CAPTURING PROSPERITY FROM CO_2 AND WASTE

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

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1. EXECUTIVE SUMMARY

Northern Ireland (NI) faces many challenges in the drive to reduce climate change caused by emissions of gases such as CO_2 and methane. Carbon capture is one approach to avert further global warming and will be an essential technology for the prevention of carbon emissions across the UK. However, in NI, this option could add considerably to the costs of business, risking competitiveness in global markets and local jobs as we have no transportation infrastructure or long-term storage available in Northern Ireland[1]. Alternatives to purely capturing, transporting and geological storage of carbon emissions that offset the expense of carbon capture by turning captured CO_2 into useful products such as chemicals, oils, fuels, or animal feed may be more economically suitable to NI's industry mix, geography, and resources.

To investigate the potential of utilisation of CO_2, the Department for the Economy in NI commissioned the Bryden Centre and CASE at Queen's University Belfast to investigate the prospects for using emerging biologically based methods, such as biorefineries, to capture and turn CO_2 into useful products. The objectives for the work included reviewing current state of the art, evaluating the potential economic viability and the quantities of CO_2 that could be utilised for such approaches as well as consulting with stakeholders across the region.

In many respects, NI is an ideal location to best exploit the potential of alternative carbon capture, utilisation and storage technologies, reducing the economic risks of carbon taxes, carbon capture and storage costs and offering the potential of negative emissions. The region has a strong agricultural heritage with resources such as waste biomass and nutrient streams which can support such endeavours. Additionally, the land has extensive basalt deposits and there are many waste heat sources from industry and the public sector that could be effectively exploited to enable effective use of captured CO_2.

NI does not have a preponderance of high CO_2 emitters but mainly moderate (<100,000 t CO_2) to low scale emitters (<1,000 t CO_2). Many of these utilise natural gas for heat generation and so could be converted to biomethane as recent work on fully decarbonising the NI gas grid has shown[2]. Switching to a biogenic fuel, such as biomethane, allows many of these installations to come close to net-zero emissions. Coupling a biomethane powered furnace (for example) to carbon capture and utilisation potentially enables atmospheric Carbon Dioxide Removal (CDR) where the end product stores all or part of the biogenic carbon long-term.

Beneficially, this will create jobs in a new industry across the region that could deliver raw materials for our animal feed industry, provide biogenic fuels and chemicals as well as producing food that is currently imported.

Where we can successfully combine maturing technologies in CO_2 capture, biogenic uses for CO_2 together with the use of surplus nutrients from agriculture then this will both prevent carbon emissions to the atmosphere and the release of excess nutrients that cause pollution of land, rivers, and lakes.

This report looks at the opportunities in NI based on enhanced biogenic methods for utilising CO_2 either directly from exhaust gas streams or captured, purified and shipped to point of use. Two main biogenic routes are explored:

1. Biorefineries: Algal and bacterial based biorefinery technologies can utilise CO_2 emissions from industry and liquid digestate from anaerobic digestion (AD) of farm wastes to produce products such as biogenic fuels, omega-3 fatty acids, proteins and lipids for use in fish and animal feeds.

2. Vertical farming: Using CO_2 to increase yields in greenhouse crops has been a common practice for decades. More recent innovations have seen the introduction of vertical farms with artificial lighting and other innovations to increase yields and hence uptake of CO_2. The second part of this report estimated the potential economic value and environmental impact of vertical farming and aquaponics and their carbon sequestration potential compared to other biological carbon sinks.

Across the world a lot of work has gone into developing biorefinery technology and methods. Production of ethanol through fermentation is probably the most well-known and widely appreciated. However, in this report we focused our investigation on biorefineries that could utilise waste streams in NI focusing on CO_2, excess nutrients from agricultural wastes and waste heat to grow microalgae, minimising the addition of sugars or other additives. Biorefineries have a lot of potential but present-day standalone systems and technologies are generally only viable with niche, high value products. Integration of a biorefinery into a circular economy system utilising waste feedstocks offers more potential but work on a pilot scale facility for each end product would need to be undertaken to establish the full economic returns.

The results for a biorefinery based model to produce e-methane in this report show the potential economic viability with a e-methane price of £0.12/kWh assuming co-location with a CO_2 source, electrolyser (electricity at £50/MWh), and sale of co-products such as oxygen. The ultimate breakeven price of the e-methane is highly dependent on the input electricity price for the electrolyser and price achieved for oxygen.

The model was based on taking CO_2 from a hypothetical, co-located 1 MW AD plant which generated 0.92 MW of e-methane per hour for injection into the gas grid.

Alternative sources of CO_2 could similarly be utilised. In this model, around 1300 tonnes of CO_2 would be converted to e-methane each year. The e-methane model was selected as this integrates well with initiatives to decarbonise the gas grid in NI and there is a ready market for the product.

There are many other products from biorefinery systems that would be a good fit to the local economy. Another example of the economic potential for NI is production of protein or higher value additives for feed production. The agri-food sector in NI imports 389 kt of soya beans as a protein source for animal feed at a cost of c£109m each year. Displacement of expensive imported soya by locally sourced feed would not only improve support for the local economy but also save considerable carbon emissions due to shipping across the world.

It is also worth noting that combining AD and biorefinery approaches including processing of digestate to biochar or other carbon products can make a substantial difference to NI agriculture's carbon footprint. NI is already one of the most carbon efficient locations for protein production in the world. Further reducing greenhouse gas emissions from the sector would improve competitiveness and prevent displacement in local markets by protein produced from areas of the world that have lower production costs but are much less carbon efficient.

Aquaponics and vertical farming are rapidly developing technologies that are commercially viable and attracting increasing investment. In a vertical farm, multiple layers of crops are stacked on shelves generally in a hydroponic or aeroponic system to supply water and nutrients to plant roots in the absence of soil. Complimentary to vertical farming, aquaponics combines aquaculture (fish farming) with hydroponics into a system where the input of plant nutrients is provided via the food supplied to the fish and the requirement for artificial fertilisers and pesticides is minimal. Combining aquaculture with vertical farming creates a system that is more efficient in resource utilisation, compared to conventional crop farming. However, they require some additional resources above conventional agriculture such as the electricity needed for the lighting used by vertical farms.

Vertical farming and aquaponics are easily combined into an agricultural production system with minimal needs for chemical inputs. As a closed system, they prevent the release of environmental pollutants and protect plants from pests and disease in an environment controlled to achieve optimum growth rates. Switching from conventional, open arable farming to enclosed vertical farming reduces the total amount of land needed for crop production, reduces the growing cycle, and can remove the need for imports of out of season produce, reducing food miles and carbon footprints. Vertical farming also has a productivity up to 516 times greater per unit area[3] than conventional agricultural techniques, depending on the system configuration. Potentially up to 6000 tonnes of CO_2 per hectare of vertical farm could be saved using this technology and environmentally sensitive land and waterways protected from excess nutrients[3].

A number of organisations were consulted during the development of this report both individually and in group discussions – these are listed in in section 5.4 on page 65. Apart from one organisation, there was no awareness of the potential of biorefineries or vertical farming for sequestering of CO_2. Once informed, there was a general appreciation of the potential offered by these routes in a circular economy approach and interest in seeing these approaches demonstrated.

Key recommendations:

The prospects for biorefinery based methods look promising and justify further steps:

1. E-methane production looks to be a good fit with Northern Ireland's ambitions to decarbonise the gas grid and could economically utilise local sources of CO_2. Support for the following steps should be taken forward in sequence:

   1.1. A pilot scale trial to assess technology and costs.

   1.2. A full design study and market support assessment should be undertaken.

   1.3. Support for a demonstration plant at suitable size and scale for CO_2 sources in Northern Ireland.

2. Further detailed investigations of alternate biorefinery systems which could use waste streams to produce products of direct use to Northern Ireland's economic sectors should be performed. Suggestions for these include:

   2.1. Other e-fuels such as e-methanol or Dimethyl ether (DME).

   2.2. Animal feed additives.

3. Seaweed aquaculture is also worth exploring although NI's territorial waters are limited there is potential for both carbon sequestration and for absorption of excess nutrients ultimately from run-off from land but delivered by river systems to the sea.

Vertical farming is a growing industry but exploiting the potential for carbon sequestration and for using other waste streams such as oxygen, heat and nutrients have not been explored beyond the desk-based study in this report. Future work should include:

4. A pilot scale investigation to verify the modelling, business models and confirm economic viability in this report.

5. Work with retailers in NI to determine the most viable crops and the food miles/carbon saved by growing locally.

6. The potential for growing crops such as hemp in a vertical farm where CO_2 can be turned into durable products to sequester carbon for the long-term.

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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
Capex	Capital Expenditure
CC	Carbon Capture
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilisation
CCUS	Carbon Capture Utilisation and Storage
CHP	Combined Heat and Power
CO_2	Carbon dioxide
CO_2e	Carbon dioxide equivalents
COP	Coefficient of Performance
CPPS	Closed Plant Production System
DACCS	Direct Air Carbon Capture and Storage
DAERA	Department of Agriculture, Environment and Rural Affairs
DfE	Department for the Economy
DME	Dimethyl ether
EGR	Enhance Gas Recovery
EOR	Enhanced Oil Recovery
ETS	European Trading Scheme
EU	European Union
FIFO	Feed In/Feed Out
GEF	Generation Emissions Factor
GHG	Greenhouse Gas
kt CO_2	Kilo tonnes CO_2
kW	Kilowatt
kWh	Kilo Watt hour
LCA	LifeCycle Assessment
LCOE	Levelized Cost Of Energy
Mt CO_2	Mega tonnes CO_2
NAEI	National Atmospheric Emissions Inventory
NI	Northern Ireland
NPP	Net Primary Productivity
NPV	Net Present Value

OPEX	Operating costs
PFAL	Plant Factory with Artificial Lighting
RHI	Renewable Heat Incentive
ROCs	Renewables Obligation Certificates
RUE	Resource Use Efficiency
SOC	Soil Organic Content
SONI	System Operator Northern Ireland
tCO_2	Tonnes CO_2
UFCC	Up Front Capital Cost

AD
AFLU
BECCS
BECCUS
BEIS
BEV
CC
CCC

1. INTRODUCTION

1.1 Background

Achieving the ambitions of the recent NI climate change act 2022, Department for the Economy's (DfE) Energy Strategy and Department of Agriculture, Environment and Rural Affairs (DAERA) Green Growth strategy will help the region and the UK to meet our commitment to achieve net zero carbon emissions by 2050. As yet, the pathways to meet this target are not yet fully mapped out and there are many routes that could be taken. A transition away from fossil fuels and decarbonisation to achieve net zero offers not only environmental benefits but opportunities to advantageously reshape the NI economy to become less dependent on fuel and other imports. A central part of reducing carbon released to atmosphere will be to capture CO_2 emissions and either store them long-term in geological formations - Carbon Capture and Storage (CCS) or use them to create new fuels or products - Carbon Capture Utilisation and Storage (CCUS). Ultimately, to prevent the worst effects of climate change, CO_2 will need to be removed from the atmosphere in much greater quantities than is currently achieved by the natural world. While there are engineered removal systems in development, using enhanced biogenic or geological processes offers much in terms of both cost and immediacy. For example, Bioenergy, Carbon Capture Utilisation and Storage (BECCUS) offers a route to energy/biogenic fuels and CO_2 removal from the atmosphere.

A recent report[1] considered the best options to capture CO_2 emissions from industry and the public sector in NI. The conclusions of that report included both that conventional CCS/CCUS was expensive given the volume and shipping requirements for CO_2 and that emerging biogenic based processes could offer an alternative solution for NI emitters. This new report is the result of a study commissioned by the Department for the Economy (DfE) in NI to investigate the potential for the production of food, biochemicals, fuels and other high value products from CO_2 and other waste streams (e.g., heat and excess nutrients) through biogenic processes. The Bryden Centre and CASE at Queen's University Belfast were asked to evaluate the opportunities and economic potential in NI given the potential biogenic and carbon resources of the region in order to help inform the NI Energy Strategy, Green Growth strategy and other policy decisions.

NI faces a unique situation in the UK's attempt to decarbonise human activities, with 26.6% of Greenhouse Gases (GHG) emissions arising from its agricultural sector[4]. In contrast the average UK figure is 10%. Sector GHG emissions for NI in 2020 are shown in Figure 1.2 and Figure 1.3 presents a comparison of GHGs emissions by sector between NI and GB[5].

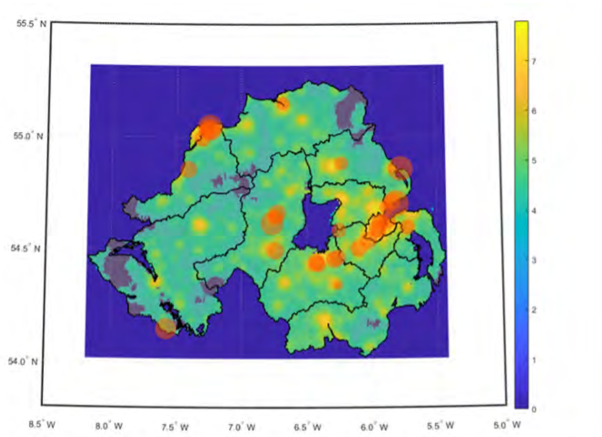


Figure 1.1 Map of 2018 fossil fuel combustion CO_2 emission data for NI using the Open-Data Inventory for Anthropogenic Carbon dioxide (ODIAC). Scale given in natural log of tonnes of CO_2 as Carbon. Circles shown are taken from the UK National Atmospheric Emissions from [1]

NI does not have the large industry clusters of high CO_2 emitters which justify building pipelines to transport captured CO_2 for undersea storage. Instead, NI has two gas-fired and one coal fired power stations[1] and then only a handful of significant scale industrial emitters (such as cement and glass manufacture) plus several factories, hospitals etc which all emit less than 10,000 tonnes CO_2. All of these are geographically dispersed around NI as shown in Figure 1.1. Finding effective methods for capturing and utilising emitted CO_2 from the widely dispersed industry and power generation plants is key to meeting NI's commitments under the Climate Change Act (Northern Ireland) 2022 and the UK's Sixth Carbon Budget

While the agricultural sector is the biggest emitter of GHGs in NI it is also of major economic importance. The total value of annual NI food production is around £5.4bn[2] which makes it vital for the NI economy and jobs in rural areas. NI farms also feed a population (protein requirements) of 10 million[3], from a population of just 1.8 million people. Cutting production in NI would in the short-term just attract imports from areas of the world that are less carbon efficient in terms of protein production. However, despite the economic contribution, GHG emissions within the agricultural sector in NI must be reduced to control the consequences of climate change.

[1] *Kilroot is in the process of being converted from coal to gas leading to three gas power stations*
[2] *2020 figures – see https://www.daera-ni.gov.uk/news/report-northern-ireland-food-and-drinks-processing-sector-6*
[3] *See: https://factcheckni.org/topics/economy/does-northern-ireland-produce-enough-to-feed-10-million-people/*

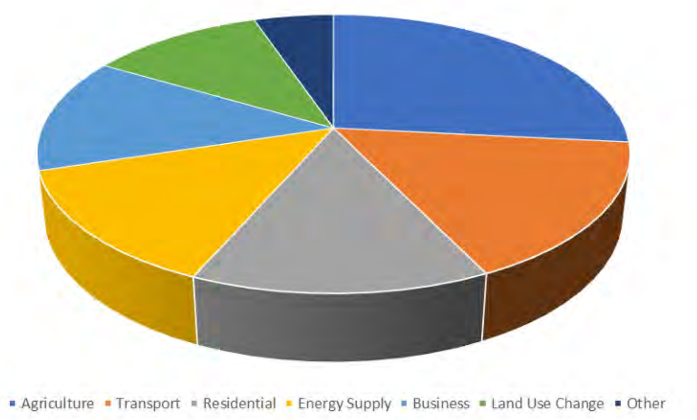


Figure 1.2 GHG emissions NI by sector 2020[4]

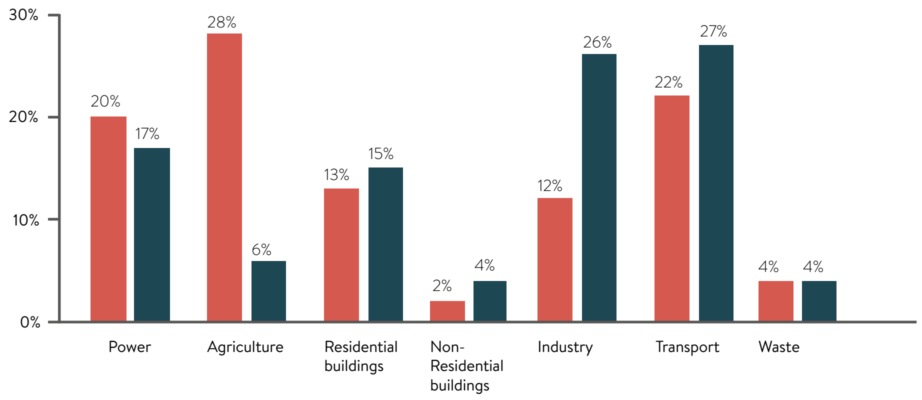


Figure 1.3 Comparison of 2016 GHG emissions by sector between NI and GB[6]

Annual emissions of GHGs from NI agriculture from 1998 to 2019 (Figure 1.4) show an increase since 2009 peaking in 2017. Agricultural activities within NI in 2019 emitted the equivalent of 5.6 million tonnes CO_2 [7]. In 2020 the majority of GHGs emissions in NI are still from agriculture and transport and constitute 40.2% of the total annual emissions. The latest analysis of GHG statistics for NI, undertaken by the local DAERA, has projected a rise of 35% by 2030 unless significant action is taken [6].

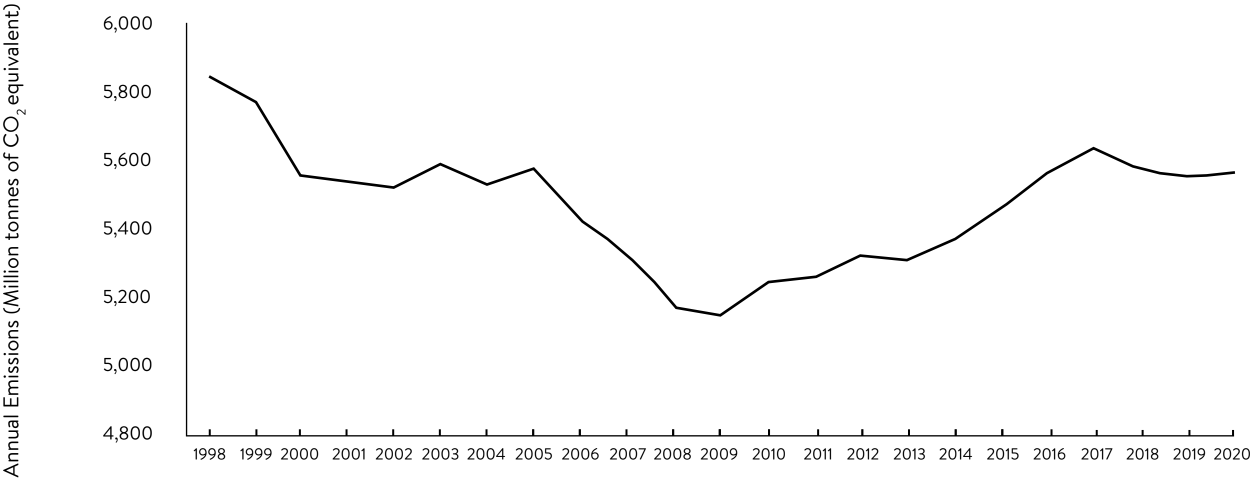


Figure 1.4 NI Agricultural Greenhouse Gas Emissions 1998 to 2020

The Northern Ireland Executive has responsibility for NI energy policy and by 2030 an emission reduction of 35% is needed to meet the UK's 5th carbon budget[5]. If this reduction in NI's GHG emissions is to be achieved by 2030, targeting the agricultural sector is vital.

The UK's 5th carbon budget identified agriculture as a problematic sector to decarbonise while maintaining food production. One route to decarbonisation of NI agriculture is through innovative, cost effective and sustainable technologies such as anaerobic digestion (AD) to convert currently polluting agricultural waste streams into useful beneficial products such as biomethane which can displace natural gas and also offers routes to atmospheric CO_2 removal via long-term sequestration of carbon in products such as Biochar. This would decrease environmental pollution from agriculture, assist meeting the targets of the UK's 5th carbon budget and stimulate technological development for NI.

1.2 Biorefineries

Biorefineries are generically where biological systems (e.g., bacteria, algae or fungi) are used to process different feedstocks to produce a desired end-product. Fermentation to produce ethanol and anaerobic digestion (AD) to produce biomethane are two common examples of biorefineries. Bacterial and algal based processing of wastewater from sewage plants has been an established field since the 1950s. Over recent decades this has extended to look at the processing of other waste streams with suitable feedstock qualities such as food waste, bioenergy crops and animal waste streams such as chicken litter or cattle slurry. Processing these feedstocks into biogas (a mixture of methane and CO_2) using an AD plant is now well established. However, these AD plants additionally produce a waste stream of digestate that requires disposal via land spreading or another route. Land spreading is the most common route of disposal in NI and has caused significant problems due to excess nutrient loading on land and subsequent run-off into waterways and eutrophication or emitted ammonia affecting sensitive habits and causing air pollution. Fortunately, liquid digestate from AD systems (a form of biorefinery) offers great potential as a nutrient source for both further use in other biorefinery systems and for hydroponic based vertical farms. Utilisation for these applications offers a more productive and environmentally friendly use than simply land spreading.

Over the last few decades there has been substantial research into biorefineries with pilot scale demonstrations of plant for the production of a wide range of products including biofuels, cosmetics, pharmaceuticals, biochemicals and for use in human or animal feed. Economic viability has been achieved for production of the higher added value products under the right environmental conditions but there is still some way to go for many products such as biofuels where fossil fuels are ubiquitous and cheap. Important, at this stage of technology development, is the adaptation of the process for regional feedstocks, environment and to match the requirements of local markets. This report looks at eco-innovative solutions combining biorefinery technology that can utilise CO_2 at scale from a variety of sources at different concentrations.

Biogenic processes are extremely effective in removing pollutants, a micro algae bacteria consortium identified by previous research was shown to be capable of removing 48% of CO_2, 87% of NO_x and 99% of SO_2 respectively[8]. Other clean technologies which could make use of/compliment such waste streams are curtailed electricity, green hydrogen production from electrolysis of water, aquaponics, vertical farming or a combination of all of these.

Fuel type definitions

e-fuels, *such as e-methane and e-methanol, are produced using renewable electricity. Typically, green hydrogen is produced by electrolysis which is used as a feedstock in combination with CO_2 or other molecule to produce the e-fuel. Biological processes using green hydrogen and CO_2 produce e-fuels even when the CO_2 is of biological origin.*

Biofuels, *such as biomethane or bioethanol, are produced by the biological processing of biomass by living organisms such as bacteria and algae.*

Synthetic fuels *(or Synfuels) are created by the processing of solid feedstocks (e.g., biomass or coal) via physical/chemical processes.*

Fossil fuels *(oil/coal/natural gas) – fuels formed in the earth's crust over millions of years from the remains of plants and animals.*

In this report the output of a model biorefinery system to produce e-methane is considered as this fits closely with proposed NI strategy to decarbonise the gas grid by displacing fossil gas with biomethane. In this report E-methane is produced using green hydrogen and CO_2. Another example with a different product is the economic potential for animal feed. The agri-food sector in NI imports 389 kt of soya beans as a protein source for animal feed at a cost of c£109m each year. Displacement of expensive imported soya by locally sourced feed would not only improve support for the local economy but also save considerable carbon emissions due to shipping across the world.

1.3 Aquaponics and vertical farming

In addition to considering biorefineries for carbon sequestration, a model was also developed to look at advanced agricultural techniques such as aquaponics and vertical farming. These could be deployed in NI to reduce the carbon footprint of farming and as a sustainable end use for waste streams of CO_2. A transition to vertical farming also reduces the area needed for crop growth either within NI or in other locations where crops are imported from. Figure 1.5 shows the current (2021) distribution of crop growth in NI. It is apparent that the area is devoted to cropland is concentrated in three regions, the north coast, a few regions around Lough Neagh and the lowland areas in the southeast. Land released from growing food crops then becomes available for bioenergy crops, for afforestation, re-establishment of bogs and other carbon sinks or for amenity use.

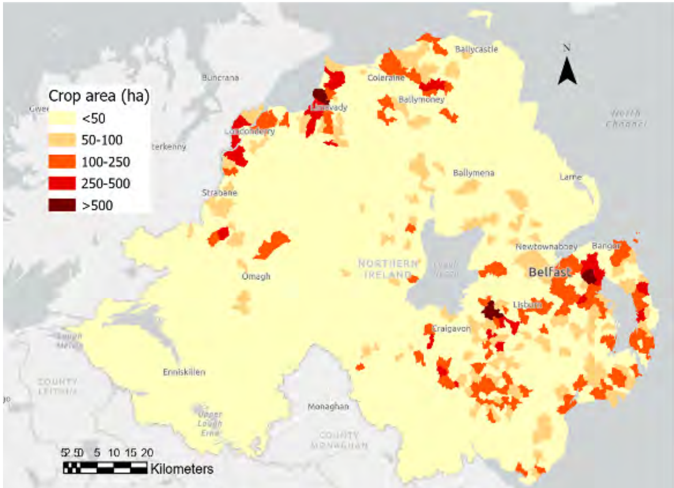


Figure 1.5 Distribution of cropland area in Northern Ireland

Vertical farming technology could integrate the use of waste CO_2, liquid digestate and the oxygen co-product from electrolysis (primarily used to produce green hydrogen), both improving cost effectiveness and environmental sustainability. Waste CO_2 enhances plant growth, by increasing the atmospheric concentration in controlled environments, such as greenhouses or vertical farms, to optimal levels ranging from 1000 to 1300 ppm yields increase by 37%[9]. Green oxygen generated during the electrolysis of water for production of green hydrogen is normally considered a waste and vented to atmosphere. This could be supplied to the plant roots via the circulating nutrient solution. Super saturating the nutrient solution with pure oxygen rather than air doubles the yield of hydroponically grown crops[10], and additionally inhibits fungal growth on roots[11]. Under the IEAs sustainable development scenario global hydrogen production and use are projected to increase by a factor of 7 by 2070[12], consequently increasing the supply of oxygen. By identifying clearly, the agricultural applications and economic advantages of using green oxygen generated from water electrolysis, the higher costs associated with green hydrogen production would be reduced, improving the payback period and stimulating the deployment of electrolysers.

In this report Chapter 2 reviews biorefinery technologies and develops and analyses a model system to look at the economic viability. Chapter 3 develops a vertical farm and aquaponics model and looks at the potential of common greenhouse crops. Both models are developed in light of the unique NI situation and present conclusions and recommendations for the next steps.

> "Vertical farming reduces the area needed for crop growth....Land released from growing food crops becomes available for bioenergy crops, for afforestation, re-establishment of bogs and other carbon sinks or for amenity use"

2. BIOREFINERY METHODS: ALGAE AND BACTERIA FOR CARBON SEQUESTRATION

Microalgae are photosynthetic microorganisms that contribute significantly to oxygen production and serve as the base of most aquatic food chains [13]. Numerous research works have investigated the effect of their mixotrophic nutrition on organic compounds during growth for carbon transformation and storage [14-16]. It has been proven that they can utilise nutrients from wastewater [17-19], CO_2 and other emissions from industrial processes [20]. Therefore, growing microalgal biomass along with existing industrial or municipal treatment activities might substantially lower economic and environmental costs while delivering a vital remediation function and carbon sequestration[21-24].

Microalgae produce several biotic compounds with various applications in the chemical, food, medicinal, carbon capture, and biofuel industries [25]. Due to technical obstacles, microalgae cultivation on a wide scale is limited, which is one of the key factors limiting its commercialisation [26, 27]. Therefore, this report aims to assess and critically characterise the essential variables in using microalgae as a carbon sequestration method for atmospheric carbon removal.

The growth of algae is affected by water availability and culture methods. Microalgae can be cultivated in two distinct methods:

- Closed systems such as photobioreactors where algae are circulated through a sealed transparent pipe or tank system;
- Open systems such as artificial ponds and lakes. Every system has advantages and disadvantages. Open farming (open pond) is recognised as the most fundamental and earliest approach for mass production and cultivation of microalgae but is prone to contamination from less desirable microalgae species and works best in warmer and drier locations. Photobioreactors by contrast have comparatively high capital and operational expense. Microalgae in these systems are completely enclosed in vessels or tubes.

2.1 Integration of algae in various applications

2.1.1 Renewable fuel production

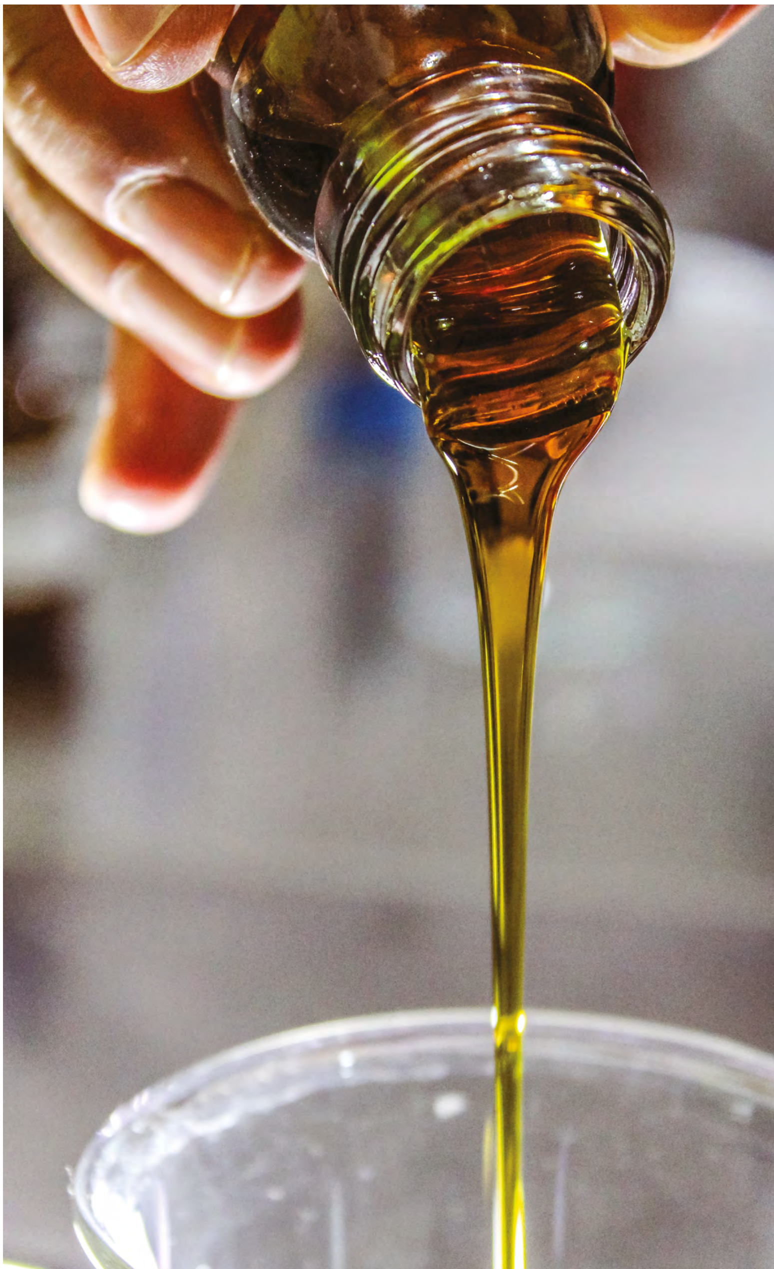
Recent interest has focused on biodiesel as a renewable, biodegradable, and non-toxic fuel that produces fewer pollutants than conventional diesel. Biodiesel offers superior chemical and physical qualities compared to petro-diesel fuel, including a greater cetane number, lower sulfur concentration, higher flash point, and improved lubricating efficiency due to the presence of oxygen. Direct usage of biodiesel or biodiesel blends has a favourable effect on exhaust emissions compared to diesel [28-30]. Biodiesel's comparatively high oxygen content greatly decreases combustion gases and carbon monoxide emissions.

In addition, biodiesel is devoid of aromatic chemicals and other chemical components; thus, it has no or low detrimental impact on the environment. Global biodiesel output was approximately 1.8 billion litres in 2003 [31]. In recent years, the manufacturing of biodiesel has increased significantly. Biodiesel production is anticipated to increase as the global demand for fuels and cleaner energy rises. Biodiesel made from microalgae has the potential to totally replace petroleum; however, the cost of microalgal oil production must first decrease from around $2.80/L to $0.48/L [32].

Compared to other feedstocks for biofuels, microalgae-derived biofuels are the most economical and sustainable; photoautotrophic microalgae, for instance, transform sunlight into biomass more efficiently than higher plants [33]. Algae have a photosynthetic efficiency of 3–9 percent, whereas terrestrial plants have a photosynthetic efficiency of less than 4 percent [34]. This light utilisation efficiency is shown in the rapid growth rate of microalgae and the production of biomass. In addition, algae are more tolerant of a broad range of light intensities than higher plants, allowing them to thrive autotrophically via photosynthesis. Using organic carbon sources such as glucose, certain microalgal species can generate a relatively high concentration of energy-rich molecules [35-37].

Heterotrophs are non-photosynthetic algae that feed on organic carbon, which represents a promising opportunity for NI if energy could be supplied [16, 38-40]. Phototrophic microalgal growth is more efficient than heterotrophic microalgal growth because the organic supply necessary for heterotrophic development is provided by another photosynthetic crop [16, 41]. Therefore, energy must first be used to develop the crop in the heterotrophic mode, whereas energy is used directly for algae growth in the photoautotrophic mode.

Algae have evolved into a variety of habitats, from hot springs to snow [42]. The vast majority of algae species inhabit freshwater, brackish, marine, and hypersaline waters, among others [43]. Green algae, cyanobacteria (blue-green microalgae), diatoms, yellow-green algae, golden algae, red algae, brown algae, dinoflagellates, and pico-plankton are the nine major kinds of algae [43]. Due to the fact that algae are highly varied, and many species remain to be discovered and investigated, there is the prospect of additional innovations and uses. Their genetic and metabolic diversity may account for their capacity to live in numerous habitats [44].



2.1.2 Anaerobic digestion (AD)

AD is an efficient method for transforming organic wastes and biomass with a high moisture content into biogas (a mixture of CH_4, CO_2 and traces of H_2S and other gases). Through a series of biochemical processes, bacteria decompose organic materials anaerobically into biogas containing carbon dioxide, methane, and other gases such as nitrogen and hydrogen sulphides. Using anaerobic digestion technology, microalgae can be used as a renewable and sustainable substrate for biogas production. However, the content and type of microalgae cell walls have a considerable impact on their biodegradability and suitability for AD processing, hence species need to be selected carefully.

The cost-effectiveness of the anaerobic digestion of microalgal biomass could have a substantial effect on the production of sustainable energy. Thus, substantial effort is required to advance this technology [45]. Appropriately selected, microalgae's biodegradable nature can make it an ideal substrate for anaerobic digestion and methane production [46]. Diverse microbial populations undergo a series of metabolic activities, including hydrolysis, acidification, acetogenesis, and methanogenesis, during anaerobic digestion. Using enzymes, the first set of microorganisms degraded complicated chemical compounds into monomers, which were then converted into volatile fatty acids, hydrogen, and acetic acid.

"Anaerobic digestion has a number of advantages over other biofuel industries, including high energy yields of biogas compared to biodiesel"

Acetogens convert volatile fatty acids, such as propionic and butyric acid, to hydrogen, carbon dioxide, and acetic acid. Hydrogen, carbon dioxide, and acetate are finally transformed by methanogenic bacteria into methane and CO_2 [47, 48]. Anaerobic digestion is inhibited by a variety of variables, including substrate condition and co-digestion with other substances. Adjusting the microbial community to accommodate microalgal biomass digestion could boost the methane yield.

Two factors impact the cost of biogas production: microalgae cultivation and the anaerobic digestion process. Nutrient-rich wastewater can be used as a growth medium for microalgae propagation [46]. The microalgae effectively bioremediates the wastewater, generating several bioproducts and energy carriers from algal biomass which can be used as feedstock in an AD plant [49].

Membere & Sallis (2018) found that the yields of biogas and methane from Laminaria digitata, a brown macroalgal species, are strongly affected by temperature over a period of 40 days. Their findings suggested that biogas could be produced at varying temperatures of digestion, which affected biogas yield. At 25, 35, 45, and 55 °C, methane yields were 318, 294, 271, and 352 mL methane/g volatile solids, respectively. According to their findings, the maximum cumulative biogas output was attained at 35 °C, while the optimal methane dual potential was at 55 °C [50]. Utilising nanoparticle catalysts, such as Fe_3C nanoparticles and iron oxide nanoparticles (Fe_3O_4), could also increase the biogas generation efficiency. Adding Fe_3O_4 nanoparticles to an anaerobic waste digester increased biogas yield by 180% and methane production by 234% at 37 ° ambient temperature for 60 days [51]. Nickel and cobalt nanoparticles, together with various metal oxide nanoparticles such as Fe_2O_3 and MgO, produced varying increases in biogas and hydrogen generation yields [52].

Anaerobic digestion has a number of advantages over other biofuel industries, including high energy yields of biogas compared to biodiesel, no need for drying, microalgal biomass mineral composition that meets the requirements of anaerobic methanogens, the possibility of co-digestion, the culture used for biogas production can be reused for biogas upgrading via CO_2 sequestration, and the offensive odour is reduced below the specified unprocessed waste level. The disadvantages of anaerobic digestion include a low carbon-to-nitrogen ratio in the feedstock due to the high nitrogen content of microalgal biomass, the presence of cell wall, which reduces the bioavailability of intracellular compounds, a high initial investment cost, the infeasibility of anaerobic digestion on smaller waste water sources, a lengthy operational and maintenance period, and the use of a large area of land [53, 54].

2.1.3 Biohydrogen production

Hydrogen is a clean, more versatile, efficient, and sustainable renewable energy carrier that can replace fossil fuels due to its high energy yield in comparison to conventional hydrocarbon fuels. Utilising bacteria, biological hydrogen generation is a method for producing hydrogen gas [55]. Due to their metabolic and enzymatic capabilities, microalgae can generate hydrogen via photobiology. Eukaryotic microalgae may create H^+ and oxygen while fixing CO_2 under anaerobic circumstances. Hydrogen ions are reduced to form hydrogen gas molecules in the presence of hydrogenase enzymes (Fe-hydrogenase and Ni-hydrogenase). Using glucose as a model substrate, several hydrogen production pathways are directed by either acetate or butyrate production. Both dark fermentation and photo fermentation are effective methods for anaerobic hydrogen generation. Butyrate fermentation requires more energy than acid fermentation[53, 56].

Deoiled microalgal biomass containing lignin-free cellulose is a suitable substrate for dark fermentative hydrogen generation due to its composition. Various factors, including physical, biological, and operational factors, affect hydrogen production efficiency from the deoiled algal cake. There are two phases in the conversion of deoiled microalgal biomass to hydrogen. Hydrolysis of deoiled algal biomass to simple sugars is the first step. The second step consists of acidogenic bacteria fermenting simple carbohydrates into hydrogen [57].

In all bioconversion processes, the compatibility of fermenting microorganisms with substrate feedstocks and the output values of the products are crucial. Clostridium species is a prevalent bacterial model for hydrogen production from organic substrates [58]. Carbon-rich macroalgae produce hydrogen and methane when coupled with nitrogen-rich microalgae in a two-stage process, according to Ding et al. (2016). In their work, hydrolysis and acidogenesis were assisted by the co-fermentation process, resulting in an increase of 15.5% to 18.5% in the hydrogen output from Laminaria digitilia biomass. Significant amounts of energy left in hydrogenogenic effluents were recovered as biomethane in the second stage of methane co-fermentation, boosting energy efficiency from 4.6% to 6.6% during hydrogen fermentation and from 57.9% to 70.9% during combined hydrogen and methane synthesis [59].

Utilising cutting-edge techniques, such as genetic engineering, microalgae bacterium consortiums, enhanced biohydrogenation technology, and nanomaterials for enzyme stability and hydrolytic efficiency, are strategies for improving hydrogen production. Dark fermentation is favoured over photofermentation, biophotolysis, and microbial electrolysis because it can create hydrogen repeatedly without the need for sunshine.

2.2 Global market and expansion of microalgae-based bioenergy

Multiple developed and developing nations have demonstrated an increasing interest in identifying sustainable feedstock for bioenergy production in order to address global energy demand. Microalgae are being investigated as feasible sources that have historically contributed to producing numerous chemicals and extracts, such as carotenoids and proteins. In 2024, the global markets for keratin oils and proteins are projected to reach 2.0 and 35.54 billion US dollars, respectively [60]. Consumers are increasingly concerned with decreasing environmental pollution, living longer, and preventing the onset of chronic diseases. To improve environmental conditions, this rising demand has led to a major movement toward producing microalgal biomass as a fossil fuel substitute [61]. Due to demand to switch away from petroleum-based fuels, microalgae bioenergy commercialisation has increased. It has resulted in economic growth benefits and has been aided by new technology that has directly reduced production costs. However, there remain obstacles to making and selling microalgae for commercial use such as yield and production efficiency. Biorefining of microalgae has the potential to overcome these challenges and possibly earn an attractive income [62]. Unfortunately, microalgae derived fuel is not yet cost competitive with fossil fuels in terms of price or able to be produced in the volumes needed. Electrification of transport may limit the future market apart from for the hard to abate sectors like shipping and air travel.

Utilising microalgae derived from lipids for bioenergy generation is one of the most prominent biorefinery methods. The extracted lipid is processed into biodiesel, while the residue is utilised in the anaerobic digestion process to generate biomethane. The average price of biodiesel and biomethane on the global market is 0.83 USD/L and 0.76 USD/L, respectively. In developing nations like India, the biomethane and biodiesel market prices are approximately 0.59 and 0.89 USD/L, respectively [60]. It is also desirable to increase the production of lipids, carbohydrates, and proteins by employing microalgae as cell factories. As biorefineries have substantially fixed capital expenditures and labour charges, economies of scale play a crucial role in the economics of the process [62]. Even though commercial production and microalgal biofuels are still in their infancy due to cost inefficiency, algal cultivation for value-added product extraction and biofuels could boost the market opportunities due to the possibility of scale-up and profitability.

2.3 Outstanding problems

During the past 50 years there has been a substantial amount of research on microalgae-based biofuel generation. Due to limitations such as strain selection for higher biomass production, microalgae culture system selection, the quantity and quality of bio-based product recovery from microalgae, and operational and environmental variables, commercial microalgae production has not yet been recognised and implemented in the real world. For the effective implementation of large-scale microalgae production for bioenergy, it has been proposed that a few essential factors be addressed, such as biomass composition and productivity, bioconversion platform selection, and other technical and administrative expenditures. A few areas in microalgae processing for bioenergy, such as growth and harvesting, remain a significant problem for developing cost-effective techniques.

There are numerous obstacles to the commercialisation of microalgal biofuels, including the inability to manufacture cost-effective fuels due to substrate composition, conversion platform, and technology. Many traditional fossil fuel companies have invested heavily in the study and optimisation of commercial microalgae production and cultivation, partly driven by obligations to provide biodiesel or other biofuels in countries across the globe. The research to date has indicated that the production of microalgae at a commercial scale is difficult. One of the obstacles is the scaling-up procedure, which includes the preparation of seed cultures for a 300,000-L manufacturing facility. There are also a lack of suitable handling equipment and skilled people for large-scale production. Currently, multiple governments in industrialised nations are aiding this industry in developing a sustainable and ecologically friendly production system although oil companies have stepped back from the large-scale investment seen in the previous two decades. This is because of the relatively high cost of production as the technology still needs development. Other biofuels such as corn-based bioethanol and biodiesel are generally less expensive to produce and therefore allow oil companies to achieve the different mandates for biofuel content more cheaply at the forecourt. Governments have not provided as much support for microalgae biofuels as they have for other renewable energy sources, such as solar and wind power.

Through the production of biomass, microalgae can aid in the mitigation of global warming. Microalgae typically require between 1 kg and 2 kg of CO_2 for every kilogram of biomass produced so are efficient at sequestering carbon. Growth conditions, such as the temperature, light intensity, and nutrient availability, and the desired product can also affect the amount of carbon dioxide required. For example, microalgae

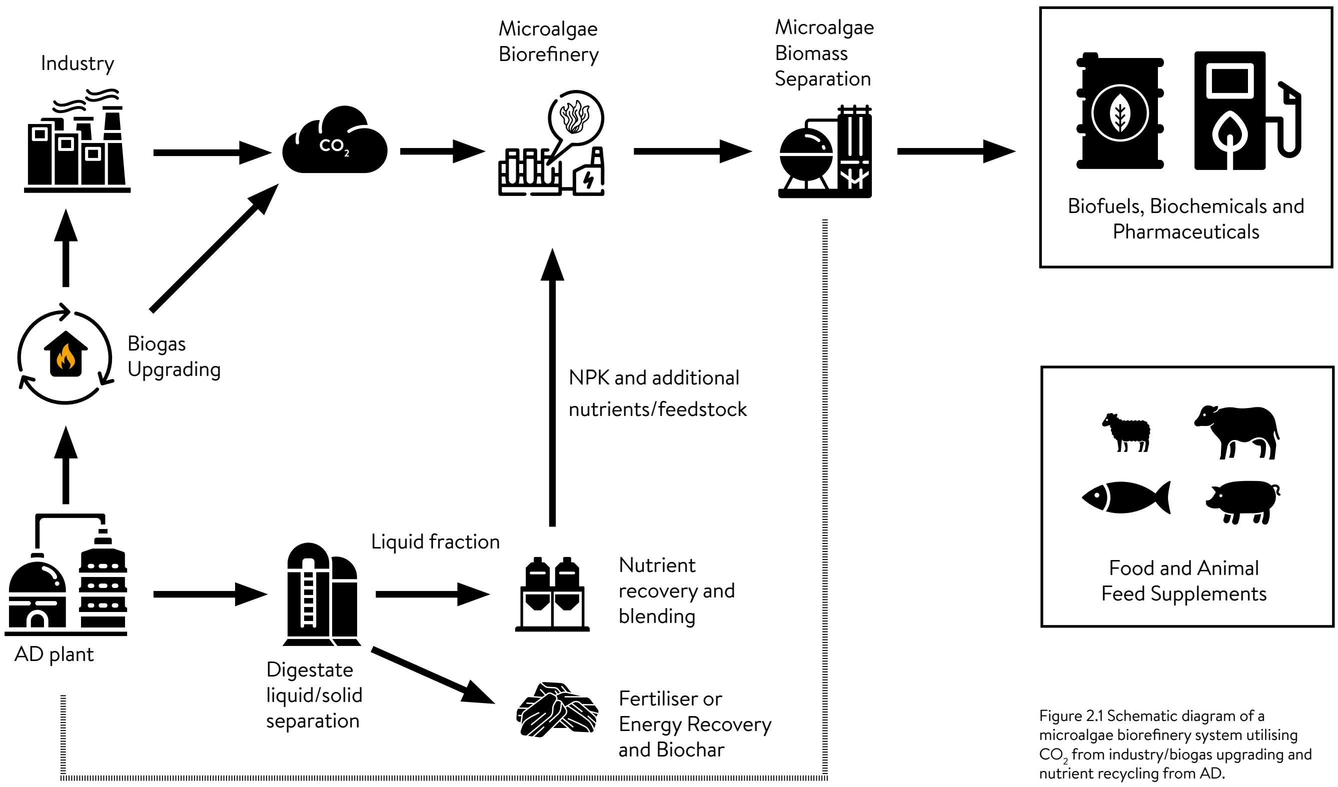


Figure 2.1 Schematic diagram of a microalgae biorefinery system utilising CO_2 from industry/biogas upgrading and nutrient recycling from AD.

grown for biofuel production may require more carbon dioxide than those grown for food production. Opportunities also exist for dual use applications, for example treating wastewater, lowering environmental pollution, and producing biomass cheaply, resulting in recovering products with added value – see Figure 2.1 for illustrative example. The combination of bioenergy with value-added product recovery has the potential to improve market demand for biofuels while cutting production costs [60]. However, microalgae growth and bioenergy harvesting continue to be major problems for cost-effective manufacturing.

2.4 Decarbonisation and carbon sequestration via microalgae

Carbon is an essential component for maintaining ecological stability, as it is part of a balanced cycle of capture from atmosphere mainly through photosynthesis and eventual release through respiration or other biological processes. This balance has been dramatically disturbed by human activity. Due to the disruption created by rising industrialisation, the environment has been detrimentally impacted [63].

Global ecosystems are threatened by the post-industrial era's rising atmospheric CO_2. In 2021, 80% of all greenhouse gas emissions in the UK[4] consisted of CO_2, which contributes to global warming. Consequently, carbon capture, use and storage (CCUS) strategies are of the utmost importance to reduce emissions of CO_2. There are three effective ways for sequestering carbon dioxide: chemical, physical, and biological:

- Chemical techniques for CO_2 sequestration include those based on washing with alkaline solutions or CO_2 immobilisation using multi-walled carbon nanotubes, adsorption materials, and amine-coated activated carbon.
- Physical methods include directly injecting CO_2 into the earth, oceans, depleted oil/gas wells, and aquifers.
- The biological fixation of CO_2 by living organisms involves photosynthetic bacteria, algae, and plants [64].

Every technique has advantages and limitations and there are proponents for each approach. Large-scale CO_2 sequestration is possible using physical methods, including direct injection. However, this requires the existence of geological and geomorphological structures, separation equipment, and CO_2 collecting and compression technology. This is expensive and is dependent on the absence of long-term leaks from the geological storage site. Chemical neutralisation procedures are safer and allow long-term CO_2 fixation; however, the high cost of the reagents required for neutralisation limits their utilisation. In order to capture CO_2 from diffused or nonpoint sources at low concentrations, both physical and chemical techniques require energy intensive processes and expensive capital equipment making CO_2 capture by this route as one of the least financially attractive approaches.

A DfE commissioned review of CO_2 capture options for NI looked at the technologies available and the costs involved for NI industry[1]. A subsequent BEIS commissioned study[65] produced a number of reports looking at technology options for CO_2 removal at a scale of the order of 1000 tCO_2/day suitable for different industries and undertook an in-depth technoeconomic assessment of options. These options considered in the BEIS report are only relevant to the three power stations and a small number of industrial sites in NI. It is clear from this earlier work that conventional chemical and physical approaches are expensive in an NI context, not just because of the technology cost but also the energy requirements coupled with the transport and storage costs make this expensive compared to other locations in the UK and overseas.

Biological alternatives were considered to be an option for NI mainly because the large majority of NI CO_2 industry emitters are below 10,000 tCO_2/annum[1] and this was a scale at which biological systems could be useful. Later in the report, the potential of controlled atmosphere systems such as greenhouses and vertical farms are considered. Here we consider microalgae/bacteria-based solutions. It has been shown[66] theoretically that up to 513 tCO_2/annum could be collected by microalgae per hectare of open ponds in an ideal system. However, this is very unlikely in an NI context due to ambient temperatures, solar irradiation, and rainfall levels. An enclosed, biorefinery system was considered more appropriate as all aspects of the environment could be better controlled to maximise growth/absorption of CO_2 and the biorefinery systems could be scaled vertically as well as ground footprint to match the CO_2 source.

CO_2 absorption rates vary considerably depending on the operating parameters, pond chemistry and physiology of algae or bacteria used. Capture rates of 80% to 99% of CO_2 emitted are reported as achievable using microalgae[67] and it is notable that some species of microalgae are tolerant of contaminants such as NOx and SOx as found in some sources of CO_2 such as from combustion[68]. Herzog[69] reported that 80% of the CO_2 emitted by a 200 MWh natural gas power station can be absorbed by a 3600 acre microalgal pond during daylight hours. This is not the scale which is envisaged for NI but demonstrates what is possible. The RICE project in Wales[5] gives the closest approximation to NI ambient conditions and where a high value product is the endpoint. Here, in a small-scale pilot, 27 kg CO_2 is consumed per week once the 7500 litre system is established.

Microalgae are photosynthetic organisms that employ their photosynthetic machinery to remove CO_2 from the environment with a photosynthetic efficiency 10 to 15 times greater than that of conventional plants [70] they offer a highly effective route for CO_2 sequestration. They can typically capture 1 kg to 2 kg of CO_2 for every 1 kilogram of biomass produced. Microalgal species absorb and store carbon dioxide, and their photosynthetic systems can capture photons of light and inorganic carbon. These bacteria collect and utilise CO_2 effectively for biomass development, making them a potential resource for the bioenergy and food industries [71].

[4] *https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/1134664/greenhouse-gas-emissions-statistical-release-2021.pdf*

[5] *https://www.rice.cymru/en/algae-at-vale*

Microalgae absorb light energy and convert it into adenosine diphosphate, nicotinamide adenine dinucleotide phosphate (NADP), adenosine triphosphate, and the reduced form of nicotinamide adenine dinucleotide phosphate (NADPH). This energy is subsequently directed towards the dark cycle, which transforms CO_2 into viable organic compounds via the Calvin-Benson cycle. To maximise CO_2 sequestration, appropriate environmental conditions must be maintained, including temperature, pH, salinity, aeration, nutrition, and illumination. A closed system such as a bioreactor, in which the operational parameters may be modified to boost productivity, offers the best opportunity to maximise production. Selection of prospective microalgae species and tuning of the design parameters for the bioreactors can optimise CO_2 capture and conversion to useful products after harvesting the microalgae. Effective design can be regarded as a breakthrough in sustained microalgal based sequestration [72].

2.4.1 Mechanism and tolerance of microalgal carbon dioxide sequestratione

Microalgae are autotrophic, photosynthetic microorganisms with a greater metabolic rate than comparable-weight higher plants. Microalgae require carbon, nitrogen, phosphorus, potassium, magnesium, calcium, and sulfur to thrive, with carbon being the most essential. To adjust to changes in the quantity of inorganic carbon in water, certain microalgae activate a system that actively converts inorganic carbon within their cells. This is known as the CO_2 concentration mechanism, which is a crucial mechanism for microalgae since the CO_2 concentration mechanisms are the sole means for microalgae to utilise CO_2 throughout their photosynthetic activity. Organisms with concentration processes have a high affinity for CO_2, which is a fundamental physiological trait that enables them to efficiently use low CO_2 concentrations to satisfy their photosynthetic needs. In vivo, the ribulose1,5bisphosphate carboxylase/oxygenase (RuBisCo) limiting enzyme is catalytically immobilised due to RuBisCo's poor affinity for CO_2 and typical reactions, which require a large concentration of CO_2 [73].

The level of affinity and tolerance for CO_2 differs among microalgal strains. Microalgae can live in situations with varying levels of carbon dioxide. At carboxylated locations, microalgae have evolved mechanisms such as concentration processes to live in low CO_2 environments. A rise in the concentration of CO_2 exerts an anaesthetic effect on microalgal cells, which inhibits photosynthesis and algal growth. Initial CO_2 concentration affects growth, which in turn influences lipid output and composition. Low CO_2 concentration inhibits the synthesis of fatty acids, whereas high CO_2 concentration stimulates fatty acid accumulation regardless of the occupied carbon's effect on saturation and elongation [70].

Microalgae utilise bicarbonate and CO_2 gas as carbon sources. However, bicarbonate is regarded as the predominant carbon species in the most common pH range (6.5 to 10) for microalgae production mediums. When an industrial flue gas stream is given to microalgae cultures, the CO_2 concentration is often higher than that of ambient air, resulting in enhanced biomass production. CO_2 dissolved in the medium is employed as a buffer to increase biomass production by increasing carbon content. The chloroplast of microalgae produces lipids. Chloroplasts converts ambient CO_2 into Acetyl-CoA, which is then converted into carbon in the fatty acid chain. The most promising microalgae for the production of lipids and triacylglycerol are Chlorella sp., Chlamydomonas reinhardtii, Nannochloropsis sp., Ostreococcus tauri, and Phaeodactylum tricornutum.

By means of photosynthesis, microalgae collect monosaccharide glucose. This glucose is a source of energy in addition to proteins, lipids, and other carbs. Increased irradiation or nutritional depletion can cause a cell's glucose production to exceed its consumption rate. Excess glucose might disrupt the osmotic balance of the cell; therefore, excess glucose is transformed into polysaccharides and lipids for storage. In the future, these items will function as a source of energy and carbon [74].

"When an industrial flue gas stream is given to microalgae cultures, the CO_2 concentration is often higher than that of ambient air, resulting in enhanced biomass production"

2.4.2 Advantages of sequestering carbon using microalgae

Figure 2.2 depicts how the cultivation of photosynthetic microalgae can provide a viable alternative to terrestrial plant systems for carbon sequestration. Microalgae are a possible alternative due to their simple harvesting, rapid production, minimal requirements, higher tolerance to environmental stress, increased CO_2 tolerance, strong photosynthetic ability, and increased biomass production rates. Algae species are more efficient at CO_2 fixation than higher plants and hence offer increased biomass production due to their exponential growth rates if conditions are optimum.

Carbon dioxide in the atmosphere and soluble carbonates can be used by microalgae as carbon sources. Microalgae can also reduce the elevated CO_2 levels in industrial flue emissions and some species are tolerant of contaminants in the flue gas. Due to microalgae's ability to grow in wastewater and their utilisation of numerous trace elements, including heavy metals, they are widely used for mitigating environmental concerns. Microalgae are therefore recommended for use in bioremediation, particularly for wastewater treatment and heavy metal removal from water bodies [75].

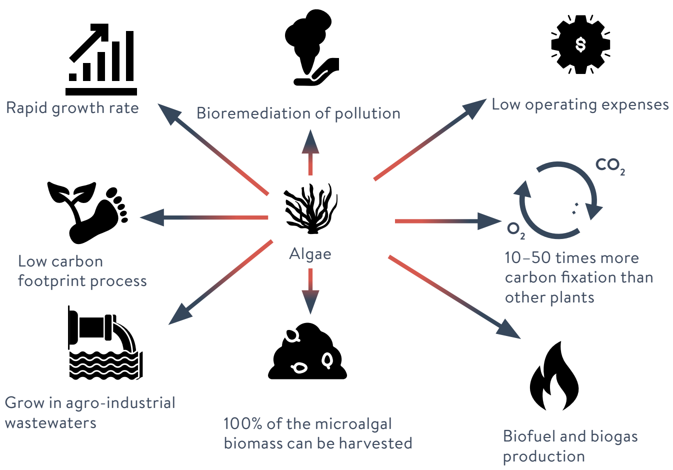


Figure 2.2 Compared to terrestrial plant systems, the cultivation of photosynthetic microalgae can provide a viable alternative for carbon sequestration, as microalgae can grow 10 times faster than terrestrial plants. Microalgal biomass can be turned into carbon-neutral biofuels such as bioethanol, biodiesel, and biogas.

Typically, microalgae are grown and then harvested for processing either by filtering out the entire crop or by continuous syphoning out of a fixed amount. The harvested macroalgae can then be processed to remove specific compounds, used as a feedstock for AD and/or used for the production of biochar[76]. Microalgae used for bioremediation will need appropriate treatment and disposal if they contain heavy metals or other contaminants.

Examples of studies on the use of microalgae, varying CO_2 concentration under different scenarios:

- Yadav et al. (2019) cultivated microalgae in closed photobioreactors using organic and inorganic nutrients derived from industrial wastewater and coal-fired flue gas for waste bioremediation and biomass production. Chlorella sp. and Chlorococcum sp. were cultivated in industrial effluent with various quantities of coal-fired flue gas ranging from 1 to 10% CO_2. The results demonstrated a 1.7-fold increase in biomass production, while microalgae cultured with industrial effluent and flue gas containing 5% CO_2 displayed the greatest growth and CO_2 fixation [77].

- Tu et al. (2019) investigated the effects of power plant tail gas on CO_2 reduction by using tail gas as a carbon source and cultivating the freshwater microalga Chlorella pyrenoidosa. In the presence of power plant tail gas, an increase in dry weight and lipid production of 84.9% and 74.4%, respectively, was found. The optimal carbon fixation sequestration of microalgae was 1.12 g/L with an average carbon fixation rate of 0.21 g/(Ld), which was 134.2% and 107.1% greater than the growth of microalgae in the open air. The tolerance of C. pyrenoidosa to sulfur dioxide and nitric oxide is consistent with the investigation mentioned above. Tolerance is 0.04%; however, desulfurisation and denitrification are necessary as pre-treatment operations [78].

- Aghaalipur et al. (2020), in their research study, analysed the assessment of CO_2 by fixation of two microalgal species, Scenedesmus obliquus and Chlorella vulgaris. Additionally, two new species, Monoraphidium contortum, and Psammothidium sp., were also studied for their capability of CO_2 inputs in two types of photobioreactors, including glass bottles and vertical columns. This study aimed to assess the CO_2 bioremediation rate, growth kinetics, and protein content of microalgal species of different types of photobioreactors with varying amounts of CO_2 ranging from 0.04% to 10%. According to the results, Chlorella vulgaris (3.35 g/L/day) was most significant as Chlorella vulgaris showed maximum CO_2 sequestration at 10% CO_2 in the vertical column photobioreactors, followed by Psammothidium sp. (3.24 g/L/day), Scenedesmus obliquus (2.40 g/L/day), and Monoraphidium contortum (1.40 g/L/day). Psammothidium sp. showed maximum CO_2 recovery (CR%), which was 41.70%. Chlorella vulgaris has also depicted maximum protein content during Chlorella vulgaris cultivation in a glass flask photobioreactor with 10% CO_2 [79].

In conclusion, microalgae can be utilised to absorb CO_2 efficiently and be converted to biofuel, thereby simultaneously addressing two of the world's most pressing problems. To maximise outcomes a focus on the selection of prospective microalgae and design parameters for bioreactors in conjunction with CO_2 capture is essential. However, to employ inorganic sources for carbon dioxide, such as flue gas, a gas treatment system that reduces or eliminates inhibiting factors must be implemented.

Utilising potent microalgal strains in efficient bioreactor designs to sequester CO_2 can be challenging. Microalgae may theoretically use up to 9% of light energy to capture and convert 513 tons of CO_2 into 280 tons of dry biomass per hectare each year in both open and closed cultures[66]. To create an effective system for removing CO_2 from the atmosphere, algal biomass culture must be combined with thermochemical processes, such as pyrolysis.

The economic and environmental benefits of biofuel co-products need to be considered. The value of biofuels extends beyond their use as a transportation fuel and the creation of new materials can play a significant role in mitigating future environmental damage. Diverse generations of biofuels minimise greenhouse gas emissions while decreasing dependency on crude oil, hence promoting energy diversification and the establishment of a substantial number of rural jobs[80]. To expedite adoption, the fundamental objective of integrated algae waste operations should be to optimise productivity and product accumulation while decreasing inputs such as energy, water, nutrients, and land footprint, especially for large-scale production and future research. To fully implement algal biomass and enable commercially viable bioenergy co-production, biorefinery technology capable of producing various high-value products will be necessary [81].

Microalgae are considered a promising possibility for biodiesel generation. The combination of microalgae and wastewater purification can cut CO_2 emissions while simultaneously decreasing the cost of biodiesel production, enabling its practical deployment. Microalgae production and efficiency are affected by temperature, salinity, pH, light intensity, photobioreactor design, nutrient ratio, and CO_2 flow rate. However, successful oil extraction from microalgae biomass is one of the primary obstacles to overcome. Transesterification is a prevalent biodiesel manufacturing technique [82].

There are several techniques for extracting energy from algae, each with its own advantages and challenges. Several of these techniques are still in the early phases of development. As such, the production of biofuels from algae is considered economically viable but given the current stage of research and the high cost, the process of algal biofuel generation has not yet been significantly advanced to be commercially adopted [83]. After extraction of the liquid inside algal cells for biofuel or other products, the residual algal biomass can be used for the production of value-added goods [57]. A method that combines cell destruction with liquid extraction in a single process [84] is considered the most efficient for processing purposes, leaving the residual biomass for onward use via AD or other route. While the use of algae in atmospheric carbon removal should be less constrained than that used for biofuel production (biodiesel), a species with a rapid growth rate and low oil content is necessary, as algae will be readily transformed into solid biochar for long term sequestration.

"microalgae can be utilised to absorb CO_2 efficiently and be converted to biofuel, thereby simultaneously addressing two of the world's most pressing problems"

2.5 Seaweed for climate change mitigations

Seaweeds are marine photosynthetic organisms, usually referred to as "macroalgae," that supply the energy basis for many aquatic organisms, hence playing a significant part in the equilibrium of the aquatic ecosystem. Seaweed offers a variety of environmental advantages, including carbon sequestration, eutrophication mitigation, ocean acidification modification, coastline protection, and habitat creation. Seaweeds are often categorised into three types: brown seaweeds with >2000 Phaeophyceae species, red seaweeds with >7200 Rhodophyta species, and green seaweeds with >1800 Chlorophyta species [85]. When cultivated utilising sustainable ways, seaweeds are a rich supply of unutilised biomass that can be used to address global problems. As indicated in Figure 2.3, seaweeds can address climate change, bioenergy production, agriculture, food consumption, animal and human health, valuable chemicals, bioactive components, and coastal management issues. Moreover, if correctly implemented, seaweeds could contribute to a sustainable circular bioeconomy approach [86].

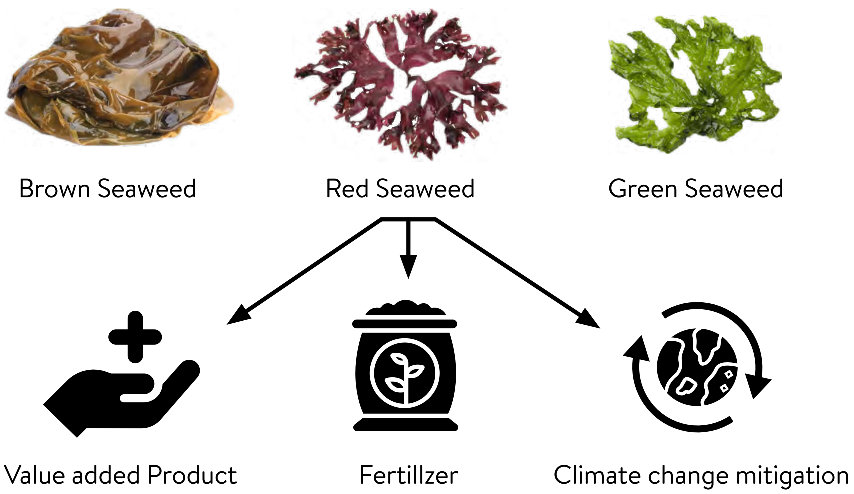


Figure 2.3 When made into a stable form of carbon like biochar, cultivated seaweeds are recognised as a carbon sequestration technology because they utilise CO_2 from other sources used in refineries and the sun to trap carbon inside their biomass.

Due to their quick growth rates, enormous yields, and lack of global area needed for culture, seaweeds are more suitable for biorefinery applications than lignocellulosic biomass from terrestrial plants [87]. Additionally, the lack of recalcitrant lignocellulosic assemblies raises the possibility that less energy may be needed to recover highly valuable bioproducts of commercial interest, which favours economic and life cycle analyses of any hypothetical biorefinery bioprocess that uses seaweed as feedstocks. Additionally, the presence of distinct hereditary polysaccharides in different seaweed species offers distinctive properties for direct use or as bioeconomy chemicals. Seaweeds are, therefore, third-generation or possibly fourth-generation feedstocks [88, 89]. However, research into the possible uses of harvested seaweed as feedstock in biorefineries is still in its early stages, and advancements outside of the laboratory scale are gradual. The interest in using seaweed biomass in various innovative biorefineries is shown in Figure 2.3.

In particular, the application of seaweeds for crop enhancement, animal feed additives, fish diets, carbon sequestration tools, bioplastic manufacturing, biofertiliser production, biochar production, antimicrobials, anti-inflammatory, anticancer, contraceptive, cosmetics, and skin care agents was mentioned.

The integration of seaweeds and bioprocesses can undoubtedly result in the commercialisation of seaweed biorefineries and call attention to the significant need for cooperative funding in this extremely promising research area, as well as the need for ongoing seaweed projects around the globe. It is predicted that the market for commercial seaweed will grow from $15.01 billion in 2021 to $24.92 billion in 2028. The seaweed market has also grown due to its use in a range of industries, including the food sector, livestock feed, agar, alginate, pharmaceuticals, and others [90].

2.5.1 The role of seaweed in climate change mitigation

The concept of "blue carbon" emphasises how the oceans and coastal environments absorb and store organic carbon, with coastal vegetation ecosystems playing a large role in global carbon sequestration. In particular, seaweed may remove a large quantity of CO_2 from the aquatic ecosystem and provide a range of ecological advantages, including removing toxins from the coast and providing habitat for other aquatic creatures. Macroalgae, more commonly known as seaweed, has all the requirements for designation as a blue carbon reservoir with a significant carbon sink potential. Globally seaweeds are estimated to store an average of 173 megatonnes of carbon annually with the majority reaching the ocean floor. In nature there are two ways for seaweeds to be transported to the sediment and depths of the ocean: the drift of seaweed particles through marine canyons and the sinking of negatively floating seaweed debris. There are current projects that aim to grow seaweeds and sink them to the deep ocean floor as a Carbon Dioxide Removal (CDR) technique, mimicking what happens in nature.

Seaweed has the potential to sequester almost 50% of the world's carbon [91, 92]. This is not just through sequestration on the ocean floor but also through the prospective contribution of seaweed to the bioeconomy through replacing fossil fuels and delivering human nutrition, biofuels, renewable biomass, and animal feed can also make a major difference to carbon emissions. For example it is estimated that seaweed has the potential to offset 50% of the world's bioenergy, which will help reduce greenhouse gas emissions [93].

Seaweeds grown along the shore effectively absorb CO_2 from the air and function as organisms that fix carbon in the deep ocean and marine sediments. Between 61 and 268 megatonnes of carbon might be stored by seaweeds annually, on average this is about 173 megatonnes. Biomass transfer into the deep sea helps to trap about 90% of the carbon, with the remaining 10% ending up in coastal sediments[94]. Cultivating seaweed has the potential to sequester up to 1,500 tonnes/km^2, of CO_2[95].

The potential for seaweed sequestration is very dependent on location and varies considerably for different species. For example, Jagtap and Meena [92] estimated that several seaweeds have the following potential for sequestering carbon: Eucheuma spp. can absorb 68.4 tonnes of carbon/hectare/year, Kappaphycus striatum can absorb 125.5 tonnes of carbon/hectare/year, Laminaria spp. can absorb 1156 tonnes carbon/hectare/year, Ecklonia spp. can absorb 562 tonnes carbon/ hectare /year, Sargassum spp. can absorb 346 tonnes carbon/ hectare /year, and Gelidium spp. can absorb 17 tonnes carbon/ hectare/year. Seaweed can absorb carbon from the atmosphere and lower levels of carbon dioxide, so reducing the consequences of global warming. Seaweed also absorbs nutrients from water sources, using nitrogen and phosphorus, while fixing carbon through photosynthesis. This has a number of advantages, including lowering carbon and nitrogen levels in the water, reducing ocean acidification, and raising oxygen levels to revitalise and restore aquatic habitats [96].

A carbon sink is not achieved through consumption of seaweed's biomass because seaweed's carbon consumed as human food or fed to livestock enters the carbon cycle and is eventually reemitted[97]. Seaweeds are therefore regarded as a carbon sink when they are introduced to the deep ocean and sediments or transformed into biochar. Due to its quick growth rate and high photosynthetic efficiency, seaweed is not only a great carbon sink but also a great candidate for removing CO_2 from the atmosphere. In order to accelerate seaweed development and carbon sequestration, the carbon dioxides released during the combustion process in carbon-based power plants may be pumped into closed or open systems of seaweed. Dry seaweed biomass can take up almost 960 kilograms of CO_2 per ton during cultivation. Seaweed also provides additional environmental advantages, such as lowering acidification, eutrophication, and global warming. Phosphorus, potassium, and nitrogen can all be fixed using seaweed [93].

Seaweed-derived biochar, a powerful tool for reducing climate change, has outstanding qualities, including a large surface area, a high porosity, an aromatised carbon pattern, an abundance of functional groups, and a high mineral content. Due to its special characteristics, biochar can be employed in a variety of fields, including agriculture, livestock farming, biogas generation, water treatment, composting, building, energy storage, soil remediation, and carbon sequestration [98]. When compared to biochar made from lignocellulosic biomass, seaweed-derived biochar often contains higher levels of inorganic nutrients like calcium, phosphorus, magnesium, and potassium, which may be good for the soil and boost crop output [99, 100].

By lowering greenhouse gas emissions, biochar made from seaweed may be able to mitigate global warming. According to some researchers, incorporating seaweed biochar into soils may increase the amount of methane-oxidising microbes that lower methane emissions from crop areas [101, 102]. Chubarenko, Woelfel [103] assessed that approximately 20–6000 tonnes of beach-cast seaweeds/ km of the shoreline might be collected annually in the southern Baltic Sea area. As a result, the natural biodegradation of seaweed along the coast greatly increases greenhouse gas emissions. Therefore, correctly managing shoreline seaweed helps mitigate climate change as well as other issues like eutrophication and pungent odours [104].

Wen, Wang [105] evaluated the life cycle of beach-cast seaweed through pyrolysis and found that pyrolysis of washed seaweed at 600 °C could result in carbon emission of - 790.89 $kgCO_2e$ and negative overall energy demand of - 2.98 gigajoules. According to the author, beach-cast has the potential to sequester up to 1600 tonnes of $kgCO_2e$ per year, or 0.5 $kgCO_2e$, for every kilogram of dry beach-cast. Furthermore, this study showed that producing biochar at an ideal temperature of 500 °C while maximising energy savings from natural drying reduced $kgCO_2e$ emissions. Seaweed has a bio-charring conversion ratio of 48–57%, which is equal to high-quality plant biochar. As a result, by preventing greenhouse gas emissions from biomass breakdown, bio-charring can be a promising environmentally acceptable alternative to beachside seaweed disposal [106].

The authors have previously shown the potential of biochar to sequester carbon from the atmosphere via land-based energy crops[76]. However, this approach is limited by available land area for energy crops and the comparatively low rates of CO_2 absorption by crops such as willow, miscanthus and grass. Devoting some of the sea area around NI to aquaculture would allow substantial CO_2 sequestration which could stably be stored as biochar. For example, 1000 hectares of Laminaria could absorb >1 $MtCO_2$ per annum as well as providing other benefits.

> "Devoting some of the sea area around NI to aquaculture would allow substantial CO_2 sequestration which could stably be stored as biochar"

2.6 Biorefineries for Northern Ireland

There are many published studies (see [107-115] for a recent sample) on the economics of biorefinery systems which cover a very large range of different situations, most utilising a range of feedstocks, micro algae or bacteria and operating environment not relevant to CCU in NI. High levels of solar irradiance in a relatively dry and hot climate create the near ideal situation where energy costs are low, yield high and relatively inexpensive open tank based growing systems are feasible. NI does not have such an advantageous climate so algae biorefinery systems for CCU have to be as a minimum enclosed and for best results, they require some heat and could need artificial light for optimum growth.

In general, the costs of building and operating a biorefinery for CO_2 capture can be significant. Capital costs for building the facility could range from tens of £million to over £1 billion, depending on the scale of CO_2 capture and complexity of the facility. Operating costs, such as the cost of feedstocks and electricity, can also be substantial. However, biorefineries can also generate revenue from the sale of products such as biofuels, chemicals, and bioplastics to offset operating costs and could also attract savings in carbon emission taxes. In terms of return on investment, it can vary widely depending on the specific project and market conditions. A few studies have estimated the internal rate of return (IRR) for biorefineries with carbon capture and utilisation (CCU) technologies:

- A study by the National Renewable Energy Laboratory (NREL) in the US estimated that the IRR for a biorefinery with CCU could range from 10-20% depending on the specific configuration and market conditions.
- The European Biorefinery Research Institute (EBRI) suggested that the IRR for biorefineries with CCU could be as high as 20-30%.
- A report by the Carbon Trust (UK) suggested that some advanced bioenergy technologies, including biorefineries with CCU, have the potential to achieve returns on investments (ROI) of 10-15%.

For this report a range of different biorefinery systems were reviewed with varying end-products. Many of these have promise, such as production of amino acids for animal feed or the production of bio-oils given the needs of the NI economy. Each system needs an individual in-depth investigation as to feasibility given the varied requirements for growing the different strains of microalgae required and the harvesting and processing necessary for a market ready product. Further investigation should potentially include pilot plant trials as well as an assessment of future market demand. Decisions on future studies and biorefinery strategy will need to reflect that the majority of CO_2 from combustion sources such as large heating boilers may potentially not be available in the future because of many factors. These include the switch to low-carbon heat when existing boilers reach end of life, or that the cost of carbon capture and transport may be prohibitive.

One source of CO_2 that is likely to be consistently and readily available is the biogenic CO_2 produced alongside methane in the process of AD. The initial product is biogas, which is 42 - 75% methane depending on feedstock with the majority of the rest of biogas made up by CO_2. This CO_2 component can be stripped from the biogas or upgraded with the potential to achieve close to 100% biomethane. Depending on feedstock and operating parameters the composition of biogas from an AD system is typically ≈52% methane and ≈48% CO_2 for most systems using animal slurries in NI. Given the push towards decarbonisation of the gas grid using biomethane, AD systems will have longevity out to 2050+ and are forecast to increase in size and overall biomethane output.

> "Many of these (biorefineries) have promise, such as production of amino acids for animal feed or the production of bio-oils given the needs of the NI economy"

2.6.1 Biorefinery economics

In this work we deliberately selected an established system demonstrated at pilot plant scale which suited NI's environment, a variety of industry CO_2 sources, and where there was an established market. This biorefinery utilises a strain of proprietary methanogenic archaea which has been selectively evolved by Electrochaea GmBH[6] who also developed a pilot scale biorefinery using their archaea for converting CO_2 to methane[116]. Electrochaea's archaea were selected to be tolerant to contaminants in typical industrial CO_2 gas streams such as from AD systems, flue gases and cement works and should be suitable for most sources of waste CO_2 from NI industries. The original Electrochaea biorefinery has been further developed by NREL[7] to reduce capital costs and double the rate of production of methane[117] amongst other improvements.

The NREL biorefinery system for biomethane production has basic input requirements of CO_2, hydrogen and nutrients and can be easily combined with an existing AD to convert the ≈48% of biogas that is biogenic CO_2. The biorefinery can be directly fed with biogas as the methanogenic archaea will only convert the CO_2 in a biogas mix and pass the biomethane through the refinery. The recent work on decarbonising NI's gas grid has shown there is a potentially large demand for biomethane. A price comparison between AD methane (approximately 52% of biogas by composition) and biorefinery converted CO_2 to e-methane is therefore straightforward. This NREL system could also be applied to other sources of CO_2 as required.

Significant work has also been published in the literature investigating directly injecting hydrogen into an AD bioreactor to increase biomethane yields or using chemical methods to upgrade biogas[118-121]. These systems offer an alternate route to utilising the CO_2 component of biogas but were not considered as part of this analysis.

In the model developed for this report, a 1 MWh AD plant was used as the source of CO_2 as feedstock for the biorefinery. In NI, with a typical animal slurry/grass silage feedstock such a plant produces biogas with a typical composition of ≈100m³ of methane and ≈92m³ of CO_2 per hour. This would equate to ≈1300 tonnes of CO_2 converted to e-methane each year and gives a sense of the possibilities for CO_2 use from other sources.

Upgrading the CO_2 in the biogas requires four times the volume of hydrogen gas for the NREL biorefinery system as the archaea convert the CO_2 to methane and water via the chemical equation below:

$$CO_2 + 4H_2 \longrightarrow CH_4 + 2H_2O$$

A 1.84 MW electrolyser powered by renewable electricity is required to produce 368m³ (4 x 92m³) of H_2 per hour required to convert the CO_2 which gives ≈92m³ of e-methane per hour. At present, electrolysers have very long lead times, and it is a sellers' market, so a reasonable estimate is between £3m and £3.5m just for the electrolyser and installation. Capital costs for electrolysers from different manufacturers vary considerably but by installing on site the CAPEX and OPEX expenses associated with compressing, shipping and large-scale storage of hydrogen are avoided. An alternate scenario where hydrogen is produced off-site and shipped in may be feasible but only if an electrolyser has access to very low-cost electricity such as delivered by a wind-turbine or solar farm that is not grid connected. Production savings may then partly offset the costs associated with transport to the biorefinery site.

The AD model assumes feedstock and transport costs of £454,000 which consists of 9200 tonnes of grass silage at £45/tonne plus £40,000 for transport based on indicative prices from AD operators in NI. Cattle slurry is assumed to be zero cost apart from transport with no gate fee charged. This gives a price for grid injected biomethane of £0.14 - £0.15/kWh which is consistent with biomethane prices when used for RTFOs. If feedstocks used in AD are purely waste streams and have no economic value, then the AD model predicts a price for biomethane of around £0.09/kWh which is consistent with the more optimistic end of published prices. This is unlikely to be the cost for a completely new AD system but would be realistic for example if feedstock costs were negligible and/or for an established AD system where commercial loans had been paid off. For this model it has been assumed for the base case that a new AD system is built which is utilising feedstocks that are readily commercially available and hence are replicable for a significant number of new AD plants across the whole of NI.

One of the drawbacks of green hydrogen production is the high dependency on the cost of electricity. Consequently, the cost of e-methane production is directly related to the price of electricity. While many proposals for economical green hydrogen production have been predicated on inexpensive (or free), curtailed renewable electricity or use of dedicated renewable energy assets, this model assumes that there is an uninterrupted supply of electricity to allow continuous operation of the biorefinery. In part, this is because the AD process is continuously producing biogas, which either would have to be stored for when hydrogen was available, or hydrogen storage introduced into the system if there was dependency on curtailed electricity. Either option would require a higher capacity of electrolyser

[6] *https://www.electrochaea.com/*
[7] *The National Renewable Energy Laboratory, USA – www.nrel.gov*

to produce the required volume of hydrogen in the limited time that it was operating and an upscaled biorefinery for the higher gas flows if operation was non-continuous. The increase in capital costs for such an intermittently operating system are estimated to offset cost savings from cheaper electricity.

When developing the model, several different scenarios were evaluated. Common to each was that the capital costs were fully funded via a commercial loan at an interest rate of 5.8% which was the best rate available at the time of model development (Q1 2023). The loan repayment period was set to 15 years. A real project may have different financing arrangements, and these will be dependent on market rates at the time, risk profile, secured supply contracts for e-methane/biomethane etc. The key scenarios were:

(i) Addition of electrolyser and bioreactor to an existing AD plant assuming gas grid connection – price for e-methane.

(ii) As per (i) with the capture and sale of Oxygen[8] (a co-product from hydrogen production) to offset costs.

(iii) A whole system cost for a new AD, electrolyser, bioreactor and gas grid connection – whole system price for biomethane/e-methane injection into grid.

(iv) A whole system cost as for (ii) but capturing and selling the Oxygen produced as a co-product from the electrolyser.

It should be noted that the model just estimates the economic production costs and price required for e-methane and/or biomethane to achieve a net-positive income. No assumptions are made about desired profit levels, current or speculative future incentives, or cost savings from avoided carbon taxes. As such, the results give a basis on which future government interventions could be designed to make e-methane production attractive from any source of CO_2. Similar models could be constructed for any e-fuel which should be considered especially for candidate replacements for home heating oil, which is a particular challenge on NI's journey to decarbonise.

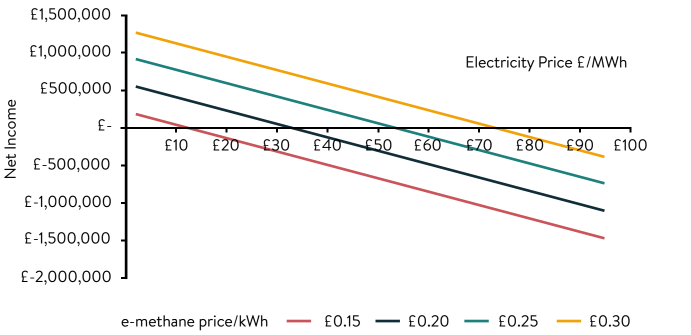


Figure 2.4 Scenario (i) - Net income for e-methane production at different electricity price points and at different price points for e-methane. Assumes biorefinery and electrolyser added to existing AD plant (or other CO_2 source).

[8] *Price for Oxygen taken as $0.2/m3 from https://www.globenewswire.com/en/news-release/2022/04/12/2420689/0/en/Oxygen-Market-Report-Size-Production-Trends-and-Forecast-to-2030-IndexBox.html*

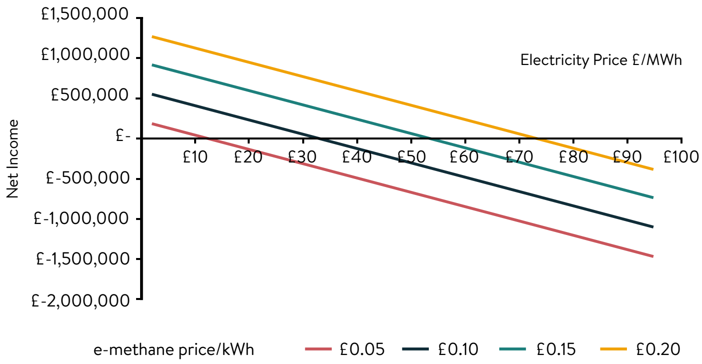


Figure 2.5 Scenario (ii) - Net income for e-methane production at different electricity price points and at different price points for e-methane. Assumes biorefinery and electrolyser added to existing AD plant (or other CO_2 source) and Oxygen sold to offset production costs.

The outcomes from scenarios (i) and (ii) shown in Figure 2.4 and Figure 2.5 above show that for e-methane production:

- A low electricity price (<£10/MWh) is essential for e-methane to be comparable to biomethane pricing (assuming no oxygen sales).
- At a typical UK wholesale electricity price of £50/MWh the economics are not attractive without oxygen sales.
- E-methane, assuming £50/MWh electricity and no oxygen sales, is about 10x the long-term (pre-2022) price for fossil gas (c.£0.03/kWh), falling to around 4x the price with oxygen sales. The comparison to current market prices for fossil gas is much more favourable (but highly volatile) and security of supply may be a compelling advantage in the marketplace.
- Capturing and selling oxygen produced from electrolysis nearly halves the price for e-methane such that e-methane is marginally cheaper at £0.12/kWh than biomethane £0.14-£0.15/kWh, assuming £50/MWh electricity.
- Electricity prices below £20/MWh would mean e-methane was at a price point similar to present day fossil gas prices. This is valid where the CO_2 source and electrolyser are next to the biorefinery so no storage or transport costs.
- Simply capturing CO_2 from biogas and selling it would net from £134,000 (pre-2022 prices of £100/tonne) to >£4 million (at peak of CO_2 shortage in 2022 due to fertiliser plant closure). Additional costs would be incurred to separate, purify, compress, and ship CO_2 and these have not been estimated. At the upper end of the CO_2 price range, it would be more economic just to sell CO_2 rather than upgrade to e-methane, but these scarcity prices are unlikely to be long-term.

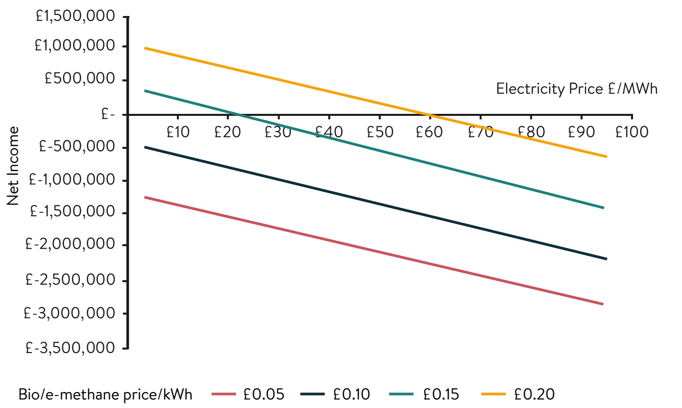


Figure 2.6 Scenario (iii) - Net income for bio/e-methane production at different electricity price points and at different price points for bio/e-methane. Assumes completely new AD plant with biorefinery and electrolyser. Oxygen not collected or sold.

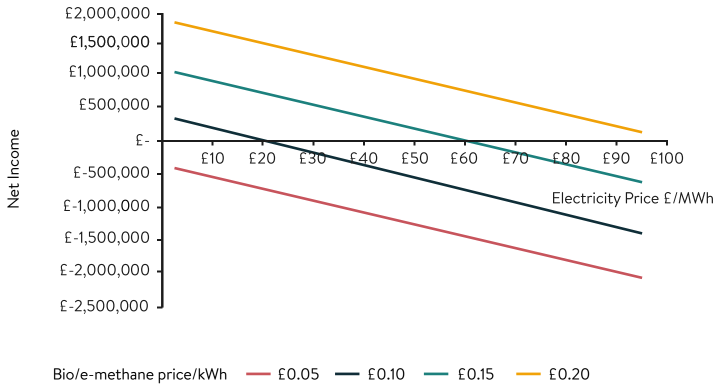


Figure 2.7 Scenario (iv) - Net income for bio/e-methane production at different electricity price points and at different price points for bio/e-methane. Assumes completely new AD plant with biorefinery and electrolyser. Oxygen collected and sold.

The conclusions from the last two scenarios as shown in Figure 2.6 and Figure 2.7 are similar to the first two in that the sale of oxygen has a big impact on the financial return. In scenario (iii) the effect of diluting the price of e-methane with the lower cost biomethane can be seen with improvements on the net returns for different electricity prices. This situation is reversed for scenario (iv) where biomethane is nominally more expensive than e-methane produced at the £50/MWh electricity price point.

The model developed offers the prospect of CO_2 conversion to e-methane where resources are co-located and when a waste flow (oxygen in this case) is valorised. This offers a tantalising prospect of being able to economically address CO_2 gas streams across the region and turn them into a marketable product. Realistically, a full engineering design study and market appraisal now needs to be performed as assumptions will need to be tested and the outcome is highly correlated with the price achieved for oxygen and input electricity prices. There are opportunities to increase income/reduce costs through activities such as utilising night-time electricity or participating in grid balancing schemes when electricity network demand is high. The electrolyser/biorefinery can be turned off for short periods of time and the AD system has a limited capacity to store biogas production if required. Similarly, the waste heat from the electrolyser could be of value for example in heating of buildings or industrial drying.

There are many other possible scenarios that could be considered, such as the production of syngas and biochar from the AD system digestate or various options for co-locating glasshouses or vertical farms to use oxygen/ CO_2 and nutrient streams. These circular economy approaches could spread operating costs but would require further capital investment. For this exercise, the oxygen utilisation in (ii) and (iv) above shows the impact on economics that could be achieved by stacking income streams based on valorisation of waste streams and/or co-location of related business activities.

“Offers a tantalising prospect of being able to economically address CO_2 gas streams across the region and turn them into a marketable product”

2.7 Biorefinery methods – Conclusion and Recommendations

Biorefinery based systems for CO_2 capture and conversion into products have significant promise especially when co-located with the additional feedstocks that they require. The model of an e-methane producing biorefinery showed that e-fuel production from CO_2 was comparable to the costs of biomethane production. E-methane could therefore play a role in decarbonising NI's gas grid alongside biomethane if carbon taxes for natural gas use or a support scheme for non-fossil gas was introduced. Overtime, as electrolyser and other capital costs reduce, then e-methane could become more directly cost-competitive with natural gas, but it is unlikely to ever match the historic price of natural gas.

Decisions about how best to meet the targets set out in the Climate Change Act (Northern Ireland) 2022 have to weigh many different factors. The use of e-fuels to decarbonise different areas of the economy such as the gas grid, off gas grid home heating, transport and manufacturing are one of the only options where electrification is not possible. E-fuels and biofuels also offer a potential longer-term energy storage solution to the inherent intermittency problem with most forms of renewable energy generation.

Production of e-fuels via biorefineries is still in its infancy. Originally sold as the future of liquid fuels production by major oil companies, investment has now been withdrawn in light of a buoyant oil price and a recognition that bioengineered algae will be needed to achieve the production efficiencies that are essential both for the volumes required and an acceptable price point. Academic research continues in this field, but it may take a decade or longer before the challenges have been addressed. The roll-out of carbon taxes on a wider range of CO_2 emitters or the introduction of price support mechanisms would change the situation.

Biorefineries are not just used to produce e-fuels but also many other products from animal feed to pharmaceutical precursors. This report didn't model such systems but there are clear opportunities to support local industries directly with the production of food additives such as amino acids or protein and carbohydrate for chicken, pig, or cattle feed. There may also be potential within NI's vibrant life sciences and pharmaceutical sectors.

Recommendations:

E-methane production looks to be an immediate opportunity that should be explored within NI. Delivering ambitions to decarbonise the gas grid will necessitate a number of large-scale AD plants around the region which would be ideal for co-location of a e-methane producing biorefinery utilising the CO_2 component of biogas. Integrating an AD system, biorefinery and pyrolysis of digestate for maximum energy recovery and sequestration of carbon as biochar would make a major difference to energy supply and NI's carbon emissions. Displacing CO_2 emissions from fossil gas and sequestering CO_2 from the atmosphere looks to be a big step towards achieving carbon budgets. Future biorefinery systems could economically utilise other local sources of CO_2 such as from cement manufacturing, biomass plants or furnaces.

To advance the use of biorefineries in NI the following steps should be taken forward:

1) A pilot scale trial to assess technology and costs. This should be the full integrated model utilising an existing AD plant as a source of biogas and suitably scaled electrolyser and biorefinery such that results can be used in the design and assessment of a commercial scale plant.

2) A full design study and market support assessment should be undertaken. This is an essential step given the current increases in costs, limited availability of key equipment and the essential need to reduce the investment risk as much as is practicable. The study should also address any regulatory or grid related challenges that need to be overcome, including if a market support mechanism is required.

3) Support for a commercial scale demonstration plant at suitable size for CO_2 sources in NI. De-risking a commercial scale biorefinery system using CO_2 may be a necessary step if it is a first-of-a-kind development.

Biorefineries offer many opportunities to develop NI's economy by both displacing current imports and developing new products for exports. The potential warrants further detailed investigations of alternate biorefinery systems which could use waste streams to produce products of direct use to NI's economic sectors. As a starting point these should include:

4) Other e-fuels such as e-methanol or DME. A key requirement for NI is the replacement of kerosene which is used by ≈2/3 of NI households for heating. A close to drop-in replacement is desirable for those homes not close to the gas grid or suitable for a heat pump. Alternatives to current fossil fuels for all forms of transport may also be fruitful avenues to explore, particularly where there are no easy options for alternatives such as in aviation.

5) Animal feed additives. Probably the next best opportunity for either protein production or other feed additive given the import of soya and the large market for animal feed in NI.

Seaweed aquaculture is also worth exploring, although NI's territorial waters are limited there is potential for an economically viable business that also sequesters carbon and absorbs excess nutrients ultimately from run-off from land but delivered by river systems to the sea. It would be useful to consider seaweed aquaculture as part of a wider marine development activity, perhaps co-located with prospective offshore wind farms and/or designed to enhance local fisheries for fish or other sea food.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3 ENHANCING BIOGENIC SEQUESTRATION

3.1 Vertical Farming

Vertical farming increases the area available for plant growth by cultivating plants in layers stacked one upon each other, under artificial lighting in controlled indoor environments. Some of these systems have increased productivity up to 516 times[3] that of conventional agriculture per unit area due to the advantages of stacking plant cultivation layers. They have a higher light use efficiency than plants cultivated under greenhouse plant growth conditions, converting 1.9 to 2.5 times more Photosynthetically Active Radiation (PAR) to the chemical energy stored in the dry mass in plants, a theoretical maximum light use efficiency of 10%, whereas photosynthesis under conventional conditions is typically 1%. The concept was developed from research into long distance space exploration, to enable astronauts to be fed fresh produce, regenerate air, recycle water, recycle waste and produce useful biomaterials[122]. On a space craft the area available is limited so research into how to increase the yield of crops in a controlled indoor environment commenced. Due to high population densities and urbanization in south-east Asia, this was developed further using technologies such as hydroponics, aquaponics and aeroponics to maximise the density of plant growth that can be achieved per m^2.

Figure 3.1 A typical vertical farm showing multiple shelves of crops in an enclosed environment with artificial light.

In contrast NI has a high proportion of its land area devoted already to agriculture. With the recent dramatic increase in the cost of energy and the need to reduce the agricultural contribution to GHG emissions, NI is an ideal location for vertical farming technology. NI has a high proportion of open land along with a massive untapped wind energy resource enabling the use of onshore wind electricity which has a current cost of £0.06/kWh to provide the large input of electrical energy required with a Generation Emissions Factor (GEF) 30 times lower than grid supplied power. Enhanced plant growth efficiency and productivity using nutrients obtained from waste would improve food security, provide new rural job opportunities and be a biogenic method of Carbon Capture and Utilisation (CCU). The required inputs for vertical farming in NI could nearly all be supplied from:

- waste heat
- nutrients from anaerobic digestate
- oxygen from electrolysis
- CO_2 from CHP, AD, or power plants

Optimum operational costs would see the utilisation of curtailed or night-time electricity for lighting and other equipment. Vertical farms can be used to improve the capacity factor of installed power generation equipment, particularly wind turbines, as the need for power curtailment is reduced. Alternatively, off peak nocturnal energy generation could be utilised with vertical farms as the light required for crop growth can supplied at any part of the day. Vertical farms can also be used for grid balancing as short-term intermittency in light is tolerated by crops.

Vertical farming has numerous advantages for the NI economy, NI environment and the global environment:

- An increase in resource use efficiency, as vertical farming is a Closed Plant Production System (CPPS), water and nutrients are continually recycled. CO_2 levels can be enhanced to 1500ppm using flue gases to promote plant growth. Previous studies noted a 19% increase in fruit production at an enriched CO_2 concentration of 700 $\mu mol\, mol^{-1}$ at higher levels yield increased to 37%. Theoretically, a vertical farm can fix all the CO_2 supplied.

- Can protect cultivation systems and provide fresh produce through the year.

- Climatic extremes are avoided, and more constant growing conditions are provided.

- Reduction in methane emissions from reusing digestates. (Methane has a warming potential 30 times that of CO_2)

- A reduction in fertiliser inputs (nitrogen and phosphorus) to land as no longer needed for crop growth. A reduction in fertiliser application, especially in NI, is a positive environmental step due to the risk of nutrient runoff and accumulation associated with current practice.

- A potential reduction in eutrophication[9] for rivers and lakes as vertical farms are a closed system with water circulated internally there will be zero run off from nitrates and phosphates.

- Curtailed power or nightly generation could be used making use of otherwise wasted electrical energy, improving the performance of transient renewable energy systems such as solar photovoltaics or wind turbines. Vertical farms can use renewable resources as light intermittency does not adversely harm plant growth.

- Increased vertical farming of crops could free up land area for more sustainable enterprises and end uses, like for example, for the restoration of wetlands and meadows or afforestation, which could act as carbon sinks or perform useful functions such as flood prevention. Adoption of these, would have positive impacts on nitrogen, phosphate, carbon and hydrological cycles.

- Reducing the requirement for purchasing artificial fertilisers by integrating aquaponics with vertical farms which will also provide a source of protein. In 2020 333,000 tonnes of fertiliser costing £76.3 million was used for agriculture in NI[123].

- A reduction in food miles and imports by providing produce normally out of season which may be imported from as far away as Kenya (4585 miles).

- Increase in security of supply avoiding the additional administration associated with plant imports from GB or other non-EU states[124].

- New job and agricultural opportunities through constructing vertical farms and developing new markets by exporting new developments in vertical farming techniques.

[9] *Excessive richness of nutrients in a lake or other body of water, frequently due to run-off from the land, which causes a dense growth of plant life.*

3.2 Aquaponics

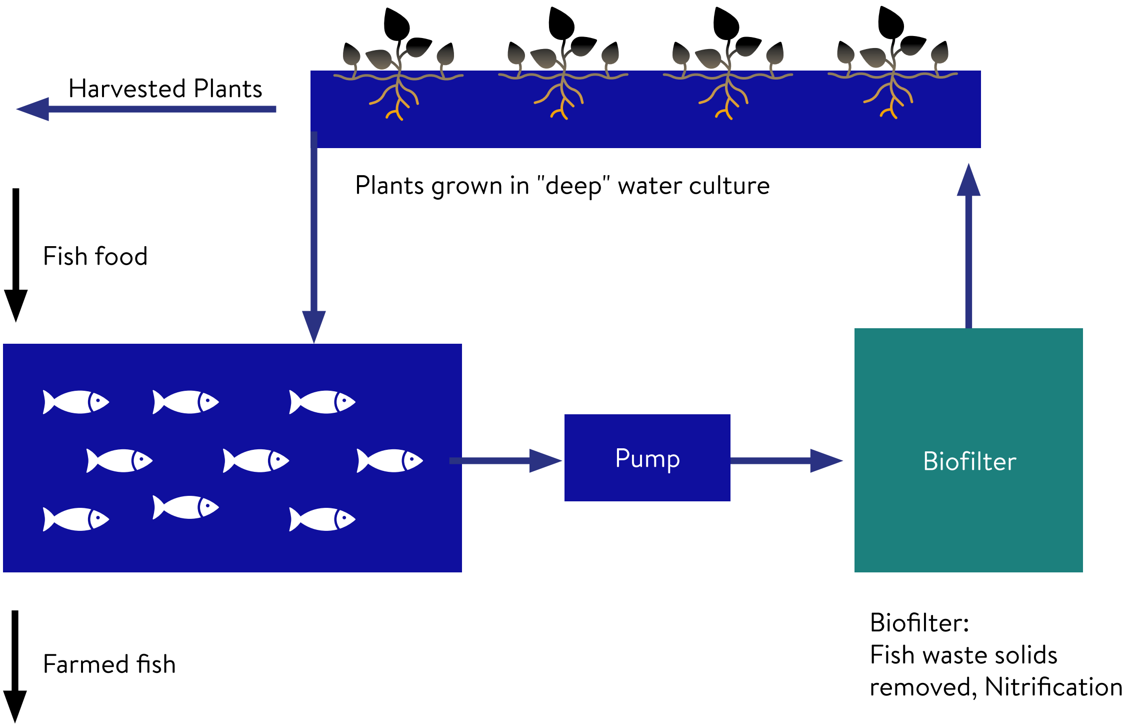

Figure 3.2 Schematic outline of an aquaponics system

Aquaponics combines the techniques of hydroponics and aquaculture; cultivating plants using nutrients supplied from fish wastes. An obviously more sustainable and less costly agricultural circular economy technique than hydroponics or aquaculture as the nutrients required for plant growth are supplied from the natural wastes excreted from the fish being farmed. Artificial fertilisers are not needed nor released, reducing local water pollution, GHG emissions and input costs. A schematic diagram outlining the operation of an aquaponics unit is shown in Figure 3.2.

Wastes excreted by the fish are removed by the pump and converted via the biofilter into the nutrients required to fertilize the plants grown in a deep-water hydroponic cultivation system. The only inputs to this system are fish food and electricity for the pump. If grown under artificial light, then electricity is required.

In an aquaponic system, the fish are fed, the plant roots absorb the nutrients from the wastewater after it passes through the biofilter, cleaning it before being returned to the fish and the cycle continues. A recent study from the USA by Kralik et al (2022) investigated consumer perceptions of the fish raised using aquaponics finding that these can compete with wild caught fish on grounds of taste as well as having sustainability advantages[125].

Due to the respiratory oxygen requirements of the plant root system[126], green oxygen could potentially be used to increase plant growth rates and additionally offset some of the higher costs associated with green hydrogen generation.

An experiment using insects to convert organic waste into proteins for fish food found that, juvenile seatrout (a species native to NI) could be successfully raised using fish meal containing a 20% mixture of insects[127]. Further investigations have found that black soldier fly larvae can be grown and when mixed with residues from processing algae a fish food suitable for the production of rainbow trout and Atlantic Salmon[128] can be produced. Both fish species are already sold in NI. Other sustainable plant or biowaste based fish feeds require more careful consideration in their production[129]. Typical aquacultural practices used to produce Atlantic Salmon are responsible for considerable localised marine pollution as well as negatively impacting native populations. In this process, if the fish food was produced using biorefinery products derived from currently polluting biomass and waste streams, this would provide a more sustainable circular economy approach within the NI agricultural sector.

3.3 Carbon farming and avoided emissions from vertical farms and aquaculture

Vertical farming units produce economically valuable fish and crops when combined with aquaculture. The internal plant production systems interact with the carbon cycle as plants take in carbon dioxide and emit oxygen as part of normal photosynthesis/growth processes. It is therefore important to understand carbon inputs and output from vertical farming versus conventional farming. Conventional arable farming involves the sequestering of carbon by plants from the atmosphere and the emission of oxygen in the process. The carbon absorbed by plants in an open system can move down to the soil medium and remain in the soil store until there is a disruption to the soil ecosystem. As the crops in the conventional system are harvested each year, the soil medium is disrupted which can have a negative impact on the ability of the soil to retain the carbon in the long term. Runoff of soil material to adjacent rivers represents a movement of carbon from the important soil carbon store. Vertical farming, as an enclosed version of the above process, allows more control over material flows in and out of the unit, has a significantly lower risk of soil disruption, runoff and carbon losses through this pathway.

Crops grown in a vertical farming unit are in an enclosed relatively airtight space therefore carbon dioxide can be supplied to these crops for biogenic uptake during photosynthesis. The net balance and sustainability of carbon absorption versus carbon use in vertical farming will depend on the source of the carbon dioxide added to the vertical farming unit. The carbon dioxide used could be an output of another process for example carbon dioxide from an anaerobic digestion unit, an onsite internal combustion engine-based generator or if available, CO_2 generated from other industrial processes. If that carbon dioxide output is collected and added to vertical farming units for the supply of the gas to the crops, this is a closed and more sustainable system. The source of carbon dioxide supplied means that the carbon used in the vertical farm is prevented from release to the atmosphere by being fixed by the growth of crops. It should be noted that many sources of CO_2 such as flue gases or biogas from an AD system will need to be cleaned of contaminants such that a relatively pure stream of CO_2 is introduced into the growing environment.

If vertical farming technology is adopted instead of a fully conventional open farming system, less land for agriculture is needed so historical farmland can be transitioned to other more sustainable land use types. Previous farmland can be left to develop as carbon sinks by being returned to its natural state such as former bog lands, with wetland restoration significantly underway in 5 to 10 years[130]. The carbon farm calculator[10] quantifies that around 12 tons of carbon dioxide equivalent is emitted per hectare from a land use change from wetlands to arable farmland[131]. Approximately one third of the global soil carbon pool 455Pg is stored in Boreal and sub artic peatlands, annually they have sequestered 0.076Pg of atmospheric carbon. Reversing the transition of peat bogs to farmland would encourage annual carbon dioxide emissions to the atmosphere to be sequestered when former ecological services are restored.

Vertical farms are suited to the circular economy as water and nutrients are recirculated and reused. If aquaculture is integrated, then the Resource Use Efficiency (RUE) would be further improved and provide an additional income stream of fresh fish. Integrated aquaponic systems could be supplied with fish food derived from insect proteins produced from the digestion of organic bio waste streams[127], if native salmonoid type fish could be grown then this would also alleviate the pressures on natural fish stock associated with the current aquaculture technology used for salmon or trout farming.

[10] *https://calculator.farmcarbontoolkit.org.uk/*

3.4 The integrated vertical farming and aquaponics unit

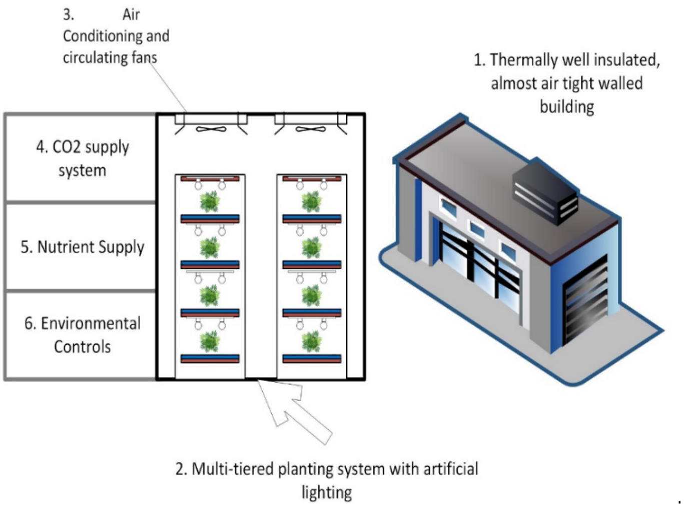

Figure 3.3 Schematic of Vertical Farming/Closed Plant Production System

Figure 3.3 is a schematic diagram of a vertical farm outlining the required main sub components[132].

Vertical farms are also known as; Plant Factories with Artificial Light (PFAL), Closed Plant Production Systems (CPPS) and typically consist of 6 separate interlinked subsystems[132]:

1. A well-insulated air-tight opaque building (minimises heating costs, conditions easily controllable and existing buildings can be retrofitted).
2. A multi-level hydroponic system increases the area available for plant growth with each layer equipped with artificial lighting such as fluorescents or LEDs.
3. Air conditioning and circulating fans for space cooling and air circulation.
4. A CO_2 supply system (improves plant growth assimilates carbon).
5. A supply of nutrients (potentially derived from AD digestates or aquaponics).
6. Environmental Controls- Control of lighting, supply of heat.

The integration of vertical farming with aquaponics will require the integration of a separate seventh subsystem. A considerable amount of research on these has been previously carried out in Asia where vertical farming was developed due to pressures from urbanization, high population densities and land costs[133]. These CPPS have been demonstrated to have a productivity 100 to 516 times greater than conventional open field agriculture. Whilst they are more resource efficient, they are much more resource intensive[133],[134].

The capital (CAPEX) and operating costs (OPEX) of vertical farms or CPPS are considerably higher than greenhouses with a Japanese study finding the initial cost in 2014 to be 15 times greater than greenhouses for growing lettuce, with costs estimated at $4000/ m^2 [133]. A Danish study (2020) using the same method but for the production of basil estimated that with 50% of the CAPEX met using a loan taken out over 10 years, assuming an interest rate of 6.5%, a payback period of 4 years that an Internal Rate of Return (IRR) of 34.7% was achievable[135].

3.5 Techno-economics of vertical farming for NI

3.5.1 Vertical Farm and modelling assumptions

Applying the methods of previous investigations to the NI context enables a cost estimation for deploying vertical farming in NI to be made and the hurdle rate to be determined. Any assumed costs were adjusted for inflation to 2022 values with a € equal to £0.871. This was carried out for six economic scenarios by varying the immediate capital cost of installing a vertical farm by assuming that financing is available, and three vertical farm configurations (Normal, CO_2 enhanced, CO_2 and O_2 enhanced) were considered. The energy requirements for a vertical farm located in NI were calculated using TRNSYS 18 software[11] using the optimal values for plant growth in vertical farms reported by [133] and are reproduced in the appendices.

The quantity of carbon that could be sequestered by growing basil in a vertical farm and avoided by reducing food miles was compared to other biogenic methods of carbon storage such as industrial hemp production by adapting previous methodologies reported by [135], [3] and [133]. The modifications used for calculating the economics of vertical farming in NI by this report were:

1. Costs from the original study were converted to the value of pounds in 2022 sterling from Euros at a rate of £1=€0.871.
2. Building heating and cooling loads were estimated using TRNSYS computer simulation software at hourly time steps taking into consideration any solar gains during daylight hour across the day over a typical metrological year. This software also allows the scheduling of lighting with controls to maintain the set point temperatures for heating and cooling.
3. A source of CO_2 was available on site from a CHP system or nearby industrial plant to enrich the atmospheric concentration in the VF to the optimal levels (1000 to 1300 ppm) reported from previous studies to increase yields by 37% and reduce potential emissions. The impact of this was integrated into the economic Life Cycle Costing to determine its effects.
4. Pure oxygen was available on site to super oxygenate the roots using O_2 from an electrolyser producing green hydrogen which is usually vented. Previous work has found this doubled the harvest[10] so these enhanced yields were compared to the normal value expected from commercial greenhouse crops.
5. Land was purchased not rented with local agricultural land costs obtained from NI agricultural publications[136].
6. The Labour costs used were the UK national minimum wage currently, £9.50/hr[12].
7. Local metrological conditions were used to determine the energy requirements as the climate in NI is subject to a northern maritime not continental climate with reduced temperature variation[13].
8. Cooling energy was supplied using a closed water circulation loop using nearby ground or a simple coiling coil as a heat sink rather than using air conditioning supplied from machinery using vapour compression cycles.
9. The cost of electricity supplied from onshore wind was £0.06/kWh.
10. The crop grown was basil with an assumed cost of 6.36kg with a yield of 75kg/m^2 with 10 harvests annually[137] for a standard vertical farm.
11. Nutrients were supplied via aquaponics with the fish food derived from insect protein generated by black soldier flies fed on waste biomass which was enriched with waste processed by algae to improve the Omega 3 content. It was assumed that the waste stream was waste generated onsite from other agricultural activities.

Costs for land[136], labour[12], lighting equipment[14] and environmental controls were found for NI. The latest wholesale cost of Basil £6.36/kg[15] was used to calculate the likely annual income from produce. Locally produced, high value, normally imported crops with a rapid growth rate should improve the economic return from vertical farming. Table 3.1 outlines the input parameters used for the computer simulation of the vertical farm grow area which were collected from previously published research on the optimal conditions required for plant growth in a vertical farm[133].

[11] http://www.trnsys.com/
[12] "The National Minimum Wage in 2022 - GOV.UK." https://www.gov.uk/government/publications/the-national-minimum-wage-in-2022 (accessed Jul. 25, 2022).
[13] "Belfast Newforge (County Antrim) UK climate averages - Met Office." https://www.metoffice.gov.uk/research/climate/maps-and-data/uk-climate-averages/gcey2u2yw (accessed Jul. 26, 2022).
[14] "PHLIZON CREE COB2500 450W Full-spectrum LED Grow Light – PHLIZON UK Official." https://www.phlizon.co.uk/products/phlizon-cree-cob2500-full-spectrum-led-grow-light (accessed Jul. 25, 2022).
[15] https://www.tridge.com/ (accessed 26th July 2022)

Parameter/input	Value used	Units
Lighting on	16	(hours)
Lighting off	8	(hours)
Heating on	≤22	(°C)
Cooling on	≥24	(°C)
Energy required for lighting	6029800	kWh
Ventilation rate/ number of air changes per hour	0.01	ACH
Vapour pressure difference	0.85	kPa
Power needed for lighting	1033	kW

Table 3.1 Optimal conditions for plant growth in a vertical farm

In NI the land used for the vertical farm was rural agricultural land is considerably lower cost at £2.47/m² [136] than[135] or [138] which both proposed using urbanised land. In Berlin the current (2022) cost of land is £1566/m² which is 634 times greater than the land costs incurred for a vertical farm installed on typical agricultural land in NI. The proposed building footprint of the vertical farm in NI would be 625m², so land costs in NI would be £1544 for just the building area but the total footprint could be larger and hence costs higher.

The height, width and length of the proposed vertical farm was adjusted to accommodate ten rather than the six grow levels used by the research from Denmark, previously published work has demonstrated that ten tiers are optimal[133]. In addition, an aquaponics, germination, environmental controls, and a water storage tank were included which weren't included by this study. The cost of the aquaponics, germination, environmental controls and processing section was derived from the investigation on the economics of vertical farming carried out in Berlin, Germany[3] likely costs were scaled and a per unit area value determined in £/m², as this study used a building with a footprint of 0.25 hectares (2500m²) and 37 levels. Figure 3.4 shows a schematic of the six different zones, Nutrient solution/water, environmental controls, grow space, germination area, processing level and aquaponics level.

Zone	Building	Level
Nutrients/Water		13
Grow area		12
Grow area		11
Grow area		10
Grow area		9
Grow area		8
Grow area		7
Grow area		6
Grow area		5
Grow area		4
Grow area		3
Environmental control/germination		2
Processing level		1
Aquaponics		0

Figure 3.4 Schematic showing zones of proposed NI vertical farm

The level used for germination was combined with the environmental controls of the building and each assumed to occupy 50% on the internal space of that level. The area used from growing crops for harvest assuming ten grow levels was equivalent to a floor area of 6250m^2 with the grow beds occupying 5162.5m^2 of this assuming that 82.6 % of the floor area available was used as crop growth area. The same assumption was applied to the growth area available for the germination zone giving a grow area of 258.1m^2. The zone used for aquaponics was located at the lowest level to enable returned water cleaned by the plants to be transported by gravity, before being returned to the grow zone by pumping water from the aquaponics section to a water tank located on the uppermost floor. The space requirements for each activity in the vertical farm are shown in Table 3.2 and operational parameters in Table 3.3.

Zone	Height (m)	Levels	Area (m^2)
Nutrients/water	1	1	625
Grow area	12.5	10	6250
Environmental controls/germination	1.25	1	625
Processing level	2	1	625
Aquaponics	1	1	625
Total	17.75	14	8750

Table 3.2 Zones for NI vertical farm

Parameter	Value	Units
Land Costs	2.47	(£/m^2)
Width of building	25	(m)
Length of building	25	(m)
Height of building	17.75	(m)
Building foot print	625	m^2
Grow space %	0.826	%
Growth-area per level	516.25	(m^2)
Grow levels	10	n
Growth size total	5162.5	(m^2)
Lighting/grow unit area	0.2	kW/m^2
Total lighting capacity	1033	kW/m^2
Annual electricity consumption for lights	6029800	kWh/year
Annual ventilation requirements	1085	kWh/year

Table 3.3 Vertical farm parameters/assumptions

Different levels of capital investment; 100%, 90%, 75%, 50%,25%, 10% and 0% were considered and then each of these scenarios considered the influence of the time value of money using a discount rate of 8.8% to determine the Net Present Value (NPV) of the project, the Payback Period (PP), cost/benefit ratio and the Return on Investment (ROI) to determine if and how profitable such an investment would potentially be, and additionally what configuration of capital and technology would provide the greatest economic return to the farmer and the amount of CO_2 that could be sequestered annually from the predicted crop growth. Each vertical farming scenario that required external investment, assumed a discount rate of 8.8% with the loan repaid over 10 years. The NPV of the capital costs, the OPEX the annual profits, the carbon sequestered and the carbon savings resulting from selling a locally produced basil crop were then calculated for each configuration. Table 3.4 and Table 3.5 respectively show the CAPEX and OPEX values used for these calculations.

Proposed system for NI	Levels	Floor area (m^2)	Height (m)	Volume	Cost (£)
Grow Area for crops	10	6250	12.5	78125	6,300,000
Area for Aquaponics	1	625	1	625	630,000
Germination/ Environmental floor	1	625	1.25	781.25	630,000
Processing area	1	625	2	1250	630,000
Water/nutrients area	1	625	1	625	630,000
Equipment	14	8750	17.75	81406.25	41,702
Land					1,556
Total Capex					8,863,258

Table 3.4 Calculated CAPEX for VF building in NI

OPEX	Cost (£)
Electricity	375,355
Water	0
Nutrients	0
Seeds	4,000
Labour	99,750
Total	479,105

Table 3.5 Calculated OPEX for VF in NI

3.5.2 Fish

The German study[3] assumed that Tilapia (Oreochromis niloticus) were produced from the aquaponics zone with a feed in/feed out (FIFO) efficiency of 1.5 to 2 depending on the quality of the fish food and the environmental conditions under which they are reared. This ratio does not consider the nutrient content of the feed supplied to the fish.

The production of Atlantic Salmon via aquaculture has been previously successfully carried out, with a Norwegian study[139] which alternatively, used a marine nutrient dependency ratio reporting that 0.7kg of marine protein was able to produce 1kg of Salmon protein. The FIFO value of Salmon production is greater ranging from 2 to 8.5. Further research from Norway has also suggested that production of salmon is one the most efficient aquacultural systems currently in use [140], [141]. Additionally, Salmon fillets have a current UK value of £18.25/kg fillet[16] compared to Tilapia at £9.50/kg and most salmonoid type fish either Salmon, seatrout or rainbow trout can be reared on a mixture of black fly soldier larvae protein mixed with the residues from algal processing of wastes[128] without impacting on the quality of the fish produced[17]. Assuming that the vertical farm uses fish feed derived from wastes generated on site which usually have a disposal cost means that the cost of the fish food used could be assumed as zero. Typically, 65% of a salmon's body mass is considered to be edible as fillets for human consumption[139] in comparison the value for Tilapia is 40.2%. Some 90% of the trimmings of Salmon can also be used as an economic product, and even inedible offal which can be used as pet food has a value of £2.15/kg so in total each kg of salmon has an economic value of £12.61. Salmon are also native to NI with wild stocks under considerable pressure from conventional aquacultural techniques used in their production. Salmon are more valuable and also more likely to be more acceptable to local consumers. Using a conservative assumption that the same mass of Salmon could be reared per unit area as the tilapia in the German study, then the proposed vertical farm would provide 28.4 tonnes of salmon annually with an economic value of £358,334.

[16] *"RPI: Ave price - Salmon fillets, per Kg - Office for National Statistics." https://www.ons.gov.uk/economy/inflationandpriceindices/timeseries/zptx/mm23 (accessed Sep. 28, 2022).*
[17] *This investigation is theoretical and is assuming that these feeds can be entirely produced from the waste products generated on site. These could be replaced with worms which again use waste products to feed, grow and reproduce.*

3.5.3 Crops and CO_2 Fixation

Different crops are more suitable for growing in vertical farms than others, the annual mass of CO_2 equivalent fixed in tonnes are shown in Table 3.6 though it must be noted that vertical farms have a productivity of at least 15 times greater than greenhouses [28]. Assuming this translates to sequestration increasing by 15 times for vertical farming, the estimated values are shown in Table 3.7.

The research on vertical farming by Kozai[132] has estimated that the mean resource use efficiency in vertical farms supplied with enriched CO_2 is 0.88 compared to 0.5 for a greenhouse with closed ventilation and enriched CO_2.

Greenhouse Crops	Annual CO_2 equivalent fixed tonnes per hectare	Citation
Tomato	31.9	[142]
Peppers	22.02	[142]
Watermelon	5.87	[142]
Melon	7.34	[142]
Lettuce (Cogollo)	24.96	[142]
Lettuce (Romaine)	25.33	[142]
Basil	18.1	[28]

Table 3.6 CO_2 sequestration by greenhouse crops

From Table 3.6 basil was chosen as the crop to be produced, as it has a rapid growth rate, low final harvesting height and has the highest wholesale cost of each of the crops detailed in table 3.6 at £6.36/kg [43].

Vertical farm Crops	Annual CO_2 equivalent fixed tonnes per hectare	Annual CO_2 equivalent fixed kg/m^2
Tomato	478.5	47.85
Peppers	330.3	33.03
Watermelon	88.05	8.80
Melon	110.1	11.01
Lettuce (Cogollo)	374.4	37.44
Lettuce (Romaine)	379.95	37.99
Basil	271.5	27.15

Table 3.7 Estimated maximum CO_2 sequestration rate from vertical farms

Using the figures from the study on basil growth in vertical farms in Denmark an annual yield of 50kg/m^2 was estimated under standard conditions, in total this vertical farm with an active growth Area of 5162.5m^2 would produce 258.1 tonnes of basil annually. From Table 3.7, growing basil in the assumed vertical farm could potentially sequester 140.2 tonnes CO_2/yr under normal operating conditions, with CO_2 enrichment and O_2 enrichment this value should increase further.

With the addition of CO_2 enrichment, yield would be increased to 68.5kg/m^2 (353.6 tonnes per annum) and sequester 192 tonnes per annum. Saturating the nutrient solution with green oxygen would double this to 137kg/m^2 (707.3 tonnes per annum) sequestering 384 tonnes[10, 11, 143, 144]. The value of produce from both vegetable (£1,641,516) and fish (£358,334) production annually for a standard vertical farm would be £1,999,850. Assuming a 20-year life span the total income would amount to £39,997,000.

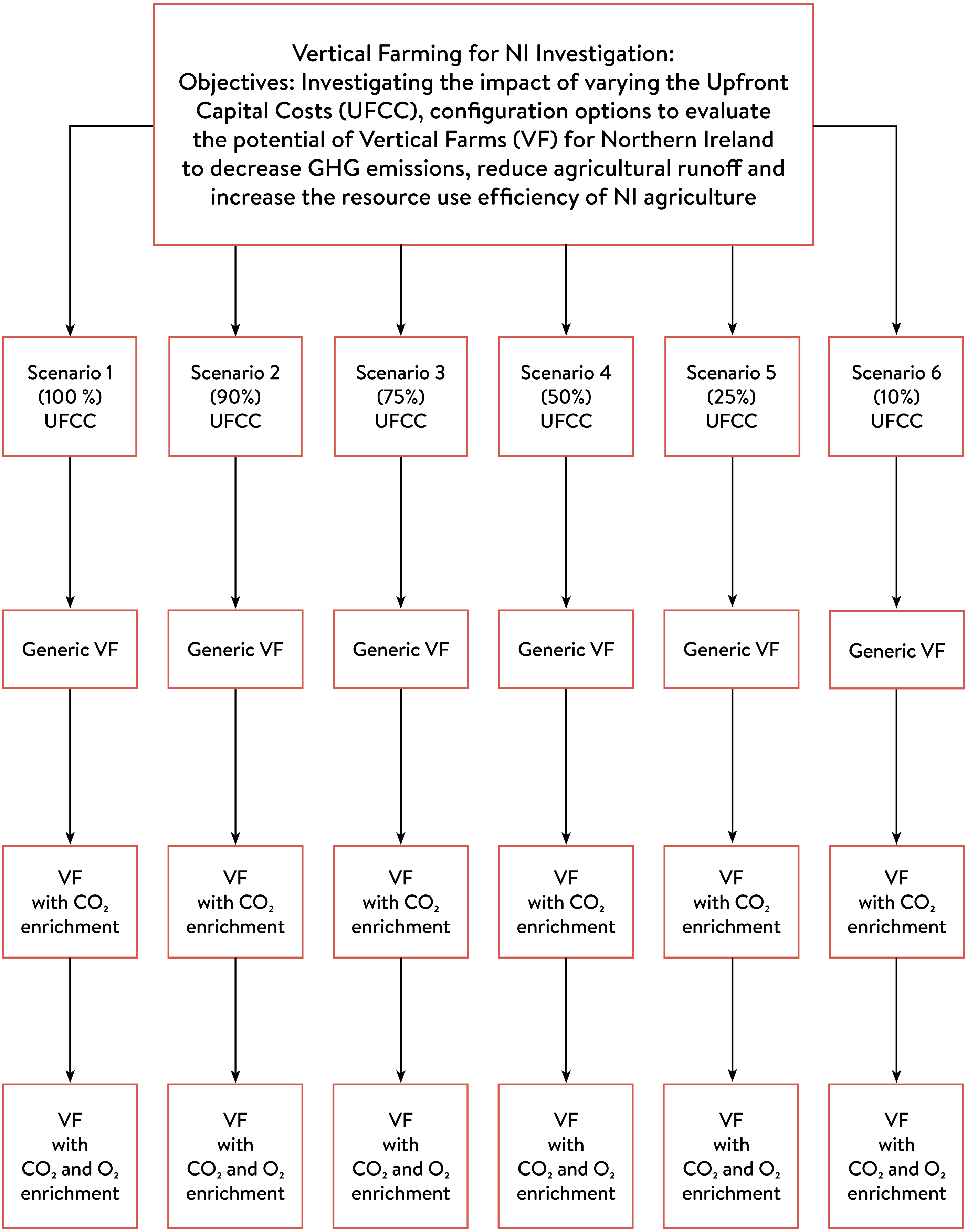

Figure 3.5 High level Outline of Scenarios investigated

3.5.4 Modelling approach

The Net Present Value (NPV) of investing in a vertical farm for deployment in NI using the data shown in the above tables was estimated for six different economic scenarios as shown in Figure 3.5 (100%, 90%, 75%, 50%, 25% and 10% of Up Front Capital Cost (UFCC)), to simulate the potential impact of capital investments being made available to help finance individuals intending to construct VFs in NI and three different operational situations (Normal, CO_2 enriched, O_2 and CO_2 enriched). A discount rate of 8.8% was applied to estimate the Net Present Value (NPV) of cash flows.

Firstly, a base case of “normal” operation was established using previously published data on vertical farms and local (NI) conditions. Then the impact of enriching the atmospheric concentration of CO_2 within the VF was considered assuming that annual yields increased by 37% as reported by previous research, next supplying pure oxygen to the roots was simulated assuming that yields doubled. The production of fish was assumed to be constant. The Life Cycle Costing (LCC) was calculated for the derived operational scenarios using the CAPEX and OPEX costs shown, in Table 3.4 and Table 3.5.

3.5.5 Life cycle costing results

Using the values in describing a vertical farm installed in NI the following economic parameters where determined; the NPV of investment, The Return On Investment (ROI), , the benefit-cost ratio (BCR) and the Payback Period (PP) in years of the initial investment, for each scenario described by Figure 3.5 were calculated using equations 2 to 4. The calculated data are shown in Figure 3.6 to Figure 3.9.

$$NPV = \sum_t^n \frac{R_t}{(1+i)^t} \qquad [2]$$

Where R_t was the net cash inflow minus the outflow over the operational period of the vertical farm, i the discount rate and t the life time (20 years).

$$ROI = \frac{(NPV\ of\ benefits - NPV\_UFCC)}{NPV\_UFCC} \qquad [3]$$

$$BCR = \frac{PV\ of\ Expected\ \ economic\ benefits}{PV\ of\ Total\ project\ cost} \qquad [4]$$

$$PP = \frac{Capital\ cost}{Average\ Annual\ Profits - OPEX} \qquad [5]$$

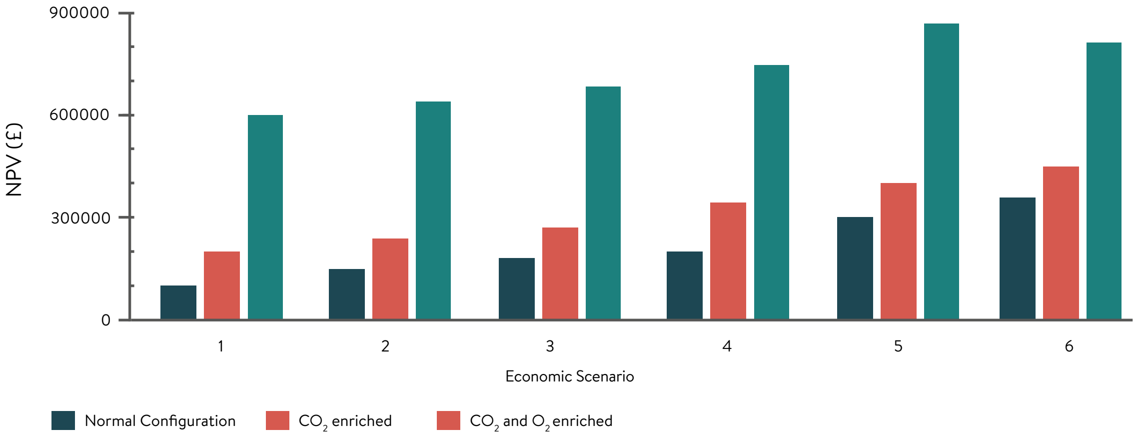

Figure 3.6 NPV of investment for each economic scenario in vertical farm for NI

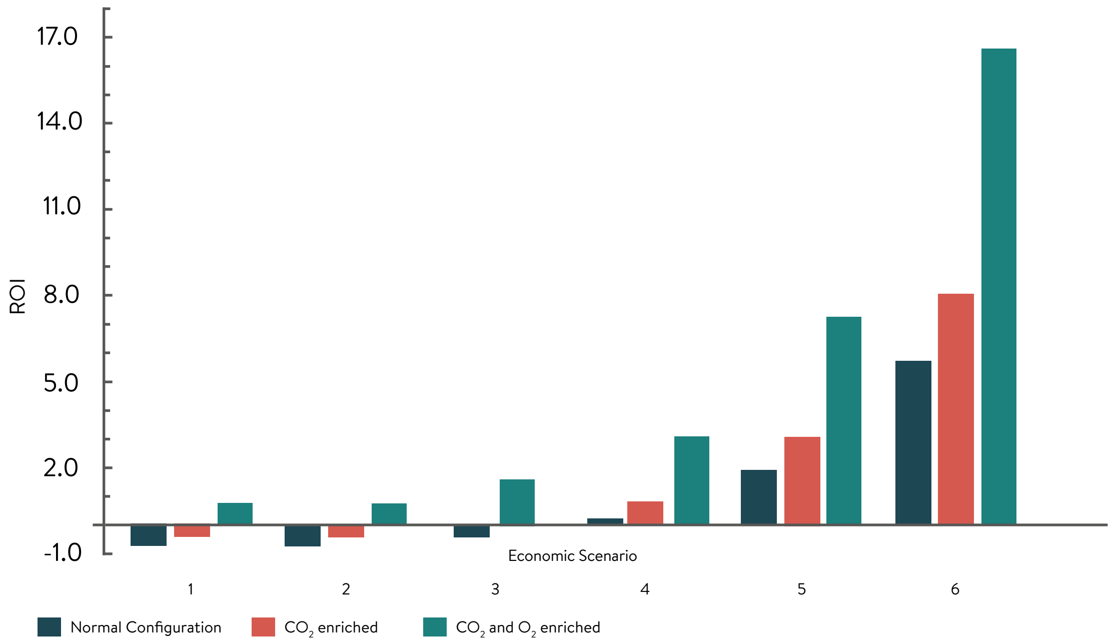

Figure 3.7 ROI for vertical farming economic and technical configurations investigated

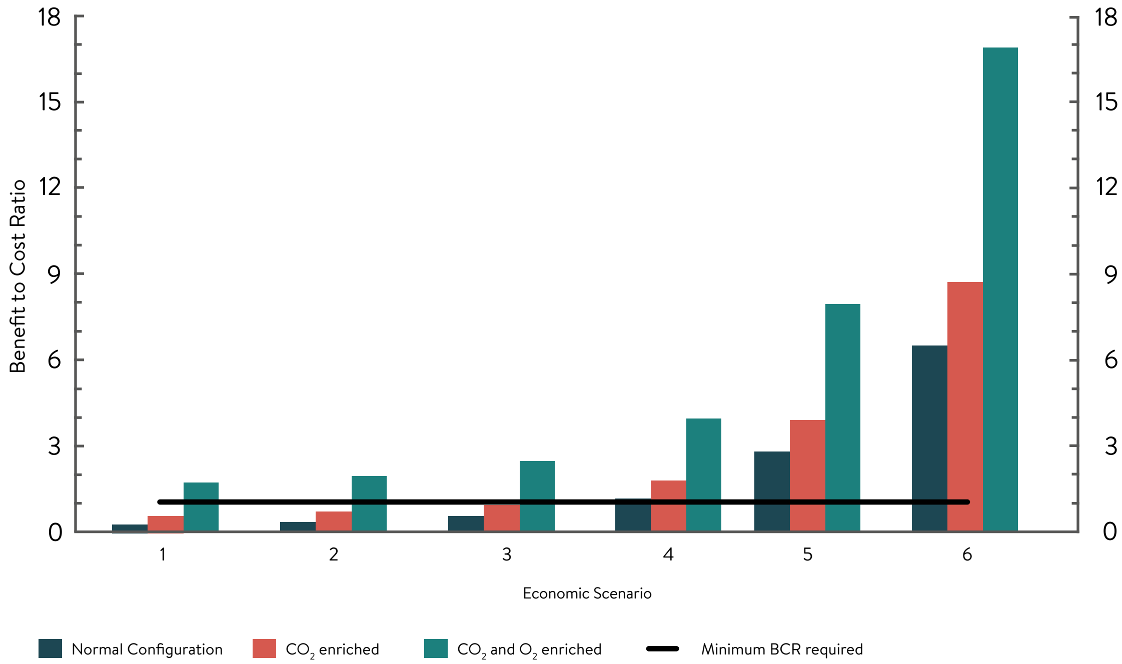

Figure 3.8 Benefit cost ratio for vertical farm scenarios

When the benefit to cost ratio exceeds 1 then the project can be considered as economically cost effective, the line representing this value is shown in Figure 3.8 to easily identify which scenario and configurations are worthwhile.

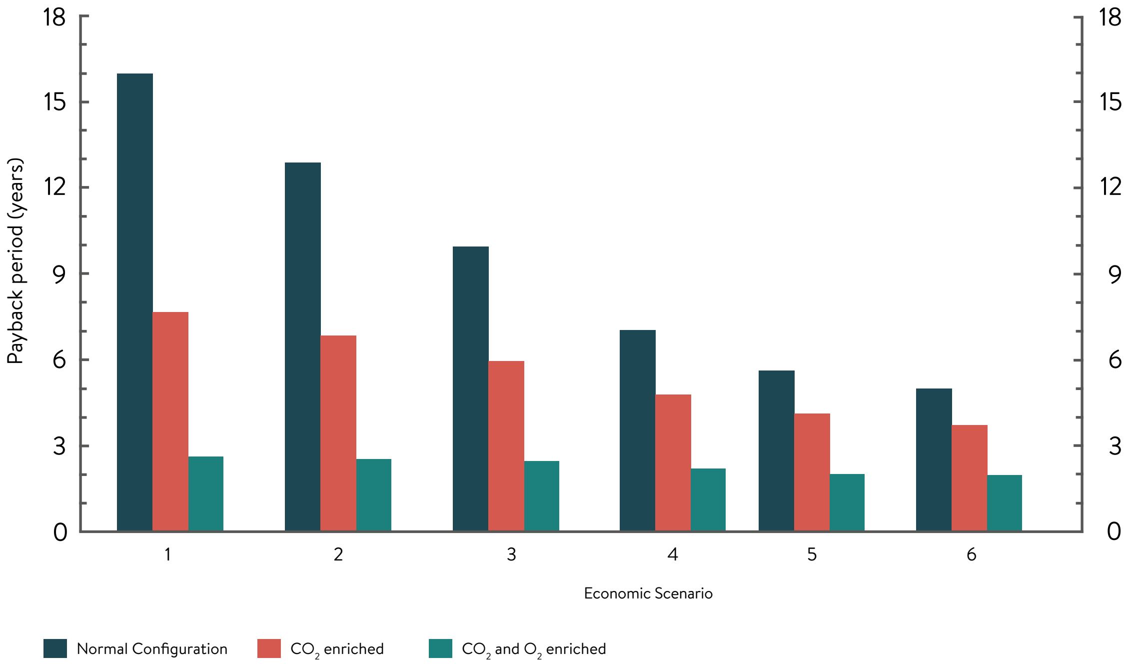

Figure 3.9 Payback periods for vertical farm scenarios

All scenarios have a positive NPV, but the other economic parameters must be considered, Figure 3.8 shows which scenarios and configurations are cost effective options. Figure 3.9 shows that if a payback period of under 5 years is required then the configuration using both CO_2 and O_2 enrichment achieves this for all economic scenarios, using CO_2 enrichment alone requires a loan of 50% or less of the upfront capital to achieve this. The normal configuration only meets this criterion for economic scenario 6.

The results show that the main barrier to the uptake of vertical farming technology in NI is the availability of capital for the initial investment and the amount that has to be secured via a commercial loan which can be repaid from the resulting annual profits of the vertical farm. Enriching both CO_2 and O_2 increases the economic impact considerably as well as removing CO_2 from a local source. The addition of green oxygen, a by-product of green hydrogen production, will increase annual yields. Additionally, it will reduce the cost of producing green hydrogen and potentially provide a market for green oxygen for locations with electrolysers but no vertical farming unit.

3.5.6 Carbon sequestration and savings

Using the value of carbon sequestration by basil shown in Table 3.7 the vertical farm described in this report could potentially sequester at 142.2 tonnes per hectare without CO_2 or Oxygen enrichment. Food that is imported rather than produced domestically results in CO_2 emissions from transportation using refrigerated or chilled containers and are known as food miles. Globally the majority of Basil (36.3%) is produced in China and India [49]. Switching to locally sourced production would reduce the food miles and hence the CO_2 associated with packaging, shipping, and storage. Examples of typical CO_2 emissions per tonne of crops are shown in Table 3.8 below.

Food	kg $C0_2$ per kg produce
Apples	0.3
Potatoes And Root Vegetables	0.3
Onions	0.5
Garlic	0.5
Lettuce	0.6
Broccoli	0.7
Squash	0.7
Cauliflower	0.9
Kale	0.9
Asparagus	1.1
Spinach	1.2
Cucumber	1.3
Tomatoes	1.3
Strawberries	1.7
Herbs	2.1
Nuts And Seeds	2.3
Mushrooms	4.1

Table 3.8 Greenhouse gas emissions from farming practices, the agricultural machinery required to harvest crops, methane burps, transport to shops and other requirements for fuel, processing, and packaging.

3.5.7 Analysis

The vertical farm modelled for this report has an active growing area of 6250m^2 and would always have a higher rate of CO_2 fixation than open field agriculture or greenhouse production and was estimated to sequester 140.2 tonnes annually, 192.1 tonnes by increasing CO_2 concentrations or 384.1 tonnes enriching both CO_2 and oxygen. Figure 3.10 shows the annual estimated carbon sequestered by each configuration investigated.

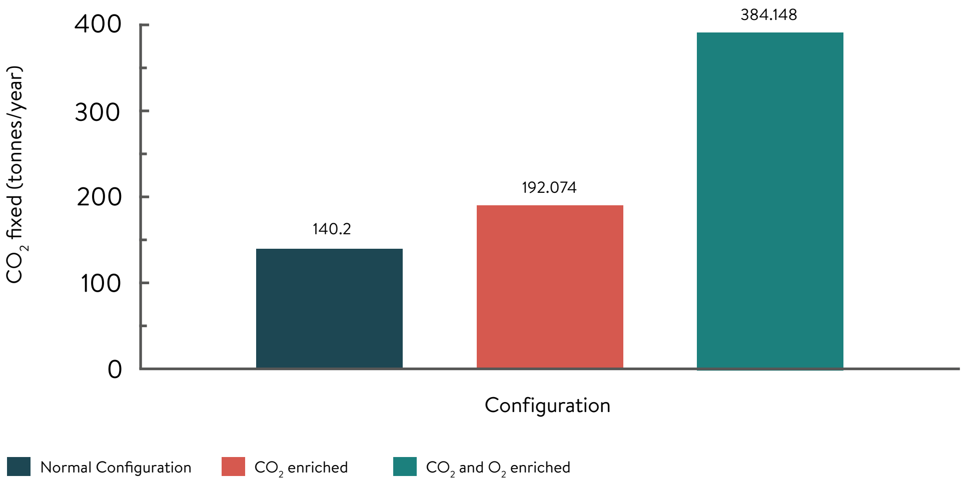

Figure 3.10 Estimated annual CO_2 sequestration

The electricity required by the vertical farm if supplied by wind results in the production of 4.1 tonnes of CO_2 annually or 0.656kg/m^2. The emissions associated with the production process were assumed to be the same as those presented in Table 3.8. The overall carbon balance was determined by subtracting likely emissions from the sequestration values shown in Figure 3.11.

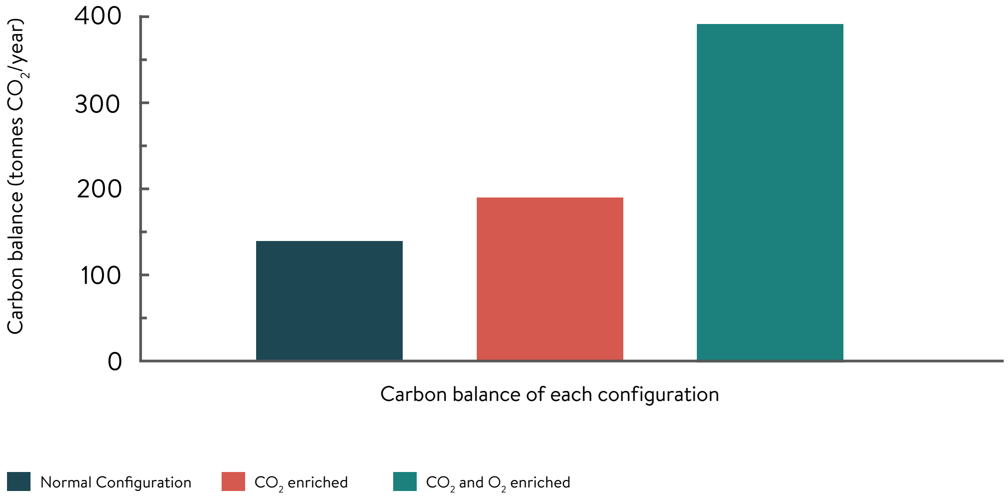

Figure 3.11 Overall Carbon balance for each configuration of vertical farm

From Figure 3.11 the vertical farm described in this report with O_2 and CO_2 enrichment will remove a maximum of 383 tonnes CO_2 per annum[145]. Figure 3.11 clearly shows that vertical farming provides significant biogenic carbon sequestration under the conditions used for this report due to its increased productivity, higher efficiency of photosynthesis and its carbon use efficiency. The values shown in Figure 3.11 are determined per unit area and shown in Table 3.9.

Vertical farm configuration	Normal Configuration	CO_2 enriched	CO_2 and O_2 enriched
Carbon balance of each configuration tonnes/m^2	0.22	0.31	0.61
Carbon balance of each configuration tonnes/hectare	2234	3061	6123

Table 3.9 Carbon savings from vertical farming

The model is for a crop for human consumption so while substantial amounts of CO_2 could be taken up by the plants, most would be eventually reemitted through biological processes. Different crops whose fruit is consumed that have a large residual biomass such as tomatoes or crops grown just for sequestering carbon could be processed to give end products which sequester carbon long-term (e.g., composite materials for construction, biochar). Such crops would have a greater benefit beyond the carbon savings from avoided importation.

3.6 Vertical Farming for Carbon Sequestration: Conclusions and Recommendations

This desk-based study has shown that biogenic carbon capture and storage using vertical farming has a potential role to play in reducing the net carbon emissions from NI. This is by:

- Direct sequestration through the enhanced crop productivity in a vertical farm.
- Reduction in imported food – vertical farms can grow many crops currently imported from overseas and hence greatly reduce food miles and carbon footprint.
- Freeing up farmland for use to grow energy crops or afforestation – both offer routes to long-term carbon sequestration.

The other benefits to a vertical farming industry in NI include, new jobs, greater food security and an increase in the size and profitability of the agri-food sector. Vertical farming integrated with aquaponics is also economically viable and potentially vertical farming could be used for non-traditional greenhouse crops for non-food uses such as medicinal products or fibre production for construction and manufacturing industries.

The economic viability of vertical farming is dependent on an economically priced supply of electricity. The business model is not dependent on ultra-cheap curtailed wind/solar power but would benefit from using lower cost night-time electricity. It is worth emphasizing that vertical farms could be integrated into a grid-balancing scheme as crops are tolerant of short-term fluctuations in light levels. This could be an additional source of income.

Vertical farms are attractive as part of a wider, circular economy approach. They could, for example, be integrated with an AD based biorefinery system as modelled in section 2.6 of this report. A proportion of the CO_2 from the AD plant could be utilised to enhance the vertical farm atmosphere and oxygen from the electrolyser directly used to super oxygenate the water as part of the hydroponics. Nutrients from the waste liquid digestate from AD have potential use for plant growth as does waste heat from the electrolyser which may be beneficial for crops best grown in higher temperatures. Similar schemes could be conceived for other sources of CO_2 such as cement works, furnaces, or large biomass boilers.

Recommendations:

1) A pilot scale investigation to confirm the modelling in this report and verify the business models including their economic viability determined in this study. There is very limited data on sequestration potential of vertical farming when integrated with a circular economy approach. The assumptions used in the model for this report need to be tested, particularly around the increases in yields due to the combination of CO_2 and Oxygen enrichment. Experimental verification of the amount of carbon that can be sequestered from different crops would then give confidence to a commercial scale trial.

2) Work with retailers in NI to determine the most viable crops and the food miles/carbon saved by growing locally. This work did not investigate the true economics of vertical farming integrated into the food retail sector of NI or the actual carbon savings from a reduction in imports. An investigation and consultation exercise are necessary to properly assess the opportunity and optimum crops for the NI and wider Irish market.

3) The potential for growing crops such as hemp in a vertical farm where CO_2 can be turned into durable products to sequester carbon for the long-term. Crops currently grown in vertical farms are for consumption and have no significant role in carbon sequestration. There is potential to look at the use of dual-purpose crops, such as tomatoes where the fruit is consumed and the plant potentially used for energy generation and/or biochar production, as well as plants solely grown for use in non-food products such as composites or building products. Such crops offer may offer a better route to longer-term carbon sequestration.

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5 APPENDICES

5.1 Resource Use Efficiency

RUE is calculated as follows[133]

Water Use Efficiency (WUE) is calculated using equations 1 and 2.

$$WUE = \frac{(W_c - W_p)}{W_s} = \frac{(W_s - W_L)}{W_s} \quad [1]$$

$$W_L = N \times V_A \times (X_{in} - X_{out}) \quad [2]$$

Where W_c was the mass of water (kg), W_p the change in the mass of water within the plants and substrate, W_s the mass of water supplied to the CPPS and W_L the mass of water vapour lost to the exterior via air infiltration. In equation 2 N is the number of air changes per hour in the growing room (h-1), V_A the volume of air (m^3) and X_{in} and X_{out} the mass of water vapour contained within the air inside and outside respectively of the grow room. Assuming that CO_2 is supplied to the plants, the CO_2 Use Efficiency (CUE) is calculated using equations 3 and 4.

$$CUE = \frac{C_p}{(C_s + C_R)} = (C_s - C_L)/(C_R + C_s) \quad [3]$$

$$C_L = k_c \times N \times V_A \times (C_{in} - C_{out}) \quad [4]$$

Where C_p is the net photosynthetic rate; C_S the supply rate of CO_2; C_R the respiration rate of culture room workers (0.05kg/hr/person); C_L the rate of CO_2 loss from air infiltration. In equation 4, k_c converts the volume of CO_2 to mass (1.8kg/m^3 @ 25°C). C_{in} and C_{out} are the internal and external concentration of CO_2 (mol mol^{-1}) respectively. Equations 2 and 4 assume X_{in} and C_{in} at time t are equal to those at time (t +δ) where δ was the time interval. Otherwise (X_{in} (t)-X_{in} (t+ δ) V_A)/δt and (C_{in}(t)-C_{in}(t+δ) V_A) are added respectively to equations 2 and 4. For situations where X_{out} and C_{in} vary with time the mean value should be used.

The Light Energy Use Efficiency of lamps and the plant community (LUEL and LUEP) is calculated using equations 5 and 6.

$$LUE_L = f \times D / PAR_L \quad [5]$$

$$LUE_P = f \times D / PAR_P \quad [6]$$

Where f is a conversion factor, converting dry mass to the chemical energy fixed per unit of dry mass 20 MJ kg^{-1}, D was the increase in dry mass of the plants ($kg/m^2/h$). PAR_L and PAR_p is the photosynthetically active radiation emitted from the lighting system and that incident on the plants leaf's in the CPPS ($MJ/m^2/h$) LUE_L is alternatively defined as $b \times C_p / PAR_L$ and LUE_p as $b \times C_p/PAR_p$ where b represents the minimum PAR energy required to fix one mole of CO_2 in plants (0.475MJmol^{-1}) and C_p is the rate of plant photosynthesis ($mol/m^2/h$). The ratio of PAR_p to PAR_L is also known as the utilization factor of illumination.

The Electric energy use efficiency of lighting (EUE) is calculated from equation 7.

$$EUE_L = h \times LUE_L = h \times f \times \frac{D}{PAR_L} \quad [7]$$

Where h is the conversion coefficient of electrical energy to PAR_L energy, values of 0.25 have been assumed for fluorescent lights[31] , LEDs have been found to have a factor 0.6 [51]. Equation 8 is used to determine the electrical energy used for lighting.

$$A_L = PAR_L/h \quad [8]$$

Equation 9 is used to determine the efficiency of the space conditioning system.

$$COP = {}^{H_h}/_{A_A} \quad [9]$$

Where H_h is the heat transferred to or from the culture room and A_A is the consumption of electrical energy for this ($MJ/m^2/h$).

Inorganic Fertiliser Efficiency usage FUE_I is calculated using equation 10

$$FUE_I = I_U/I_s \quad [10]$$

Where I_U was the absorption rate of the fertiliser and I_s the rate at which fertiliser was supplied 'I' includes nitrogen (NO_3^- or NO_4^+), phosphorous (PO_4^-), potassium (K^+) allowing the use efficiency of each element of the nutrients supplied to be calculated.

5.2 NPV of each economic scenario and configuration

Economic Scenario	Normal Configuration (£)	CO_2 enriched (£)	CO_2 and O_2 enriched (£)
1	101519	213956	630279
2	126863	239301	655623
3	164880	277317	693640
4	228241	340678	757001
5	291602	404039	820362
6	329619	442056	858378

5.3 ROI of each economic scenario and configuration

Economic Scenario	Normal Configuration	CO_2 enriched	CO_2 and O_2 enriched
1	-0.7	-0.4	0.8
2	-0.6	-0.2	1.1
3	-0.4	0.0	1.6
4	0.2	0.9	3.1
5	1.9	3.1	7.3
6	5.8	8.1	16.6

5.4 Benefit Cost ratios

Economic Scenario	Normal Configuration	CO_2 enriched	CO_2 and O_2 enriched
1	0.29	0.61	1.80
2	0.40	0.75	2.07
3	0.62	1.04	2.60
4	1.25	1.86	4.14
5	2.94	4.08	8.28
6	6.75	9.06	17.59

5.5 Payback period of each scenario and configuration

Economic Scenario	Normal Configuration (years)	CO_2 enriched (years)	CO_2 and O_2 enriched (years)
1	16.2	7.7	2.6
2	12.9	6.9	2.5
3	10.0	5.9	2.4
4	7.2	4.8	2.2
5	5.6	4.1	2.0
6	5.0	3.7	1.9

5.6 Organisations consulted during production of this report

A wide range of individual and group consultations were undertaken across NI during the development of this report where decarbonisation was the focus of discussion. The organisations consulted (apart from Thompsons) had no awareness of the concepts of biorefineries and vertical farming as routes to sequester carbon dioxide. Hence, no illuminating comments were received apart from a general interest in the potential of these routes to carbon neutrality as part of a circular economy approach.

Action Renewables

AEL
Agri AD
Alderhill Digital
B9 Solutions
Balcas
Ballycoose Farm
Belfast City Council
Bell Architects
CAFRE
Cambium LLP
Causeway Chamber
Causeway Coast and Glens District Council
Cookstown Cement Ltd
Cooneen Group
Dale Farm
Derry and Strabane District Council
Dunbia
EANI
Electricast
ENCIRC
EPEC
Everrun Ltd.
Farming Carbon
Fermanagh & Omagh District Council
Fermanagh Enterprise
Food, Farming and Countryside Commission
Forged Innovation
GES Group
Glanbia Cheese
Glenarm Castle Estate
Glover Farms
GM Energy Management
Granville Cold Stores
Halls Farms
Hegan Biomass
HG2P
Invest NI
Irish Central Border Area Network (ICBAN)
Keep NI Beautiful
Kerry Group

Keystone

Kilwaughter Minerals Ltd
Lakeland Dairies
LCC/Go Power
LEDCOM
Linden Foods
Mannok Holdings
McCue
Mid and East Antrim Council
Mid Ulster Council
Millicent Pharma
MJM Renewables LTD
Moore Concrete
Moyola Precision Eng
MPANI
Nicobrand
NIE Networks
Norbev
Northern Regional College
Northway Mushrooms Ltd
Powerhouse IRL Ltd
PPL PWR
Recon
RES
RSC Group
Ryobi Aluminium Castings
SGN Gas
SIB
SMAC Coating Suplies
Smart Grid Ireland
Solar Renewables
South West College
Strathroy Diaries
Terex
Terumo BCT
Thompsons
Tobermore
Ulster Farmers Union
Ulster Shredders /Ulster Engineering
Ulster University
W D Meats