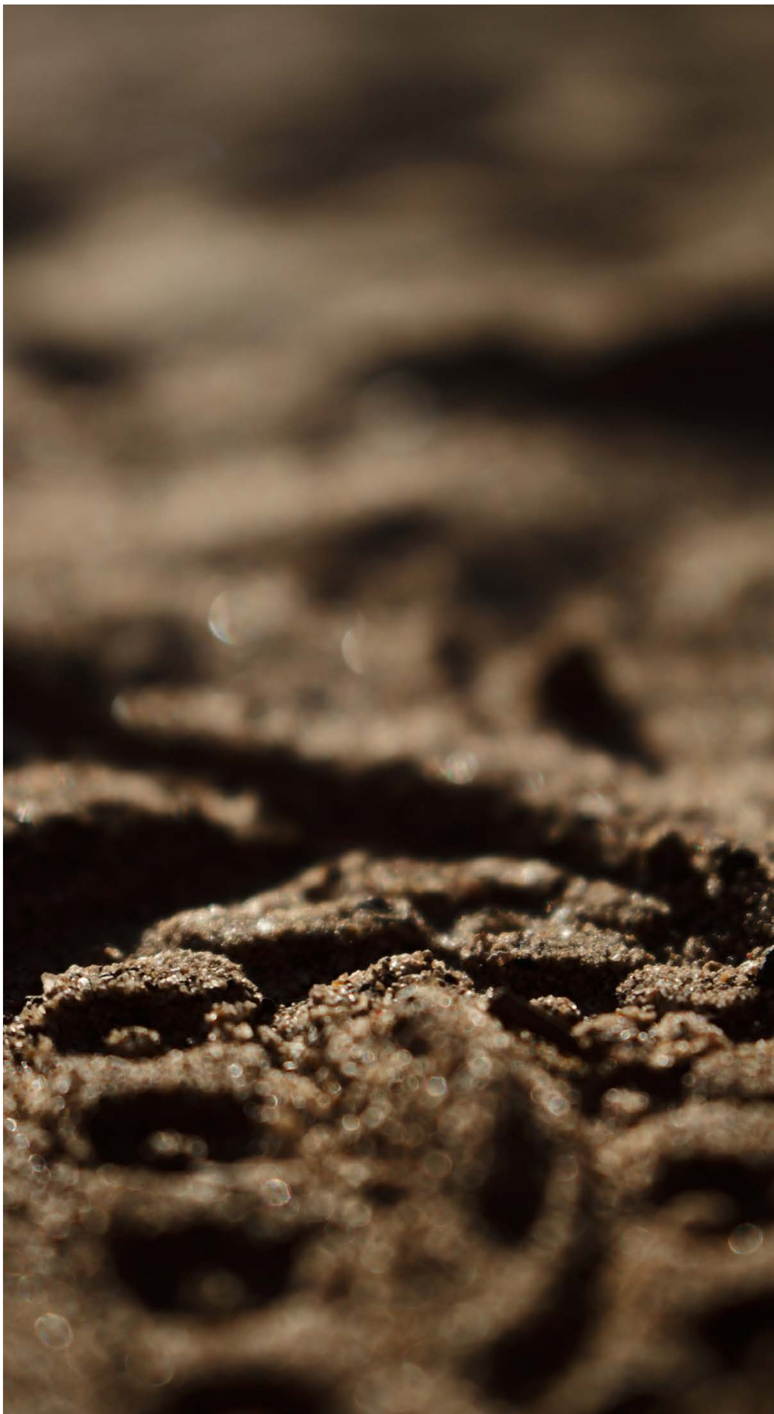
7. COMPARISON OF MISCANTHUS, SRC WILLOW AND GRASS SILAGE DIGESTATE FOR BIOENERGY GENERATION AND CDR

The second objective of this report is to provide "An economic feasibility assessment based on a rural, low-carbon cooperative concept built on an existing farming cooperative model where local farmers collaborate to share the necessary infrastructure. This will be compared to a centralised model involving collection and transportation of feedstocks to major centres for processing."

It is important to note that the specific size of a bioSNG plant is usually determined based on a variety of factors, including the availability of feedstock, local regulations and restrictions, and the demand for the syngas and biochar produced.

Based on discussions with project developers, technology providers and a literature review, bioSNG plants vary in capacity from 4 to 40 megawatts (MW) and use between 40kt to 400kt tons of feedstock per year.

Plants require a relatively large land area, typically between 2-10 hectares, to accommodate the feedstock handling and processing facilities, gas upgrading equipment, and storage facilities for both feedstock and product gas. The plant may also require other supporting infrastructure such as access roads, utilities, and waste treatment facilities.



In Europe, where the bioSNG industry is more developed, there are currently around 30 operating plants and over 50 planned or under construction, according to a report by the European Biogas Association, ***Gasification – A Sustainable Technology for Circular Economies***, with bioSNG capacities of between 20 and 40MW, requiring between 200kt and 400kt of feedstocks per year. Most of these plants are located in Germany, which is the leading country in the bioSNG industry. Other European countries with significant numbers of bioSNG plants include Sweden, Denmark, and the Netherlands. Outside of Europe, there are also several bioSNG projects in North America and Asia, though the industry is still in its early stages in these regions. In the United States, for example, there are a few pilot-scale bioSNG projects, but commercial-scale plants are still relatively rare.

Early on in the development of this work, a model with two or three large scale plants for the whole of Northern Ireland was considered. However, this was determined not to be a viable option for a number of reasons:

1. Based on the European model of the deployment of large scale centralised bioSNG plants, even the lowest end of the scale of deployment in Europe of 20MW of bioSNG and 200kt of feedstock per year, would require 14 to 15 kha of a land take to grow the bioenergy crop feedstock. Using the CCC 6th Carbon Budget Methodology for land use change in NI to the growing of bioenergy crops, depending on the feedstock used, it would take 10 to 12 years to build up the feedstock land bank needed to provide for the plant. The securing of feedstock supply is essential to securing financing of any biomass project and feedstock supply cannot be secured until a feasible project can be demonstrated to potential feedstock growers.

2. While government intervention to focus conversion of the necessary 15 kha land area around a bioenergy site for energy crops at a faster rate is a possibility, given the importance of small farmers to agriculture in NI and the resistance to move away from traditional farming practices, this was thought to be politically unpalatable.

3. An alternative government incentive scheme to increase conversion of land to energy crops could be a possibility but would likely lead to dispersed production. Transport costs of feedstocks then become a major barrier at c.£5/tonne per 10 km travelled. This additional cost outweighs cost savings due to scaleup of the plant. An additional consideration is the increase in HGV traffic across NI required to feed a centralised plant.

Therefore, given the scale of a centralised bioSNG project, the low base of bioenergy crop production in NI and prohibitive transport costs a centralised model is a non-starter in the short to medium term to meet 2030 Net Zero Targets and a high-risk strategy to meet longer term, 2050 targets.

If the focus of the project is shifted towards a co-product approach, emphasizing the production of biochar for CDR and syngas for local energy needs instead of bioSNG production, it would avoid the significant capital expenditures required to upgrade syngas to bioSNG. This, in turn, would allow for the deployment of smaller plants that are better suited to a scale appropriate in Northern Ireland. Additionally, this approach could enable the development of a rural, low-carbon cooperative concept based on the existing farming cooperative model, which is well established in the region.

The increased need for CDR, which has been emphasised by the IPCC and is being incorporated into government policies in the UK, EU, and US, has stimulated the development of smaller, modular gasification/pyrolysis systems. These systems prioritize the production of both syngas and biochar, in response to the increasing CDR revenues generated from biochar.

Several technology providers now supply commercial units with an output of one tonne of biochar per hour over 8000 operational hours per year. This means that the plant needs to process a total of 24,000 ODT of biomass annually, which corresponds to around 40 kt of biomass feedstock with a Moisture Content (MC) of 35%. This scale of feedstock supply, as highlighted above, is suitable for Northern Ireland and facilitates the development of low-carbon farming cooperatives.

In this chapter, regarding feedstock supply, three scenarios will be considered each consisting of using a different bioenergy crop that has 36 kha of planting built up over time (as per recommendation of the CCC). These scenarios are:

1. Grass Silage Digestate (GSD)
2. Miscanthus (Misc)
3. SRC Willow (SRC)

Miscanthus and SRC willow represent two important bioenergy crop feedstocks to consider for gasification and the production of biochar in Northern Ireland. Figure 7.1 is a schematic diagram of a process that uses the energy crops miscanthus and SRC willow as a feedstock for the process of pyrolysis, to produce both a syngas and a biochar for CDR.

In the miscanthus and SRC willow scenarios, the target for planting of each by 2050 is 36 kha. The crops are harvested and routed through pyrolysis, representing a capturing of biogenic carbon by the plant which is then partitioned between a syngas (67%) for local energy needs or upgraded to bioSNG as a fuel, and a biochar (33%) which can be added to soil, or added to products like concrete for CDR.

In the grass silage digestate scenario, it is grass that is grown in the new bioenergy area of 36 kha per year up to 2050, harvested and used within BECCS biomethane i.e., routed through an AD plant for the generation of biogas. The output digestate from the AD process undergoes gasification to produce biochar for CDR, this is presented in Figure 7.2.

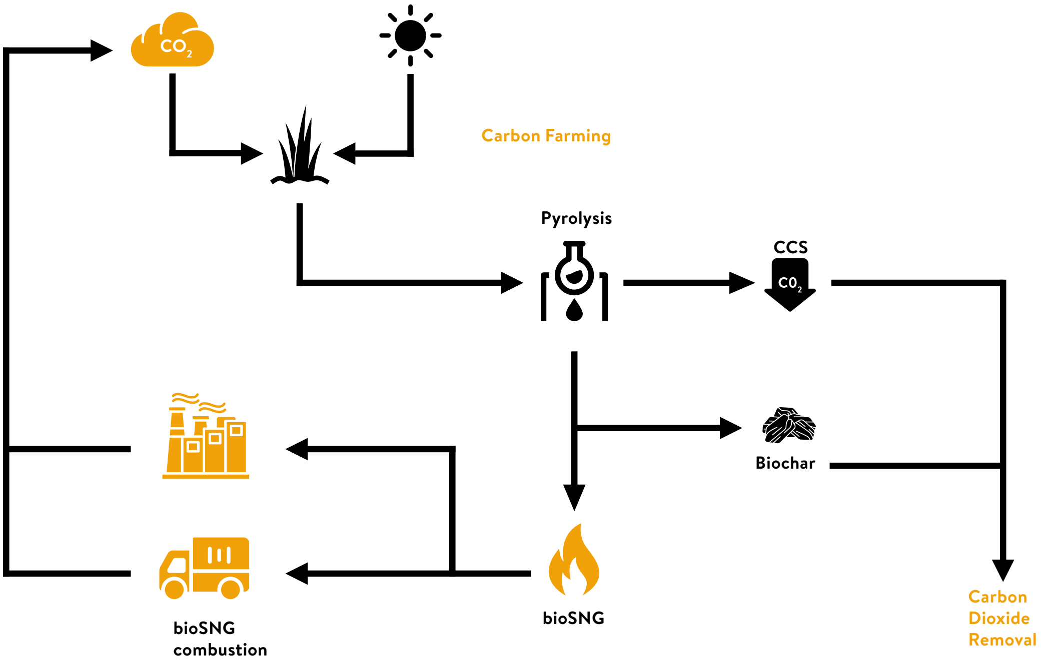


Figure 7.1 Schematic diagram of the pyrolysis process on miscanthus and SRC willow

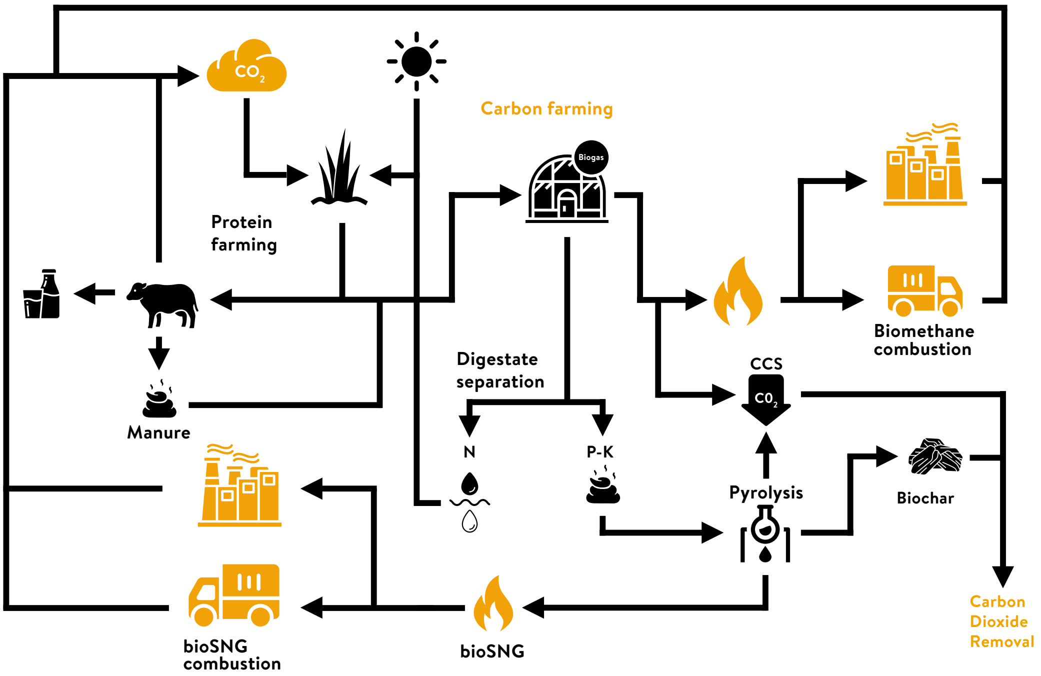


Figure 7.2 Schematic diagram of the AD and pyrolysis process on manure and grass silage

The three scenarios result in the production of biochar, as a pathway of CDR. Table 7.1 shows the three feedstock pathway characteristics of grass silage digestate (GSD), miscanthus (Misc) and Short Rotation Coppice Willow (SRC). The biochar figures are based on the analysis by Eurofins (Annex 2). The cost of feedstock is based on current market prices in Northern Ireland of £45 per tonne for grass silage with a dry matter (DM) of 30% which equate to £1.50 per % DM and therefore £150 per Oven Dried Tonne (ODT). The feedstock output figures are based on DAERA co-efficient values.

	GSD	Misc	SRC
Year of harvesting after planting	1st yr	3rd yr	3rd yr
Soil emissions associated with planting; tCO_2eq	0.5	1	1
Year of replanting	10th yr	15th yr	N/A
Yield ODT/ha	12	14	14
Annualised yield ODT/ha	12	11	11
Cost of feedstock per ODT	£150.00	£150.00	£150.00
Energy content; kW per ODT	5064 kW	5064 kW	5064 kW
Pyrolysis conversion factor; 67%	3393 kW	3393 kW	3393 kW
Load required for drying, 30% MC to 10%MC; 15%	509 kW	509 kW	509 kW
Load required for pyrolysis; 27%	916 kW	916 kW	916 kW
Balance of syngas for bioSNG	1968 kW	1968 kW	1968 kW
bioSNG produced	1574 kW	1574 kW	1574 kW
Biochar conversion	33%	33%	33%
Organic carbon content of biochar	55%	80%	80%

Table 7.1 The three feedstock pathway characteristics of grass silage digestate (GSD), miscanthus (Misc) and Short Rotation Coppice Willow (SRC)

It is important to note that all three scenarios start from a zero base – i.e., they assume there is no existing planting. In reality, most of the land that would be allocated to bioenergy crops is existing grassland. Therefore, grass silage will offer much greater potential for early impact as it will require just conversion from animal grazing to silage for bioenergy with the bonus for farmers of no additional costs for planting. All scenarios assume the availability of suitable AD, pyrolysis or gasification facilities and no account is made for delays in construction, planning etc.

> “MISCANTHUS AND SRC WILLOW REPRESENT TWO IMPORTANT BIOENERGY CROP FEEDSTOCKS TO CONSIDER FOR GASIFICATION AND THE PRODUCTION OF BIOCHAR IN NORTHERN IRELAND”

7.1 Yield and CO_2 absorption potential of energy crop

The yield per hectare is higher for both Miscanthus and SRC willow compared to grass. However, due to the planting and harvest cycles, the total area of potential harvest each year up to 2050 for grass silage is higher than both, Figure 7.3.

With Miscanthus, the crop is not harvested until the 3rd year after the planting year and must be replanted after 15 years with a subsequent 3-year delay in harvesting.

This would result in only around 26,700 ha being harvested of the 36,000 ha planted for the Miscanthus feedstock scenario by 2050. For SRC Willow, the bioenergy crop also takes 3 years to establish prior to harvesting, but unlike Miscanthus does not need to be replanted, once established. However, SRC willow can only be harvested every 3 to 4 years. As grass can be harvested in the season it is planted and needs reseeded every 10 years the total area available for harvest is the highest up to 2050.

Although more hectares are harvested for the grass silage biomass pathway over the years to 2050, meeting the schedule of 36 kha planted and harvested by 2050, the productivity of Miscanthus and SRC willow compensate in terms of Oven Dried Tonnes (ODT) harvested, see Figure 7.4 below.

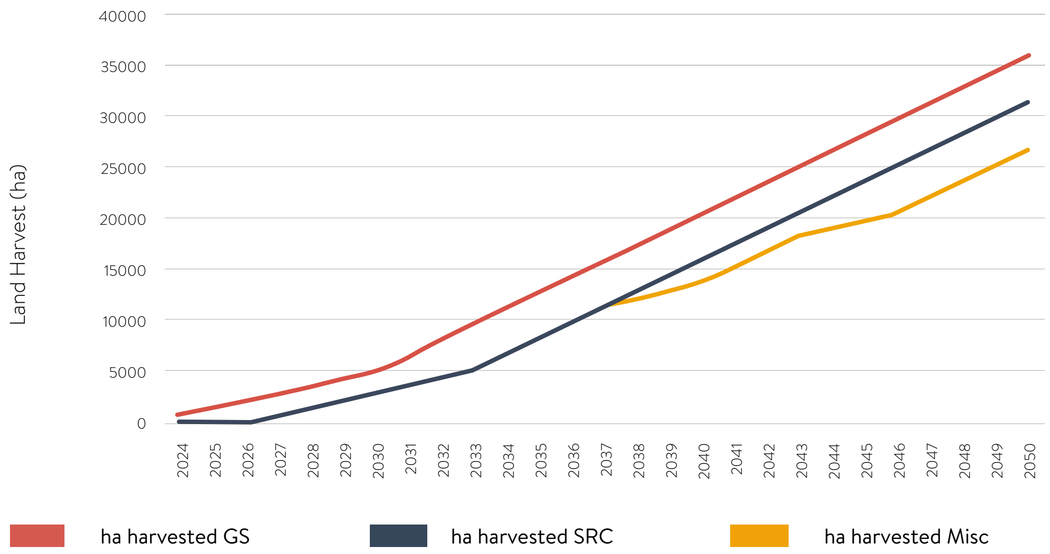


Figure 7.3 Land area harvested per year to 2050

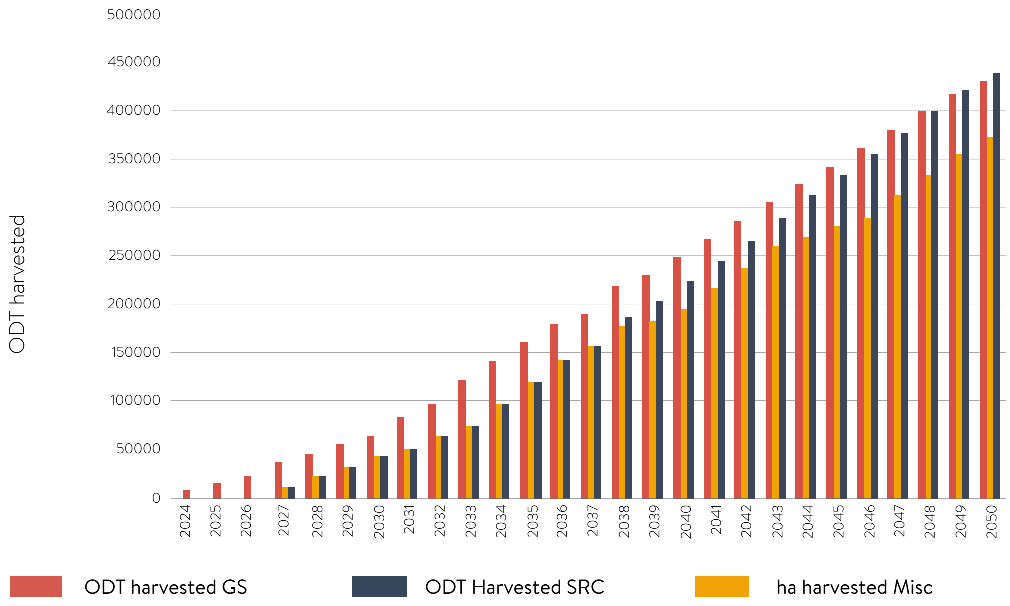


Figure 7.4 Harvested energy crop in Oven Dried Tonnes (ODT)

The higher biomass yield per hectare for Miscanthus and SRC willow results in a higher average CDR per hectare, compared to the grass silage pathway, up to 2050, Figure 7.4.

The combination of all factors including yield, growth and harvest cycle and the organic carbon content of the biochar produced means that by 2050 all feedstock scenarios sequester between 530 and 620 ktCO_2e per year (Figure 7.6).

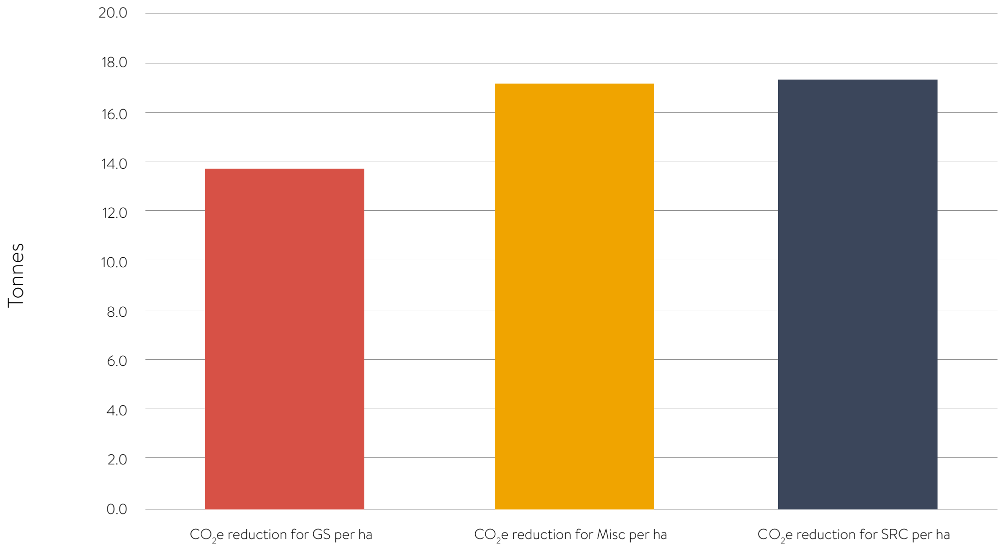


Figure 7.5 Average CO_2e tonne reduction per hectare per year until 2050

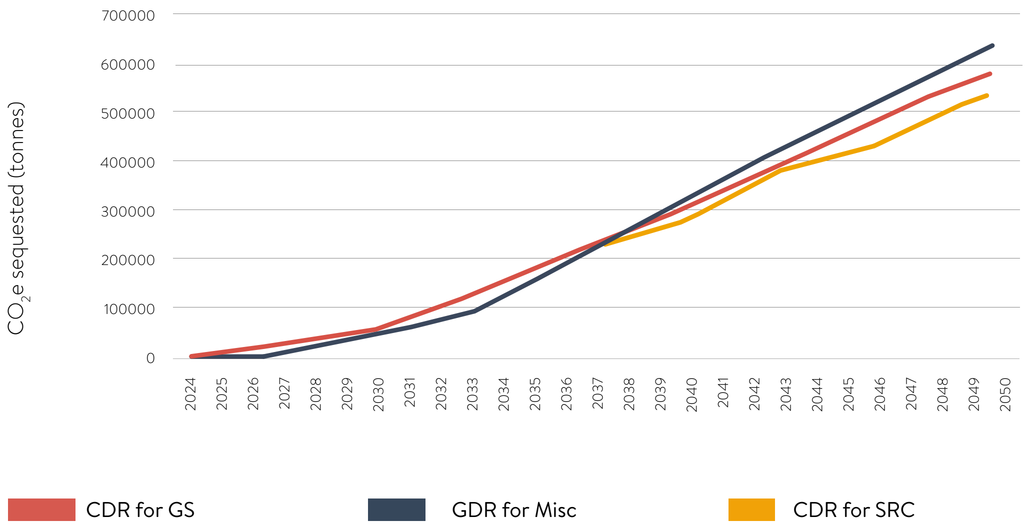


Figure 7.6 Carbon sequestered from the three energy crop scenarios, grass silage, miscanthus and SRC willow in CO_2e tonne per year to 2050

7.2 Emissions reduction and biochar potential

In discussion with gasification technology providers and based upon the analysis of the miscanthus biochar produced in the CASE funded BioChar Project, the CO_2 removal figures for the gasification of miscanthus was calculated to be -258 g CO_2e. per kW of bioSNG produced, tallying with the median figure used in the CCC 6th CB methodology.

Taking the planting schedule for bioenergy crops in Table 7.1, the harvested yield figures per hectare for miscanthus and SRC willow and applying the CO_2 removal figure for biomass gasification to bioSNG with CCS in Table 6.2, the emissions reductions for the agriculture sector due to increasing biomass gasification are shown in the graph below. Both feedstock pathways utilised as biomass for gasification to produce bioSNG with CCS will have a significant impact increasing out to 2050 resulting in a cumulative emissions reduction of between 1.8 Mt CO_2e and 2.0 Mt CO_2e over the period to 2050.

However, as shown in the graph below, Figure 7.8, if the CDR of the biochar produced in the gasification to bioSNG with CCS technology pathway is included in the CO_2 removal calculation, then cumulatively over 6 Mt CO_2e from the agricultural sector can be sequestered by 2050 with the planting of 36 kha of bioenergy crop for this CDR technology pathway.

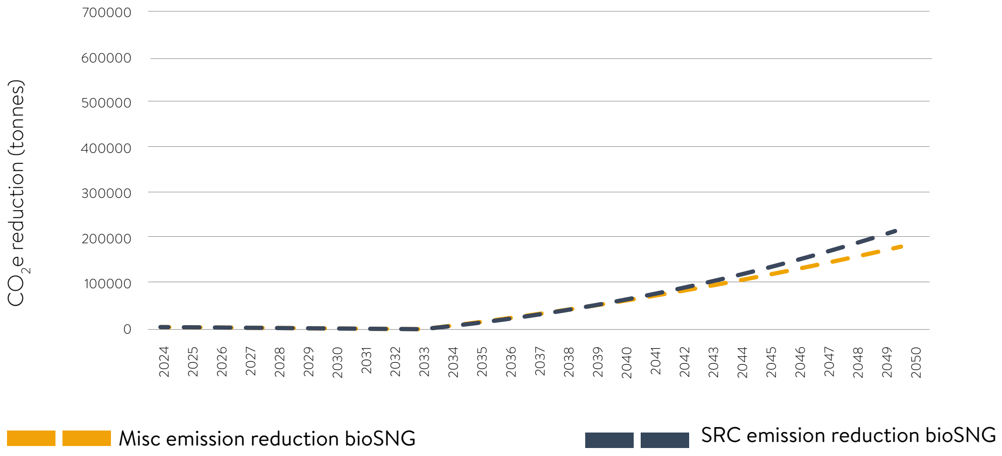


Figure 7.7 Cumulative total annual emissions reduction from Miscanthus and SRC willow gasification with CCS

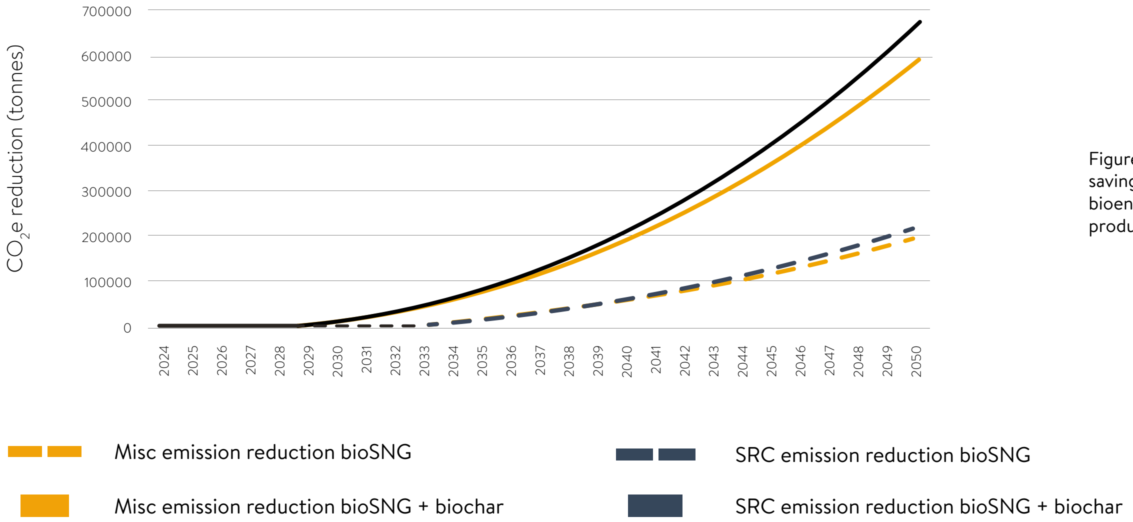


Figure 7.8 Cumulative emissions savings for Miscanthus and SRC willow bioenergy crops with CCS and Biochar production.

This scale of emissions reduction would obviously have a significant impact on the agricultural sector in Northern Ireland.

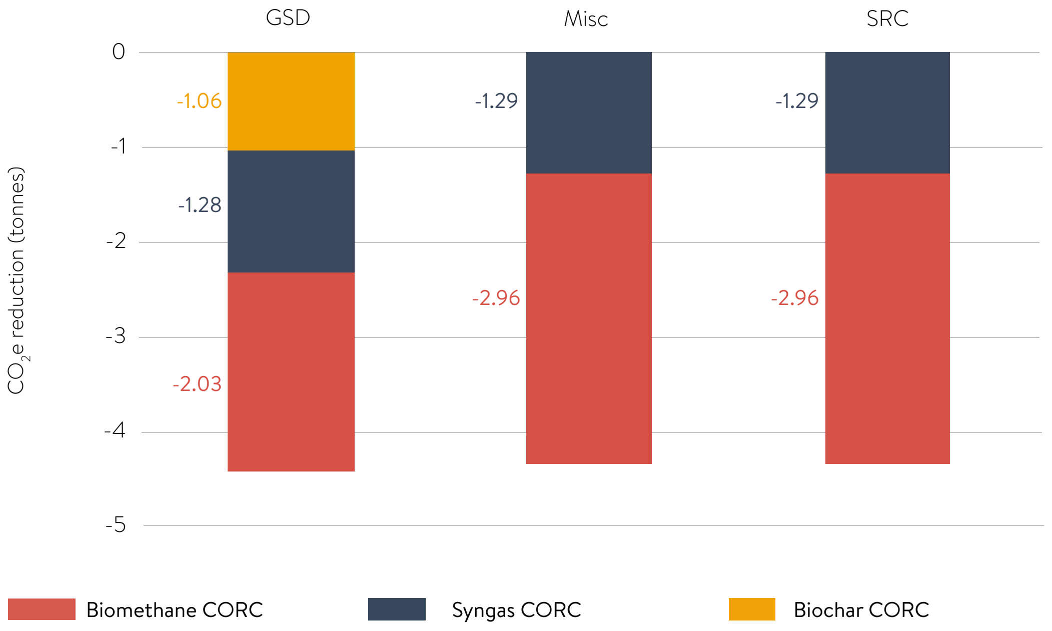


Figure 7.9 Carbon Dioxide Removed (tonnes CO_2e) per one tonne of biochar produced

The grass silage digestate pathway has the benefit of capturing additional CO_2 through biogas to biomethane with CCS of grass silage prior to gasification with CCS of the digestate. Based on the figures from the CCC 6th Carbon Balance methodology this is currently -49g CO_2e/kWh and rises to 118g CO_2e/kWh by 2050 through improvement in technology and recovery efficiency. However, there is a decrease of 15% in the ODT of the digestate output compared to the ODT of the grass silage input due to fermentation to produce the biogas. Figure 7.9 compares the feedstock scenarios using volume of carbon dioxide removed per tonne of biochar produced.

Gasification and formation of biochar from grass silage digestate does not better the ~5.9 Mt CO_2e sequestered using miscanthus or SRC as the bioenergy crop, because some of the energy in the grass silage digestate has already been fermented, through AD, to produce biogas. Using the CDR technology pathway proposed in the CCC 6th Carbon Budget Methodology of biogas to biomethane with CCS to capture the CO_2 in the biogas stream prior to gasification of the grass silage digestate from the AD process, then an additional 1.5 Mt CO_2e can be removed from the atmosphere, see Figure 7.10 below.

> “THE GRASS SILAGE DIGESTATE PATHWAY HAS THE BENEFIT OF CAPTURING ADDITIONAL CO_2 THROUGH BIOGAS TO BIOMETHANE WITH CCS”

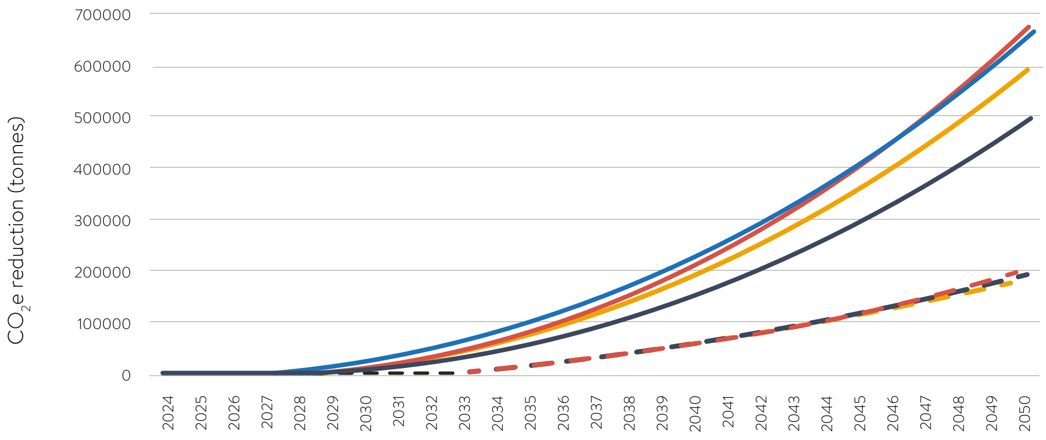


Figure 7.10 Cumulative emissions reductions comparing Grass Silage Digestate to Miscanthus and SRC Willow (tonnes CO_2e) with additional biomethane CDR contribution.

The CCC target of 36 kha of bioenergy crops per year by 2050 and the biochar production figures in the biomass gasification with CCS technology pathway equals to the production of over 120 kt of biochar per year by 2050 for all three biomass scenarios as shown in Figure 7.11.

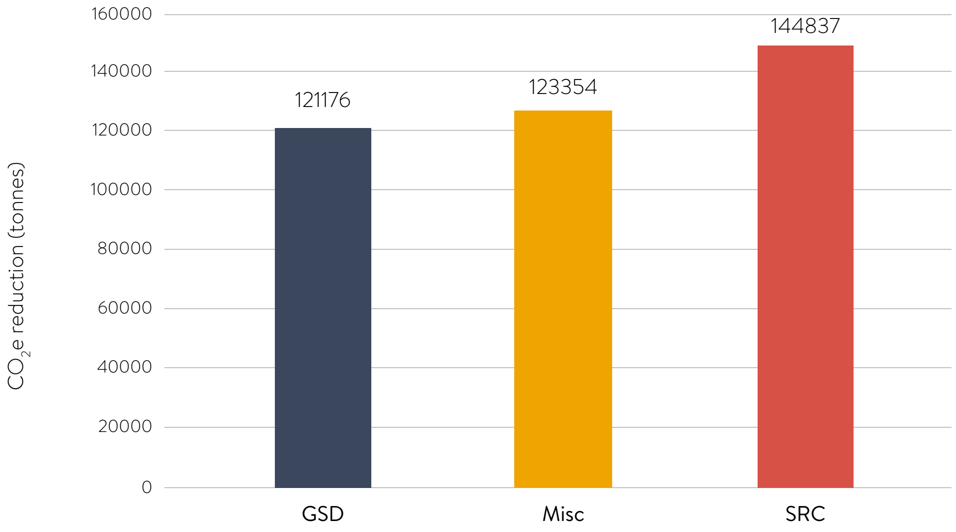


Figure 7.11 Annual production of Biochar (tonnes) for Grass silage, Miscanthus and SRC Willow

The carbon content of biochar differs depending on the process conditions used and the initial feedstock with different proportions of carbon making up the final composition of biochar. For the three scenarios presented, this means that biochar from SRC Willow and Miscanthus have higher percentage carbon content than for biochar from grass silage digestate. This is shown in Figure 7.12 below.

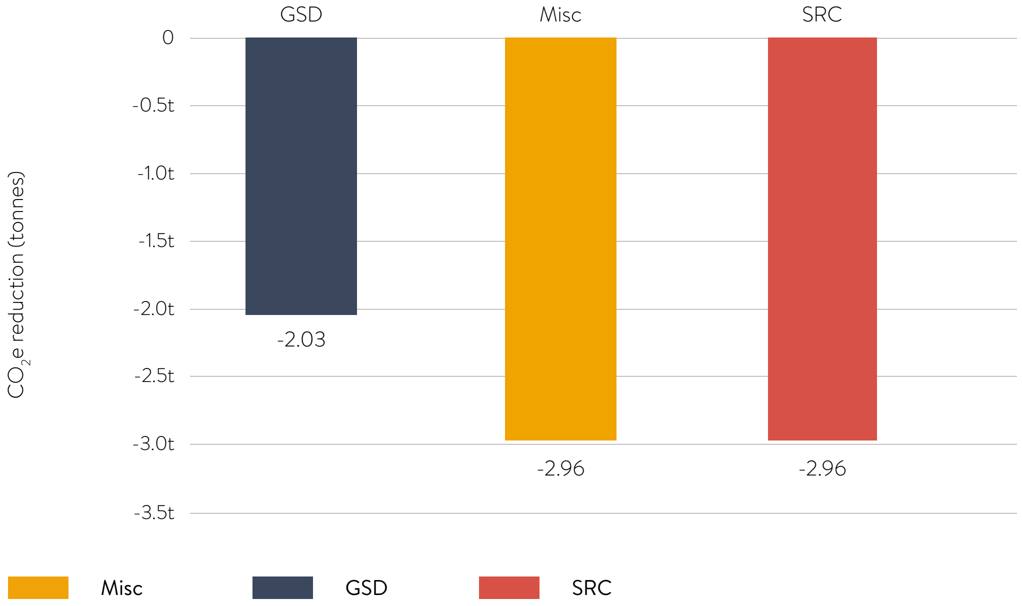


Figure 7.12 Carbon Dioxide Removed (tonnes CO_2e) per tonne of biochar produced

7.3 Potential to displace aggregates in concrete

Currently, 932 kt of aggregates are required per year for current concrete production in Northern Ireland. In order to help decarbonise concrete production and lock down the carbon sequestered in biochar an inclusion rate of biochar by weight of 10% to replace aggregate would be possible using results from this analysis. The inclusion of biochar in concrete provides for a very high level of permanence of CDR, as discussed in chapter 8, with a low MRV requirement.

The potential for the energy crop biochar pathways presented above to contribute to the displacement of aggregates by biochar in concrete is variable as seen above in Figure 7.12. By 2050 in total the CDR pathway of biochar incorporated in concrete could be capturing and permanently storing between 240 and 430 ktCO_2e. per year for all feedstock scenarios. If deployed from 2024 this CDR will have cumulatively, permanently captured and stored up to 4.6 MtCO_2e from the atmosphere in concrete by 2050. Using miscanthus as the feedstock for biochar would result in the greatest CO_2 storage potential of biochar inclusion as the aggregate in concrete.

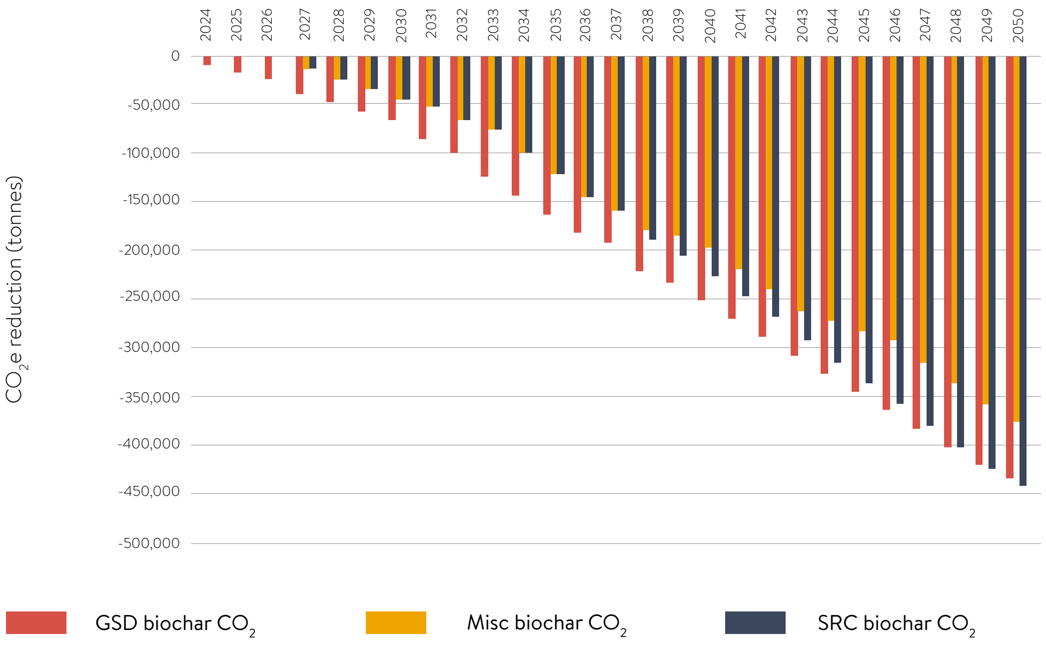


Figure 7.13 CO_2 storage potential of biochar inclusion as aggregate in concrete in NI (tonnes)

The CO_2 emissions associated with clinkering to produce cement (204 kt CO_2e per year) will be captured in biochar and stored permanently in the concrete produced by 2047 for the grass silage digestate pathway and earlier by 2041/2042 for the Miscanthus and SRC biomass pathways (Figure 7.14).

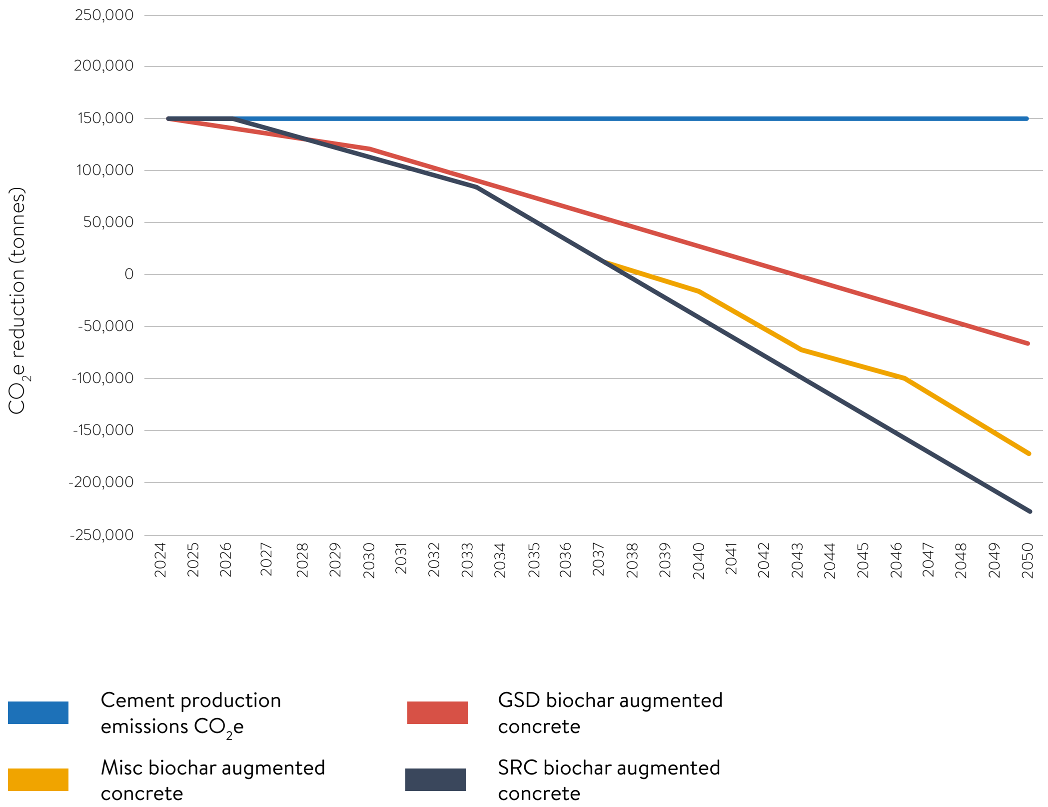


Figure 7.14 Emission reductions from Cement Production with biochar augmented concrete

7.4 Economic comparison

7.4.1 Farmer incomes

Miscanthus and SRC willow biomass pathways have significant planting costs, ~£2,000-£2,500 per ha, and require long-term commitment of 15+ years per ha of growing due to the planting and harvesting cycles of each crop. Transitioning grassland in Northern Ireland to Miscanthus/SRC willow makes this area unusable by livestock, which would increase dependence on and cost of external feed for animals if the land that is being transitioned is currently grazed and there is no increase in existing grassland utilisation efficiency through the tightening of stocking rates.

Growing grass silage as a bioenergy crop requires no additional planting or land commitment costs due to the existing grass-based farming enterprise in Northern Ireland. Also, existing farm infrastructure and machinery that is currently being used for silage production, can be used to harvest, and store grass silage as a bioenergy crop. In addition, increasing the land area for grass silage feedstock can occur in conjunction with ongoing grassland and/or cropland farming, rotating within the existing cycle of Northern Ireland livestock farming, providing an additional income from CDR.

In terms of farmer incomes for growing bioenergy crops, the above factors of planting, harvesting and plant productivity have a major impact on the CDR potential of each of the three bioenergy crop pathways. CDR value is an important determining factor in farmer income per hectare of area.

Considering biomass yield per hectare, and a bioenergy crop value of £150 per ODT (Table 7.1), then Miscanthus and SRC willow have clear economic attractions to carbon farmers due to the ODT content of the crops – see Figure 7.15 below.

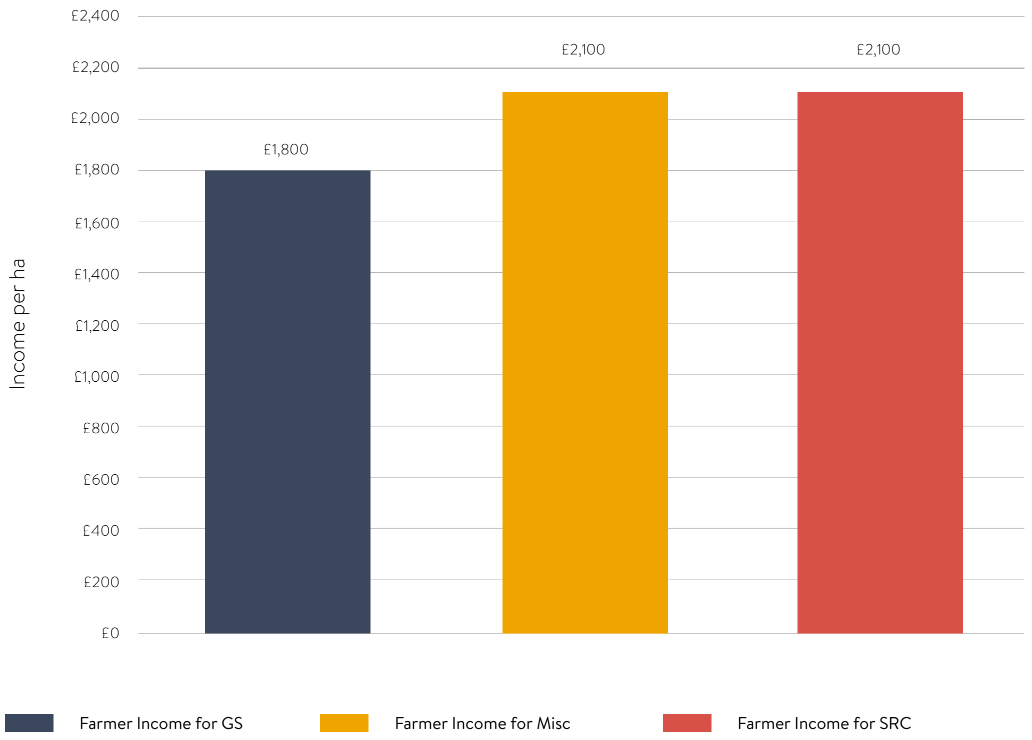


Figure 7.15 Income from growing energy crop per hectare

However, factoring in the planting and harvesting schedules, then the carbon farmer's income per hectare favours the grass silage digestate biomass pathway over the Miscanthus and SRC willow biomass pathways, see Figure 7.16 below.

If these income figures are extrapolated up to the CCC's 36 kha 2050 bioenergy target for Northern Ireland, then the revenue for farmers for growing bioenergy crops is shown below in Figure 7.17.

Farming and land use in NI, as for the rest of the UK, is very well established and there is no "free ground" available for land use change to meet climate change mitigation requirements. However, based upon the CCC 6th Carbon Balance Methodology of increasing stocking rates and plant productivity, there is the potential for "freeing up" agricultural land for the planting of bioenergy crops and this only represents the conversion of 3-4% of the current Northern Irish farmed land to bioenergy crops.

The increase in the land use efficiency proposed by the CCC to allow for bioenergy crop production will generate **additional revenue** to augment current farm incomes. This could provide a significant increase, by the agricultural sector, to the GVA of the Northern Ireland economy and could potentially help to displace the current subsidy dependence of the sector on the wider economy. However, this will require further economic analysis beyond this report.

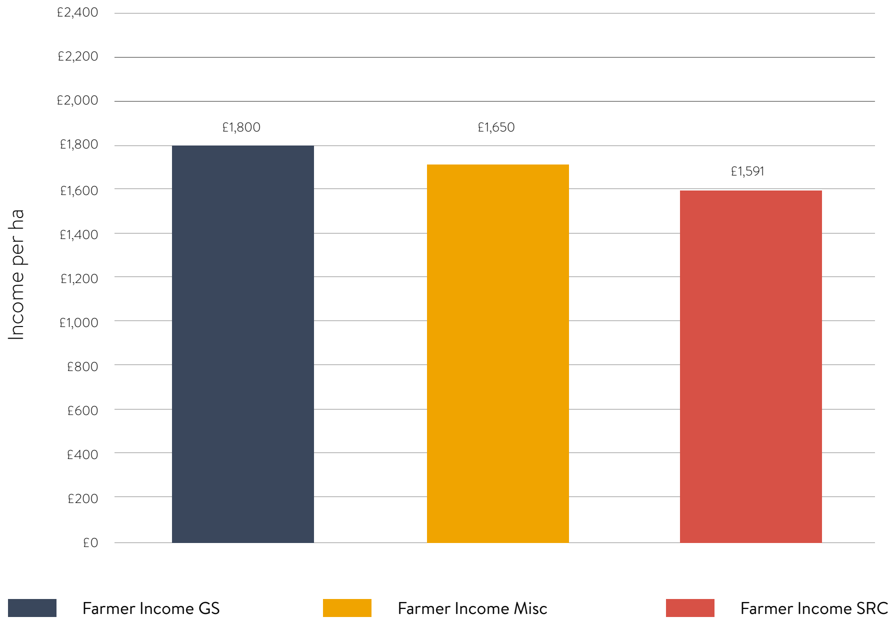


Figure 7.16 Income for growing energy crop per hectare allowing for productivity

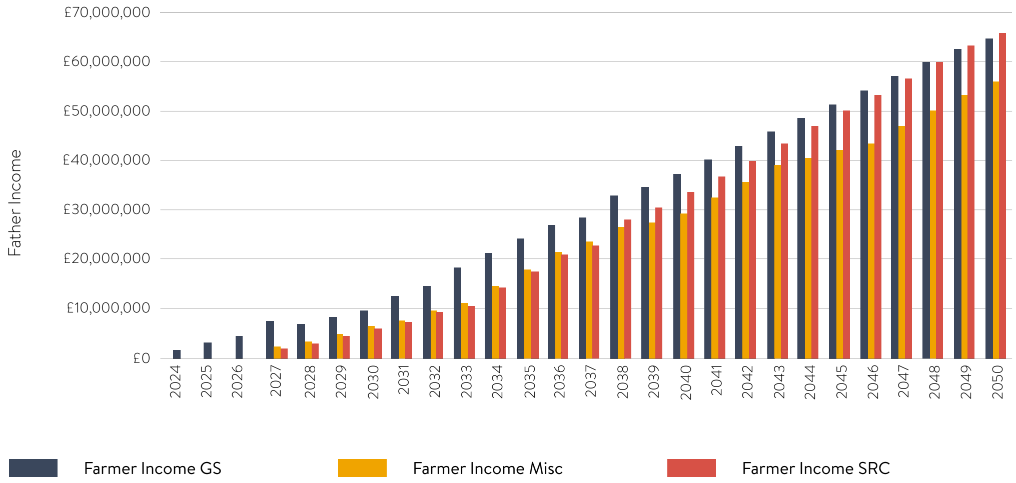


Figure 7.17 NI Farm Income for 36 kha of Energy Crops

7.4.2 Cost of producing the biochar

Based on the results of the analysis of the digestate and miscanthus biochar a preliminary financial assessment was carried out with researchers at QUB to determine Capex and Opex costs and potential returns to produce the biochar. This preliminary assessment was corroborated by discussions with leading technology providers in the sector.

A high-level financial model was then constructed for the production of biochar from the biomass feedstocks of digestate and miscanthus at a scale appropriate to potential feedstock supply in Northern Ireland

Energy content of biomass per t of total solids	5064 kWh
Quantity of biomass total solids	3.0 t
Biochar conversion	33%
Quantity of biochar produced	1.0 t
Quantity of syngas produced	1.9 t
Quantity of syngas required for pyrolysis	0.5 t
Quantity of syngas available for bioSNG production	1.4 t
Quantity of bioSNG produced	4770 kWh

Table 7.2 Assumptions of the financial model

> “THE INCREASE IN THE LAND USE EFFICIENCY PROPOSED BY THE CCC TO ALLOW FOR BIOENERGY CROP PRODUCTION WILL GENERATE ADDITIONAL REVENUE TO AUGMENT CURRENT FARM INCOMES”

An output of one tonne of biochar per hour over 8000 operational hours per year, was used to determine the scale of industrial plant needed for each scenario. This output rate requires 24,000 ODT of biomass per year which at 35% Moisture Content (MC) equates to ~40 kt of biomass feedstock, which is an appropriate scale for feedstock supply in Northern Ireland.

This scale would require an industrial plant construction schedule, as shown below in Figure 7.18, to meet the biomass harvesting schedule as dictated by the 2050 target of 36 kha of bioenergy crops.

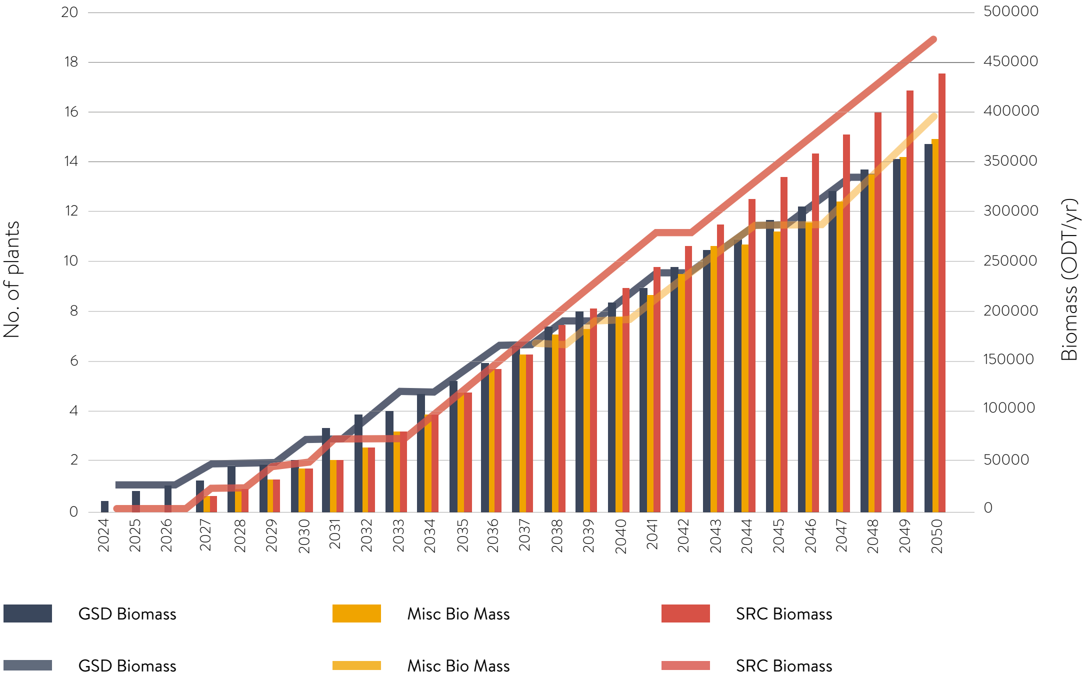


Figure 7.18 Number of industrial plants required each year as bioenergy crop production ramps up

Capex and Opex were estimated, based on developer's experience of building, and operating other biomass energy plants and in discussions with gasification/pyrolysis technology providers. These costs were then compared with costs from a report referenced by the CCC, *The feasibility and costs of biochar deployment in the UK, 2011*[27], in the 6th Carbon Budget Methodology and from costs in the 6th Carbon Budget Methodology for the technology pathway, biomass gasification to bioSNG with CCS.

A difference was found in the overall costs, and this was determined to be mainly due to underestimated feedstock costs, which have seen an increase since the publishing of the CCC 6th Carbon Budget and a substantial increase since the publishing of, *The feasibility and costs of biochar deployment in the UK* report in 2011[27].

Feedstock costs are a key variable in the production of bioSNG. A report by IEA Bioenergy Task 41, **Advanced Biofuels – Potential for Cost Reduction**[28], clearly underlines this; "The analysis also confirms the impact of using low-cost waste-based fuels and the significant impact of these lower costs on the overall production costs of the fuels. The data shows clearly that producing biofuels or bio-methane from wastes is significantly cheaper than from biomass feedstocks. Capital costs are not significantly different for plants using the two different feedstocks, while operating costs for waste-based plants are higher, but this cost increase is more than offset by the negative feedstock costs."

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[27] *https://doi.org/10.4155/cmt.11.22*

[28] *https://www.ieabioenergy.com/wp-content/uploads/2020/02/T41_CostReductionBiofuels-11_02_19-final.pdf*

	This work	IEA Low	IEA High
Capital cost per MWh	€30	€33	€49
Feedstock cost per MWh	€110	€15	€33
Operational cost per MWh	€28	€14	€30
Total production cost per MWh	€167	€62	€112

Table 7.3 Comparison of CAPEX and OPEX costs from this work compared to IEA Low and High range estimates

The comparison shown in Table 7.3, between the cost per MWh from the IEA report and the costs calculated for this report, clearly highlights the factor of feedstock costs and underlines the difficulty in the commercial operation of bioSNG production plants given the historic low price of natural gas at ~€30/MWh especially with biomass as the feedstock.

Biochar production is a co-product of bioSNG production and there is very little additional Capex associated with it. The increasing value placed on CDR provides an opportunity to turn the business model for bioSNG production on its head.

Excluding costs included in, *The feasibility and costs of biochar deployment in the UK* report from 2011[27] to make a like for like comparison, the cost of production of one tonne of biochar was £462/t in the 2011 paper[27]. The cost calculated and included in the modelling for this work is £694/t.

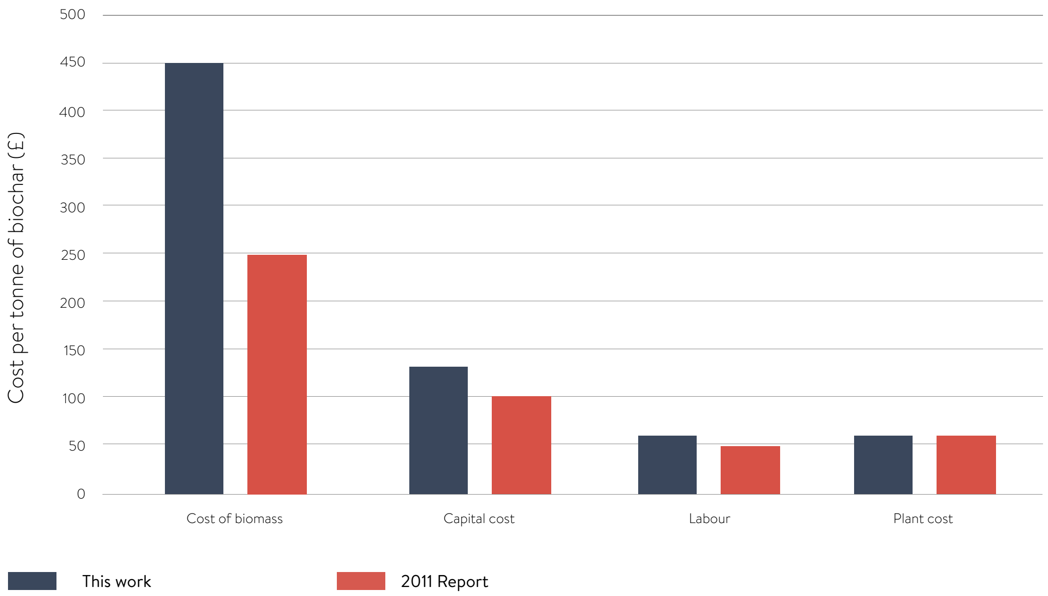

Figure 7.19 Biochar production cost comparison per tonne of biochar, values from this project compared to 2011 report[27]

Again, this clearly demonstrates the key issue of the variability of the cost of feedstock on the required return. Apart from feedstock, other costs have not varied significantly in over 10 years due to improvements in technologies and efficiencies. A way to reduce feedstock costs is to cascade the value of biomass across several processes. The biomass cost of the grass silage digestate scenario has been shared with the production of biomethane on a 50% cost basis determined by the ratio of biomethane to syngas production per ODT of grass silage.

Based on the value of a CORC at £200 and of the biochar as a product at £200, the costs compared to the returns for each biomass scenario is shown in Figure 7.20 above. The returns for the production of biochar CDR are marginal at 14% for both the Misc and SRC biomass pathways. The GSD shows a better return of 28%, even though less income is generated per tonne of biochar. This is due to the lower organic carbon content of 55% for GSD biochar compared to 80% for Misc and SRC biochars. The better return for GSD biochar is due to the sharing of 50% of the biomass cost per tonne in the GSD scenario with the production of biomethane. However, all returns are dependent upon the value of the CORC for the biochar over the value of the biochar as a product in itself. In this scenario it should be noted that it is assumed that the bioSNG has no market value given the nascent state of production of bioSNG derived fuels. In reality, in this case, the bioSNG would be consumed on site for heating, electricity generation or some other purpose, offsetting costs.

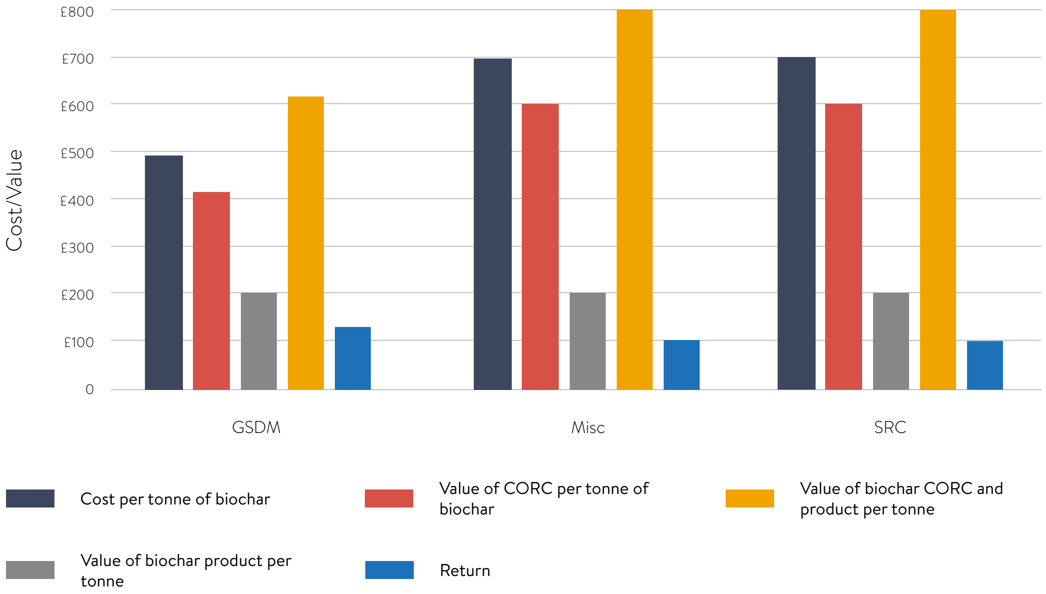

Figure 7.20 Costs and returns per tonne of biochar for each biomass scenario (excluding syngas as assuming no market for it without further upgrading in this scenario)

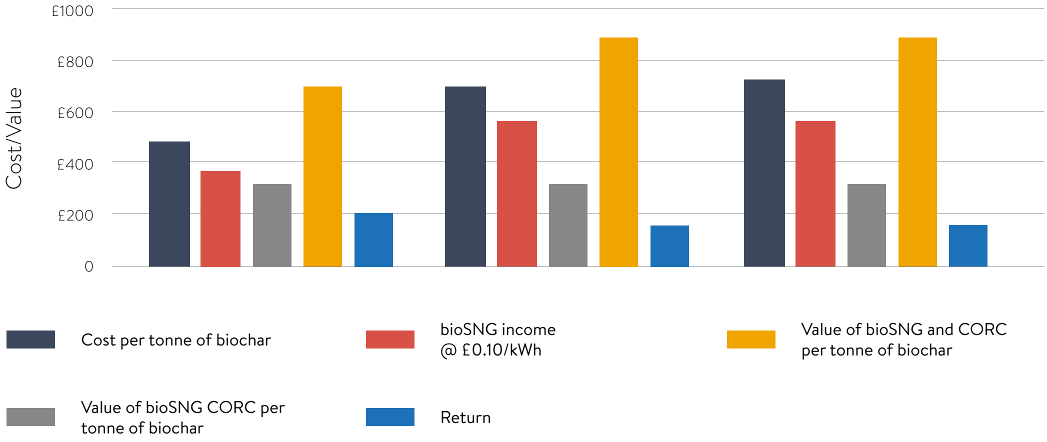

Figure 7.21 bioSNG costs and returns per tonne of biochar. Note that it is assumed in this analysis that bioSNG attracts a CORC ("bioSNG CORC" in this figure) as well as income from fuel sales. The syngas co-product from biochar production has been upgraded to bioSNG in this work since there is an offsite market for bioSNG.

If a market for bioSNG is available, then with a bioSNG price of 10p/kWh all feedstock scenarios provide positive returns. But several issues should be noted:

1. Without additional income for CORC's from CCS with bioSNG production then net positive income for bioSNG is 8-9p/kWh for Misc. and SRC as shown in Figure 7.22, these prices are significantly above the historic prices for fossil gas of 2-3p/kWh;
2. The development of markets for syngas derived fuels are at a very early stage and whilst as, shown below the inclusion of bioSNG and bioSNG CORC's provide for a good level of return, as shown above incomes are stacked and interdependent;
3. Over 50% of income is dependent on CORC's which require Government intervention and the creation of a stable and investable market for CDR.

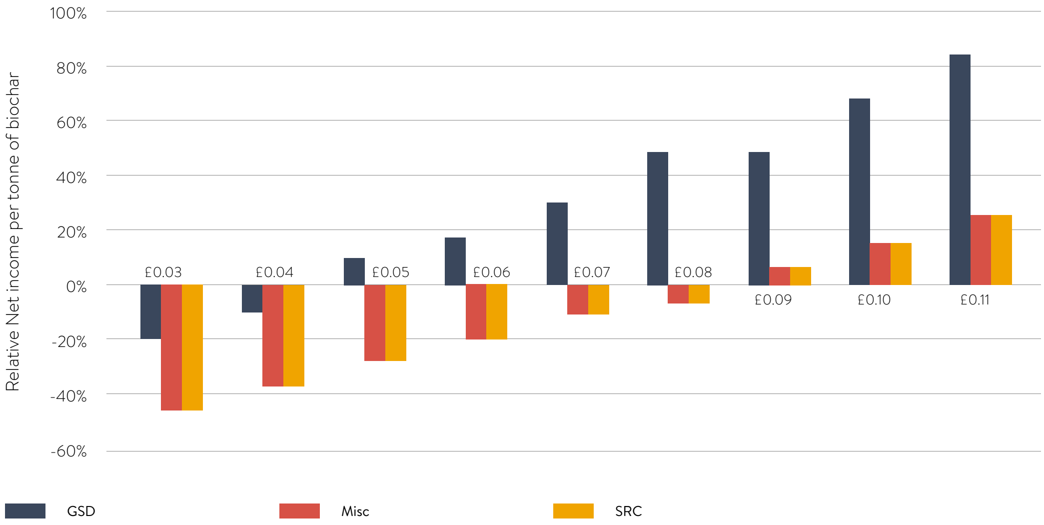

Figure 7.22 Relative Net Incomes per tonne of biochar @£200 per tonne for biochar for a range of bioSNG prices per kWh excluding CORC's

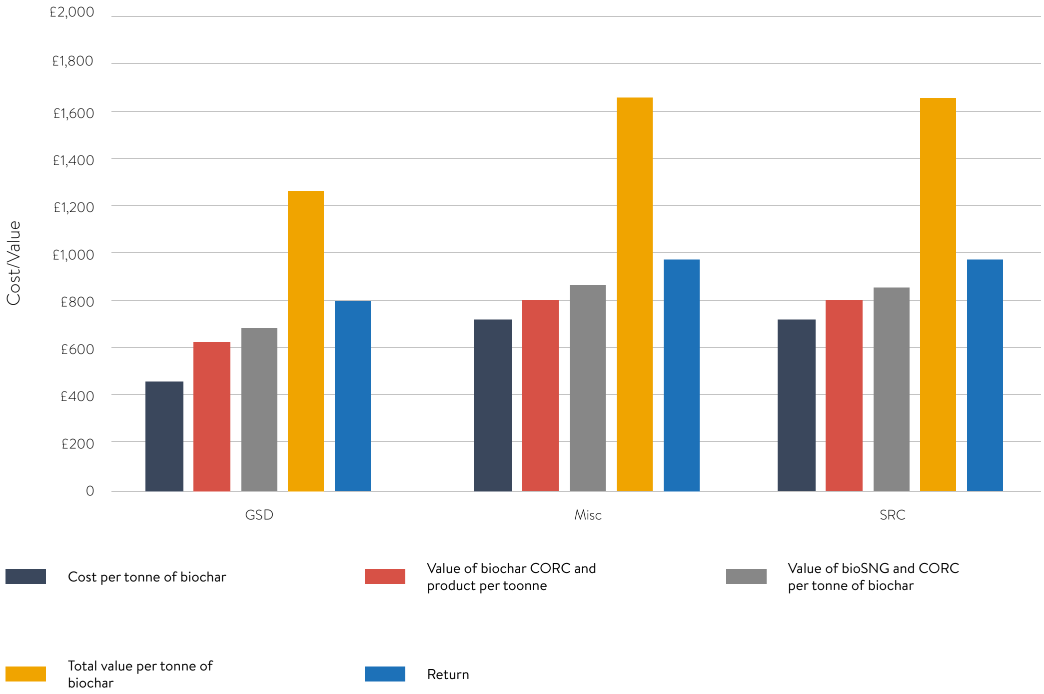

Figure 7.23 Total biochar costs and returns for biochar, bioSNG and CORC's

Despite the uncertainties above around incomes, Northern Ireland has a significant biogenic resource and given the need for CDR to meet Net Zero target by 2050 to limit global climate warming, the region is very well placed to avail of the developing CDR market. Even the limited bioenergy crop planting of 36 kha by 2050, less than 4% of NI farmland, can bring significant financial returns to Northern Ireland by 2050, see Figure 7.25 below.

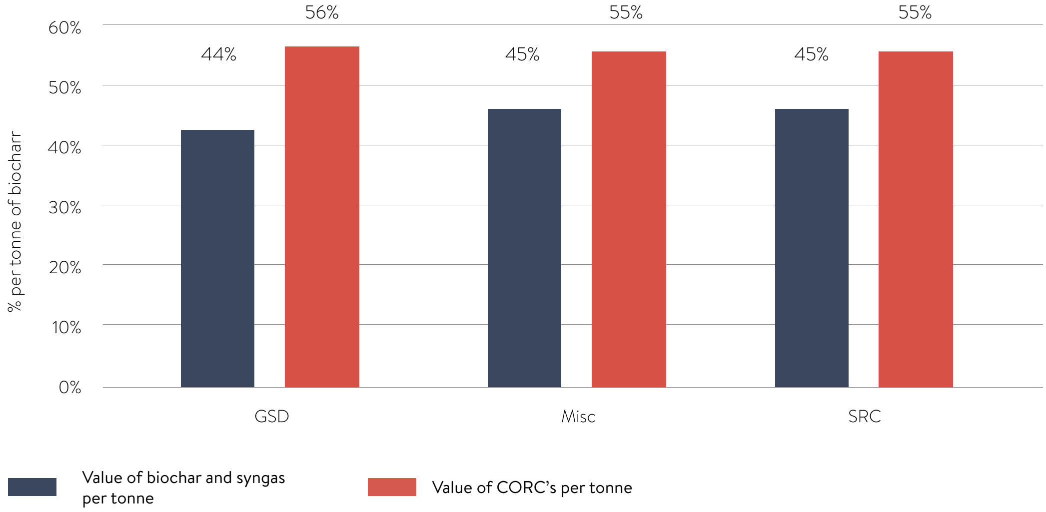

Figure 7.24 Split of income between products and CORC

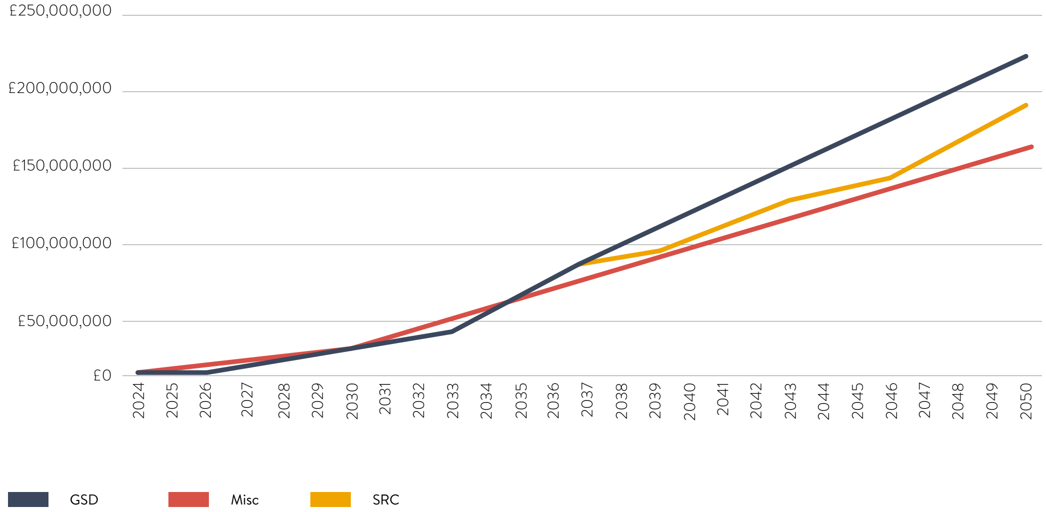

Figure 7.25 Land Based CDR Revenue for the three bioenergy crop scenarios excluding biomethane production

The conversion of 36kha of agricultural land to bioenergy crops, a 3% to 4% take of current agricultural land use, to provide biomass feedstock to the CDR technology pathway of biomass gasification to bioSNG with CCS and biochar, would generate additional revenues to NI of £160M to £220M by 2050, depending upon the bioenergy crop. In addition, if the integrated CDR technology pathway of biogas to biomethane with CCS and biomass gasification to bioSNG with CCS utilising grass silage and grass silage digestate is pursued, then revenues would rise to over £300M by 2050, see Figure 7.26 below. This income is additional to existing farm incomes from grass-based livestock farming because, as recommended by the CCC in their 6th CB Methodology, land use for the growing of bioenergy crops can be "freed up" from grassland by the increasing of stocking rates on existing grassland.

> "NORTHERN IRELAND HAS A SIGNIFICANT BIOGENIC RESOURCE.... THE REGION IS VERY WELL PLACED TO AVAIL OF THE DEVELOPING CDR MARKET"

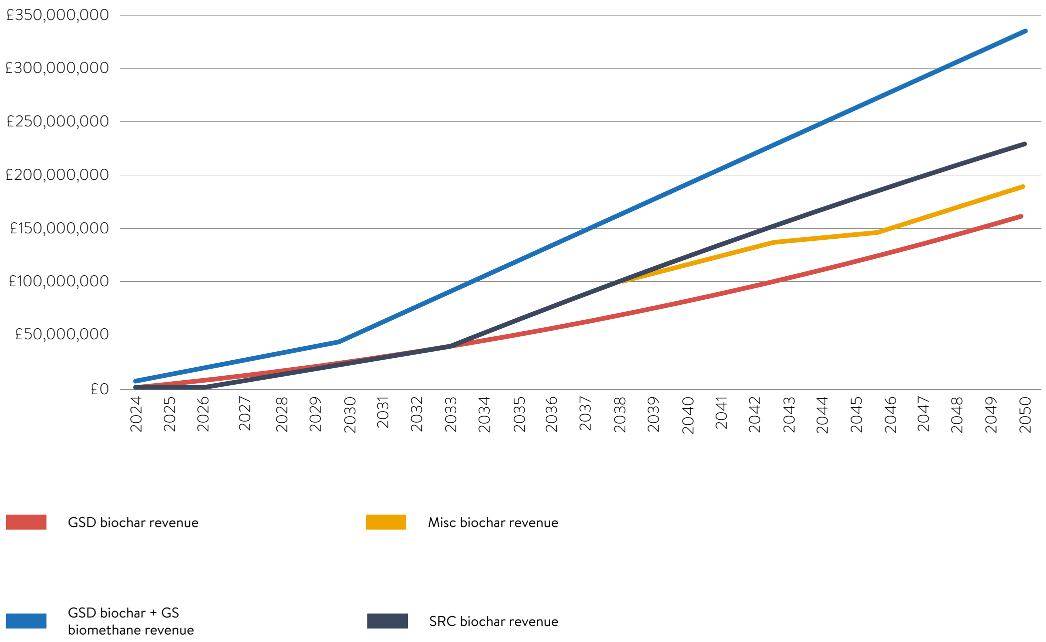

Figure 7.26 Land Based CDR Revenue for the three bioenergy crop scenarios including biomethane production

7.5 Additional benefits of the pathways to Northern Ireland

The current cost of energy and cost of living crisis underlines the vital importance of energy and food security for Northern Ireland. The CASE funded Decarbonisation of Heat report[3] highlights the potential in Northern Ireland to displace all imported natural gas consumption with biomethane produced from indigenous biomass. The production of biomethane using biomass is a key part of the EU's repower action plan to phase out Russian fossil fuels by 2027 and boost the EU's renewable energy production and therefore energy security.

Security from the energy independence from local supply would mitigate the substantial price volatility in the cost of natural gas as shown in Figure 7.27 below. Prices increased from less than 2p per kWh to nearly 20p per kWh in the period from Feb-22 to Sep-22 caused by the Ukraine crisis. This has made the cost of production of goods complex to predict and has put the cash flows of the manufacturing sector under severe pressure.

There is even more uncertainty on the predicted future price of natural gas. The EU natural gas price is predicted to be between €150 and €300 per MWh over the next 12 months. Also, CNG Services, a leading supplier of natural gas and biomethane for the transport sector, predict a range of prices of between 5p and 25p per kWh for the next year for natural gas in the UK. These sources all highlight the potential instability of natural gas prices in Northern Ireland.

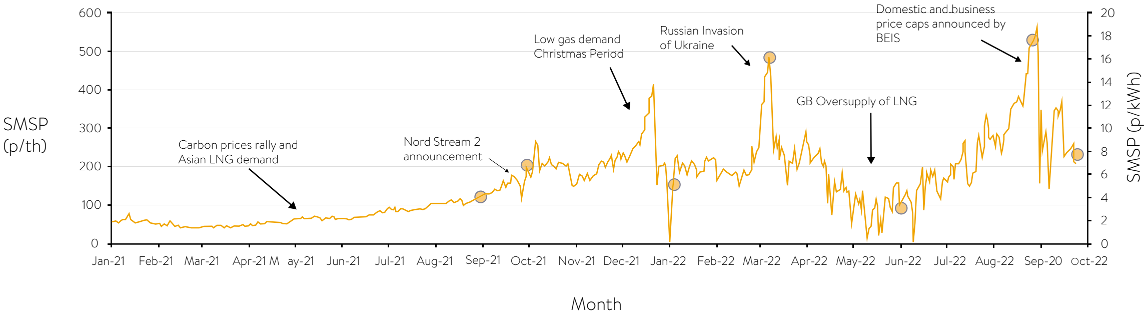

Figure 7.27 Natural gas price volatility Jan-21 to Oct-22

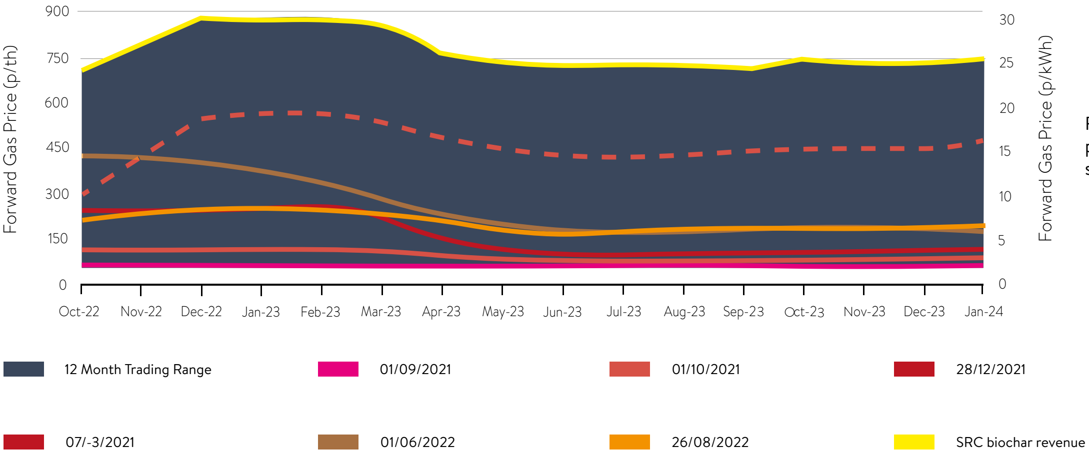

Figure 7.28 Forward gas price progression, adapted from CNG services

Whilst the cost of production of biomethane and bioSNG have both been higher than the historical natural gas prices of 2 to 3p/kWh, the current high cost of natural gas makes the production of biomethane/ bioSNG attractive commercially. However, the current price volatility and the uncertainty of future gas prices make the funding of biomethane and bioSNG projects difficult, based on energy prices alone.

The use of biomass for gasification with BECCS as proposed in the CCC 6th Carbon Budget and presented in the previous section, will increase energy security, providing for Northern Ireland nearly 800 GWh of zero carbon bioSNG available by 2050 based on the target of 36 kha of bioenergy crops grown in Northern Ireland.

Results show that integrating low energy generation with CDR through the AD of silage for the production of biomethane accompanied by biochar production from the digestate, has significant GHG reduction and decarbonisation potential for the agriculture sector and Northern Ireland as a whole.

As of yet, pyrolysis has not been integrated with biogas production, represented by the grass silage feedstock scenario in the above analysis. However, if this "whole system approach" was rapidly adapted, results show that there would be multiple benefits for Northern Ireland in relation to decarbonisation of both heat and of the agricultural sector, as well as providing additional income to farmers. This contributes to the concept of a low carbon cooperative in Northern Ireland, based on the existing farming cooperative model where local farmers collaborate to share the necessary infrastructure. This system utilises silage material to generate low carbon energy and introduces CDR to remove carbon from various parts of the system. This concept can be compared to a centralised model involving collection and transportation of feedstocks to major centres for processing.

These revenues do not consider any additional incomes from potential premiums being paid for NI agricultural produce being Net Zero or loss of incomes from proposed carbon taxation on high GHG emitting sectors. These revenues also displace purchases of fossil gas sourced from outside NI and therefore retain the value of those purchases within the NI economy. A comparable example of the country level economic benefit was evident in a recent press release[29] by Biogas Danmark, the Danish biogas trade association, "Danish biogas has displaced Russian gas of DKK 3.7 billion in the first eight months of the year. This means that biogas currently takes up 40% of the methane in the natural gas grid supplied to companies and private customers. According to the Danish Energy Agency's forecast, biogas will account for 72% of the gas flowing in the natural gas grid by 2030"

At current exchange rates this is worth an additional £440 million of retained revenue to the Danish economy from the purchase of indigenous biomethane over imported fossil gas in just 8 months and has considerably contributed to Denmark's energy security.

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[29] https://www.bioenergy-news.com/news/biogas-takes-up-40-of-methane-in-denmarks-natural-gas-grid

7.6 Job Creation

With the increasing demand for CDR, one of the key benefits for NI from securing and retaining the long-term revenue streams that could be provided by the CDR market, is the creation of stable jobs with a broad range of skills in the rural Northern Irish economy. The European Biogas Association conducted an in-depth analysis on job generation across the European Biogas sector and calculated the European weighted average direct and indirect jobs/GWh at 0.32/GWh and 0.77/GWh respectively. Applying these findings to Northern Ireland, indicates the potential to generate between 700 to 800 new direct and indirect jobs across the rural economy in Northern Ireland, helping to stimulate and sustain rural communities for the CDR technology pathway of biomass gasification to bioSNG with CCS and biochar.

On the same basis, If the target of 1.4TWh of biomethane production by 2030 is met, as proposed in the KPMG report[26] "Supporting a Renewable Gas Sector in Northern Ireland", the integrated CDR technology of biogas, biomethane and bioSNG with CCS and biochar, has the potential to secure over 2,000 new jobs by 2030.

8 ECONOMIC AND POLICY BARRIERS AND LEVERS

8.1 Trading of carbon offsets and removals

The carbon offset concept has rapidly developed into a multi-million-pound market, having been embraced by many companies as a means of meeting carbon reduction or net zero targets. As the carbon offset market has grown, environmentalists, banks and regulators have been increasingly concerned with the integrity of offsets being offered. Typically, carbon credits and offsets are bought and then 'retired' on an independent registry and fall into two varieties: regulated and unregulated.

The EU Emissions Trading System (ETS) is the largest multi-country, multi-sector GHG emissions trading system in the world; a mandatory, regulated, emissions cap-and-trade scheme. It sets an EU-wide cap on the total amount of GHG emissions from energy intensive sectors, including power stations and industrial plants. The cap decreases over time to reduce overall emissions and if the emissions cap is exceeded, the associated companies are required to buy additional allowances or sell carbon credits if their emissions are lower than their allocation (Figure 8.1).

Whilst EU and the UK ETS are regulated markets, the carbon offset market is un-regulated, meaning the purchasers of carbon offsets are doing so on a voluntary basis with limited or no guarantees of validity. Carbon offsets vary considerably in price ranging from as low as £1 per tonne to many hundreds of pounds per tonne. The target audience for the companies' selling offsets vary from private individuals looking to offset their own carbon footprint to large corporate entities seeking to decarbonise entire operations. There are many private companies offering carbon offsets for sale, with varying levels of credibility, authenticity and accountability of the offsets being offered. There are also several companies taking on the role of acting as a carbon marketplace, each jostling to take the position of the authority in the sector, and each with their own set of quality control measures and standards.

The unregulated nature of the carbon credit and offset market is a challenge for the development of CDR pathways and can be seen as a barrier to the development of this scheme.

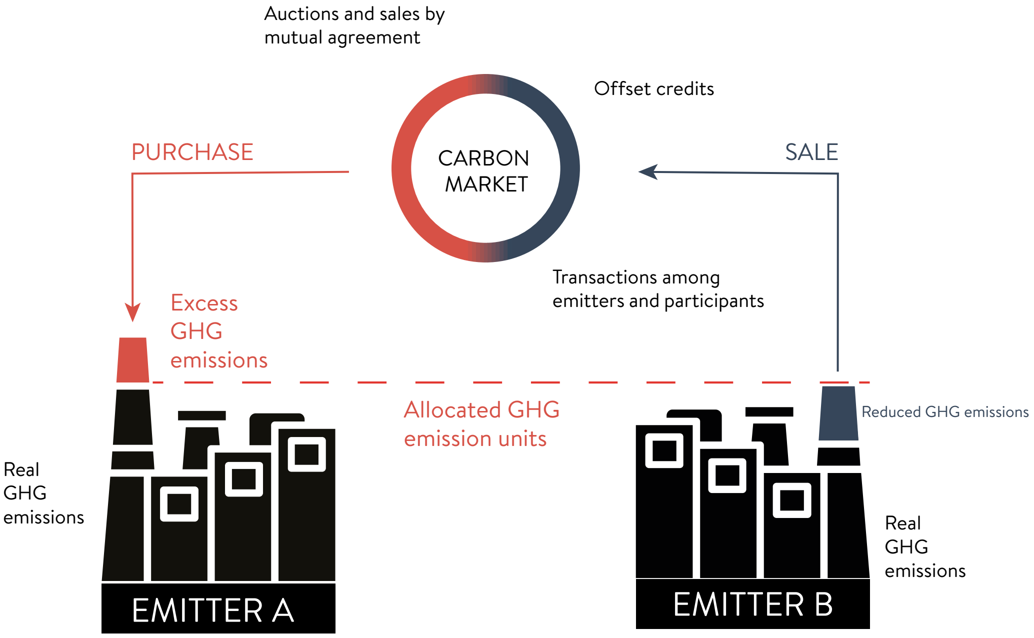

Figure 8.1 Schematic diagram representing the EU Emissions Trading System (ETS)

8.2 Carbon removal certificates

Carbon removal certificates differ greatly from carbon offsets as the carbon is accounted for on a physical and quantitative basis. The market is still however voluntary and unregulated and there are less companies offering carbon removal certificates in comparison to carbon offsets.

The largest company offering carbon removal certificates is Puro, who have taken a marketplace approach that offers CORC's (CO_2 removal certificates). Puro have a published set of standards that must be adhered to, and audits are undertaken to ensure compliance before suppliers can be registered and allowed to sell in the marketplace. Applications that qualify for CORC's, include construction materials, geological storage, and biochar, therefore CORCs offer a lever to the progression of a market for biochar. At the time of this report, 22 out of the 30 products available from Puro are biochar based, with prices ranging from €100 to €535/CORC.

The premiums currently being paid for CORCs on the Puro platform are a result of the commitment from a small number of large corporates that recognise the true long-term value to the planet of carbon removal and are prepared to support the initial movers in the market to promote growth of CDR projects for the long term.

Due to the absence of a regulated marketplace for CDR, the likelihood of significant support from the investment community remains low and many important supporting projects to date have been small scale, undertaken on an ad-hoc basis. The UK Government are seeking to accelerate and take a lead on meeting Net Zero Targets through CDR and have recently launched a consultation to accelerate investment in engineered carbon removals. This includes proposals for a number of ways in which the output from carbon removals can be valorised, including recognition within the Emissions Trading Scheme and Contracts for Difference.

> "CARBON REMOVAL CERTIFICATES DIFFER GREATLY FROM CARBON OFFSETS AS THE CARBON IS ACCOUNTED FOR ON A PHYSICAL AND QUANTITATIVE BASIS"

8.3 EU and UK support for carbon offsets and removals

The EU (2021)[30] acknowledges the important of GHG removal. The legally binding European Climate Law for climate neutrality by 2050 acknowledges the role of carbon dioxide removals, stating it is important for the sectors where decarbonisation is more challenging.

The UK Government's ambition is to deploy at least 5 $MtCO_2$ of engineered removals per year by 2030, potentially rising to around 23 $MtCO_2$ annually by 2035 to meet the indicative pathway for the 6th Carbon Budget. The UK Net Zero Strategy suggests that 75-81 $MtCO_2$ of engineered removals will be required annually by 2050 to cost-effectively reach the UK's net zero target. The UK Government also announced that projects across the UK will benefit from a share of over £54 million to develop technologies that remove carbon emissions from the atmosphere. The programme provided support for four main types of greenhouse gas removal:

- Direct Air Carbon Capture (DACC) - DACC technology uses chemical reactions to capture carbon dioxide from the air as it passes through the system. The carbon dioxide can then be permanently stored or used in various products or applications.
- Bioenergy Carbon Capture and Storage (BECCS) – captures and stores carbon from organic materials, converting it into useful energy such as heat, electricity, liquid or gas fuels.
- Biochar - This is a form of charcoal produced when organic matter is burned without oxygen. The biochar is rich in carbon and can be used as a fertiliser.
- Seawater - The oceans naturally absorb carbon dioxide but because of a large increase in carbon dioxide emissions from our activities the oceans absorb more than previously. The result is that the oceans are becoming more acidic. Seawater GGR technology can remove CO_2 from seawater directly to help restore this natural balance.

However as significant and as impactful as this £54 million of funding is, Northern Ireland is the only region within the UK not to secure funding under the programme. This represents another barrier to the development of new CDR pathways in Northern Ireland.

Insufficient investment is a barrier to upscaling, and contributes to limited large scale production facilities, high production costs as producing at small scale, lack of agreed approach to MRV and limited knowledge, standardisation, and quality control, restricting user confidence[31].

Northern Ireland's planning system is another barrier as highlighted in the recent report[32] 'Planning in Northern Ireland' by the Northern Ireland Audit Office. This is of particular concern in the delivery of decarbonisation and Net Zero Targets considering the time critical aspect of their delivery and the complex nature of the projects required to be delivered. The vast majority of Net Zero projects will require Environmental Impact Assessments and for the NI Audit Office this is a particular area of delay.

Applications involving an Environmental Impact Assessment (EIA) typically take much longer than other types of application: 125 weeks compared to 45.8 weeks where an EIA was not required. The time of delivery of 125 weeks, nearly two and half years is just an average figure, and it is not unknown for projects to take five years to get through planning. This is grossly inefficient and incompatible with the timescales required to meet Net Zero Targets.

The increase in food and fuel costs is putting a significant financial burden on domestic households. Decarbonisation and the vital importance of a low carbon future has been difficult to convey to consumers during the previous period of low-cost fossil fuel-based energy and food supply. However, with the current and ongoing disruption to these global supply chains, there is an ability for Northern Ireland to stabilise energy and food costs through the provision of indigenous low carbon energy at an often-fixed cost and the avoidance of the importation of expensive fossil fuel based fertilisers through the recovery of manure based nutrients.

Also, the economic benefit message of a low carbon future can be further backed up by the increased job security, in uncertain times, through the growth of local businesses in low carbon clusters and the attraction of international businesses to these low carbon clusters.

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[30] https://climate.ec.europa.eu/eu-action/european-green-deal/european-climate-law_en

[31] Gwenzi et al. 2015 - DOI: 10.1016/j.jenvman.2014.11.027

[32] https://www.niauditoffice.gov.uk/files/niauditoffice/media-files/NIAO%20Report%20-%20Planning%20in%20NI.pdf

9 CONCLUSION

Given the current climate emergency, it is critical to develop carbon removal systems that are both technically and economically viable. Recently, there has been a growing interest in biochar-based carbon removal, which has driven the need for a deeper understanding of the entire value chain. The final application of biochar is essential to its validation as a carbon sink and should be conducted as sustainably as possible while following regulatory and technical requirements so that biochar as an approach may serve its carbon removal objective. Biochar may be utilized in a wide range of applications so long as it is not employed for energy generation. Moreover, the biochar must not undergo heat deterioration or oxidation during or after its service life. In this context, we evaluated the most important biochar-based carbon sink applications, including agriculture, animal farming, anaerobic digestion, composting, environmental remediation, construction materials, and energy storage. In addition to the carbon removal potential, it is possible to extract additional value in each of the discussed applications, as demonstrated.

The deployment of low carbon energy generation is accepted as being a key part of the path to net zero and indigenous energy security, however increased CDR is crucial in Northern Ireland to reach net zero by 2050. Current digestate streams represent an important untapped feedstock for biochar production in Northern Ireland, equating to a CDR potential of 118 $ktCO_2e$ if this strategy was implemented.

New strategies of increased anaerobic digestion as suggested in the KPMG report[26], *Supporting a Renewable Gas Sector in Northern Ireland* and the CASE, *Decarbonisation of Heat* report[3] would increase the CDR potential in the region significantly if the two technology pathways of biogas to biomethane with CCS and biomass gasification to bioSNG with CCS and biochar were integrated. However, more analysis is needed on the implications of what this would be as agricultural trade-offs will be a concern for farmers.

Northern Ireland has the potential to transition land use to bioenergy crops (miscanthus, SCR willow and grass silage) and use these crops as a feedstock for low carbon energy and biochar production. Analysis in this report simulated 36 kha of additional crop area by 2050 for each crop and results show the potential CO_2e in 2050 from biochar is around 365 kt from miscanthus, 428 kt for SRC willow and 246 kt for grass silage (digestate). Although results show a higher biochar potential for the miscanthus and SRC scenario, it is noted that utilising grass silage will require less change to the agricultural sector, and with efficient planning could co-exist in the intense livestock region.

From a CDR viewpoint based on the CCC's BECCS technology pathways, of biogas to biomethane with CCS and biomass gasification to bioSNG with CCS and the additional CDR of including biochar, then the bioenergy crop pathways of highest value from this analysis is grass silage, when land utilisation, planting and harvesting cycles are taken into consideration.

In relation to land area, the conversion of 3-4% (36 kha) of the agricultural land in Northern Ireland to growing of bioenergy crops has the potential to significantly decarbonise the sector by 2050, based upon the methodology set out in the CCC 6th Carbon Budget.

The strength of the MRV protocols for a particular CDR pathway will have an impact on the value of the CDR credit issued against that pathway. Given the large biogenic carbon resource available in Northern Ireland, it is vital that the MRV protocols are robust to maximise the value of the CDR credits generated from this local resource.

In order to achieve the potential of CDR based on Biochar production the following steps are recommended:

1. Cross departmental (DfE and DAERA) support for CDR is needed. This should consider both agricultural and carbon balance unintended consequences. It is important for a future sustainable economy that a holistic approach is taken. This means that policies are not developed in narrow siloes but designed to integrate across departmental boundaries and mutually support economic, social, and environmental priorities in a circular economy.

Actions:

- Establish an effective cross-department coordination group to review new and existing policies, regulation and legislation in light of the NI Climate Act such that opportunities are not missed which sit across departmental boundaries.

- Fit specific policies into a wider framework and mandate policy choices that advance a holistic, sustainable economy. This may mean that specific interventions may cut across policy and departmental borders.

Timeframe: Immediate

2. Engagement with DESNZ is needed to align new policy with upcoming UK wide policy. As UK national policy develops in areas such as emissions trading, carbon offsetting/removals, and bioenergy then Northern Ireland will need to both influence the development and adopt or adapt regulations, support schemes or guidance as appropriate for devolved administrative responsibilities. Northern Ireland can also directly benefit from research undertaken in GB and the higher level of support for decarbonisation.

- Action: Ensure representation on relevant UK national committees developing policy and look to participate in or observe UK studies as they are commissioned.

- Timeframe: Immediate

3. Further research is required:

   i. To understand implications of GHG removal solutions, including holistic assessments of their feasibility and acceptability.

   ii. To deliver innovative monitoring, reporting and verification (MRV) tools, technologies and techniques that assess the effectiveness, integrity, and longevity of land-based carbon dioxide removal.

   iii. To work with industrial manufacturers, such as the concrete industry, to determine the best utilisation of CDR products to decarbonise manufactured products whilst also ensuring the long term permeance of the carbon dioxide removal.

   iv. An investigation of land utilisation to maximise the sustainable biomass output of our land for food, animal feed, bioenergy, bioproducts, timber products and carbon dioxide removal needs.

- Action: Commission listed studies. Ensure that these are delivered jointly with industry, farming and other interest groups to both address research needs and socialise concepts for CDR/decarbonisation across economic sectors.

- Timeframe: Deliver by 2025 to inform future policy.

4. Community and stakeholder engagement is needed to communicate the concept of whole system carbon farming co-operatives. This is due to the general low-level of awareness noted during discussions with stakeholders. If biochar production at scale is to be achieved, then farmers will need to be bought into the concept as they are the main source for feedstock. Communities will also need to accept local bioenergy facilities at a scale larger than current AD plants.

Actions:

- Develop a proactive dialogue with existing farm cooperatives, Ulster Farmers Union, Councils, and community groups to raise awareness of new opportunities such as CDR via Biochar while listening to and addressing local and individual concerns.

- Provide funding for farmers and communities to come together and explore the opportunities of cooperative working to provide local economic growth while decarbonising and improving sustainability.

- Develop an approved legal framework for local farmers, businesses, councils, and individuals to form a cooperative (or similar collaborative venture) to help attract funding to establish the facilities and functional operation of the cooperative.

  Timeframe: Deliver by 2025

Annex A: List of organisations consulted

Organisation	
Action Renewables	Gas Market Operator
AFBI	Gas Networks Ireland (UK)
AgendaNI	GMO NI
Arthur Cox LLP	GO Power
BBC	Invest NI
Belfast City Council	IoD NI
BH Estate	Irish Farmers Journal
Birnie Consultants	John Thompson & Sons Ltd
Bryden Centre	KPMG
CAFRE	Lagan
Cambium	M&EA
Camlin	Mutual Energy
CBI	MW Advocate
CBS Consulting	NI Chamber
CEF NI	NI Grain Trade Association
Centre for Advanced Sustainable Energy (CASE)	NIE Networks
Cherton	NIEA
Clyde Shanks	NIFDA
CNG Services	NIHE
Colloide	Phoenix Natural Gas
Consumer Council	QUB
DAERA	Resolve Planning

DAERA Green Growth Official	Semple & McKillop Ltd
Dairy UK	SGN
Danske Bank	Stream BioEnergy
David Quinn	Ulster Farmers Union
Devenish	United Renewables Ltd
DFE Energy Group	United/Dale Farm
DUP	Utility Regulator
Electric Ireland	UUP
EnCirc	Victus Energy
Fane Valley	Zero Consulting
Farming Carbon	NI Water
Firmus	NREL
Flogas	Belfast Harbour Commission
	ABC Council
	Fermanagh and Omagh Council
	Mid Ulster Council

Annex B Digestate Biochar properties from Eurofins

Biochar properties

Bulk density < 3 mm	FR		In Anlehnung an VOLUFA-Methode A 13.2.1 VOLUFA-Methode A		kg,m^3		475
specific surface (BET)	SND2/o		DIN ISO 9277: 2014		m^2/g	-	463.68
Moisture	FR	RE000FY	DIN 51718: 2002-06	0.1	%(w/w)	5.5	-
Ash content (550°C)	FR	RE000FY	DIN 51719: 1997-07	0.1	%(w/w)	40.0	42.3
Total carbon	FR	RE000FY	DIN 51732: 2014-07	0.2	%(w/w)	52.4	55.4
carbon (organic)	FR	RE000FY	berechnet		%(w/w)	52.0	54.9
Hydrogen	FR	RE000FY	DIN 51732: 2014-07	0.1	%(w/w)	0.5	0.5
Total nitrogen	FR	RE000FY	DIN 51732: 2014-07	0.5	g/kg	10.5	11.1
Sulphur (S), total	FR	RE000FY	DIN 51724-3:2012-07	0.3	%(w/w)	0.58	0.61
Oxygen	FR	RE000FY	DIN 51733: 2016-04		%(w/w)	0.7	0.8
Total inorganic carbon (TIC)	FR	RE000FY	DIN 51726: 2004-06	0.1	%(w/w)	0.4	0.5
carbonate-CO$_2$	FR	RE000FY	DIN 51726: 2004-06	0.4	%(w/w)	1.6	1.7
H/C ratio (molar)	FR	RE000FY	berechnet			0.11	0.11
H/Corg ratio (molar)	FR	RE000FY	berechnet			0.11	0.11
O/C ratio (molar)	FR	RE000FY	berechnet			0.010	0.011
pH in CaCl2	FR		DIN ISO 10390: 2005-12			11.9	-
Conductivity	FR		BGK III. C2: 2006-09	5	µS/cm	4760	-
salt content	FR		BGK III. C2: 2006-09	0.005	g/kg	25.1	-
salt content	FR		BGK III. C2: 2006-09	0.005	g/l	11.9	-

Elements from the micro wave pressure digestion acc. to DIN 22022-1: 2014-07

Arsenic (As)	FR	RED00FY	DIN EN ISO 17294-2 (E29}: 2017-01	0.8	mg/kg	-	1.3
Lead (Pb)	FR	RED00FY	DIN EN ISO 17294-2 (E29}: 2017-01	2	mg/kg	-	2
Cadmium (Cd)	FR	RE000FY	DIN EN ISO 17294-2 (E29}: 2017-01	0.2	mg/kg	-	<0.2
Copper (Cu)	FR	RE000FY	DIN EN ISO 17294-2 (E29}: 2017-01	1	mg/kg	-	163
Nickel (Ni)	FR	RE000FY	DIN EN ISO 17294-2 (E29}: 2017-01	1	mg/kg	-	16
Mercury (Hg)	FR	RE000FY	DIN 22022-4: 2001-02	0.07	mg/kg	-	<0.07
Zinc (Zn)	FR	RE000FY	DIN EN ISO 17294-2 (E29}: 2017-01	1	mg/kg	-	459
Chromium (Cr)	FR	RE000FY	DIN EN ISO 17294-2 (E29}: 2017-01	1	mg/kg	-	31
Boron (B)	FR	RE000FY	DIN EN ISO 17294-2 (E29}: 2017-01	1	mg/kg	-	46
Manganese (Mn)	FR	RE000FY	DIN EN ISO 17294-2 (E29}: 2017-01	1	mg/kg	-	764
Silver (Ag)	FR	RE000FY	DIN EN ISO 17294-2 (E29}: 2017-01	5	mg/kg	-	<5