climate change

Scotland's centre of expertise connecting climate change research and policy

Understanding Opportunities for Developing a Scottish CO_2 Utilisation Economy

Silvian Baltac, Amelia Mitchell, Enrique-Garcia Calvo Conde
(Element Energy), Richard Platt (E4tech)

November 2021

DOI: http://dx.doi.org/10.7488/era/1683

Executive summary

Context and objectives

Since 2019, Scotland has committed itself to net-zero emissions by 2045, requiring rapid action and technology innovation across all sectors. Carbon Capture, Utilisation and Storage (CCUS) are an important set of technologies to achieve this, with a recent study indicating that by 2050 up to 13 Mt CO_2 may be captured annually from industries across Scotland[1].

CO_2 utilisation is thought to be a complementary technology to CO_2 sequestration. Whilst geological sequestration can permanently store CO_2, CO_2 utilisation can be used to produce conventional products such as carbon containing fuels, chemicals, and polymers without reliance on additional extraction of fossil carbon. CO_2 utilisation is therefore of interest for sustainable manufacturing and the circular use of resources, particularly if biogenic or atmospheric CO_2 is utilised. Although storage of the carbon in products is often non-permanent[2], CO_2 utilisation could offer wider emission reductions as well as economic opportunities through substituting fossil-derived products.

ClimateXChange, on behalf of Scottish Government, commissioned Element Energy and E4tech to investigate opportunities for the development and demonstration of CO_2 utilisation technologies in Scotland. The aim of the study is to:

- highlight potential economic opportunities for Scotland;
- identify specific sectors and sub-sectors where development of utilisation technologies could have an impact; and
- recommend factors which could support the sectors

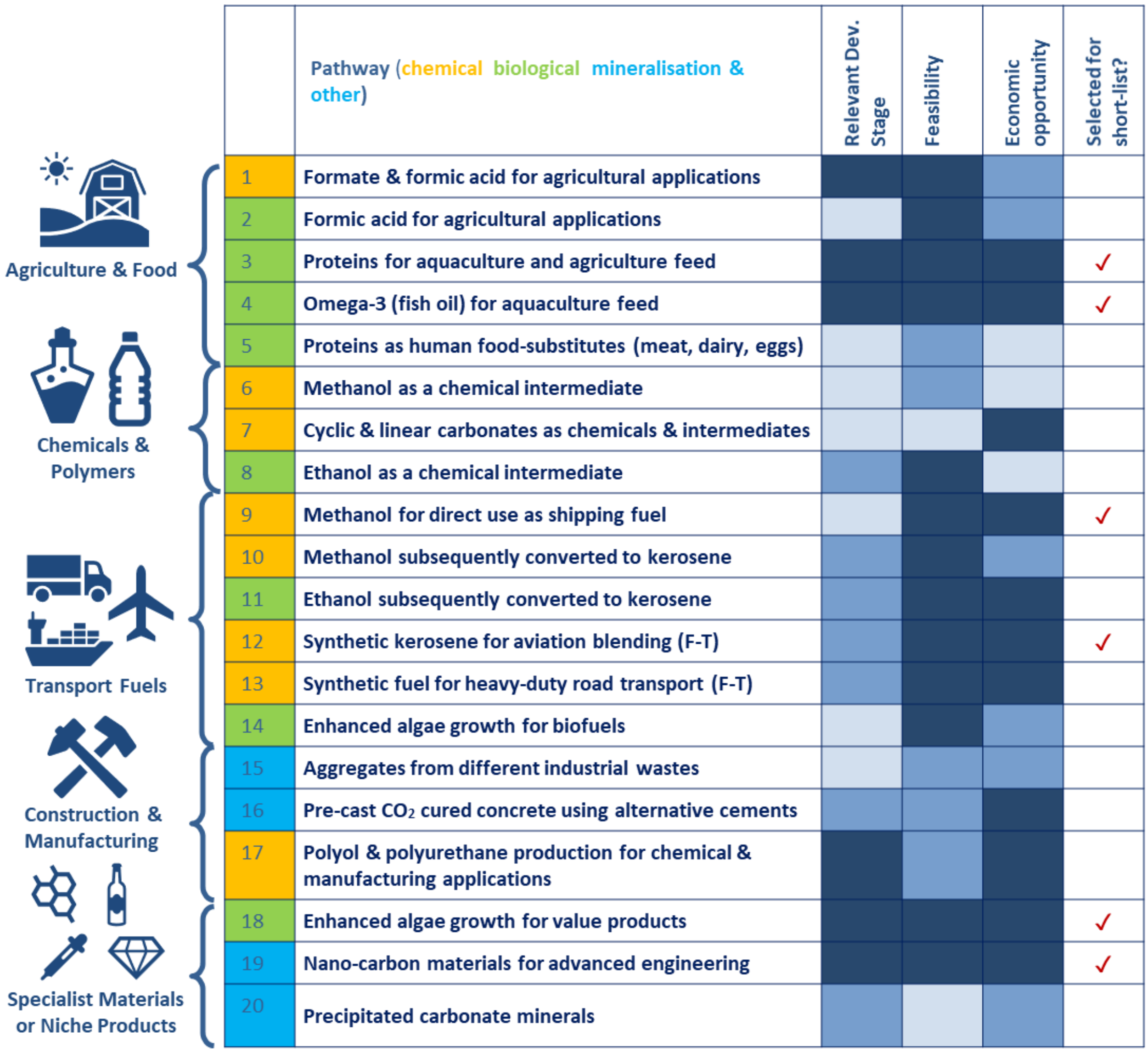
The work focuses on technologies that are ready to be deployed at demonstration scale, and outlines factors that could be considered when evaluating the feasibility and market potential of technology development in Scotland.

---

[1] Element Energy & Vivid Economics 2021, CCUS Economics Impacts Study – 'ambition' scenario

[2] Some pathways such as carbonation to mineral products, such as aggregates or concrete, can offer permanent sequestration of CO_2.

A large number of technology pathways are available for development in Scotland, and we explored these on the basis of: Development stage, Feasibility, and Economic Opportunity. Of all the pathways, six were considered in further detail under the combined groupings of: Gas fermentation and microalgae growth techniques, Synthetic fuels, and Carbon nanomaterials.



	Pathway (chemical biological mineralisation & other)	Relevant Dev. Stage	Feasibility	Economic opportunity	Selected for short-list?
🟨 1	Formate & formic acid for agricultural applications	█	█	▒	
🟩 2	Formic acid for agricultural applications	░	█	▒	
🟩 3	Proteins for aquaculture and agriculture feed	█	█	█	✓
🟩 4	Omega-3 (fish oil) for aquaculture feed	█	█	█	✓
🟩 5	Proteins as human food-substitutes (meat, dairy, eggs)	░	▒	░	
🟨 6	Methanol as a chemical intermediate	░	▒	░	
🟨 7	Cyclic & linear carbonates as chemicals & intermediates	░	░	█	
🟩 8	Ethanol as a chemical intermediate	▒	█	░	
🟨 9	Methanol for direct use as shipping fuel	░	█	█	✓
🟨 10	Methanol subsequently converted to kerosene	▒	█	▒	
🟩 11	Ethanol subsequently converted to kerosene	▒	█	█	
🟨 12	Synthetic kerosene for aviation blending (F-T)	▒	█	█	✓
🟨 13	Synthetic fuel for heavy-duty road transport (F-T)	▒	█	█	
🟩 14	Enhanced algae growth for biofuels	░	█	▒	
🟦 15	Aggregates from different industrial wastes	░	▒	▒	
🟦 16	Pre-cast CO_2 cured concrete using alternative cements	▒	▒	█	
🟨 17	Polyol & polyurethane production for chemical & manufacturing applications	█	▒	█	
🟩 18	Enhanced algae growth for value products	█	█	█	✓
🟦 19	Nano-carbon materials for advanced engineering	█	█	█	✓
🟦 20	Precipitated carbonate minerals	▒	░	▒	

Main findings

<u>Gas fermentation and microalgae growth techniques</u> could build on Scottish expertise and have local product markets in aquaculture.

- Producing proteins from CO_2 gas fermentation and value products from enhanced algae growth presents an opportunity for biotechnology Research and Development (R&D) in Scotland, building on strong Scottish expertise and ambition in this sector.
- These technologies can produce feed ingredients (proteins, carbohydrates, Omega-3) which are in high demand for the Scottish aquaculture sector. Such ingredients are currently imported into Scotland with increasing volatility of security, price and sustainability.
- Market uptake is enabled by local markets and expertise in fish nutrition.

<u>Synthetic fuels</u> could benefit from Scottish renewable electricity and have large European market potential.

- High availability of renewable electricity in Scotland makes it an advantageous location for development of hydrogen-based fuels at competitive costs.
- Existing crude oil refining knowledge and distribution networks enable deployment of Fischer-Tropsch technologies, with possible benefits linked to job retention in the refining sector and continued operation of assets.
- European and UK policy drivers are expected to create distinct markets for synthetic fuels including those derived from CO_2. The ReFuelEU initiative contains a notable proposal for renewable fuels of non-biological origin to account for 5% of aviation fuel by 2035 and 28% by 2050. This represents a large export opportunity.
- Methanol is proposed as one of the main alternative fuels for shipping, and global shipping companies are investing in methanol-powered vessels. The UK ambitions for clean maritime clusters could present an opportunity for e-methanol at Scottish ports for both local and international markets.

Carbon nanomaterials are an emerging opportunity linked to high-value lightweight materials and manufacturing of electrical devices.

- Production of carbon nanomaterials from CO_2 is reported to be cost-competitive and could represent a niche area for development and technology leadership.
- Development of such new and competitive technologies in Scotland could allow early access to this emerging market and would link to Scotland's ambition to increase its expertise in advanced manufacturing.
- Applications may also link to wind turbine and battery development.

Conclusions and recommendations

CO_2 utilisation technologies can offer an economic opportunity for Scottish sectors through their development in Scotland. Development of utilisation technologies from small-scale pilots towards commercialisation in Scotland could provide economic opportunities for a range of Scottish sectors. These range from ongoing knowledge creation via research and design, job retention or creation at new facilities, and both local and export market opportunities.

In the case of proteins and algae growth for feed, CO_2 utilisation offers the chance of local production and reduced reliance on imports, improving security of supply and avoiding price volatility. There are also opportunities to leverage Scottish industrial heritage and existing supply chains, whilst offering significant synergies with the ambition to scale up hydrogen production in Scotland.

Factors to be considered for Scotland to unlock the full potential of CO_2-utilisation:

- Funding will be required to increase the TRL level.
- CO_2 utilisation may benefit dispersed sites or small-scale emitters where capture, transport & sequestration is challenging.
- CO_2 utilisation can offer economic opportunities for emitters of biogenic CO_2 able to easily capture their emissions (e.g. distilleries).
- The relevant scale and investment requirements vary with technology and application.
- Whilst some products can be cost-competitive and feed directly into local supply chains, other products require new policy incentives or development of new applications.
- Close integration of value chains and synergies with existing industries should be considered when locating utilisation projects.

Contents

1 Introduction

1.1 Context

Since 2019, Scotland has committed itself to net-zero emissions by 2045, requiring rapid action and technology innovation across all sectors. Carbon Capture, Utilisation and Storage (CCUS) are an important set of technologies, with numerous applications across the low-carbon energy system. CCUS can help decarbonise power generation and industrial sites, produce low carbon hydrogen, and deliver negative emissions. A recent study for Scottish Enterprise and Scottish Government showed that by 2050 in the 'ambition' scenario up to 13 Mt CO_2 may be captured annually from industries across Scotland, of which 1 Mt could be biogenic, and that additional capture from direct air capture technologies could reach 3 Mt[3]. The Scottish Government's Programme for Government 2020/21 committed to consult stakeholders on the scope, operation and governance of a £5 million Carbon Capture and Utilisation Challenge Fund, now referred to as the CO_2 Utilisation Challenge Fund, which will deliver funding to projects from April 2022 for two years[4].

1.1.1 CO_2 utilisation

CO_2 utilisation refers to the process of using captured CO_2 as a feedstock for production of valuable products. This could be either through direct use, for example in carbonated beverages or fire extinguishers, or via conversion to chemicals, polymers, fuels, or mineral products. Carbon atoms (alongside hydrogen) are a key component of many chemicals, polymers and fuels and this carbon is conventionally derived from fossil sources. CO_2 utilisation can provide an alternative carbon source for production of these essential commodities. It is therefore of interest for sustainable manufacturing and the circular use of resources, particularly if biogenic or atmospheric CO_2 is utilised[5]. CO_2 utilisation is thought to be a complementary technology to CO_2 sequestration. Whilst geological sequestration can permanently store fossil-derived CO_2 or otherwise provide negative emissions, CO_2 utilisation can produce conventional products without reliance on additional extraction of fossil carbon. The need for this is such however that CO_2 utilisation is expected to occur at much smaller scales compared to geological sequestration.

1.1.2 Economic and decarbonisation opportunities

In Scotland, the development of manufacturing capabilities that utilise CO_2 as a feedstock could lead to economic regeneration opportunities, leverage existing skills and supply chains, and support a just transition for heavy industries moving away from fossil-based commodities. For example, CO_2 and hydrogen can be used to produce a synthetic crude product that may be refined into fuels or chemicals (such as ethylene) - both relevant products for the Scottish refining sector. The ambitious roll-out of hydrogen in Scotland could lead to the proliferation of such CO_2 utilisation pathways based on hydrogenation, whilst the availability of biogenic CO_2 from distilleries could open-up opportunities for closed-loop circular economy solutions for local communities. In some cases, CO_2 utilisation may act as a driver for CO_2 capture from sites where geological

---

[3] Element Energy & Vivid Economics 2021, CCUS Economics Impacts Study – 'ambition' scenario includes capture of approximately 3 Mt from industry, 1 Mt for bio-CCS, 2Mt from power, 7 Mt from blue-hydrogen and 3 Mt from direct air capture

[4] Scottish Government 2020, Protecting Scotland, Renewing Scotland (www.gov.scot)

[5] For example, if recently atmospheric CO_2 is utilised to make aviation fuel and then this fuel is combusted, the CO_2 is returned in a closed cycle back to the atmosphere.

sequestration would not be economically viable – for example those in dispersed locations, those with small volumes, or those without economic incentives.

Whilst CO_2 utilisation often does not result in permanent storage of CO_2, it is still of interest for wider emissions reductions. Although utilised CO_2 may be eventually emitted to the atmosphere at the end of the product's life (e.g. fuel combustion), the pathway to producing CO_2 derived products may be less emission intensive than the conventional production pathway. In this way, the substitution of conventional products with products from CO_2 utilisation can act to avoid emissions. In some utilisation pathways, such as those resulting in mineral products (e.g. aggregates or concrete), the CO_2 can also be permanently sequestered. Therefore, these routes could provide more localised, small-scale storage solutions.

1.1.3 Technology development

Many techniques for converting CO_2 to products are novel and have not yet been demonstrated at scale. Moving from small-scale piloting (Technology Readiness Level, TRL 5) to commercial realisation (TRL 9) is a key challenge faced by novel technology developers. It requires capital intensive investment in at-scale demonstration projects combined with high financial risks as the technology is yet to be proven under such conditions. To facilitate the bridging of this technology readiness gap external support is often required, such as grant support within demonstration competitions (e.g. the UK greenhouse gas removal and DACCS competition).

This study focuses on technologies that have been successfully prototyped, and in some cases demonstrated, with the next development step requiring a scaled-up demonstration (typically denoted by TRL 5-7). We then identify potential economic opportunities for Scottish sectors in supporting the development of these technologies.

1.2 Project objectives and scope

ClimateXChange, on behalf of Scottish Government, commissioned Element Energy and E4tech to investigate opportunities for the development and demonstration of CO_2 utilisation technologies in Scotland. The aim of the study was to highlight potential economic opportunities for Scotland and identify specific sectors and sub-sectors where development of utilisation technologies could have an impact. The work focuses on technologies that are ready to be deployed at demonstration scale, and outlines factors that could be considered when evaluating the feasibility and market potential of technology development in Scotland.

The scope of the study was limited to:

- Evaluation only of the **CO_2 utilisation component** of the carbon capture and utilisation (CCU) chain[6]
- Inclusion only of technologies that are **beyond lab research**, having been successfully prototyped, and being at a development stage requiring scaled demonstration.
- Focusing on **economic potential** and sectoral opportunities[7].

Following this introduction, the report is structured into three further chapters following the analysis steps conducted. **Chapter 2** provides an overview of utilisation pathways, covering the following tasks:

---

[6] Meaning that detailed consideration was not given to the potential sources of CO_2 nor the impact on emitters.

[7] Environmental impacts of pathways were not evaluated.

1. Identification and mapping of utilisation technologies based on both literature review and analysis of developer and project databases.
2. Selection of a long-list of 20 pathways for investigation based on initial criteria
3. High-level assessment of feasibility and opportunity for deployment in Scotland, considering feedstock requirements, existing industrial expertise, and market considerations.
4. Selection of a short-list of CO_2 utilisation pathways for detailed investigation.

Chapter 3 deep-dives into each of the short-listed technologies and summarises the outcomes of an assessment into the economic opportunities for Scotland, including details on the investment requirements for reference plants and associated job and GVA impacts.

Chapter 4 presents key findings from the work conducted and further factors that should be considered for demonstrating CO_2 utilisation technologies in Scotland.

In addition to the above tasks, this project collated a list of developers and CO_2 utilisation experts that could inform Scottish Government in the development of utilisation technologies in Scotland.

2 Overview of CO_2 utilisation routes

2.1 Screening of CO_2 conversion pathways

CO_2 utilisation technologies requiring an at-scale demonstration project exist across all types of CO_2 conversion techniques. This study focused on technologies that are beyond lab research, having been successfully prototyped and potentially demonstrated in a small-scale pilot – typically denoted by a TRL of 5-7[8]. At this level of development, the next stage towards commercialisation requires a scaled-up integrated demonstration project with sufficient run-time to provide confidence to investors in the process and realistic data for analysis.

Technology developers are emerging across the spectrum of conversion pathways, with most categories having a UK or European technology developer. The Circular Carbon Network Innovator Index acts as a database of CO_2 utilisation technology developers. The distribution of these developers within the TRL 5-7 range was analysed as part of this study (see Figure 1). This analysis alongside additional literature review revealed that utilisation technology developers in the TRL 5-7 bracket exist across chemical, biological, and mineralisation conversion pathways. More detail on these conversion techniques is provided in Box 1. The routes can be used to produce products such as fuels, chemicals, polymers, proteins/feed, building materials, and specialist advanced materials. Most technology developers for CO_2 utilisation are located either in Europe or North America with these regions covering a broad range of products and conversion techniques. Literature analysis indicates that European research projects have historically been concentrated in Germany and the UK[9].

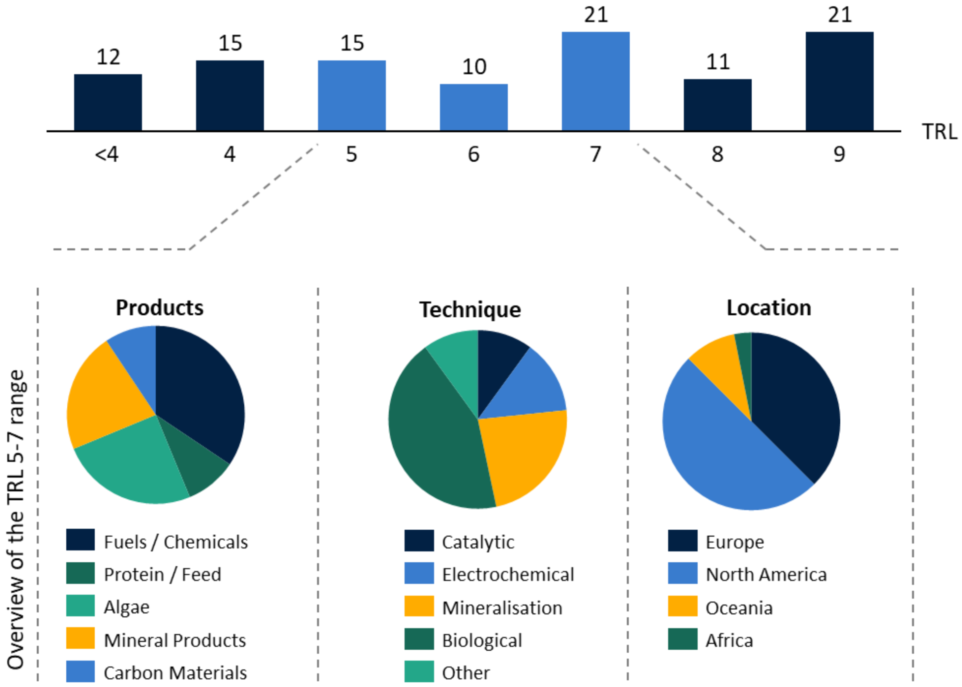


Figure 1: Distribution of CO_2 utilisation developers listed on the circular carbon network innovator index database by technology readiness level (TRL) with a breakdown of product category, CO_2 conversion technique, and location of developer headquarters for developers within the TRL 5-7 bracket (inclusive)[10].

---

[8] A description of technology readiness levels is included in the appendix.

[9] According to IEAGHG analysis of the SCOT Project and other CCU databases presented in IEAGHG 2018, GHG Emission Accounting for CCU Technologies – Synthesis of Research Findings

[10] Element Energy analysis of the Circular Carbon Network Innovator Index

Developers identified in Scotland include **Carbon Capture Machine**, focusing on mineralisation, and **Xanthella,** focusing on algae growth. Other developers in the UK include Econic Technologies (plastics - polyols), Deep Branch (proteins), Cambridge Carbon Capture (carbonate minerals), Carbon8 Systems (aggregates), and CCm Technologies (various products).

Box 1: Types of CO_2 conversion techniques

Chemical: chemical routes typically require high purity CO_2 and may involve high temperatures or pressures. Chemical conversion pathways include:

- **Catalytic** processes are a well-established reaction pathway that can be used to achieve reactions with high specificity. The routes use specialist tailored catalyst materials to react CO_2 with a co-reactant (e.g. hydrogen or higher value chemicals), or to reduce CO_2 to CO. A number of catalytic reaction pathways for conversion of CO_2 to chemicals/fuels have been successfully demonstrated. Further research is needed to improve catalyst design and lower the costs of catalyst materials.
- **Electrochemical** processes act to reduce CO_2 to more reactive CO using electrolysis followed by subsequent reactions (e.g. with hydrogen). This is energy intensive, currently expensive, and a much less-well established research area compared to water electrolysis or catalysis routes. Obtaining high specificity of products can be challenging. There is potential for co-electrolysis of CO_2 and water to reduce costs.
- **Photocatalytic** processes use solar energy rather than electricity to reduce CO_2. This area has attracted significant interest for laboratory research, but currently the conversion rates achievable are thought to be too low for commercial realisation.
- For products where the CO_2 molecule is incorporated directly (e.g. polycarbonates) the reaction is more energetically favourable and can be cost effective.

Biological: biological routes convert CO_2 to chemicals through biological reactions within enzymes, bacteria, or plants[11]. This requires finding or engineering organisms which will convert CO_2 to the desired product with a high selectivity, yield, and conversion rate. Biological pathways can be simple and low-cost – for example, having just bioreactor and product-separation steps at normal temperatures and pressures. They can also be developed to use lower purity CO_2 sources or even flue gas directly. Conversion technologies include growth of microalgae, gas-fermentation using bacteria, and enhanced plant growth (e.g. in glasshouses).

Mineralisation: mineralisation (or carbonation) routes cover reactions in which CO_2 is converted to a carbonate (CO_3^{2-}) ion by reaction with cations (e.g. alkali ions such as sodium, calcium or potassium). These can be found in alkaline wastes (such as steel slag or fly ash) or in alkaline brines, and the reaction is energetically favourable and simple once the CO_2 is in contact with these ions. The results are mineral products that may be produced in bulk (e.g. aggregates) or may be precipitated as powders (e.g. magnesium carbonate), with uses across construction and specialist applications.

---

[11] In some cases, CO_2 may first need to be converted to CO via a chemical pathway.

Other: other techniques with fewer developers include thermal routes and chemical vapour deposition.

Initial relevance criteria led to 20 specific CO_2 conversion pathways being selected for investigation. Following a review of CO_2 utilisation opportunities, a long-list was developed in which specific conversion pathways (consisting of the technique, product, and application) were first identified. This identification considered initial relevance criteria requiring that the pathway:

- Involved a conversion of the CO_2 molecule (chemical reduction or oxidation)
- Results in a value-added product (e.g. chemical, fuel, material)
- Was not already well-established in industry (e.g. use in greenhouses)
- Was sufficiently developed and prototyped to the point that it could be deployed in an integrated pilot system demonstration (i.e. considering TRL >=5)

To narrow down the options selected for investigation, further consideration was given to factors such as required feedstocks, application relevance to Scotland, and economic or market potential as an early indication of the opportunity associated with each pathway. A refined long-list was then developed considering these factors, with the aim of including a range of potentially economically interesting pathways covering multiple end-use sectors. These pathways are shown in Table 1.

Table 1: Long-list of selected CO_2 conversion pathways for investigation (including technology and application) and their key feedstocks in addition to CO_2. The Fischer-Tropsch process is abbreviated by "F-T".

				Additional feedstock		
		Pathway (🟧 chemical 🟩 biological 🟦 mineralisation & other)	Can use low purity CO_2?	Hydrogen	Higher Chemicals (epoxides)	Alkaline Wastes, Brines or Minerals
Agriculture & Food	🟧 1	Formate & formic acid for agricultural applications		✓		
	🟩 2	Formic acid for agricultural applications		✓		
	🟩 3	Proteins for aquaculture and agriculture feed		✓		
	🟩 4	Omega-3 (fish oil) for aquaculture feed				
	🟩 5	Proteins as human food-substitutes (meat, dairy, eggs)				
Chemicals & Polymers	🟧 6	Methanol as a chemical intermediate		✓		
	🟧 7	Cyclic & linear carbonates as chemicals & intermediates			✓	
	🟩 8	Ethanol as a chemical intermediate		✓		
Transport Fuels	🟧 9	Methanol for direct use as shipping fuel		✓		
	🟧 10	Methanol subsequently converted to kerosene		✓		
	🟩 11	Ethanol subsequently converted to kerosene		✓		
	🟧 12	Synthetic kerosene for aviation blending (F-T)		✓		
	🟧 13	Synthetic fuel for heavy-duty road transport (F-T)		✓		
	🟩 14	Enhanced algae growth for biofuels	✓			
Construction & Manufacturing	🟦 15	Aggregates from different industrial wastes	✓			✓
	🟦 16	Pre-cast CO_2 cured concrete using alternative cements	✓			✓
	🟧 17	Polyol & polyurethane production for chemical & manufacturing applications			✓	
Specialist Materials or Niche Products	🟩 18	Enhanced algae growth for value products	✓			
	🟦 19	Nano-carbon materials for advanced engineering	✓			
	🟦 20	Precipitated carbonate minerals	✓			✓

Some of the selected long-list routes (aggregates from waste, CO_2 cured concrete, and methanol) have already been demonstrated (TRL 6-7) or deployed commercially. These were still considered due to the potential for novel developers to emerge, and potential need for demonstrations of novel applications/integrations, feedstocks, or deployment scales.

2.2 Understanding relevance to Scotland

Several factors influence the feasibility and economic opportunity associated with developing CO_2 utilisation technologies in Scotland. The following questions were considered when evaluating the relevance of utilisation pathways for Scotland:

- Do the required feedstocks and supply chain infrastructure exist within Scotland?
- Do Scottish industries or research institutes have relevant skills and expertise?
- Is there a local market or export opportunity for the product? Is there an existing distribution network? How might this change with decarbonisation drivers?
- Could Scotland have a competitive advantage?

These factors and their impact on the types of CO_2 utilisation opportunities that could be developed in Scotland are discussed below.

2.2.1 Feedstock supply chains and infrastructure

Considering the utilisation pathways in the long-list, the feedstocks to be investigated were identified as **CO_2, hydrogen, alkaline wastes, mineral products, and epoxides**. The potential supply chains for these feedstocks in Scotland are discussed below.

Several streams of CO_2 could be considered for CO_2-utilisation, including:

The CO_2 feedstock could be supplied from capture of industrial CO_2. Whilst some industries may be able to decarbonise via fuel-switching to hydrogen or electrification, others are expected to capture CO_2 emissions produced in the processes, either in process streams or their flue-gases, using carbon capture technology. Recent analysis suggests that the scale of carbon capture from industry in Scotland could be up to 13 $MtCO_2$ per year by 2050[12]. Although most of this CO_2 is expected to be sent for geological sequestration there may be some circumstances where utilisation of the CO_2 provides a specific opportunity. It should be noted that utilisation is expected to occur at much smaller scales than geological sequestration and that in many pathways the CO_2 is not permanently stored as it is usually eventually released back to the atmosphere. This makes biogenic emissions, such as those from the whisky distilling sector, of particular interest for utilisation pathways as it maintains net neutrality[13].

- **Dispersed industrial sites or small-scale emitters may have particular interest in supplying CO_2 for utilisation.** CO_2 utilisation technologies have flexibility in their location so could be of interest for dispersed or small-scale emitters that require carbon capture but are unable to economically transport CO_2 to a storage site. Smaller emitters in the Central Belt area or isolated emitters on the West Coast are examples of such sites.
    - Some utilisation processes can take CO_2 directly from flue-gas emissions, which may benefit industries where capture could be challenging – such as small-scale emitters or those with low-concentrations of CO_2 in flue gases. Other emitters may be interested in CO_2 utilisation if a profit is achievable by the process.
    - It should be noted that the origin of CO_2 stream also plays a significant role in dictating the feasibility and economics of different utilisation pathways. For example, process stream emissions (e.g. CO2 from fermentation in whisky industry or from reformation of natural gas or ammonia production) usually have a higher CO_2 concentration and contain fewer contaminants, thus leading to reduced costs of capture. On the other hand, combustion emissions, from power stations and industrial appliances, are usually more diluted but in larger volumes. This represents an opportunity for the Scottish whisky industry as although distilleries are relatively small emitters, the CO_2 stream from fermentation is more concentrated and is of biogenic origin.
- **Direct Air Capture (DAC) technology represents another supply opportunity for CO2 utilisation.** DAC is being used to provide CO_2 for utilisation in several global demonstration projects, including the planned Norsk e-Fuel production facility in Norway (Climeworks DAC technology) and the sustainable jet-fuel

---

[12] Element Energy & Vivid Economics 2021, CCUS Economics Impacts Study – 'ambition' scenario includes capture of approximately 3 Mt from industry, 1 Mt for bio-CCS, 2Mt from power, 7 Mt from blue-hydrogen and 3 Mt from direct air capture

[13] Use of CO_2 that was recently atmospheric (e.g. from biomass or direct air capture (DAC)) in products that then release the CO_2 back to the atmosphere at end-of-life (e.g. fuel combustion) is at best a net-CO_2 neutral cycle. Biogenic and DAC CO_2 is considered to be net-neutral emission.

project, AtmosFUEL, in the UK (Carbon Engineering DAC technology). DAC developer Carbon Engineering is currently conducting preliminary engineering and design studies for deployment of a large-scale DAC facility in North-East Scotland which would capture 0.5-1 $MtCO_2$ per year. As with biogenic CO_2, CO_2 from DAC is of particular interest for utilisation pathways as it maintains net neutrality[13].

Hydrogen is expected to be available as a feedstock in the near-future and could also be produced onsite using low-cost renewable electricity. Many of the long-listed pathways producing chemicals and fuels from CO_2 require low-carbon hydrogen as a feedstock. It is expected that suitable low-carbon hydrogen supplies would be available in the near-future due to Scotland's advantageous position for low-cost offshore-wind electricity (allowing green hydrogen from electrolysis) in addition to North Sea natural gas and CCS infrastructure (allowing blue hydrogen production[14]). There is also significant interest in hydrogen production in Scotland, with pioneering projects including Acorn Hydrogen (St Fergus, blue) and Surf N Turf and BIG HIT (Orkney Islands, green). Initial designs for Acorn Hydrogen consider an annual production of 1.6 TWh production, potentially increasing to 10 TWh in the long-term[15,16]. Hydrogen islands are of interest for the ability to use local renewables that might otherwise be curtailed.

Alkaline waste and mineral products required for mineralisation pathways are available, but supply may be limited. The waste-to-aggregates utilisation pathway centres around carbonation of alkaline waste material by reacting it with CO_2. Potential sources of appropriate waste types in Scotland include dusts from Dunbar cement plant, slags from the aluminium smelter in Fort William, and fly ash from several waste incineration sites. These are however limited in supply, in terms of quantity and geographic accessibility of resources, thus restricting future scales of deployment in Scotland. Other emerging end-uses (such as demand for fly-ash as a supplementary cementitious materials in the construction industry) could increase competition for such resources and limit the business case for waste mineralisation. Access to the mineral products necessary for the precipitated carbonate minerals pathway (magnesium or calcium brines) and for alternative cement production is also expected to be limited.

Lack of production of epoxide feedstocks in Scotland limits the opportunities for polyol production. Some chemical and polymer utilisation pathways require higher chemicals (such as ethylene or propylene oxides (epoxides)) as an additional feedstock to react with CO_2. In fact, conventional polyol production facilities are typically located in the vicinity of epoxide production due to this feedstock requirement in the conventional route. Despite Scotland having two large-scale chemical production facilities producing ethylene, the subsequent oxidation step to form ethylene oxide does not currently occur in the UK and there are no plans to develop this capability in the near future. Therefore, it would be challenging for such utilisation pathways to establish themselves in Scotland.

2.2.2 Existing industries and expertise

A variety of Scottish industries may provide expertise for, or benefit from, development of utilisation pathways in the long-list. Some specific sectors of interest based on the long-list are highlighted in Table 2 below.

---

[14] note that the role of blue hydrogen in CO2-utilisation is limited, since blue hydrogen is produced from fossil fuels. However, niche applications for blue hydrogen could exist e.g. CO2-utilisation pathways could serve as a complementary hydrogen off-taker collocated with other industrial hydrogen users.

[15] Element Energy 2020, Hydrogen in Scotland: The Role of Acorn Hydrogen in Enabling UK Net Zero

[16] Pale Blue Dot Energy 2019, Acorn Hydrogen: Project Summary

Table 2: Scottish sectors of interest for CO2 utilisation pathways and their linked opportunities.

Sector	**Description of Scottish sector**	**Linked opportunities from CCU**
Biotechnology – chemical and life sciences	• The chemical sciences sector employs 11,000 workers across 250 companies and has an export value of £4.4 billion per annum[17]. • Scotland is emerging as a major player in industrial biotechnology. • The Industrial Biotech Innovation Centre facilitates collaboration between industry, academia, and government. • Ranked top 3 in the world for chemical sciences R&D.	• Microbial research and design for biological pathways (selection, engineering, characterisation) • Optimisation of microbial growth conditions and culturing techniques • Research and development into extraction and processing of chemicals from algal biomass (e.g. for pharmaceutical, nutraceutical or cosmetic markets).
Refined petroleum manufacturing	• Employs 2,000 workers and has a turnover of £4.2 billion per annum[18]. • Based on crude-oil extraction from the North Sea and additional imports. • Key site is the Petroineos refinery in Grangemouth which employs over 600 staff. • Connected downstream distribution network, including exports via the Finnart Ocean Terminal.	• Opportunity to become a major producer of synthetic fuels in Europe • Continued use or repurposing of existing processing and distribution assets for refining (e.g. pipelines, refinery units) • Retention of (at-risk) jobs linked to the refining sector
Agriculture including fishing and aquaculture	• Employs 56,000 workers and has a turnover of £6.9 billion per annum[18]. • About 50 large companies of which 10 are in the fishing and aquaculture sector. • Aquaculture alone has a turnover of £1.5 billion and generates £885 million GVA, supporting 11,700 jobs[19]. • Much of this value is in salmon production, with 156 kt of salmon harvested from farms in 2018.	• Development of local supply chains for feed raw materials (increasing security of supply and reducing price volatility) • Use of expertise in finfish nutrition to design new products from alternative CO_2 derived feedstocks • Expansion of skilled jobs in the sector benefiting rural communities.
Specialist manufacturing	• Scotland is investing in advancing its own specialist materials manufacturing capabilities. • The development of a Lightweight Manufacturing Centre is aimed at bringing manufacturing expertise to Scotland and positioning Scotland at the forefront of new techniques and processes. • It is hoped that ongoing investment will develop capabilities to supply Scottish automotive and aerospace sectors, which currently rely on overseas production due to a lack of local skills.	• Production of carbon nanomaterials from CO_2 could support the development of advanced materials and devices, such as lightweight composite materials and advanced electrical components (benefitting for example wind-turbine or electric vehicle battery development).

---

[17] https://www.sdi.co.uk/key-sectors/chemical-sciences [accessed Sept 2021]
[18] ScotGov Businesses in Scotland: 2020 tables
[19] BIGGar Economics 2020

2.2.3 Scottish and European market demands

Applications associated with the long-listed utilisation opportunities include aquaculture and agriculture feed, chemicals and polymers, transport fuels, construction and manufacturing, and specialist materials or niche products. Notable market considerations for Scottish production of CO_2-derived products within these areas are discussed in Table 3 below, with further specific details included for the short-listed pathways in Section 3.

Table 3: Notable market considerations for different applications of products from CO_2 utilisation.

Application	**Notable market considerations**
Aquaculture and agriculture feed	**Scotland has local demand for fish-feed with raw materials currently imported.** The largest external expenditure for the Scottish aquaculture sector is feed for finfish, which accounted for £290 M of spending in 2018. Although feed is mostly purchased from Scottish suppliers, raw ingredients are mostly imported[20]. There is a **growing supply gap for fish-feed** ingredients as traditional supplies come from caught wild fish or fish-waste, which cannot sustainably be exploited further due to stressed fish populations. Supply issues lead to increasing prices and price volatility. This is driving uptake of alternative sources of proteins and nutrients.
Chemicals and polymers	The INEOS site in Grangemouth produces a range of petrochemicals including olefins, polyolefins, and ethanol. Ethylene is exported via pipeline to the north of England. Chemical solvents and intermediates (such as ethanol, methanol, and cyclic carbonates) are in demand as feedstocks for speciality chemicals. Scotland has around 141 companies selling speciality chemicals targeting applications of personal care; paints, inks and coatings; and cleaning materials.
Transport fuels	Marine, aviation and Heavy Goods Vehicle (HGV) transport emissions accounted for almost half of Scotland's transport emissions in 2019. These applications are difficult to decarbonise via electrification and therefore there are **opportunities for drop-in sustainable fuels**, such as those from CO_2 utilisation. European demand for sustainable fuels is **driven by policy mandates** that are set to be updated to with sub-targets for synthetic fuels of non-biological origin (e.g. from CO_2 utilisation). This is expected to create a distinct market for such products which Scotland could be well positioned to address.
Construction and manufacturing	Scottish cement production occurs at the Dunbar cement works operated by Tarmac. Quarrying of mineral products occurs at various locations including Glensanda Quarry in Argyll, Hillhouse Quarry in Ayrshire and Ethiebeaton Quarry in Angus. Scotland imports only a low quantity of aggregate material, as it produces sufficient amounts of crushed rock, and sand and gravel locally There is a growing tendency for vertical supply chain integration within the sector.
Specialist materials or niche products	Specialist products such as chemicals from algae oils have **high-value, low volume markets** with particular opportunities for exports due to ease of distribution. Scotland has existing production of **pharmaceutical and nutraceutical products** (such as Omega-3 which is produced by BASF in Callanish) evidencing industry interest in the specialist chemicals that could be extracted from algae oils.

---

[20] Some raw ingredient production does occur at sites in Aberdeen, Greenock, and Bressey.

The UK is currently a **net-importer of carbon materials**. Future specialist manufacturing, such as in the areas of wind-turbines or batteries, could provide a local market for specialist carbon nanomaterials.

2.2.4 Competitive advantages in Scotland

It is important to consider which utilisation projects would be advantaged by being located in Scotland compared to elsewhere and therefore where Scotland specifically could become a preferred base for technology development. Two such advantages are the existence of low-cost renewable electricity and availability of high concentration biogenic CO_2 sources from the whisky industry.

- The **high availability of renewable electricity** allows for low-cost electrolytic hydrogen production. This is a substantial advantage for synthetic chemical and fuel applications with high percentages of hydrogen by composition – typically hydrogen supply is the dominant cost factor by far when chemical conversion is used.
- Availability of **high concentration and high purity CO_2**, for example from whisky distilleries and natural gas processing[21], is beneficial for applications where CO_2 costs could form a significant component of overall product costs, due to the lower cost of capture from such sources. It is also advantageous for applications where contaminants present issues, such as catalytic pathways where impurities could poison catalysts.
- Local **biogenic CO_2**, such as from fermentation within the whisky industry, presents an opportunity for negative emissions if permanent sequestration is obtained, or carbon-neutrality if sequestration is impermanent.
- In addition, it is possible that market or policy support for some CO_2 utilisation pathways might develop to include constraints on origins of hydrogen and CO_2, for example requiring additionality of renewable electricity or specifying biogenic or atmospheric CO_2 (i.e. biogenic or atmospheric). This may be of particular relevance to synthetic fuels that will contribute to obligations under the EU's RED II directive. An update on RED II legislation is due in late 2021 that is expected to clarify requirements for renewable fuels of non-biological origin (RFNBO).

These factors suggest that Scotland could be an **advantageous location for synthetic 'e-fuels' production** due to the potential for competitive hydrogen prices, guaranteed renewable electricity origins, and the option for using biogenic or atmospheric CO_2. Scotland's location, existing industry, ports and distribution networks also place it at an advantage for synthetic fuel production and exports.

2.3 Selection of short-list to investigate

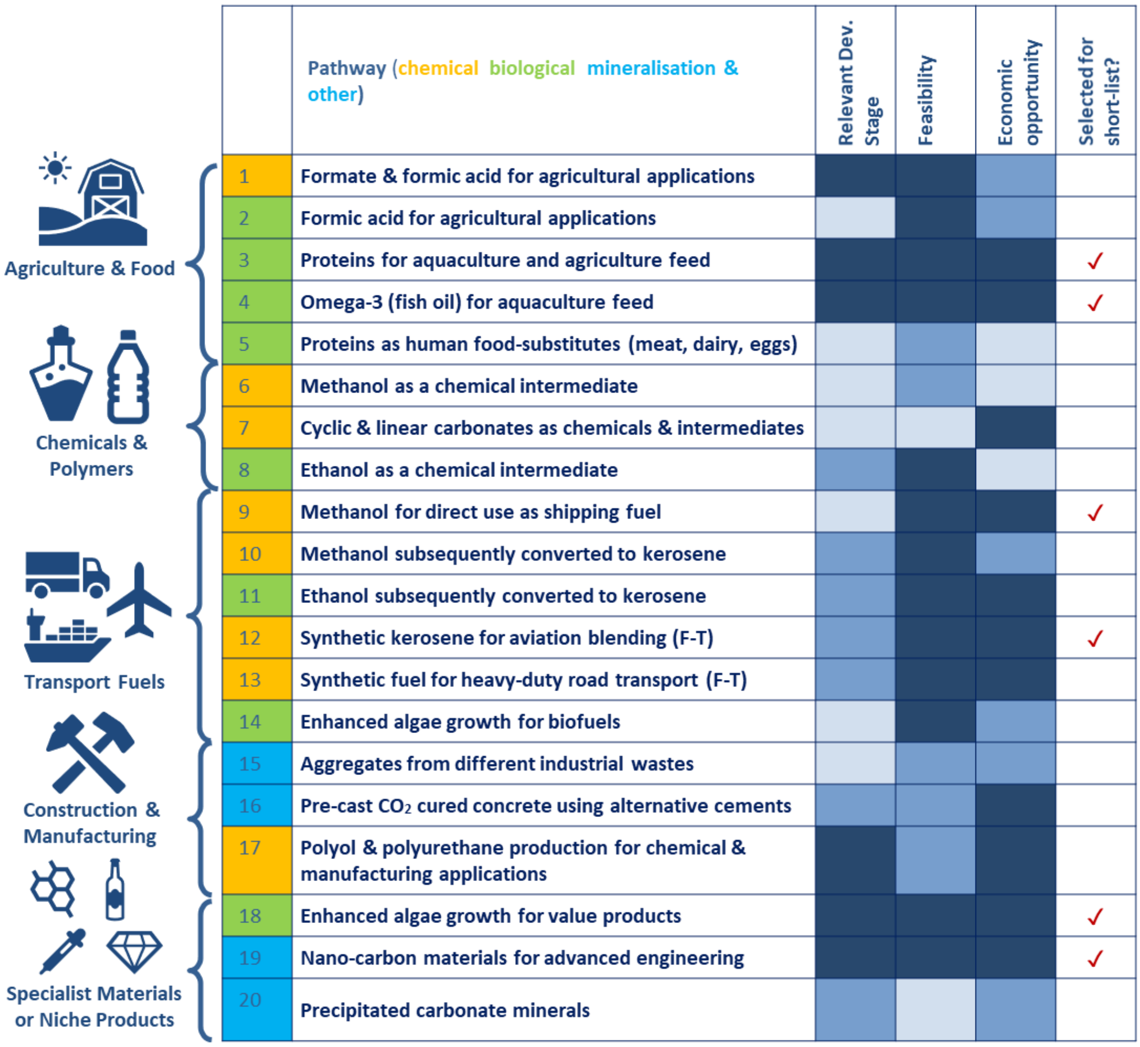
Six CO_2 utilisation pathways were selected for further investigation considering the relevance of the opportunity to Scotland. The selection process involved a RAG assessment[22] of the pathways considering three main criteria: relevance of development stage, feasibility of deployment, and economic opportunities. The outcomes of this assessment are presented in Table 4 with further details on scoring included in the Appendix.

---

[21] Although use of a high purity CO_2 stream can provide economic advantages for capture and use, the use of fossil-derived CO_2 may not be acceptable from an environmental perspective – specific product lifecycle and systems analysis should be conducted to understand relative benefits (e.g. compared to the counterfactual of permanent sequestration of the fossil-CO_2).

[22] RAG: Red Amber Green. Referring to an assessment in which items are scored as strong, moderate, weak (or alternative) against a set of criteria using a visual colour coding system.

*Table 4: RAG assessment of long-list pathways with scoring for **strong**, moderate, and weak performance against criteria (see Appendix), considering available evidence.*



	Pathway (chemical biological mineralisation & other)	Relevant Dev. Stage	Feasibility	Economic opportunity	Selected for short-list?
1	**Formate & formic acid for agricultural applications**	■	■	▨	
2	**Formic acid for agricultural applications**	□	■	▨	
3	**Proteins for aquaculture and agriculture feed**	■	■	■	✓
4	**Omega-3 (fish oil) for aquaculture feed**	■	■	■	✓
5	**Proteins as human food-substitutes (meat, dairy, eggs)**	□	▨	□	
6	**Methanol as a chemical intermediate**	□	▨	□	
7	**Cyclic & linear carbonates as chemicals & intermediates**	□	□	■	
8	**Ethanol as a chemical intermediate**	▨	■	□	
9	**Methanol for direct use as shipping fuel**	□	■	■	✓
10	**Methanol subsequently converted to kerosene**	▨	■	▨	
11	**Ethanol subsequently converted to kerosene**	▨	■	■	
12	**Synthetic kerosene for aviation blending (F-T)**	▨	■	■	✓
13	**Synthetic fuel for heavy-duty road transport (F-T)**	▨	■	■	
14	**Enhanced algae growth for biofuels**	□	■	▨	
15	**Aggregates from different industrial wastes**	□	▨	▨	
16	**Pre-cast CO_2 cured concrete using alternative cements**	▨	▨	■	
17	**Polyol & polyurethane production for chemical & manufacturing applications**	■	▨	■	
18	**Enhanced algae growth for value products**	■	■	■	✓
19	**Nano-carbon materials for advanced engineering**	■	■	■	✓
20	**Precipitated carbonate minerals**	▨	□	▨	

Based on this RAG assessment and subsequent discussions with Scottish Government and Scottish Enterprise, the following pathways were selected for detailed economic assessment:

- **Fischer-Tropsch fuels** from CO_2 and hydrogen with a focus on synthetic aviation fuel applications
- **Methanol** from CO_2 and hydrogen with a focus on direct use as a shipping fuel
- Enhanced **growth of algae** to produce high value-products including Omega-3 for aquaculture
- **Proteins** for agriculture and aquaculture feed using biological fermentation pathways to convert the CO_2 (Table 4, combination of pathways 3 and 4)

In addition, the **nano-carbon materials** for advanced engineering applications pathway was selected to be explored at a high-level due to the high overall RAG performance but lack of publicly available economic and market data.

3 Opportunities for Scottish industries

3.1 Overview

This chapter investigates the opportunities for Scotland that may arise from development and deployment of the short-listed CO_2 utilisation technologies outlined above in Table 4. The technologies involve the production of proteins, algae products, methanol, Fisher-Tropsch fuels, and nano-carbon materials.

For the purposes of this assessment, we have chosen to focus on specific applications of these products that were deemed, during the short-listing stage, to be most interesting for development in Scotland[23]. For each short-listed CO_2 utilisation pathway, the sections below present a summary of the technology and product produced (‘Technology and Product’), the key reasons why it might be of particular interest to deploy in Scotland (‘Why Scotland?’), and the potential economic impacts for such deployments (‘Investment and Jobs’) considering the investment requirements for a reference facility – see Box 2.

Whilst investigating the opportunities for each pathway, the following aspects of the value chain were considered:

- **Research and development** – Opportunities for knowledge leadership, building new skills, or capitalising upon existing expertise. Potential opportunities in the areas of academia, technology R&D, and engineering or consultancy services.
- **Feedstock supply** – Impact of feedstock production and linked opportunities for increasing feedstock demand.
- **Plant construction and operation** – Requirements for capital investment and operational costs. Impact of plant construction and operation on jobs and gross value added (GVA), based upon analysis in our economic assessment model.
- **Product distribution and markets** – The ability to leverage existing supply chains or distribution infrastructure. Whether local or export markets exist and the potential scale of these markets. Economic competitiveness of production in Scotland. Additional benefits to local markets, such as greater security of supply.

The benefits associated with each dimension are summarised in Figure 2 below and detailed in the following sections of each of the CO_2 utilisation pathway deep-dives.

Box 2: Economic impact assessment

An indicative **breakdown of the capital and operational expenditures** of reference facilities is presented in cases where sufficient techno-economic data was available in the literature. The impact of such investments on **jobs and gross value added (GVA)** was then calculated using Element Energy’s UK-specific macroeconomic impact model. More details on this model are included in the Appendix (Section 6.3).

The scale of the selected reference facility has been selected based upon the analysis available in the literature, which often considered a theoretical full-scale facility (e.g. comparable to conventional production). It should be noted that current demonstration projects have much lower capacities, and the future final full-scale set-up of these facilities is unclear.

Further details on the literature studies used and their key assumptions are included in the Appendix (Section 6.3).

---

[23] Note that there are a range of other possible applications for each of the assessed products. For example, methanol can be used as a chemical or in fuel-blending, F-T fuels can also be drop-in replacements for diesel and gasoline, proteins may be used in various feedstocks and supplements, and algae can be grown for biofuels.

Research & development

- Knowledge leadership
- Building new skills

Areas that develop:

- Academia
- Technology developers
- Project developers
- Consultancy

Feedstocks

CO_2

- Development and advances in carbon capture technology
- Benefits for biogenic CO2 producers
- Advances in DAC development

Hydrogen

- Facilitate hydrogen uptake and synergies with other uses
- Provide storage route for hydrogen production

Electricity

- Opportunity for use of curtailed electricity
- Synergies with the renewable deployment

Production

- Jobs created during construction and project management
- Jobs related to operations
- Potential opportunities for a just transition
- Asset retention
- Revenues and profits from product sales
- Potential for infrastructure synergies

Distribution

- Leverage existing supply chains
- Create new supply chains

End-use

- Potential for drop-in applications
- Cost efficiencies / reduction compared to counterfactual
- Increased circularity
- Compliance with policy mandates
- Ensuring energy and product security

Figure 2: Dimensions and key aspects considered in the assessment of benefits of the CO2-utilisation pathways in Scotland

3.2 Synthetic kerosene from Fischer-Tropsch synthesis

Opportunities overview:

- Policy drivers are expected to create a large, distinct market for synthetic aviation fuels in Europe.
- Availability of low-cost renewable electricity gives Scotland a competitive advantage.
- Synthetic crude production could be used to retain at-risk jobs and assets in the refining sector.

3.2.1 Technology and product

Fischer-Tropsch (F-T) synthesis is an established pathway to creating a synthetic crude oil from synthesis gas - a mix of carbon monoxide (CO) and hydrogen (Figure 3). The synthetic crude oil can be refined using comparable processes to conventional refining (distillation, cracking, isomerisation) into products including synthetic kerosene and diesel. For captured CO_2 to be used as the carbon feedstock to the process, an initial novel syngas generation step is required: the captured CO_2 must be reduced to CO and combined with hydrogen. Three alterative pathways are being explored:

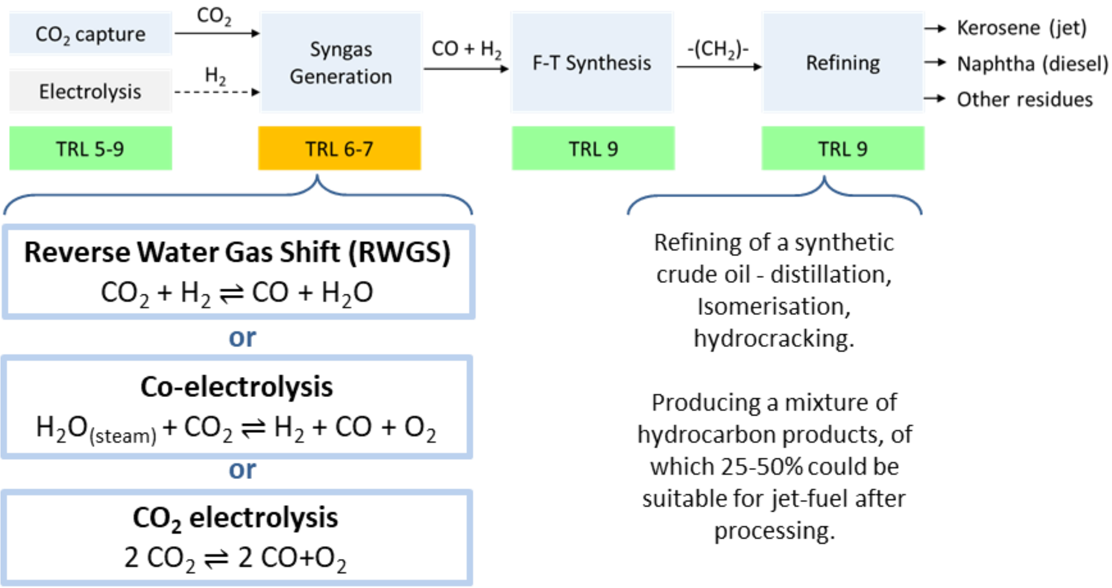


Figure 3: Overview of the CO_2 to Fischer-Tropsch fuels synthesis pathway[24].

This CO_2 utilisation pathway is of interest for the production of synthetic jet-fuel (kerosene) as a direct-drop in sustainable aviation fuel (SAF). It should be noted that the route produces a mixture of hydrocarbons and only a proportion of these (e.g. 25-50%[25]) are expected to be suitable for jet-fuel after processing. The remainder could be sold as renewable diesel or light ends.

3.2.2 Why Scotland?

Synthetic crude production could be used to retain at-risk jobs and assets in the refining sector. The UK currently produces over 50 Mtoe of crude oil and is one of the largest producers in Europe, alongside Norway. The Petroineos refinery in Grangemouth is one of six refineries in the UK and the only site with an integrated steam-cracker and hydrocracker. The continued operation of units at the facility (which employs 600 staff)

---

[24] CO: Carbon Monoxide, H_2: Hydrogen, O_2: Oxygen, H_2O: water, $-(CH_2)-$: generic hydrocarbon chain

[25] ICCT 2019, The cost of supporting alternative jet fuels in the European Union

are however under threat with Petroineos announcing plans to scale back operations in 2020 due to declining fuel demand. A move towards synthetic fuel production in Scotland could utilise existing skills in crude-oil refining, as well as maintain the use of distribution assets such as pipelines.

Policy drivers are expected to create a large, distinct market for synthetic aviation fuels in Europe. In 2019, the European demand for kerosene was 49 Mtoe with 15% of this being for domestic flights[26]. The EU's new policy proposal - ReFuelEU aviation - proposed in 2021 includes a target for renewable fuels in which there is a sub-mandate for synthetic fuels of non-biological origin that increases from 0.7% in 2030 to 28% in 2050[27]. With existing pipelines and connections such as the Finnart Ocean Terminal, Scotland is well-placed to take a proportion of this demand, with other crude-oil exporters having also announced plans to scale-up e-kerosene production (specifically Norway where the Norsk e-fuel project plans to produce 100 million litres of fuel by 2026 – 0.09 Mtoe[28]).

Availability of low-cost renewable electricity gives Scotland a competitive advantage. A significant cost component of the pathway is the electricity requirement for hydrogen production and for direct air capture if this is used. Compared to other European nations, Scotland could have a competitive advantage due to low cost, renewable electricity generated by offshore wind.

3.2.3 Investment and jobs

Using the method outlined in Box 2, we investigated the investment required for a single reference plant and conducted an economic assessment to understand the associated impact on jobs and GVA.

Reference plant: Full process including CO_2 capture via DAC and hydrogen generation via electrolysis. Capacity of 210 kt of synthetic crude (liquid+wax) per year, requiring capture of 750 kt of CO_2 per year and 819 MW power.

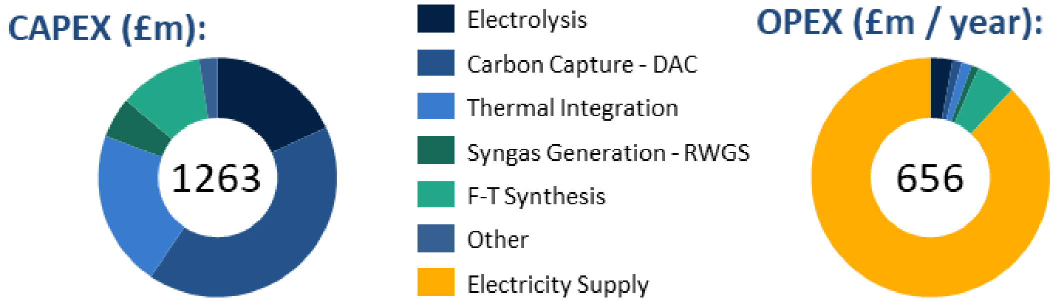


Figure 4: CAPEX and OPEX breakdown for a reference CO_2-to-synthetic crude plant[29].

Production of synthetic F-T fuels could create significant benefits for Scottish industries. For example, Figure 4 and Figure 5 present a reference plant with the capacity mentioned above, which could generate over 900 direct jobs during the construction phase[30] and 1,100 jobs during operation, with a gross value added to the economy of

---

[26] Analysis of Eurostat Oil & Petroleum Product Overview

[27] ReFuelEU Aviation - Proposal for a regulation - COM(2021)561

[28] Sunfire 2020, Press Release: Norsk E-Fuel Is Planning Europe's First Commercial Plant For Hydrogen-Based Renewable Aviation Fuel In Norway

[29] Due to uncertainties in DAC costs, values should be considered as indicative for this specific case only. Use of concentrated CO_2 sources would largely reduce the CAPEX associated with capture. Study assumed electricity price of £88 / MWh based on the cost of offshore wind.

[30] assuming build-out over a three-year period

over £100m/year. In terms of the industries involved, the capex is characterised by jobs created in the manufacture and construction of key equipment, whilst the operational jobs relate to the petrochemicals sector as well as the utilities used by the facility. These are related to both electricity use for the process as well as green hydrogen production. A significant fraction of the electricity consumption is associated with the Direct Air Capture considered for this “reference” facility, however a lower use of electricity would be expected if the CO2 was captured from point-source emissions, such as the industrial sites or the distilling sector.

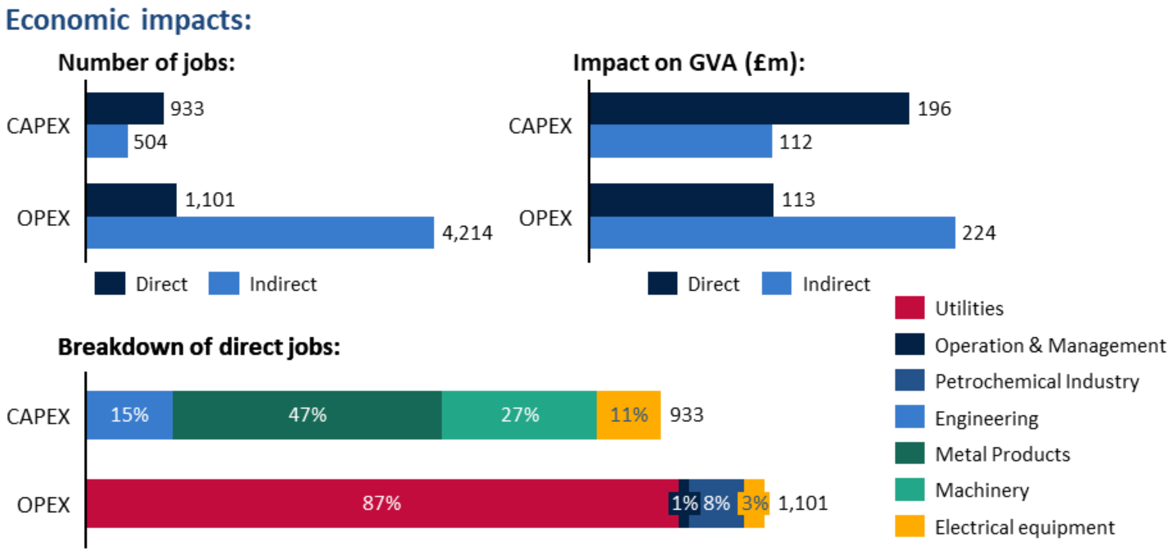


Figure 5: Economic impacts of investment in a single CO_2-to-synthetic crude reference plant.

3.3 Methanol as a shipping fuel

Opportunities overview:

- Scotland has 11 major ports each handling over 1 Mt of cargo per year.
- Methanol is one of the main alternative fuels proposed for marine transport in the UK Clean Maritime Plan.
- Scotland has a strategic advantage for e-fuel production due to high availability of renewable electricity.

3.3.1 Technology and product

Methanol is conventionally produced from a syngas derived from fossil-carbon pathways, primarily through steam methane reforming. It is then primarily used as a chemical intermediate (such as in formaldehyde production) or as a fuel (typically via blending with gasoline directly or via conversion to a fuel additive[31]). There are several pathways by which methanol could be manufactured (see Figure 6). An alternative production route is via CO_2 utilisation, in which captured CO_2 and hydrogen from electrolysis are combined into methanol. This is of interest as it removes reliance on fossil resources and can lower the overall emissions of the process if renewable electricity is used. The product is described as an 'e-fuel' due to electricity being the energy basis, and may also be classed as a renewable fuel of non-biological origin.

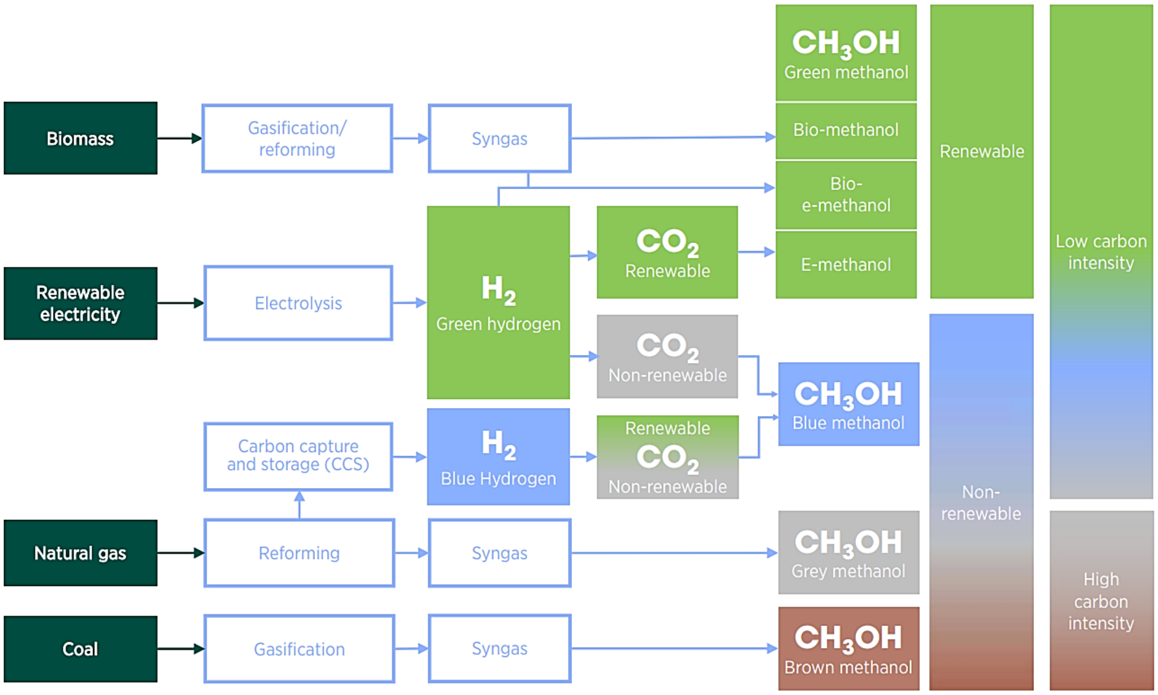


Figure 6: Methanol production pathways (Image taken from IRENA and Methanol Institute 2021)[32]

The most well-developed process involves methanol production via catalytic hydrogenation in which hydrogen and CO_2 are reacted over a copper-zinc-aluminium based catalyst. This technology has been demonstrated in Iceland by Carbon Recycling International (CRI) which has had a small-scale plant (current capacity of 4 kt methanol per year) operational since 2012. Additional CRI pilot projects have been located in Sweden and Germany demonstrating the technologies' ability to use different CO_2

---

[31] For example, methanol is used to produce methyl tert-butyl ether (MTBE) which is used as a gasoline additive.

[32] IRENA and Methanol Institute 2021, Innovation Outlook: Renewable Methanol

sources and an intermittent power supply. CRI has announced plans for industrial scale plants in China and Norway.[33] Conventional methanol synthesis technology developers are also developing this route. For example, Johnson Matthey was involved in the CRI plant and is providing technology to the planned Haru Oni project in Patagonia, Chile[34].

Although CRI technology is approaching TRL 9, there could be opportunities for other developers and technologies to emerge, for example using electrochemical or photocatalytic conversion techniques, or for new applications of the process or product that could require demonstration.

3.3.2 Why Scotland?

Methanol is one of the main alternative fuels proposed for marine transport in the UK Clean Maritime Plan. In 2019, the UK Department for Transport (DfT) announced its Maritime 2050 vision which included a commitment for the UK to actively drive the transition to zero emission shipping and be seen as a role model in the field. This was followed by the Clean Maritime Plan that included ambitions to develop clean maritime clusters and bunkering of low-emission fuels across the UK. In this plan, the port of Aberdeen was identified as a vessel energy demand cluster of interest and methanol was proposed as one of four main alternative fuels (alongside ammonia, hydrogen, and electrification). Existing projects HyDIME and HySeas III in Orkney are demonstrating hydrogen-powered shipping vessels. Figure 7 shows locations of emerging hydrogen projects and Scottish ports.

Scotland has 11 major ports each handling over 1 Mt of cargo per year. There are a variety of types of shipping vessels in Scotland ranging in size from small recreational craft to large cargo vessels for international trade, as well as specialist sub-sectors such as fishing and windfarm installation. The main fuels currently used for marine transport are heavy fuel oil, marine gasoil and marine diesel oil, which are produced from crude-oil refining and have environmental impacts both of greenhouse gas (GHG) emissions but also other pollutants (e.g. NOx, SOx, PM[35]). To achieve emission reduction targets for the transport sector it is imperative to explore alternative fuel options for a range of shipping vessels. In 2021 the container shipping firm Maersk announced its purchase of 8 large ocean-vessels to operate on carbon neutral methanol, indicating industry support for the alternative fuel[36].

---

[33] CRI website [accessed Nov 2021]

[34] JM 2021 news article: JM technology selected for world's first climate neutral methanol plant

[35] Nitrogen oxides, sulphur oxides, and particulate matter

[36] Maersk 2021, Press Release: A.P. Moller - Maersk accelerates fleet decarbonisation with 8 large ocean-going vessels to operate on carbon neutral methanol

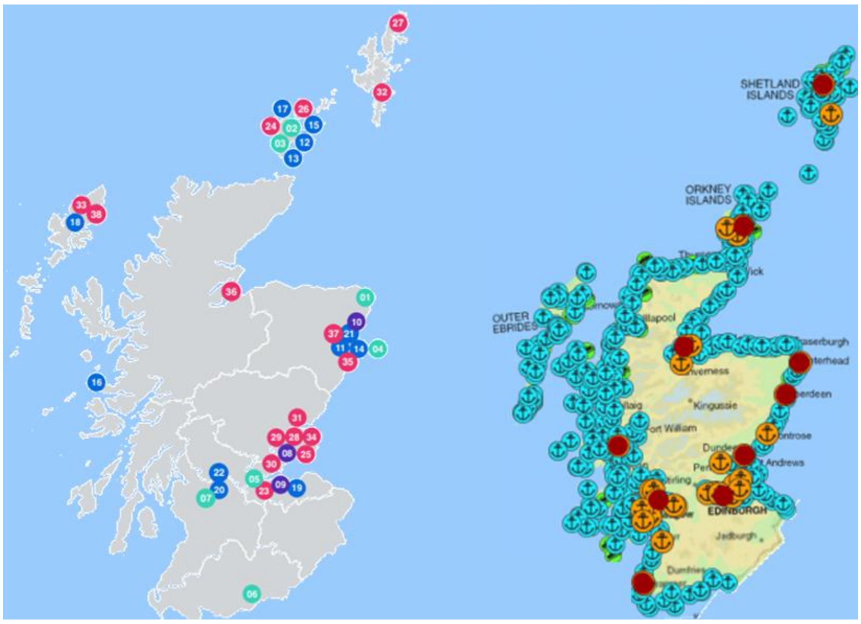


Figure 7: Overview of the emerging hydrogen projects (left[37]) and Scottish Ports (right[38])

Scotland has a strategic advantage for e-fuel production due to high availability of renewable electricity. Hydrogen production is the main cost-component for e-methanol production and this cost is driven by the cost of renewable electricity for electrolysis. The vast accessibility of offshore wind in Scotland therefore makes it an advantageous location for low-cost e-fuel production, with further opportunities for e-fuels to provide an energy storage route for excess power generation – for example on islands such as Orkney. In 2021 it was announced that Global Energy Group and Proman would develop an e-methanol plant at the Nigg Oil Terminal in Scotland able to harness excess power[39]. In addition, the availability of biological CO_2 or CO_2 from direct air capture (DAC) could be advantageous if future regulatory developments were to restrict the use of fossil CO_2 in the RFNBO[40] classification. In 2021, the DfT also announced policy support for renewable maritime fuels of non-biological origin[41].

3.3.3 Investment and jobs

Using the method outlined in Box 2, we investigated the investment required for a single reference plant and conducted an economic assessment to understand the associated impact on jobs and GVA. Whilst the plant scale used for Figure 8 is comparable to conventional methanol production facilities, it should be noted that the scales of proposed demonstration and commercial projects range from 1-100kt methanol per year.

Reference plant[42]: Capacity of 440 kt methanol per year, consuming 640 kt CO_2 and 90 kt H_2 per year. This capacity corresponds to conventional production scales, but is around 4 times greater than proposed large-scale CCU plants. The plant has an economic life of 20 years.

---

[37] Reproduced from the Scottish Hydrogen Assessment, ARUP for Scottish Government, 2020

[38] Based on the Marine Scottish Information, Scottish Port and Harbours

[39] Offshore Energy 2021, Article: GEG, Proman to build renewable power to methanol plant in Scotland

[40] Renewable Fuel of Non-Biological Origin. Further clarifications on synthetic fuels eligibility under RFNBO are expected in the updated RED II legislation, which is yet to be released at the time of writing.

[41] In the form of inclusion for Renewable Transport Fuel Obligation support, allowing them to be eligible for rewards but not yet introducing an obligation on suppliers.

[42] Based on analysis by Pérez-Fortes et Evangelos Tzimas 2016

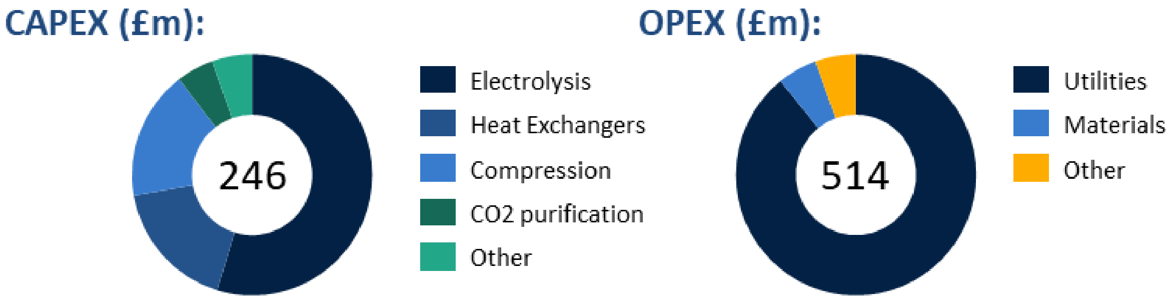


Figure 8: CAPEX and OPEX breakdown for a reference methanol plant.

Production of synthetic methanol could create significant benefits for Scottish industries. The economic benefits are similar to F-T production, and consist of over 300 direct jobs during the construction phase[43] and 1,800 jobs during operation, with a gross value added to the economy of over £180m/year (Figure 9). The industrial sectors involved are very similar to F-T production.

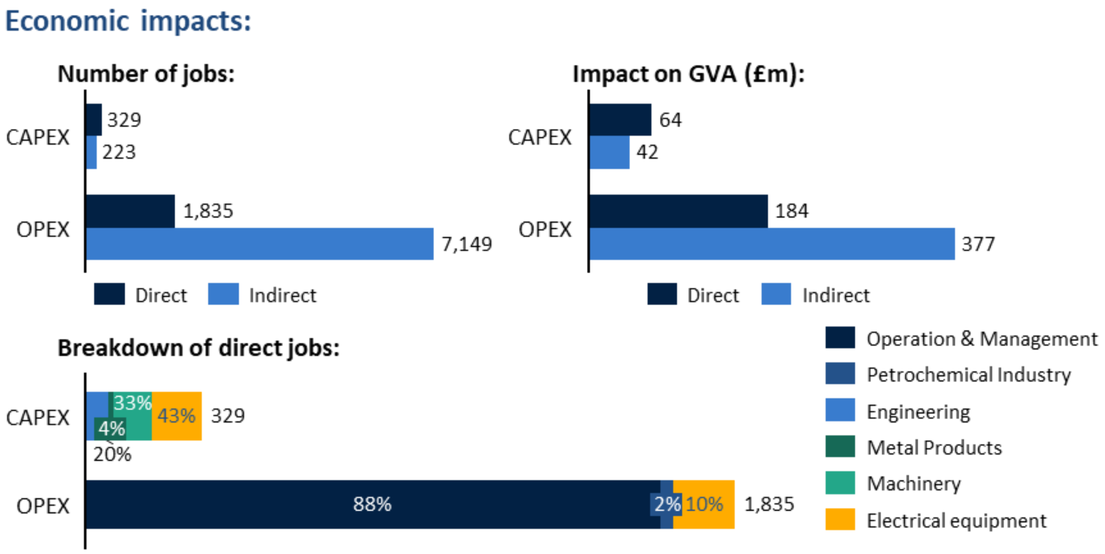


Figure 9. Economic impacts of investment in a single methanol reference plant.

Focusing on applications of e-methanol for renewable shipping fuels, the scale of demand for the UK shipping sector could reach up to 11 Mt methanol per year considering analysis by the Climate Change Committee[44]. If e-methanol were to substitute the energy requirement for all international maritime transport in the EU then this would represent a demand of 62 Mt methanol per year[45].

---

[43] assuming build-out over a three year period

[44] CCC Sixth Carbon Budget analysis indicated that around 70 TWh of low-carbon fuels are needed by 2050 for UK shipping.

[45] Based on 2019 European fuel oil consumption for international maritime transport of 33.6 Mtoe.

3.4 Enhanced algae growth for value products

Opportunities overview:

- Derivatives from algae oil have high-value applications in nutraceutical, pharmaceutical, cosmetic, and aquaculture markets.
- There is a growing supply gap for fish-feed components, and the Scottish aquaculture sector provides a local market for algae derived Omega-3 fatty acids and dry biomass.
- Opportunities for Scotland exist in research and development of photobioreactors and microalgal culturing using Scottish biotechnology expertise.

3.4.1 Technology and product

Algal biomass contains carbohydrates, proteins and natural oils which can be extracted and processed into high-value products used in **nutraceutical, pharmaceutical, cosmetic, and aquaculture** applications. The market prices achievable for the dry biomass component range from between £50-230 per kg whereas products derived from the algae oil (such as Omega-3 supplements) can achieve prices of **£700-1,700 per kg**. Algae growth can be accelerated for industrial production.

Microalgae grow via photosynthesis using light and CO_2 as inputs. There are two general methods for producing microalgae industrially: open raceway ponds and **closed photobioreactors**. The latter is of interest for higher value products due to increased control over contamination, growing conditions, and evaporative losses. Photobioreactors act to accelerate algae growth through providing optimised conditions: maximising light penetration and controlling gas concentrations in the growth medium. Key design components are:

- **Transparent growing tubes** through which the algal medium is pumped. These are designed with a large surface area-to-volume ratio to increase light penetration.
- **Degassing** in which excess oxygen is removed from the medium.
- **Harvesting** of algal biomass via gravity settlement or centrifuge.

Photobioreactors can be placed outside to exploit natural illumination or located in **indoor facilities that are artificially lit**. In Scotland the use of intermittent excess renewable energy for algae growth has been demonstrated in Scotland as part of the ASLEE (Algal Solutions For Local Energy Economy) project[46].

Further developments of the technology in the areas of photobioreactor design (e.g. condition control to optimise growth) and microalgae culturing techniques are needed to lower costs and improve scalability. Optimisation of the process of extraction and purification of products from the raw algal biomass is another opportunity for development.

3.4.2 Why Scotland?

The Scottish aquaculture sector provides a local market for Omega-3 fatty acids and dry biomass both of which can be derived from algae. These products are used in fish-feed which represents a £290m market in which Scotland currently relies mostly on imports of raw materials. **There is a growing supply gap for fish-feed components** (especially Omega-3) as traditional supplies come from caught wild fish, which cannot sustainably be exploited further due to stressed fish populations. Therefore, development of local supply chains for feed ingredients from CO_2 could improve security

---

[46] Algal Solutions For Local Energy Economy (ASLEE)

of supply, reduce cost variability, and have wider sustainability benefits related to reducing reliance on caught wild fish. The Scottish company MiAlgae is already developing Omega-3 products from microalgae using whisky by-products (pot ale and spent wash) as inputs, illustrating the existing interest in development of such local supply chains.

Opportunities for Scotland exist in research and development using Scottish biotechnology expertise. Developments are needed in microalgal culturing such as screening of new species or improving existing strains by genetic engineering, as well as characterising strains of interest to understand impacts of unknown algal metabolites and potential impurities on consumers. These could benefit from expertise within the Scottish biotechnology sector. In addition, several Scottish companies have expertise in pharmaceutical and therapeutics manufacturing, which could be used to identify and develop applications for algal products. For example, BASF have a facility for Omega-3 and Omega-6 purification located in Callanish.

3.4.3 Investment and jobs

Using the method outlined in Box 2, we investigated the investment required for a single reference plant and conducted an economic assessment to understand the associated impact on jobs and GVA.

Reference plant[47]: A 628 m^3 tubular photobioreactor plant in Central Germany over a 30-year period in a ‘cold-weather’ climate where cultivation was only possible seasonally without artificial lighting. Cultivation used 116 t CO_2 to produce 64.2 t dry algal biomass per annum. Note that the reference plant is not artificially lit.

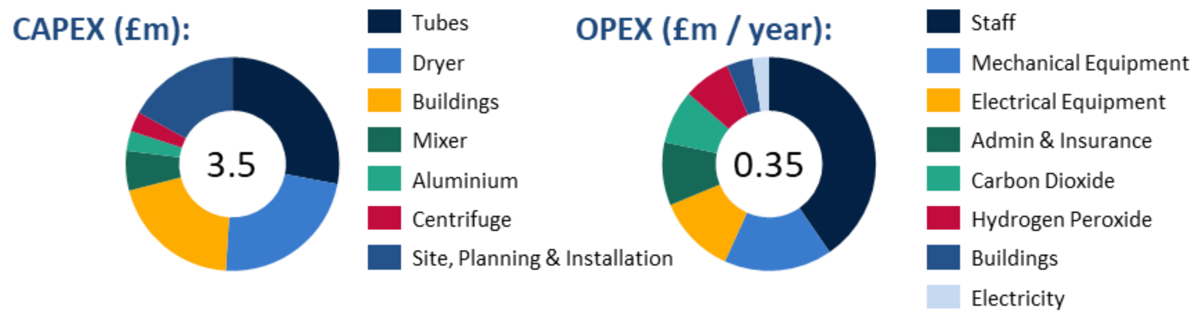


Figure 10: CAPEX and OPEX breakdown for the reference plant for algae biomass growth.

Due to the small-scale of the reference plant presented in Figure 10, the impact data of Figure 11 presents economic impacts for a plant **10 times** the capacity of the above reference plant. In terms of economic benefits, given the much smaller scale of investment compared to fuel production, algae growth could add up to £1m/year to the economy.

---

[47] Reference plant based on analysis by Schade et Meier 2021

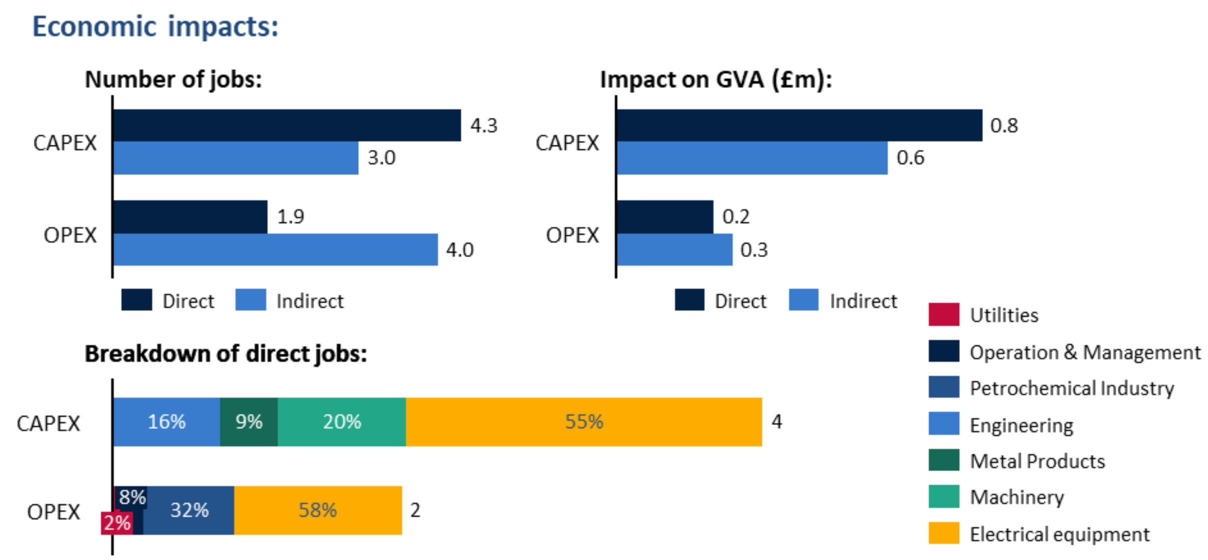


Figure 11: Economic impacts of investment in a methanol plant ten times the size of the reference plant.

3.5 Proteins for agriculture and aquaculture feed

Opportunities overview:

- Fish feed is the largest external expenditure for the Scottish aquaculture sector, with the raw ingredients mostly imported.
- Global supply of conventional raw ingredients (fishmeal and fish oil) is limited, and concerns exist around sustainability of supply (caught wild fish).
- The research and design capabilities of the Scottish biotechnology sector alongside aquaculture nutrition expertise could support development of synthetic feed.

3.5.1 Technology and product

Historically, fish feed is made from inputs of fish oil and fish meal which are derived from ground wild caught fish and fish-waste, such as bones. It is fed to farmed fish to provide protein and nutrients, such as Omega-3. As an alternative to fishmeal for a source of protein, **single-cell organisms** (such as algae, bacteria, fungi) which contain a high percentage of protein can be grown from a substrate that provides carbon, nutrients and energy source to support growth. This process is already established using various substrates (e.g. glucose, methanol) but **interest is growing in using CO_2 directly** as an input. It is claimed that the product has a comparable nutritional profile to fishmeal, with possible advantages being consistent yields, stable pricing across seasons, increased food-security and production close to point of use.

A novel route being developed is the use of **bacteria for gas fermentation in which CO_2 and hydrogen are used as feedstocks**, alongside oxygen and ammonia in small quantities. The equipment used is a fermentation vessel for cultivation, combined with protein recovery steps for separation and concentration which may include heat treatment, centrifuging, drying and homogenisation. Linked technologies are for hydrogen production, which may occur onsite at small scale, and for CO_2 capture. The next steps in technology development require the optimisation of bioreactor design, at-scale testing of gas fermentation, large-scale demonstration and establishing manufacture of components. Initial demonstrations might have a capacity of 20 kt feed per year with large-scale facilities reaching 100-200 kt feed per year[48].

---

[48] Based on developer claims and similar demonstration projects.

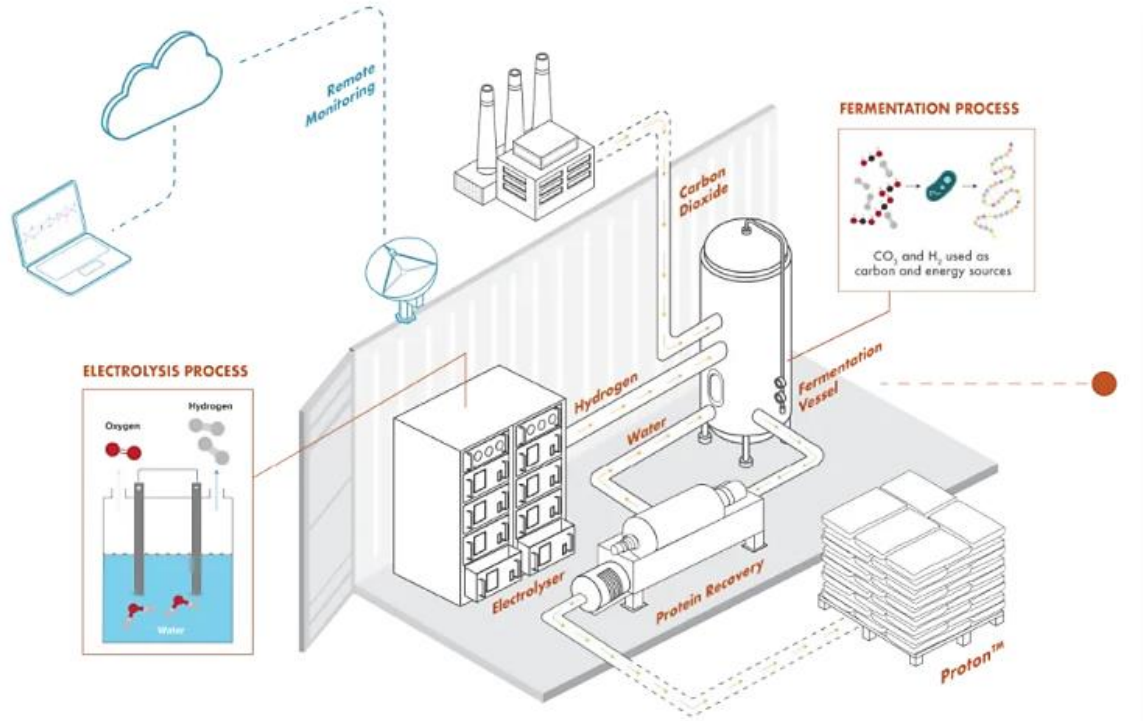


Figure 12: Diagram of the Deep Branch synthetic protein technology

There are several emerging developers globally including SolarFoods, NovoNutrients, Avecom, Deep Branch (Figure 12), Kiverdi, and Lanzatech.

3.5.2 Why Scotland?

Fish feed is the largest external expenditure for the Scottish aquaculture sector. Although there are local supply chains for fish-feed products, the raw ingredients for these products (fishmeal and fish oil) are mostly imported. For example, in 2016 the UK consumed about 100kt of fishmeal of which 70% was imported[49]. In addition, there is an increasing **global supply gap for fish-feed products** which is driving increasing prices and further concerns exist around the sustainability of feeding caught wild fish to carnivorous farmed fish. Therefore, the production of comparable fish-feed ingredients from alternative CO_2 based routes provides an opportunity to develop local supply chains, avoid reliance on imports and potentially unsustainable wild-fishing, and subsequently reduce price-volatility for the industry.

The research and design capabilities of the Scottish biotechnology sector alongside aquaculture nutrition expertise could support technology development. Further development and optimisation of this technology could utilise Scottish biotechnology expertise for the selection and/or design of bacteria to be used in the process, for the optimization of bioreactor design (e.g. to address low hydrogen solubility and safety aspects), or for the development of protein recovery processes. In addition, the expertise in fish nutrition and experience in fermentation equipment may act as further reasoning for development in Scotland (e.g. optimisation and demonstration of reactors).

3.5.3 Investment and jobs

There was insufficient techno-economic data available in the literature to conduct a full economic assessment of protein production using CO_2 feedstocks. However, knowledge

---

[49] Note that some Scottish production of fishmeal occurs in Aberdeen, Greenock, and Bressey

of feedstock requirements and investment claims from developers allowed for an indicative breakdown of product costs.

Reference plant: Production scale of 100 kt 'meal' per year using inputs of 240 kt CO_2 and 43 kt hydrogen per year. Indicative capital investment of USD 340 million.[50]

Cost breakdown (£ per kg meal):

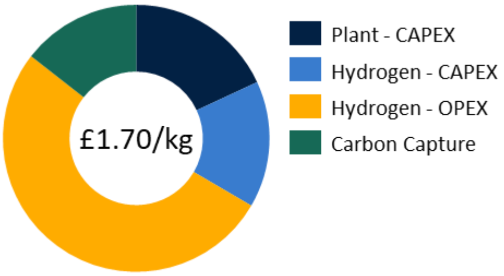


Figure 13: Indicative cost breakdown for proteins from CO_2

It is expected that hydrogen will form a significant component of the overall product costs. The final cost of fish-meal using this analysis has been estimated at £1.70 per kg with hydrogen accounting for 67% of this cost. Several developers claim that the process is competitive with conventional fishmeal (market price of £1.00-£1.20 / kg). A plant of this reference scale is large enough to supply to the UK market and at competitive market prices could achieve annual revenues of over £100 million.

---

[50] CAPEX and input requirements based on NovoNutrients 2018 Presentation with further analysis of costs included in Martinez et al. 2020. Using illustrative cost assumptions of £100 / t CO_2 supply and £0.70 / kg for hydrogen supply. Note that costs for hydrogen are projected to fall with reduced electricity and electrolyser costs.

3.6 Nano-carbon materials

Opportunities overview:

- Scotland is actively investing in advancing its own specialist materials manufacturing capabilities.
- Nano-carbon materials are an emerging, high value market with a broad range of structural, chemical, and electrical applications.
- Production from CO_2 could be orders of magnitude cheaper than conventional routes, which are energy and emission intensive.

3.6.1 Technology and product

Specialised carbon nanomaterials are high strength, flexible and lightweight materials. They are currently used in the automotive and aerospace industries but also have potential applications in electronics, polymers, packaging, batteries, furniture, fire guards, and the military. Nanotubes and nanofibers have the potential to be **principal components in high strength, light weight building materials** for instance in structural applications such as bridges and wind turbines, replacing emission-intensive steel and concrete. Carbon nanotubes also possess several exceptional electrical, thermal, and chemical properties that may be of use in specialist scientific research and biotechnology applications. As an emerging material, new uses of carbon nanomaterials are being developed which could significantly increase demand, especially if the price could be made more affordable.

Current nano-carbon production routes are expensive and complex, with existing applications limited as a result. These production routes require high temperatures and pressures, causing significant energy usage, CO_2 emissions, and expenditure. There have been novel developments in the use of CO_2 as a feedstock to produce carbon nanofibers and nanotubes which could substantially reduce energy consumption and therefore significantly reduce costs. The route also permanently stores the CO_2. There are a few developers in the space with differing technical approaches.

One approach (known as the C2NCT process) proposed by the Canada based Carbon Corp. uses electrolysis in high temperature molten salts to split dissolved atmospheric CO_2 into carbon nanotubes and oxygen. It is reported that this process has **costs an order of magnitude lower than conventional routes** and can be fed directly by flue gases without further concentration. Carbon Corp. has demonstrated their technology as part of the Carbon XPRIZE competition. A commercial scale production facility is expected to be operational by 2022 as part of the Capital Power Genesee Carbon Conversion Centre (GC^3) project. This will have an initial production capacity of 2,500 t of nanotubes per year and once completed will produce up to 7,500 t annually[51].

Another approach patented by Solid Carbon Products (SCP) is based on the Noyes Process and converts CO_2 and hydrogen gas into solid carbon (carbon black and carbon nanofibers) and distilled water. SCP currently operates a small pilot reactor and claims the continuous process lends itself to industrial scaling. SCP also states that their product is cheaper than current manufacturers once scaled to production volumes[52].

3.6.2 Why Scotland?

Scotland is investing in advancing its own specialist materials manufacturing capabilities. Due to a lack of local expertise in lightweight manufacturing technology, many Scottish automotive and aerospace companies rely on overseas production. It is

---

[51] Capital Power 2021, Genesee Carbon Conversion Centre (GC^3) Project

[52] Solid Carbon Products website [accessed Nov 2021]

hoped that ongoing investment will develop manufacturing expertise and capabilities to supply these industries. One example is the development of the Lightweight Manufacturing Centre[53] specifically focusing on evolving components for automotive and aerospace businesses. It aims to integrate new enterprise on next generation materials, and therefore could facilitate the development of carbon nanomaterial applications.

Scottish production of nano-carbon materials could exploit a **growing, high value product market** and supply UK consumption that currently relies on imports. By producing carbon nanomaterials from CO_2, Scotland could gain a competitive advantage through production expertise as well as in the associated development of carbon nanomaterial use in new applications. For example, nanomaterial use in wind turbines and lithium-ion batteries could be developed, which could enable wider decarbonisation of the energy system and proliferation of electric vehicles.

---

[53] Lightweight Manufacturing Centre

4 Key findings and recommendations

4.1 Highlighted CO_2 utilisation pathways

CO_2 utilisation technologies can offer an economic opportunity for Scottish sectors through their development in Scotland. This study highlights emerging CO_2 utilisation technologies that could be developed in Scotland, where opportunities exist for both feasible at-scale deployment and local market potential. Development of these technologies from small-scale pilots towards commercialisation in Scotland could provide economic opportunities for a range of Scottish sectors, ranging from ongoing knowledge creation via research and design, job retention or creation at new facilities, and both local and export market opportunities. Based on feasibility and opportunity considerations, a number of utilisation pathways were selected for further in-depth investigation in this study. These were: proteins for feed, algae for value-products, synthetic fuels for aviation (F-T fuels) and shipping (e-methanol), and lastly carbon nanomaterials. This selection, however, is not exhaustive and other routes may also be of interest in the future.

Gas fermentation and microalgae growth techniques could build on Scottish expertise and have local product markets in aquaculture. The biological conversion pathways of producing proteins from CO_2 gas fermentation and products from enhanced algae growth present an opportunity for biotechnology research and development in Scotland, building on strong Scottish expertise and ambition in this sector. These technologies can be used to produce ingredients for feed (proteins, carbohydrates, Omega-3) which are in high demand for the aquaculture sector but are currently imported into Scotland with increasing volatility of security, price and sustainability. The development of such CO_2 utilisation technologies in Scotland is enabled by the existence of local markets and expertise in fish nutrition. Furthermore, the availability of low-cost renewable electricity enables lower cost hydrogen supplies for the gas fermentation to proteins process, and can provide renewable artificial lighting for algal growth. Additional opportunities lie in pharmaceutical and nutraceutical products from algal oils that could be developed or marketed by Scottish companies with existing experience in this area.

Synthetic fuels could benefit from Scottish renewable electricity and have large market potential driven by policy. Electricity costs for electrolysis are the dominant cost component of synthetic fuels based on hydrogen. Therefore, the high availability of renewable electricity in Scotland and declining electrolyser costs makes Scotland an advantageous location for development of such fuels at competitive costs. Production and distribution of Fischer-Tropsch based fuels could be further enabled by existing crude oil refining knowledge and distribution networks, with possible benefits linked to job retention and continued operation of some assets. Market demand for synthetic fuels from CO_2 is expected to arise from European and UK emission reduction targets and policy incentives. Sub-targets for synthetic kerosene in the ReFuelEU aviation proposals mean that this could represent a considerable export market for Scotland. The UK ambitions for maritime clusters and support for renewable marine transport fuels could present an opportunity for e-methanol at Scottish ports for both local and international markets. Local decarbonisation of Scottish shipping vessels is needed to achieve transport decarbonisation targets, with methanol proposed as one of the main options, and global shipping companies are investing in methanol-powered vessels. In addition, e-methanol could be used in other sectors including as an intermediate to produce synthetic kerosene, in gasoline blending and to produce chemicals and materials.

Carbon nanomaterials are an emerging opportunity linked to high-value lightweight materials and electrical device manufacture. With relatively low market sizes but high product value, the production of carbon nanomaterials from CO_2 could represent a niche area for development and technology leadership. Carbon nanomaterials are of growing interest for applications in high-strength lightweight materials and electrical devices, with links to wind-turbine manufacture and battery developments. The CO_2 utilisation process is also reported to be lower cost than conventional routes. Development of such new and competitive technologies in Scotland could allow early access to this emerging market and would link to Scotland's ambition to increase its expertise in advanced manufacturing.

4.2 Opportunities for Scottish sectors

4.2.1 Research and development

Opportunities exist for academia and research institutes in linked research and development activities. Scottish universities are already active in CO_2 utilisation research, including the University of Aberdeen, University of Edinburgh, and Heriot Watt University. Investment in utilisation technologies or establishment of local technology developers is likely to encourage additional research activities, with linked value in job creation and knowledge leadership. Research opportunities identified in this study include:

- **Microbial design, selection and characterisation** – Biological conversion pathways use microbes such as bacteria and algae to convert feedstocks into dry biomass, natural oils, and other chemical products. The selection and/or genetic design of appropriate microbes, considering the synthesis conditions and product requirements, is an important area of ongoing research for these technologies.
- **Microbial growth technologies** – Optimisation of photobioreactors and fermentation vessels in biological conversion pathways is an area requiring further research, for example to increase yields, improve scalability or energy efficiency, and lower production costs.
- **Catalyst and electrode developments** – Opportunities exist to further develop catalysts used in synthetic fuel pathways, such as in the syngas generation step. Electrode developments are also of interest both for alternative electrochemical fuel production pathways, and for novel carbon nanomaterial routes.
- **Energy efficiency and process optimisation** – In general, development and scale-up of new technologies requires optimisation of the integrated plant set-up to maximise energy and operational efficiencies. For example, plant designs might differ depending on factors such as scale, use of intermittent electricity, or connection to waste heat sources.
- **Product application development** – There are research and design activities associated with developing new applications for products derived from CO_2 utilisation, such as algal oils, synthetic proteins, and carbon nanomaterials. In addition there could be developments in the use of methanol for new fuel applications, such as vessel or engine design in shipping.

4.2.2 Employment and skills

Investment in at-scale CO_2 utilisation benefits linked manufacturing industries and can create new job opportunities. The economic analysis conducted in this study showed that investment would generate jobs in the areas of machinery, metal products, electrical equipment, and engineering. There will also be jobs linked to construction and ongoing operation of new facilities, as well as feedstock supply and product distribution networks. These are expected to be high-skilled jobs, with opportunities to develop new expertise in Scotland.

CO_2 utilisation has potential to support rural and island communities. Whilst not explored in detail within this study, it is worth highlighting that many utilisation technologies are not limited in location by specific feedstock supply chains: CO_2 can be captured from dispersed emitters (e.g. whisky distilleries) or from the atmosphere and hydrogen can be generated using just renewable electricity and water. This provides an opportunity to harness local production at the point of use, and therefore CO_2 utilisation might be of interest for rural and island communities. For example, aquaculture or agriculture sectors currently support rural communities in Scotland and therefore the opportunity to produce feed locally could be of interest.

Expertise from the petroleum and refining sector could be repurposed for synthetic fuel production, protecting at-risk skills. Crude-oil refining is a sector where Scotland has considerable expertise, existing assets, and distribution infrastructure which are at risk of becoming obsolete in the transition to Net Zero. The production of a synthetic crude product from CO_2 and hydrogen via the Fischer-Tropsch process could allow such assets and expertise to be repurposed, with the product requiring similar downstream processing (e.g. hydrocracking) and distribution to conventional crude. The methanol route could also benefit from similar skills and could utilise infrastructure such as tanks and bunkering.

4.2.3 Market potential and integration

Some products can feed directly into local supply chains and distribution networks. Proteins, algal biomass, and Omega-3 oils could be used directly as raw ingredients by existing feed manufacturers in Scotland, replacing imported alternatives and providing an immediate local market opportunity as products are cost-competitive. Fischer-Tropsch fuels are of interest as a drop-in replacement for aviation fuel but can also be used directly for diesel and gasoline applications. Policy incentives would be required to make this economically viable due to the cost-premium of these fuels compared to conventional fossil products. Methanol and carbon nanomaterials do not have significant existing market opportunities in Scotland, requiring further development or incentivisation of applications.

CO_2 utilisation pathways can be profitable but may require new incentives. Developers for proteins and carbon nanomaterials claim that their processes are cost competitive with conventional products, and therefore are less reliant on additional support to penetrate markets following development. In comparison, synthetic fuels from CO_2 are reported to be over twice the costs of conventional fossil-fuels currently and therefore market demand for such fuels is dependent upon additional incentives such as renewable fuel obligations. The EU directive RED II currently mandates 14% by 2030 renewable origins for fuels in road and rail transport, however this can be achieved with biological alternatives many of which are lower cost than synthetic fuels from CO_2. Proposed updates to RED II are expected to include sub-targets for renewable fuels of non-biological origin in both road transport and aviation, creating a distinct market for synthetic fuels in Europe. Similarly, the UK RTFO incentives cover the development of low-carbon fuels within the UK.

4.2.4 Lifecycle emissions and environmental impacts

To understand whether a utilisation pathway provides overall environmental benefits, a cradle-to-grave[54] lifecycle assessment is needed. This should include appropriate system boundaries and could be a comparative assessment - comparing the product produced via utilisation to the product produced via the conventional production route. It

---

[54] A lifecycle assessment term referring to the full product lifecycle, including production and supply of the raw materials, production of the product, transport and use of the product, and final end-of-life disposal.

is important that any comparative assessment is clear about the counterfactual case(s) chosen, and ideally that this case considers future decarbonisation strategies. For example, it is particularly important to clarify assumptions around whether the utilised CO_2 would otherwise have been emitted or sequestered. To understand the potential impact of deployment in Scotland, appropriate energy sources and counterfactual production routes should be selected to ensure relevance to Scotland. Further details on the consequences of different assumptions are illustrated in a recent International Energy Agency Greenhouse Gas (IEAGHG) study “CO_2 utilisation reality check” conducted by Element Energy[55].

For a basic indication of impacts without a lifecycle assessment, the following factors could be considered:

- **Energy source:** For energy intensive processes, for example those using hydrogen from electrolysis, the emission intensity of the energy source is key. Several studies indicate that use of renewable electricity is needed to achieve benefits in power-to-liquid utilisation routes.
- **Counterfactual product:** If the product produced from utilisation acts as a substitute for a product that would otherwise be emission- or resource-intensive to produce then the utilisation pathway could provide environmental benefits. However, it is worth considering if there are ways that counterfactual emissions may reduce in future or if another low-carbon product could act as an alternative substitute.
- **Alternative CO_2 destination:** It is typically better to preferentially utilise CO_2 that would otherwise not have been abated or would otherwise be atmospheric – for example, using CO_2 from difficult to abate point sources. This is, however, dependent upon the environmental impacts of capturing such CO_2. Use of CO_2 that could otherwise be sequestered can still lead to benefits if an emission-intensive product is replaced.
- **Origin of CO_2:** Linked to the above point, in the long-term, the use of biogenic CO_2 or CO_2 from direct air capture may be preferable, to allow creation of a product that no-longer relies on fossil resources. Under net-zero decarbonisation pathways, fossil-CO_2 would likely otherwise be abated (e.g. via fuel switching or sequestration) and therefore utilisation of fossil-derived CO_2 in short-lifetime products could prolong the emission of fossil-derived CO_2. In the near-term, this however should be countered with a consideration of the emission intensities associated with CO_2 capture techniques as well as the near-term ability to abate the fossil-CO_2.

Note that although permanence of CO_2 sequestration in the product might be considered an important factor, this is not necessarily a requirement for environmental benefits to be achieved when considered relative to a counterfactual case. If a more comprehensive approach is taken for energy intensive routes, the wider impacts of energy consumption could be included – for example, energy consumption for utilisation could inhibit decarbonisation of other sectors. This issue has received similar attention for hydrogen production, with the principle of additionality for renewable energy supply being proposed for ‘green hydrogen’ recognition in the revised EU renewable energy directive.

4.2.5 CO_2 accounting

It is important for CO_2 accounting that the avoidance of CO_2 emissions should only be counted once, whether that be by the industrial emitter or by the final product user (e.g. fuel consumer). This requires guidelines to be set for CO_2 accounting in utilisation

---

[55] IEAGHG 2021, CO_2 Utilisation Reality Check: Hydrogenation Pathways

pathways. A recent proposal for the EU emissions trading scheme (ETS) includes encouragement of CO_2 utilisation with guidance that emissions liability should remain with the CO_2 producer (i.e. the site from which CO_2 is captured)[56]. This would mean that in cases where CO_2 is permanently chemically bound in a product the CO_2 producer would not need to surrender EU ETS obligations, whereas in the case where the utilised CO_2 is later emitted (e.g. synthetic fuels) those emissions should be accounted for under the original activity from which the CO_2 was captured. To support the development of CO_2 utilisation in Scotland, similar accounting guidelines need to be established in the UK to ensure utilisation pathways can claim the benefits of CO_2 use appropriately.

4.3 Unlocking the Scottish potential

This study concluded that a broad set of CO_2 utilisation technologies are at the stage where a demonstration project is the next development step. There are numerous existing developers announcing demonstrations of their technologies across Europe, including in the UK. For Scotland to be able to unlock the full potential of CO_2 utilisation, the following factors should be considered:

- **Funding will be required to increase the TRL level.** This study has identified CO_2 utilisation for protein, synthetic fuels, methanol, algae and nanomaterial productions as particularly relevant technologies for the Scottish context. Further funding, under the form of Research, Design and Development support, would be required for Scotland to demonstrate these technologies and ensure the development of the sectors. Technologies that are already established may benefit from demonstrations for new applications or feedstocks.
- **CO_2 utilisation may benefit dispersed sites or small-scale emitters where capture, transport & sequestration is challenging.** CO_2 utilisation may provide an alternative to emitters where CO_2 capture, transport and sequestration is particularly challenging – such as rural or small-scale emitters. In some cases, the CO_2 specifications (purity, pressure, concentration) for utilisation may be less stringent than for transport and storage.
- **CO_2 utilisation can offer economic opportunities for emitters of biogenic CO_2 able to easily capture their emissions (e.g. distilleries).** For the purpose of circularity and developing close to net-neutral products, it is advisable to prioritise capture of biogenic or atmospheric CO_2. The distilling sector is an area where capture for CO_2 utilisation could have distinct relevance due to: the dispersed small-scale nature of the emitters (making alternative sequestration challenging), the biogenic CO_2 origins (offering net-neutrality for products), and high CO_2 concentrations that facilitate capture.
- **The relevant scale and investment requirements vary with technology and application.** It must be noted that the appropriate plant size of an 'at-scale' facility varies with utilisation pathway, and any decision around funding or locating CO_2 utilisation facilities should consider the impact of the pathway on scale. For example, demonstration projects for synthetic fuels may use between 5-15 ktCO_2 per year whereas a typical bioreactor would be using 0.1 ktCO_2/year. Equally, risks can vary if market demand is not guaranteed.
- **Whilst some products can be cost-competitive and feed directly into local supply chains, other products require new policy incentives or development of new applications.** This study highlighted the inherently higher costs compared to the market's willingness to pay for products produced via CO_2 utilisation, with only e-fuels currently being covered by some emerging policies. A wide range of demand-side measures can aid the creation of a competitive market and give

---

[56] Brussels, 14.7.2021 - COM(2021) 551 final

investors the confidence required to scale-up CO_2-utilisation technologies. Such measures include new standards for products, mandates for uptake of e-fuels or CO_2-derived proteins, and green procurement mechanisms.

- **Close integration of value chains and synergies with existing industries should be considered when locating utilisation projects.** Many CO_2-utilisation pathways require additional raw materials, apart from CO_2, such as hydrogen or waste stream. Thus, it is important that deployment of CO_2 utilisation facilities exploit synergies with other emerging projects across Scotland, such as the hydrogen deployment around Islands or the East Coast. Similarly, certain CO_2 utilisation pathways, such as synthetic fuels, would be able to leverage existing supply and distribution chains, which should be considered in locating future projects.

Whilst this study provides an overarching review of the applicability of different utilisation pathways to Scotland, the following areas were not considered in great detail and would benefit from further work:

- Detailed assessment of the market, policy and regulatory factors needed to enable the commercialisation of different CO_2-based products.
- Mapping of the variety and relative contributions of different Scottish CO_2 sources to CO_2 utilisation pathways – for example, considering costs of capture and transport, potential drivers for utilisation, fit with emerging policy support, and long-term CO_2 availability considering industrial decarbonisation and net-zero.
- Consideration of the potential competition for different CO_2 sources (e.g. high purity biogenic) and the potential value given to different types of CO_2 sources for use across various applications.
- The integration of CO_2-utilisation with other circular economy pathways, considering ways in which industrial activities could become more resource efficient and rely less on virgin materials.
- The economic potential for communities located around CO_2-utilisation hubs, such as around distilleries or fisheries.
- A comparative techno-economic assessment to identify the relevant advantages or disadvantages of locating CO_2 utilisation in Scotland compared with other geographies.
- In addition, given the wide geographic and resource variability of Scotland, the potential for CO_2 utilisation in different regions of Scotland should be assessed (e.g. Grangemouth vs Scottish islands)
- A comparative lifecycle assessment of different utilisation pathways, considering both the end-of-life of CO_2 based products and the impacts of the conventional products they would substitute.
- Assessment of the Scottish supply chain and skill-base required for the development of different utilisation pathways

5 References

Algal Solutions For Local Energy Economy [website - https://aslee.scot/]

Capital Power (2021) Genesee Carbon Conversion Centre (GC3) Project

Carbon Recycling International [website - https://www.carbonrecycling.is]

Climate Change Committee (2020) Sixth Carbon Budget

Element Energy and Vivid Economics (2021) CCUS Economics Impacts Study

Element Energy (2020) Hydrogen in Scotland: The Role of Acorn Hydrogen in Enabling UK Net Zero

European Commission (2016) Techno-economic and environmental evaluation of CO2 utilisation for fuel production

Eurostat Oil & Petroleum Product Overview [website]

International Council on Clean Transportation (2019) The cost of supporting alternative jet fuels in the European Union

International Energy Agency - GHG (2018) GHG Emission Accounting for CCU Technologies – Synthesis of Research Findings

International Energy Agency - GHG (2021) CO2 Utilisation Reality Check: Hydrogenation Pathways

International Renewable Energy Agency (2021) Innovation Outlook: Renewable Methanol

Johnson Matthey (2021) JM technology selected for world's first climate neutral methanol plant [website article]

NovoNutrients (2018) Food from CO_2 [presentation]

Maersk (2021) A.P. Moller - Maersk accelerates fleet decarbonisation with 8 large ocean-going vessels to operate on carbon neutral methanol [press release]

Martinez et al. (2020) Potential of microbial protein from hydrogen for preventing mass starvation in catastrophic scenarios. https://doi.org/10.1016/j.spc.2020.08.011

Offshore Energy (2021) GEG, Proman to build renewable power to methanol plant in Scotland [website article]

Pale Blue Dot Energy (2019) Acorn Hydrogen: Project Summary

ReFuelEU Aviation - Proposal for a regulation - COM(2021)561

Schade and Meier (2021) Techno-economic assessment of microalgae cultivation in a tubular photobioreactor for food in a humid continental climate. https://doi.org/10.1007/s10098-021-02042-x

Scottish Government (2020) Aquaculture sector - wider economic impacts: estimates

Scottish Government (2020) Scottish Hydrogen Assessment

Scottish Government (2020) Protecting Scotland, Renewing Scotland

Scottish Government (2020) Businesses in Scotland: 2020 tables

Solid Carbon Products [website - https://www.solidcarbonproducts.com]

Sunfire (2020) Norsk E-Fuel Is Planning Europe's First Commercial Plant For Hydrogen-Based Renewable Aviation Fuel In Norway [press release]

6 Appendix

6.1 Technology Readiness Levels

The table below details a technology readiness scale used to describe the development stage of novel, innovative technologies. The descriptions in Table 5 are taken from the guidance note for the UK's DAC and GGR demonstration programme, and are seen as relevant to the development of CO_2 utilisation technologies.

Table 5 Technology Readiness Level (TRL) scale[57]

Research and development	
TRL 1 – Basic Research	Scientific research begins to be translated into applied research and development.
TRL 2 – Applied Research	Basic physical principles are observed, practical applications of those characteristics can be 'invented' or identified. At this level, the application is still speculative: there is not experimental proof or detailed analysis to support the conjecture.
Applied Research and Development	
TRL 3 – Critical Function or Proof of Concept Established	Active research and development is initiated. This includes analytical and laboratory studies to physically validate analytical predictions of separate elements of the technology. Examples include components that are not yet integrated or representative.
TRL 4 – Laboratory Testing/Validation of Component(s)/Process(es)	Basic technological components are integrated to establish that the pieces will work together.
TRL 5 – Laboratory Testing of Integrated/Semi-Integrated System	The basic technological components are integrated with reasonably realistic supporting elements so it can be tested in a simulated environment.
Demonstration	
TRL 6 – Prototype System Verified	Representative model or prototype system is tested in a relevant environment.
TRL 7 – Integrated Pilot System Demonstrated	Prototype near or at planned operational system, requiring demonstration of an actual system prototype in an operational environment.
Pre-commercial development	
TRL 8 – System Incorporated in Commercial Design	Technology is proven to work - actual technology completed and qualified through test and demonstration.
TRL 9 – System Proven and Ready for Full Commercial Deployment	Actual application of technology is in its final form - technology proven through successful operations

---

[57] From guidance note for the UK's SBRI DAC and GGR demonstration programme (Annex 3, pg. 45-6) - LINK

6.2 RAG Assessment

The RAG assessment of the long-list routes was based on the following three criteria:

- **Relevance of development stage:** Technologies within the TRL range of 5-7 were deemed most aligned with the study objectives. Those below this level of development were not considered as they require further prototyping before demonstration at scale. Higher TRL routes were considered as potentially relevant, due to possible opportunities for demonstration projects to cover novel applications or conversion techniques (such as using different flue-gases, or technologies from emerging developers).
- **Feasibility of deployment:** This criterion scored the feasibility of developing and deploying technologies in Scotland. It considered factors such as the availability of required feedstocks, the existence of relevant supply chains, industries and expertise, and the options for product distribution.
- **Economic opportunity:** This criterion scored the potential market opportunities for Scotland, considering factors such as the potential scale of product demand, product value, competitive advantages for development in Scotland, existing local off takers or distribution networks, and any additional economic opportunities, such as job or asset retention or improving security of supply.

This assessment was used to quickly identify some priority technologies of interest to be considered in detail within the study. It therefore did not involve a comprehensive review of each technology. The factors considered in the assessment are outlined in Table 6 - below.

*Table 6: Assessment of Scottish CO_2 use opportunities (triangles indicate **strong**, **moderate**, and **weak** performance against criteria, considering available evidence).*

Pathway	Development Stage	Feasibility of deployment in Scotland (feedstocks and existing expertise)	Economic opportunities for Scotland (product demand and future markets)
Agriculture and Food			
Formate and formic acid production for agricultural applications (via chemical conversion)	✓ Existence of prototypes and small-scale pilots globally ✓ No large-scale demonstrations ◣	✓ Hydrogen and high purity CO_2 feed available ✓ Existing chemicals sector, with expertise in research and development and skills from local universities ✓ Existing industry for agrochemical actives manufacture (CalaChem site in Grangemouth) ✓ Product requires minimal subsequent processing for silage applications ✗ Electrochemical and biological conversion routes may be an unfamiliar production process ◣	✓ The availability of low-cost renewables (or hydrogen) and high purity CO_2 streams (e.g. from fermentation) provide optimal economic conditions for production via both routes. ✓ Formic acid is used as an antibacterial and preservative agent in silage. Silage is in demand by Scottish sheep and cattle farmers and is produced locally, with several Scottish business linked to feed additive supply. ✓ In the future, there could be further opportunities for formic acid as a chemical intermediate or a more environmentally friendly alternative to other strong acids. Formic acid is also of interest as a hydrogen or energy carrier. ✗ However currently formic acid production is a small market (< 1Mt globally) ◣
Formic acid for agricultural applications (via biological conversion)	✗ Laboratory and reactor prototype stage ◣		
Proteins for aquaculture and agriculture feed (via biological conversion)	✓ Existence of prototype and pilot projects (e.g. ASLEE, NovoNutrients, DeepBranch) ◣	✓ Depending on pathway, access to feedstocks unlikely to be a barrier (e.g. some routes use by-products from distilleries as nutrients) ✓ Process and equipment may have similarities with existing industries ✓ Existence of downstream supply chains for feed ◣	✓ Fish feed accounts for over a third of spending in the Scottish aquaculture sector, and is the main variable cost for companies producing salmon. ✓ Existing Scottish production of fish feed relies on raw feedstocks that are often imported (e.g. fish oil, fish meal, rapeseed oil, soy meal and wheat). The CO_2 utilisation route could therefore improve security of supply and lower cost variations. ◣
Omega-3 (fish oil) for aquaculture feed (via biological conversion)	✓ Lanzatech has a small pilot-plant ◣	✓ Access to feedstocks unlikely to be a barrier ✓ Biotechnology expertise in Scotland ✓ Existing production of Omega-3: (E.g. BASF on Isle of Lewis) so potential existing supply chain ◣	✓ Links to Scottish aquaculture industry (e.g. salmon farming) - as above ✓ Globally there is a growing supply gap for omega-3 fatty acids, with most being sourced from finite marine fisheries and used in aquaculture feed. ✓ Evidence of industry interest in producing omega-3 via alternate routes (e.g. MiAlgae in Edinburgh production from whisky by-products) ◣

Proteins as human food-substitutes (meat, dairy, eggs) (via biological conversion)	✗ Lab-stage R&D	✓ Access to feedstocks unlikely to be a barrier ✓ Biotechnology expertise in Scotland ✓ Fermentation process and equipment may have similarities with existing industries ✗ May lack downstream distribution options	✓ Growing UK markets for alternative meat products ✗ Regulatory barriers could act as a barrier to uptake due to more stringent requirements than protein use in feed
Chemicals and Polymers			
Methanol as a chemical intermediate (methanol from chemical conversion)	✗ Several existing demonstration projects with plans for more commercial plants	✓ Hydrogen and high purity CO_2 feed available ✓ Existing chemicals sector, with expertise in research and development and skills from local universities ✗ Electrochemical reduction technology is an unfamiliar production process ✗ No existing local production of methanol as a chemical was identified, so local downstream supply chains may not exist	✓ The availability of low-cost renewables and high purity CO_2 streams (e.g. from fermentation) provide optimal economic conditions for production. ✓ Some demand interest in alternative carbon sources for chemicals (e.g. Unilever) ✓ **Production interest:** Global Energy Group and Proman plan to develop a green methanol plant at the Nigg Oil Terminal in Scotland, using CO_2 from industry. ✓ Methanol is currently net-imported to the UK – likely some local demand from CalaChem and laboratories ✗ **Limited CCU demand:** Production costs are expected to be twice that of conventional fossil-methanol and there is currently a lack of low-carbon incentives to justify purchase at this cost premium. Therefore, demand may be limited. ✗ Commodity rather than high value chemical (80 Mt global demand as a chemical) ✗ No known large-scale chemical-goods manufacturing in Scotland
Cyclic and linear carbonates as intermediates for chemical and polymer industries (via chemical conversion)	✗ Already an established production route (e.g. ethylene carbonate from CO_2 and epoxide)	✗ Other chemical reactants, such as epoxides, which are required for these pathways are not currently manufactured in Scotland (although could be derived from ethylene) ✗ Local downstream supply chains may not exist	✓ Ethylene carbonate is used in **Lithium-ion batteries** with increasing demand linked to the growth in battery electric vehicles. The product could therefore be supplied to future UK battery factories. ✓ Process is expected to be cost-competitive (commercialised route) ✓ Currently, ethylene and propylene carbonate are produced in Germany by BASF as the only European industrial producer – potential opportunity for Scotland to expand in this market, however it will need to develop a supply chain.

Ethanol as a chemical intermediate (via microbial gas fermentation)	✓ Commercial from CO, but pilots needed to focus on CO_2 feed ✗ Demonstration planned in UK	✓ Hydrogen and high purity CO_2 feed available ✓ Existing chemical and life sciences expertise in Scotland which could contribute skills to the research and design of engineered bacteria ✓ Fermentation process and equipment may have similarities with existing industries	✓ Some demand interest in alternative carbon sources for chemicals (e.g. Unilever) ✗ Scottish developers such as Celtic Renewables are focusing on bioethanol production from other promising waste stream routes as a low-carbon pathway, which would be in competition with the CCU pathway and perhaps more economic ✗ Commodity rather than high value chemical ✗ Lack of large-scale chemical-goods manufacturing (e.g. Unilever) in Scotland
Transport Fuels			
Methanol for direct use as shipping fuel (methanol from chemical conversion)	✗ Many existing demonstrations and a small-commercial plant ✗ Methanol-powered maritime vessels are already available	✓ Hydrogen and high purity CO_2 available ✓ Existence of chemical expertise ✓ Methanol is already shipped as cargo so infrastructure and standards for handling already exist ✓ Several ports incl. Aberdeen that could be future vessel energy hub ✗ Electrochemical reduction technology is an unfamiliar production process	✓ The availability of low-cost renewables and high purity biogenic CO_2 streams provide optimal economic conditions for production. ✓ Methanol is one of the main alternative fuels proposed for marine transport in the UK Clean Maritime Plan, which also identifies Aberdeen as an interesting vessel energy demand cluster. ✓ **Production interest:** Global Energy Group and Proman plan to develop a green methanol plant at the Nigg Oil Terminal in Scotland, using CO_2 from industry. ✓ **Policy interest:** The DfT plans to include support for renewable maritime fuels of non-biological origin. ✓ Methanol powered vessels are being adopted (e.g. Maersk)
Methanol subsequently converted to kerosene (methanol from chemical conversion)	✗ Existing methanol projects ✓ Methanol-to-kerosene was pre-commercial (1990s) but is not established	✓ Hydrogen and high purity CO_2 available ✓ Existence of chemical expertise ✗ Electrochemical reduction technology is an unfamiliar production process	**Opportunities for synthetic kerosene:** ✓ The availability of low-cost renewables and high purity biogenic CO_2 streams provide optimal conditions for low-cost production. ✓ Scotland has commercial airports in Aberdeen, Edinburgh, and Glasgow. ✓ Due to technical requirements, there are limited low-carbon alternatives for aviation fuels and therefore synthetic kerosene is seen as the main option for sustainable aviation fuel (Scottish aviation CO_2 emissions were 1.5 Mt in 2019) ✓ **Policy interest:** The ReFuelEU Aviation proposed regulation includes mandates for Sustainable Aviation Fuel (SAF) blending and possible sub-mandates for non-biological origin routes.
Ethanol subsequently converted to kerosene (via microbial gas fermentation)	✓ Commercial from CO, but piloting from CO_2 feed ✗ UK demonstration planned	✓ Hydrogen and high purity CO_2 available ✓ Existing chemical and biotechnology expertise which could contribute to the R&D of engineered bacteria	

		✓ Process and equipment may have similarities with existing industries	✓ **Industry interest:** Large-scale pilot project with planned commercial expansion being developed in Norway. ✗ Kerosene from methanol is not currently an ASTM approved route (ASTM: American Society for Testing and Materials)
Synthetic kerosene for aviation blending via F-T synthesis (syngas from chemical conversion)	**F-T fuels from CO_2:** ✓ Well-developed and piloted ✗ Large-scale pilot planned in Norway with intention of commercial upscaling (Norsk e-fuel)	**Feasibility of F-T fuels:** ✓ Hydrogen and high purity CO_2 available ✓ Existing production of refined petroleum products with a connected downstream distribution network. ✗ Existing refinery is not F-T process based so not applicable to repurpose	
Synthetic diesel and gasoline for heavy-duty road transport via F-T synthesis (syngas via chemical conversion)			**Opportunities for renewable diesel and gasoline:** ✗ Targets to decarbonise Scottish transport with limited options for HGVs (CO_2 emissions from HGVs in Scotland were 1.7 Mt in 2019) ✗ Benefits of being a direct drop-in replacement compared to hydrogen alternative, which has been trialled but would require vehicle upgrade ✗ Existing EU policy support for renewable fuels, with emphasis on advanced biofuels and those of non-biological origins. ✗ Algae growth for biofuels reported as unlikely to be economically viable.
Enhanced algae growth for biofuels (e.g. biodiesel)	✗ R&D focused on improving economic viability - likely not ready for large-scale demo	✓ Likely simple access to feedstocks ✓ Existence of biotechnology expertise ✓ Fuel distribution network	
Construction and Manufacturing			
Aggregates from different industrial wastes (via accelerated carbonation)	✗ Existing demonstration and commercial plants for cement and Energy from Waste (EfW) applications	✓ Scotland has a cement site in Dunbar and several waste incineration facilities that could act as sources of alkaline waste. ✓ Existence of local supply and distribution systems (e.g. from quarrying production) ✗ Ash-derivatives are in demand as supplementary cementitious	✓ Production of air pollution control residues (fly ash) in Scotland from EfW facilities is expected to exceed 60 kt per year. This hazardous waste product is currently exported to England for treatment and disposal at a cost. The CCU route provides an opportunity for local treatment and avoidance of additional transport and waste-treatment fees. ✓ Offers permanent CO_2 sequestration for dispersed EfW sites, and could provide opportunities for negative emissions (if coupled with biogenic CO_2 from EfW)

		materials for the construction industry due to a reduction in their availability from coal power. Therefore there could be competition for use of fly ash	✓ Lightweight aggregates are in demand from the construction sector – potential to substitute some uses of quarried products and reduce primary material extraction ✗ Low value product limited to local supply ✗ Profitability mostly reliant on avoidance of disposal fees, however alternative pathways (e.g. supplementary cementitious materials, SCM) could act as competitor for waste and thus reduce value (SCM likely higher value than aggregates)
Pre-cast CO_2 cured concrete using alternative cements (via accelerated carbonation)	✗ Past integrated pilot projects for cement (Solidia) ✓ No known commercial plants	✓ Local production of required mineral products, although geographically concentrated (quarrying, Dunbar) ✓ Skills, experience and equipment for alternative cement manufacture (Dunbar) ✓ Existence of distribution network and demand (vertical supply chains could facilitate uptake if adopted by major player) ✗ Dunbar cement plant may be likely to decarbonise via CCS so there could be limited drivers for switching to alternative cement production routes.	✓ Developers claim alternative cements can provide cost-reductions and possible production efficiencies (e.g. curing time) in comparison to conventional cement ✓ Local curing of concrete products (produced using centrally manufactured cement) could act as a CO_2 disposal pathway for dispersed sites due to storage permanence ✓ Evidence of existing industry interest – e.g. LafargeHolcim and Solidia partnership
Polyol and polyurethane production for chemical and manufacturing applications (via chemical conversion)	✓ Various small-scale pilots, with developers that have not yet deployed at scale	✓ Existing chemical R&D expertise ✓ Process and equipment may have similarities with the existing polymer manufacturing industry in Scotland (polyethylene, polypropylene, elastomers) ✗ The epoxide feedstocks are not currently manufactured in Scotland, although could be derived from ethylene	✓ Polyurethane has a wide range of applications across manufacturing and construction: mainly flexible and rigid foams, as well as coatings, adhesives, sealants, and elastomers. ✓ Downstream supply chains exist in the UK - raw materials for polyurethane systems are supplied by BASF from its plant in Alfreton, Derbyshire. ✓ Carbonate containing polyols from the CCU route could be cost-competitive with conventional polyols. ✗ Globally small market - 20 Mt for polyurethane

Specialist Materials and Niche Products			
Enhanced algae growth for value products	✓ Technology piloted ✓ Ongoing R&D into new algae types and production routes ✗ Some algae routes are already commercialised (e.g. spirulina)	✓ Likely simple access to feedstocks ✓ Existence of biotechnology expertise ✓ Product could be produced at low-volumes, so any initial lack of local demand or distribution networks likely not an issue	✓ Growth of algae for high market value products (e.g. lutein and zeaxanthin) is reported by developers to be profitable (e.g. Hy-Tek Bio) ✓ Products could link to existing life-sciences industries and pharmaceutical and therapeutics manufacturing (e.g. nutraceuticals)
Carbon nanofibers and/or nanotubes for advanced engineering applications (via thermal / other routes)	✓ Several developers that are piloting technology	✓ CO_2 supply available ✓ Product produced at low-volumes, so any initial lack of local demand or distribution networks likely not an issue ✓ Existing nanotechnology expertise within industry and universities	✓ High market value product with the CCU route expected to have significant economic advantages over conventional energy-intensive production routes ✓ The advanced manufacturing sector is an export market for Scotland and high-value manufacturing is a strategic priority for Scotland (e.g. developing the Advanced Manufacturing Innovation District Scotland) ✓ Current uses are in polymers, electrical components and energy storage devices. Promising applications include medical and sensing devices, composites for wind turbines, and chemical catalysts, as well as some interest for hydrogen storage and fuel-cells as well as concrete reinforcement. These link to the chemical and life sciences R&D, manufacturing and future hydrogen sectors in Scotland. There are also links to electric vehicles (Li-ion batteries).
Precipitated carbonate minerals (via CO_2 mineralisation)	✓ Recent early stage pilots and prototypes in progress ✗ Pilots not in advanced stages (further R&D likely)	✗ Access to appropriate feedstock supply (e.g. waste calcium or magnesium brines) may be limited	✓ Claimed to be profitable by developers ✓ Offers permanent CO_2 sequestration that could be beneficial for dispersed sites ✗ Uncertain demand and value of products - e.g. silicon dioxide, $MgCO_3$ and $CaCO_3$

6.3 Economic analysis and impact model

Table 7: Techno-economic references used for economic assessment and their notable assumptions

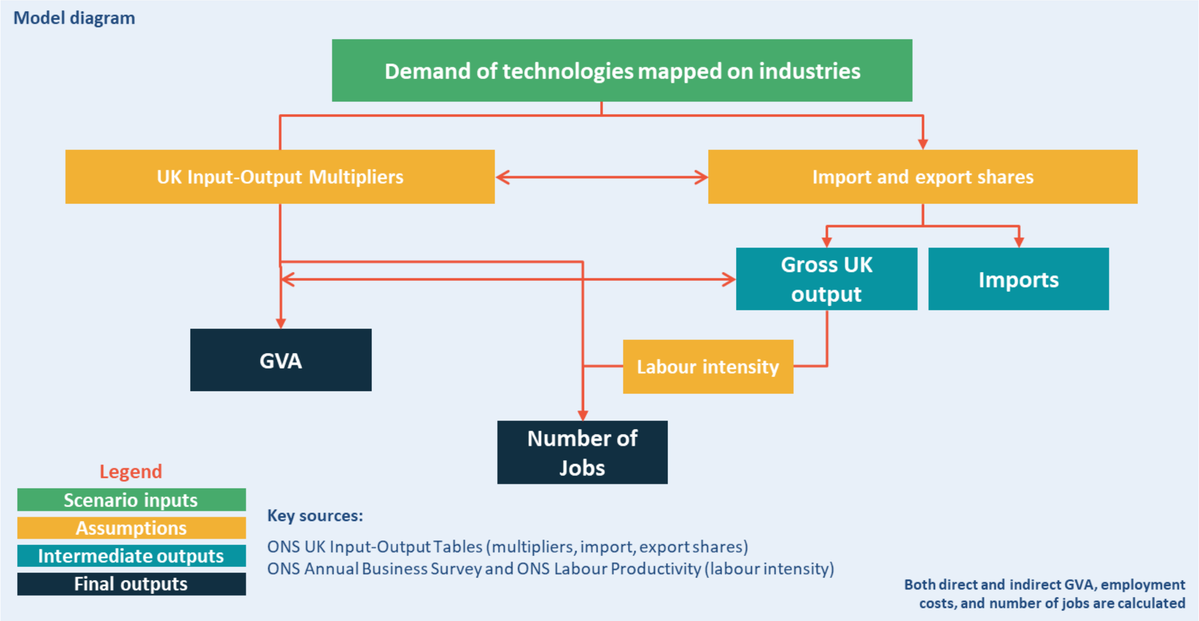
Product and Production Route	Main reference(s) used for economic assessment	Notable assumptions
Synthetic Kerosene RWGS followed by Fischer-Tropsch synthesis.	Basis for economic analysis: Marchese et al. 2020 Additional sources: • German Environment Agency 2016, Power-to-Liquids • Dieterich et al. 2020	Capacity: 210 kt of synthetic crude/ year CO_2 demand: 750 kt CO_2 / year H_2 demand: 103 kt H_2 / year Power: 819 MW (total including that needed for H_2 and CO_2 supply) Electricity price: EUR 100 / MWh CO_2 supplied via DAC: EUR 562 / tCO_2 Operating hours: 8000h / year Hydrogen production and CO_2 capture components included within CAPEX and OPEX breakdown, rather than as a supplied feedstock.
Methanol Direct hydrogenation of CO_2 using a commercial $Cu/ZnO/Al_2O_3$ catalyst.	Basis for economic analysis: Perez-Fortes et Tzimas 2016 Additional sources: • Nguyen et Zondervan 2019 • Meunier et al. 2019 • Perez-Fortes et al. 2015	Capacity: 440 kt of methanol / year CO_2 demand: 640 kt CO_2 / year H_2 demand: 90 kt H_2 / year Electricity use: 12 MWh / t methanol (0.177 MWh w/o electrolyser) Price of CO_2 capture: EUR 38.4 / tCO_2 Price of electricity: EUR 95 / MWh Economic lifetime: 20 years Does not include CO_2 capture analysis but cost of CO_2 supply included. Hydrogen production via onsite electrolysis.
Enhanced Algae Growth Algae growth within tubular photobioreactor (natural lighting)	Basis for economic analysis: Schade et Meier 2021	Volume: 628 m^3 Location: central Germany CO_2 demand: 116 tCO_2 / year Electricity demand: 464 GJ / year Natural gas demand: 221 GJ / year Algae production: 64.2t dry algal biomass / year Economic lifetime: 30 years Seasonal production with no artificial lighting.
Proteins Production of fishmeal alternative from CO_2 and H_2 using Chemoautotrophic Bacteria	Basis for economic analysis: NovoNutrients 2018 Presentation combined with assumptions on the cost of CO_2 and hydrogen. Additional sources: • Martinez et al. 2020	Reference plant scale: 100 kt meal per year CO_2 demand: 240 kt CO_2 / year H_2 demand: 43 kt H_2 / year CAPEX (excl. CO_2 and H_2 supply): £266 million Applied CO_2 price: £100 / tCO2 (£ 2019) Applied H_2 price: £2.62 / kg H_2 (£ 2019) (23% CAPEX, 5% OPEX, 73% electricity)
Nano-carbon materials	No suitable techno-economic reference identified.	

All reported costs adjusted to £ 2019 for analysis.

This study was conducted using Element Energy's macroeconomic impact model. This model has been used successfully in previous consulting projects, such as in quantifying economy-wide benefits including:

- The Hy-Impact series (conducted for Equinor in 2019)
- Analysis of decarbonising the Yorkshire and Humber cluster for the Zero Humber Consortium (2019)
- Assessment of the potential impact of the Acorn project on the Scottish economy (2020).

This model is based on the UK Government's input-output tables, import ratios, and labour statistics. The model uses an input-output methodology, capable of using cost inputs mapped by industrial classifications to generate macroeconomic outputs such as direct, indirect, and induced employment (number of jobs), GVA, and trade (domestic gross output vs imports). Note that the model uses UK specific inputs, rather than Scottish Input-Output Analytical tables (IOT).



Key sources:

ONS UK Input-Output Tables (multipliers, import, export shares)
ONS Annual Business Survey and ONS Labour Productivity (labour intensity)

Both direct and indirect GVA, employment costs, and number of jobs are calculated

- **The UK domestic output** is defined as the difference between demand and imports. The demand mapped on industries is used to calculate the UK domestic output, using historical import shares derived based on the UK's Office for National Statistics (ONS) IOTs[58].
- **Imports** are calculated as the difference between the demand and UK domestic output
- **Gross Added Value (GVA)** is calculated based on the UK gross output, using industry specific multipliers provided by the UK IOTs, following the calculation methodology published by the ONS[59].
- **The number of direct jobs** is calculated based on the relationship between UK gross output and the Labour Intensity for the relevant industries based on the ONS Annual Business Survey (ABS)[60]. The labour intensity is defined as the number of employees required to generate £1m turnover. The ABS provide information for all UK organisations, including number of organisations, the average number of

---

[58] ONS UK input-output analytical tables, 2015 issue

[59] Input-output analytical tables: methods and application to UK National Accounts, ONS, Oct 2017

[60] Non-financial business economy, UK (Annual Business Survey): 2017 provisional results

employees and their turnover, allowing the calculation of the labour intensity. Indirect jobs are calculated based on the number of direct jobs and employment multipliers provided by the UK IOTs.

climate X change

Scotland's centre of expertise connecting
climate change research and policy

✉ info@climatexchange.org.uk
☎ +44(0)131 651 4783
@climatexchange_
www.climatexchange.org.uk

ClimateXChange, Edinburgh Climate Change Institute, High School Yard, Edinburgh EH1 1LZ