UK CHEM 2050

Sustainable Carbon Ambition for the UK Chemicals Industry

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Contents

Glossary

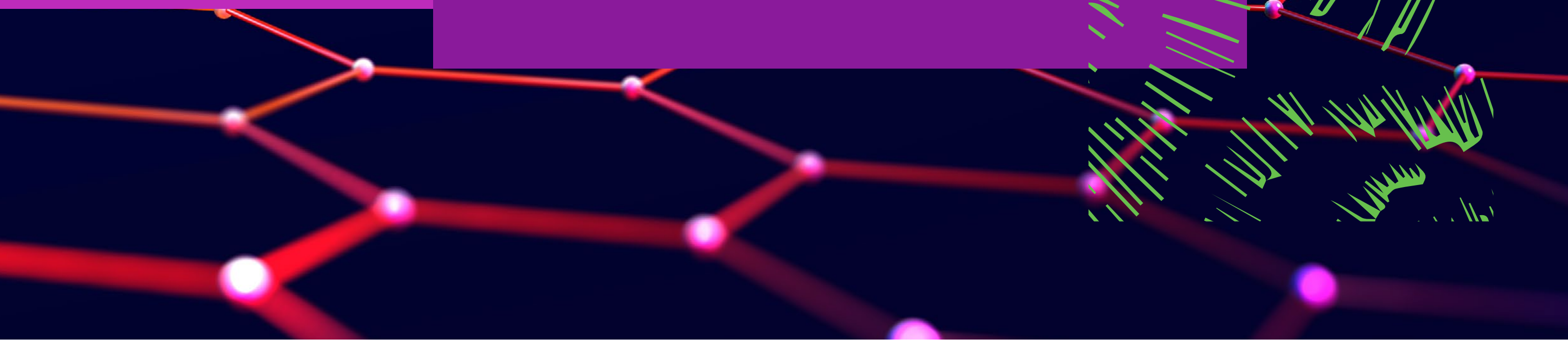
Atmosphere	The planet's carbon cycle associated with the mixture of gases that surrounds the Earth
Atmospheric carbon (AC)	The carbon derived from the atmosphere
Best available carbon	Available carbon that could be used in manufacturing while minimising GHG emissions and any other negative impacts on the environment while maintaining the economic viability of manufacturing
Biomass	Renewable organic material derived from plants and animals
Biosphere	The Biosphere is the part of the Earth, including air, land, surface rocks, and water, within which life occurs and the total sum of living organisms
Biospheric carbon (BC)	The carbon derived from the biosphere
Carbon capture and storage (CCS)	The capture of carbon dioxide (CO_2) emissions from industrial processes and storage in deep underground in geological formations
Carbon capture and utilisation (CCU)	The capture of carbon dioxide (CO_2) emissions from industrial processes, and utilisation in a range of applications through which CO_2 is used directly (i.e. not chemically altered) or indirectly (i.e. undergoes chemical transformation) in various products
Circular economy	The circular economy promotes the model of sustainable production and consumption in which raw materials are kept longer in production cycles and can be used repeatedly, therefore generating less waste
Decarbonisation	The process of reducing the amount of carbon, mainly carbon dioxide (CO_2), sent into the atmosphere
Defossilisation	Reducing dependence on fossil resources and instead using sources of renewable carbon
Direct Air Capture (DAC)	Direct air capture (DAC) technologies extract CO_2 directly from the atmosphere, for CO_2 storage or utilisation
Fossil carbon	Carbon derived from fossil resources

Fossil fuel	Hydrocarbon-containing material (e.g., coal, oil, and natural gas) formed naturally in the Earth's crust from the remains of dead plants and animals that is extracted and burned as a fuel
Fossil resource	Hydrocarbon-containing material (e.g., coal, oil, and natural gas) formed naturally in the Earth's crust from the remains of dead plants and animals that is extracted and used as a feedstock for chemicals production
Geosphere	The planet's carbon cycle associated with the solid parts of the Earth
Geospheric fossil carbon (GFC)	Carbon from crude oil, natural gas (natural gas liquids) and coal used in organic chemical production
Greenhouse Gas	Gases in the earth's atmosphere that trap heat
Organic chemical	Chemical compound that contains a carbon-hydrogen or carbon–carbon bond
Petrochemical	Chemical products obtained from petroleum by refining
Point Source CO_2 Emissions	Point source emissions come from a single identifiable source of pollution
Primary Chemicals	Primary chemicals include ethylene, propylene, benzene, toluene, mixed xylenes, ammonia and methanol
Recycled Carbon	Carbon contained within existing materials that can be recycled to form new chemicals
Sustainable Carbon	Carbon that helps contribute to climate neutrality goals
Technosphere	The Technosphere is the part of the environment that is made or modified by humans for use in human activities. It includes any technologically derived product manufactured by humanity
Technospheric carbon (TC)	Carbon obtained from the technosphere

UK CHEM 2050

Sustainable Carbon Ambition for the UK Chemicals Industry

Chemicals are integral to our lives and bring major benefits to society. They are found in almost everything that we buy, use, eat and drink, and are a vital part of the manufacturing base, with more than 96% of all manufactured products in the UK containing inputs from the chemicals industry.



The chemicals industry is inherently carbon and energy intensive, and unlike other industries, uses fossil resources as both a fuel and as a feedstock - contributing to both fossil-derived production emissions plus release of embodied fossil carbon at end of life. For the past 70 years, the abundance of inexpensive crude oil and natural gas has provided a reliable and cost-effective source of raw materials, and cheap energy, to produce various chemical products, at low prices. This has created significant economies of scale, with the development of large-scale chemical production facilities, and further cost reductions through process optimisation and technological advancements.

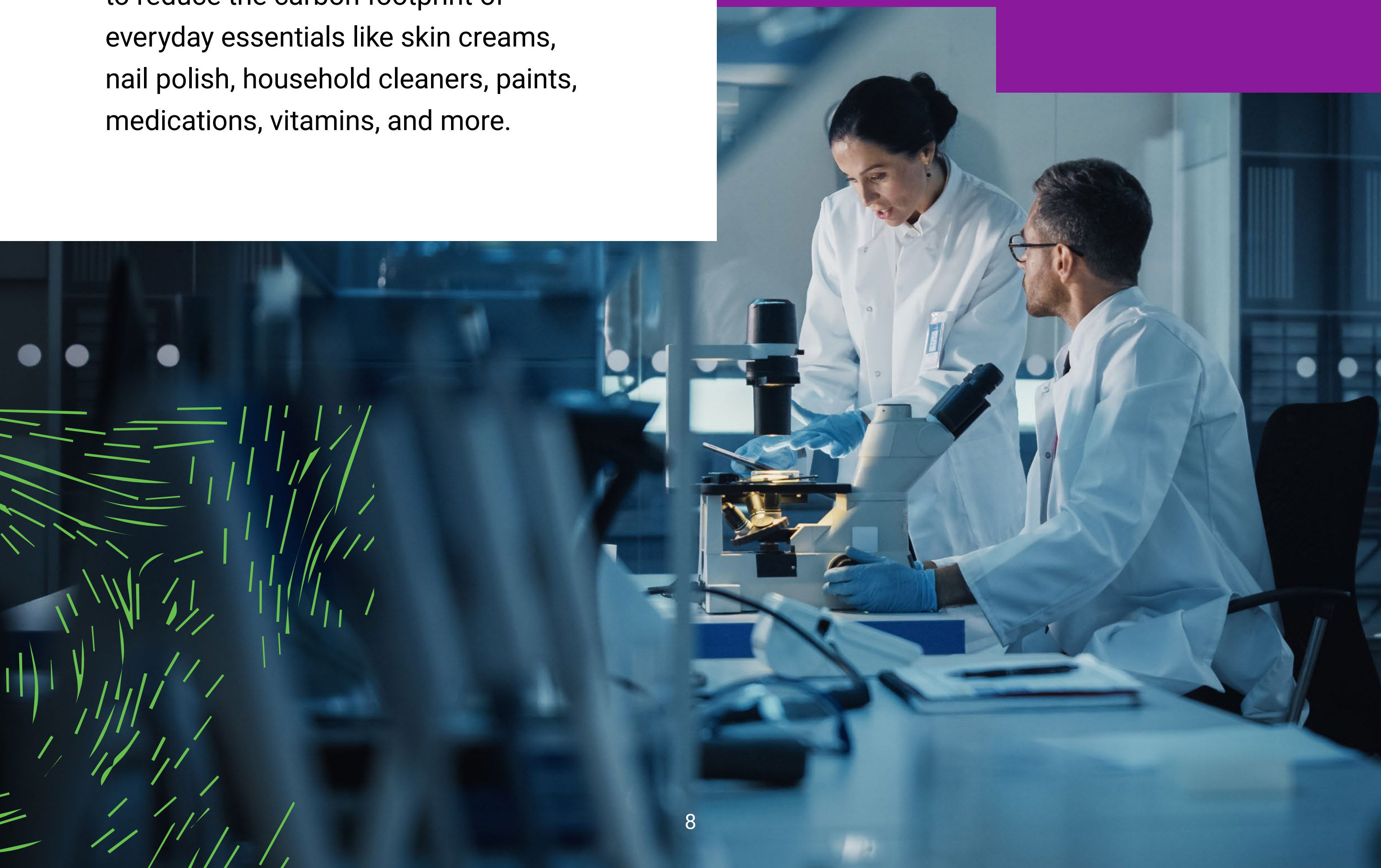
As global temperatures continue to rise, the drive towards a more environmentally friendly economy is not an option, it is an obligation. We simply cannot afford to keep digging up fossil resources and releasing more carbon dioxide into the atmosphere.

A vibrant and sustainable chemicals sector is critical to enabling a rapid transition to a net zero and circular future. However, the chemical sector is responsible for 8% of total global greenhouse gas emissions.

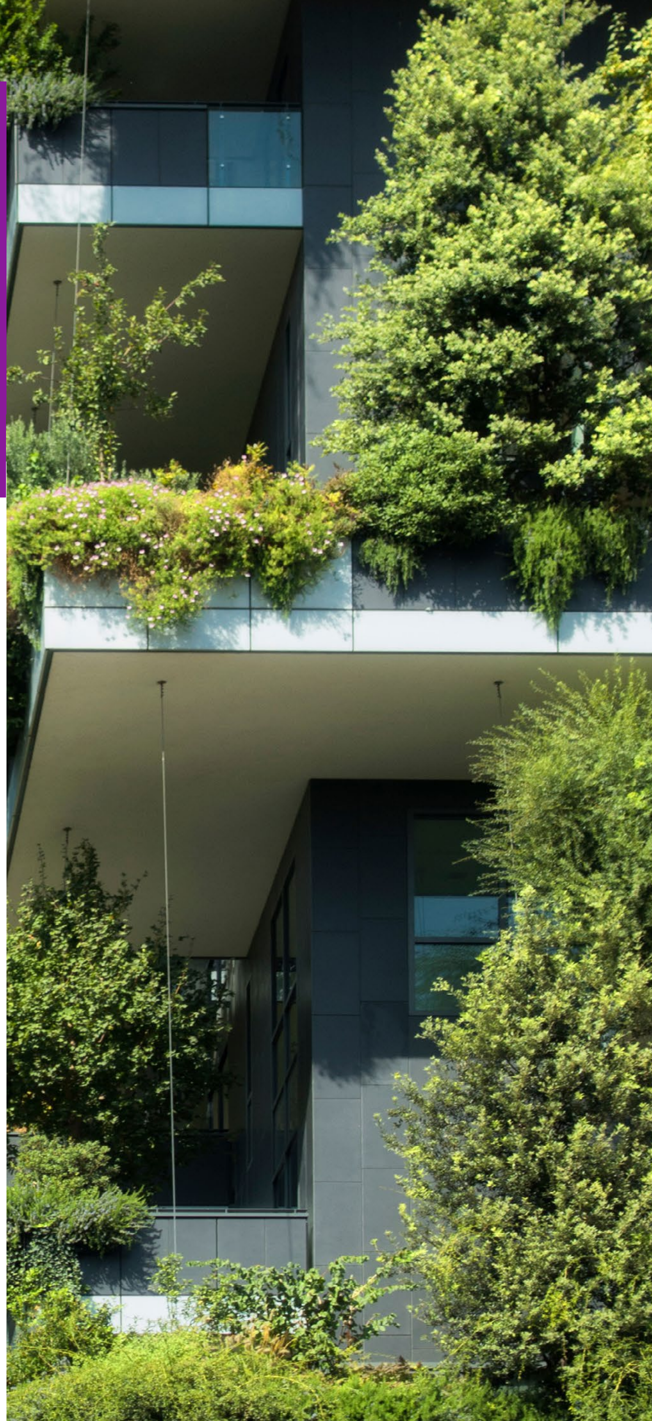
If we want to continue living our lives in the same way, but in a more sustainable manner, then we must completely change the way chemicals are produced and/or ensure that the inputs used in their production are more sustainable. Both approaches are difficult and costly.

Sustainable chemicals, manufactured using sustainable carbon, displace gas- and oil-derived chemicals, helping to reduce the carbon footprint of everyday essentials like skin creams, nail polish, household cleaners, paints, medications, vitamins, and more.

By 2050, the UK chemicals industry will have doubled economic output, but will significantly lower its GHG emissions, sourcing 80% of its carbon requirements from non-virgin fossil, sustainable carbon sources.



1. Executive summary



This is an exciting and important area and we have worked in partnership with senior leaders from industry and academia to create a Sustainable Carbon Ambition for the UK Chemicals Industry.

Stakeholders consulted during the study included large, medium and small businesses, government officials, academics, and trade bodies, covering TRLs 1-9. In total the study has engaged with **255 individuals** from **over 100 organisations,** including:

- **3 government officials**
- **187 from industry**
- **12 from RTOs**
- **9 from Trade associations**
- **16 from UKRI,**
- **24 academics**

98%

of stakeholders believe that we need to **transition away from using fossil resources** as a feedstock for the UK chemicals industry

100%

of stakeholders agree that until fossil resources are no longer subsidised, sustainable Carbon feedstocks will not be a **commercially viable alternative**

Low-carbon hydrogen and renewable energy

are **key enablers** for chemicals made from sustainable carbon

UK chemicals industry has

significant supply chain gaps

that need to be rebuilt

>90%

stakeholders believe a transition will not happen without a **long-term industrial strategy**

Ethylene and methanol

From sustainable carbon seen as **critical** for UK chemicals industry

>75%

of UK chemicals should be manufactured from green carbon sources by **2050**

Lack of communication and consumer understanding

of their daily interaction with chemicals is seen as a **barrier**

In 2030 biomass

is the most likely source of **sustainable carbon**

>75%

of stakeholders believe that the UK should either **build its own domestic supply of**, or take advantage of the ability to **import, sustainable carbon feedstocks,** to manufacture chemicals across the full supply chain, from base to speciality chemicals

>95%

Stakeholders believe that the UK chemicals industry **needs to address scope 3 emissions**, and that off-setting should only be used during a transition to Net Zero

Recycled carbon

will not be viable as a sustainable carbon source until **2040**

CO_2

will not be viable as a **sustainable Carbon** source until **2050**

Feedback from stakeholders was used to create an overarching ambition where:

By 2050, the UK chemicals industry will have doubled economic output, but will have significantly lowered its GHG emissions, sourcing 80% of its carbon requirements from non-virgin fossil, sustainable carbon sources.

Four critical observations underpin this 2050 Ambition:

1. No one form of sustainable carbon is available in sufficient quantity or at an acceptable price.
2. There are considerable uncertainties around the availability of all forms of sustainable carbon.
3. Stakeholders agreed all types of sustainable carbon were needed for the chemicals industry to transition away from virgin-fossil carbon
4. Each carbon source has critical limitations
   a. Abated fossil carbon does not fully address end of life emissions.
   b. Biogenic carbon is limited by ecosystem and social impact concerns.
   c. Recycled carbon is limited by collection rates, and delays, rather than eliminating fossil carbon emissions.
   d. Atmospheric carbon is limited by renewable energy requirements and extraction costs.

To achieve this ambition significant investment into key technologies, and policy interventions, are required to increase sustainable carbon feedstock utilisation - by 709% for biomass, 1573% for recycled carbon, and 236,000% for CO_2. Alongside this, low-cost renewable energy, low-carbon hydrogen at scale, greatly increased recycling rates, significant point source carbon capture and regenerative sustainable farming practices are essential.

The UK CHEM 2050 Ambition requires 14.7% of all UK theoretical sustainable carbon available in 2050 from biomass, recycled carbon and CO_2 from CCU. This equates to 22.4% of theoretical carbon available in 2050 from biomass, 11.5% from CO_2 from CCU, and 101.7% from recycled carbon, meaning imports of recycled carbon would be required.

UK chemicals industry

Chemicals are integral to our lives and bring major benefits to society. They are found in almost everything that we buy, use, eat and drink, and are a vital part of the manufacturing base, with more than 96% of all manufactured products in the UK containing inputs from the chemicals industry.[1]

The chemicals industry makes a significant contribution to the UK economy[2] and comprises of 4,415 businesses employing 151,000 people and supporting a further 500,000 jobs in the wider economy. It is a highly productive sector contributing an estimated £203k in Gross Value Added (GVA) per employee, constitutes more than one sixth of total UK research and development (R&D) spend and makes up a substantive proportion of UK manufacturing exports (£54bn).

For the past 70 years the chemicals industry has benefited significantly from the availability of cheap oil feedstock. During this period, the abundance of inexpensive crude oil and natural gas has provided a reliable and cost-effective source of raw materials, and cheap energy, for the production of various chemical products, at low prices. This has created significant economies of scale, with the development of large-scale chemical production facilities, and further cost reductions through process optimisation and technological advancements.

A vibrant and sustainable chemicals sector is critical to enabling a rapid transition to a net zero and circular future. However, the chemical sector is also a significant emitter of greenhouse gas (GHG) emissions. The UK's major industrial clusters (excluding iron and steel clusters) are responsible for 26 $MtCO_2eq$ of GHG emissions per year, with the oil and chemical industry responsible for a significant proportion of these emissions.[3]

The chemicals sector faces a significant challenge in transitioning to net zero as chemicals manufacture is inherently carbon and energy intensive. For most industrial activities, significantly reducing emissions may be challenging but can be achieved by switching from fossil fuel to the use of renewable energy to heat and power manufacturing processes. However, **unlike other industries, the chemical industry uses fossil resources as both a fuel and as a feedstock for manufacturing.** Petrochemicals are fundamentally carbon based (organic) molecules, and so, their production requires carbon and inevitably results in fossil-derived production emissions which is further exacerbated through the release of embodied fossil carbon at the end of the petrochemical's life. Therefore, to achieve real zero emissions, the petrochemical industry must transition from the use of fossil carbon to the use of more sustainable sources of carbon.

Sustainable carbon feedstocks

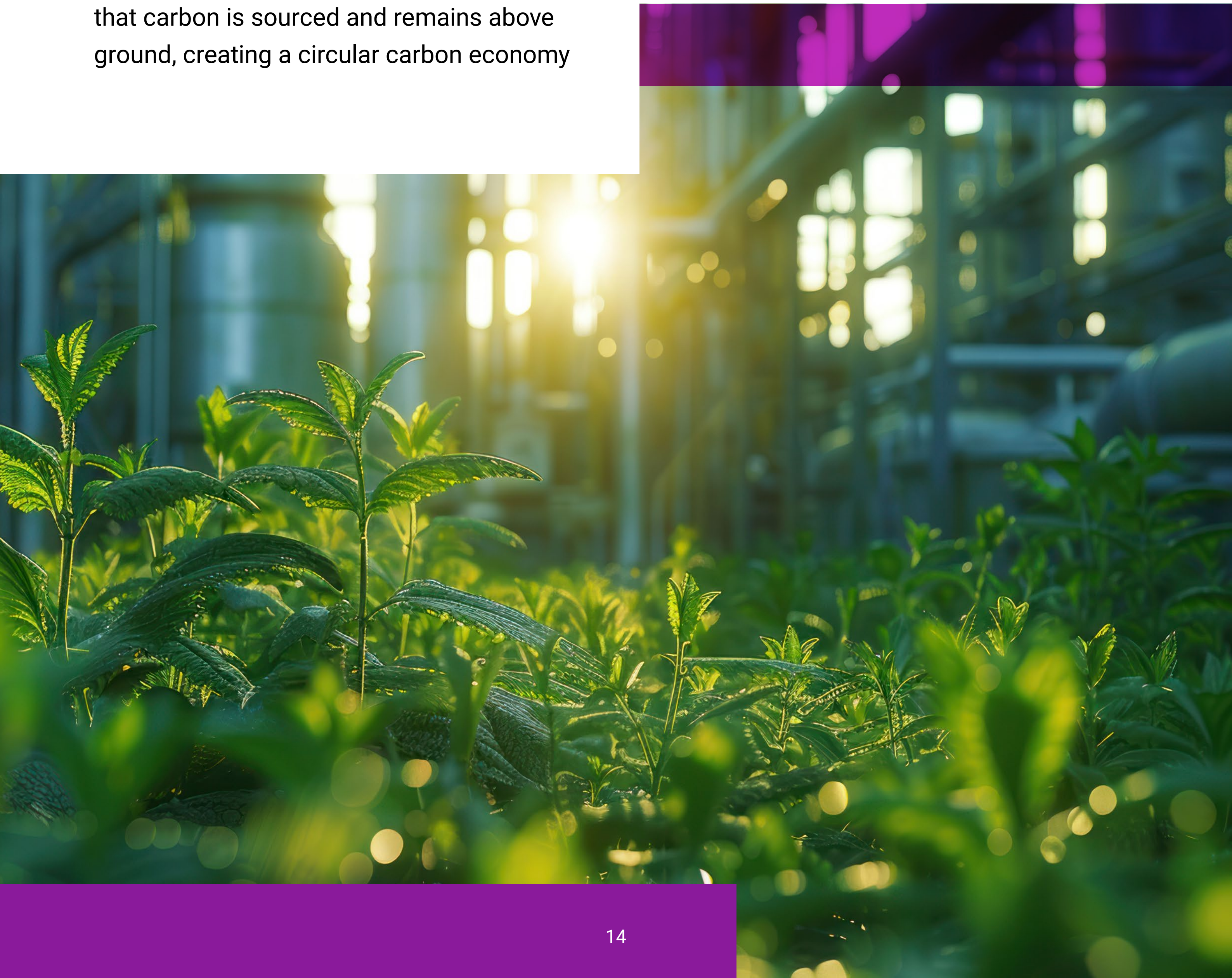
The drive towards a more environmentally friendly economy is not an option, it is an obligation. We simply cannot afford to keep digging up fossil resources and releasing more carbon dioxide into the atmosphere.

To date, the chemicals industry has been using fossil-based carbon essentially because it is cheap and widely available. To date it hasn't switched to using more sustainable sources of carbon, ultimately because that comes with a green premium. Non-fossil-based carbon feedstocks require additional processing before they can be utilised by the sector, which uses large amounts of energy and adds additional cost.

Sustainability shouldn't be seen as a destination - it is a journey. Therefore, the concept of sustainable carbon isn't about a concrete definition of what carbon source is the most sustainable, but rather a developing and constantly evolving view of what would be described as the 'Best Available Carbon' (BAC) for the production of chemicals and chemical derivatives. BAC means the available carbon that could be used in manufacturing, while minimising GHG emissions and any other negative impacts on the environment, whilst also importantly maintaining the economic and technical viability of specific manufacturing processes. Although the focus is placed on CO_2 emissions, the careful management of carbon is required to avoid undesirable and unintended knock-on consequences in other areas of planetary health, such as water availability, air and water pollution, toxicity and biodiversity.[4,5]

This study focuses on the need for sustainable carbon as the raw material for the manufacture of chemicals. Currently carbon-based chemicals (known as organic chemicals) are predominantly (~90%) produced from virgin fossil resources (oil, fossil gas and coal) mined from the Earth's geosphere. Fortunately, alternative carbon sources are available in the form of carbon extracted or recovered from the biosphere, atmosphere, and technosphere. These sources offer the opportunity to reduce, and even halt the extraction of geospheric fossil carbon, preventing any additional fossil carbon derived GHGs from entering the atmosphere. The use of biospheric carbon, atmospheric carbon, and technospheric carbon resources means that carbon is sourced and remains above ground, creating a circular carbon economy coming from feedstocks that can be regrown (i.e. biomass from the biosphere), recycled, captured and utilised (i.e. carbon in multiple forms from the technosphere), or extracted (i.e. CO_2 from atmosphere).

In reality, carbon is widely available and not generally considered a critical material. However, the availability of carbon, when considering economic and environmental sustainability, in the volumes, composition, concentration and consistency required to support a global transition away from the use of fossil resources, is limited, and in this sense, **carbon should be considered a critical material.**



The size of the challenge

Despite the acknowledgement that climate change is one of the most pressing issues for society today, with 196 countries signing the legally binding 2015 Paris Agreement,[6] between now and 2035, cumulative investments in fossil fuel supply, fossil-based power generation and end-uses are currently planned to be $3.6 trillion higher than in the IEA Net Zero Scenario.[7] Much of this investment will be in assets with long lives in which operations would need to be curtailed or lifetimes shortened if the goal of returning the temperature increase to below 1.5 °C is to be achieved.

The challenges involved in moving away from virgin-fossil carbon as a feedstock for the UK chemicals industry are sizeable and incredibly complex, but not unsurmountable. Addressing these challenges will require a coordinated effort involving industry, government, research institutions, and other stakeholders.

Petrochemical production takes place at scale through mature value chains inextricably linked to the refining of fossil resources. It is built around a small number of primary chemicals (ethylene, propylene, benzene, toluene, mixed xylenes, ammonia and methanol). Primary chemicals are converted to chemical intermediates which are further produced into a plethora of chemical and material products.

UK chemical production is based on complex international value chains with the potential for multiple border crossings of intermediate chemicals before the final end product is produced.

Although the UK maintains significant production capacity in primary chemicals, there have been notable chemical plant closures over the last 20 years and it is evident that considerable supply chain gaps exist within the UK's current chemical processing infrastructure.

What were once integrated UK value chains are now fragmented, where ownership of previously integrated and single entity owned plants within clusters (e.g. ICI Wilton), are now disconnected and in some cases mothballed, leading to a hollowing-out of the UK chemicals industry and non-optimal long- term strategies.

There is increasing global competition in primary and intermediate chemical production from regions (particularly from the United States, China and the Middle East) with lower production costs and favourable government policies. The UK is increasingly struggling to compete in the production of chemical intermediates due to high operating costs (energy costs and regulatory environment), the difficulty in attracting investment from global parent companies and skills shortages.

This intense competition poses a threat to the UK's market share and profitability in certain chemicals segments. UK historic strength in some key customer industries (e.g. aerospace and automotive) are also now being fiercely challenged by ongoing Brexit disruption and stronger growth in non-European markets, now manifesting as a medium to long-term impact on investment.

The UK's departure from the European Union (EU) has created many further uncertainties and challenges for the chemicals industry. Potential issues include tariff and non-tariff barriers to trade, regulatory divergence, and disruptions to supply chains and workforce mobility, alongside the uncertainty over the design and implementation of UK REACH.

In addition, the energy crisis, triggered by Russia's invasion of Ukraine, and ongoing civil unrest in the Middle East, is adversely impacting fossil resource cost to the UK chemical industry, cementing the fact that other sources of sustainable carbon for feedstocks are urgently required to ensure the future of a UK chemicals industry.

The UK chemical industry is increasingly positioned as a producer of added value speciality and consumer chemicals. The UK has maintained a competitive advantage in innovative and high value products due to its strong academic and industrial R&D base relative to lower cost regions.

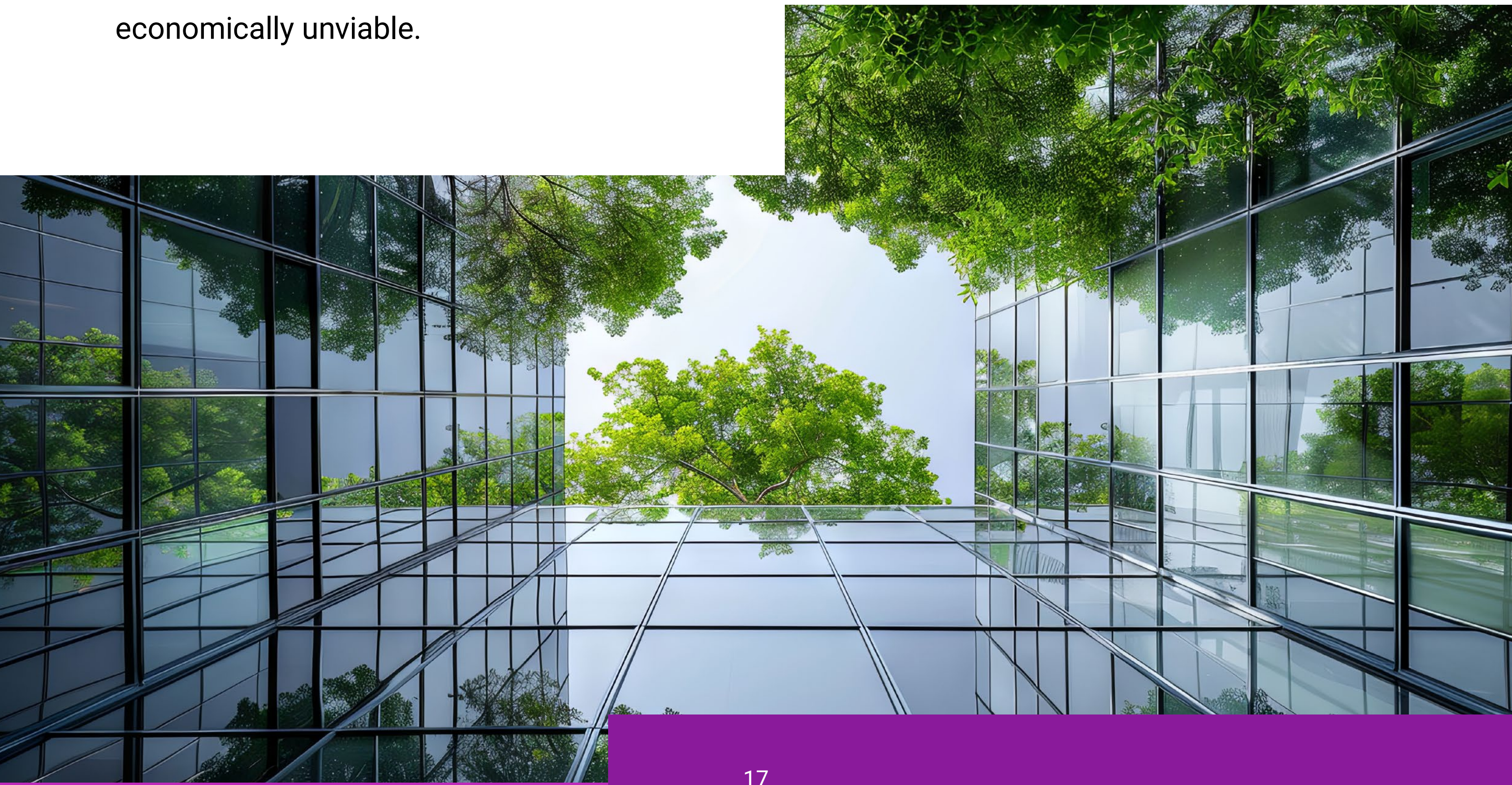
However, this shift has made the UK more reliant on the import of chemical intermediates and therefore the import of significant volumes of embedded fossil carbon.

This study highlights that market failures have created significant barriers to a transition to sustainable carbon as a feedstock for the UK chemicals industry. Therefore, to assess the barriers and levers required, this study is taking an industry-led viewpoint on this challenge, designed to be complementary and additive to other initiatives in this area, and in particular those by the Royal Society, Society for Chemicals Industry and Royal Society of Chemistry.

The same economic fundamentals that make the UK an increasingly unattractive location for fossil based primary and intermediate chemical production also apply to chemical production from sustainable carbon. High capital investment costs, limited economies of scale, and sustainable carbon feedstock prices make production economically unviable.

Other notable barriers to the adoption of sustainable carbon as a feedstock for the chemical industry include access to R&D funding, scale-up facilities and expertise; market appetite for sustainable chemicals; access to talent and skills; technology readiness; reliable access to competitively priced low-carbon hydrogen and renewable energy.

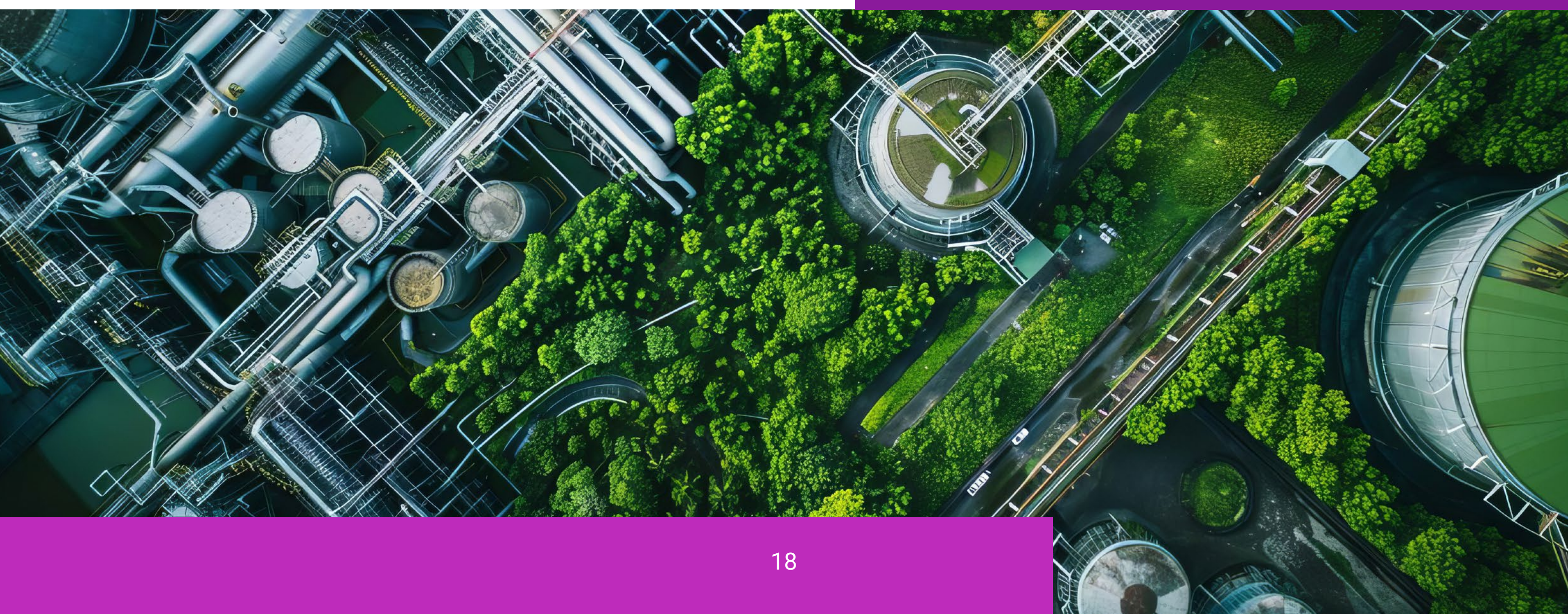
Addressing these barriers requires Government intervention. However the existence of several competing UK Government policies, regulations and standards - such as Biomass Strategy, Climate Change Agreements scheme, Plastic Packaging Tax, Standards and labelling schemes, UK Emissions Trading Scheme, Industrial Energy Transformation Fund, Renewable Transport Fuel Obligation, GHG Protocol, Hydrogen Production Business Model, Industrial Carbon Capture (ICC) business model - means that the chemicals industry is on a back foot from the start.



Transition to sustainable carbon UK chemicals industry

These observations indicate the need to support a four-pronged approach in the transition to a UK chemical industry built upon the use of sustainable carbon.

1. **Protecting and abating** current key petrochemical assets such as the UK's three steam crackers. Focus on electrification, the use of low carbon hydrogen, and carbon capture technologies. This targets hydrocarbon production.
2. **Targeting and developing** specific bio-based chemicals. Focus on biomass sustainability and increasing availability, supporting process innovation through engineering biology. This targets oxygenated chemical intermediates, such as alcohols, acids, and esters.
3. **Establishing** a chemical recycling industry as part of a wider circular economy. This targets the production of basic chemical hydrocarbon feedstocks.
4. **Preparing** for carbon capture and utilisation (CCU). Focuses on ensuring plans for carbon capture and storage (CCS) includes flexibility for utilisation and the establishment of a low-carbon hydrogen industry. This targets the production of methanol for direct use as a chemical or fuel, or as a chemical intermediate. Also, it is worth noting that there is potential to use Methanol to store renewable energy that cannot be used at the direct point of generation.



Technology development required

Overarching for UK Net Zero

Electrification of heat

Fuel switching via electrification is technically possible for a wide range of applications and has been identified as a key component of the UK's plan for industrial decarbonisation.[8] The suitability of a process for electrification depends on the temperature of the heat required. The chemical industry has multiple temperature needs and differing electrification challenges across steam generation, steam cracking, steam methane reforming and for cracking furnaces. Low temperature applications are technically easy to electrify and technologies such as boilers and heaters are commercially available. However high temperature applications, particularly for processes greater than 1000°C, are technically challenging and require further research or development. Active projects include DOW and Shell developed electric cracking technology,[9] the construction of a large-scale demonstration electrically heated steam cracker furnace by BASF, Sabic and Linde,[10] and LyondellBasell/ Chevron and Technip are also working on an electric steam cracker.[11]

Renewable Energy

The supply of low cost and low carbon renewable energy underpins both the production of sustainable carbon feedstock and the transformation of feedstock into primary chemicals, chemical intermediates and end products. The development for renewable power generation, storage and distribution technology is a key enabler of sustainable chemical production.

Low-carbon hydrogen production

Hydrogen is considered a critical low carbon solution in the UK's transition to net zero. As part of a deeply decarbonised and renewable energy system, low carbon hydrogen could be a versatile replacement for high-carbon fuels. Although low carbon hydrogen may find use as a fuel in the chemical industry it is additionally required for the production of chemicals from CO_2. It is important that the needs of the chemical industry and role of low carbon hydrogen in the production of chemicals via CCU technology is considered in the UK's hydrogen strategy.

Artificial intelligence (AI)

The use of artificial intelligence offers the potential for increased productivity, accelerated innovation, improved decision-making, and stronger customer relations. Chemical production, particularly at integrated sites, is complicated with modelling and the creation of digital twins resulting in large data sets. AI can be used to optimise processes, improve yields and optimise utility usage, all of which serve to optimise carbon efficiency and reduce GHG emissions. Industrial decarbonisation through AI is supported through the AI for Decarbonisation Innovation Programme. Although a number of process industry projects have been funded, the programme is yet to support research in the chemical industry which is an opportunity to be encouraged.

Technoeconomic and lifecycle assessment

Successful technology development is underpinned by continuous and systematic technology assessment. Assessing novel technology from its initial development allows the early identification of economic and environmental challenges which can then be targeted in subsequent phases of research. Technoeconomic (TEA) and lifecycle assessment (LCA) are common assessment tools widely used to determine the economic viability and environmental sustainability of a process or product. The wider adoption and harmonisation of approaches to TEA and LCA has an important role in ensuring that new technology is both economically viable and environmentally sustainable.

CO_2 as a feedstock

Carbon capture technology

The current global demand for CO_2 is around 230 Mt of CO_2 per year.[12] It is mainly used in the fertiliser industry for urea manufacturing (~130 Mt) and for enhanced oil recovery (~80 Mt). The development of technology for capturing carbon dioxide from industrial emissions at a purity suitable for chemical conversions and at viable costs is a key challenge in the adoption of CO_2 derived chemicals. More research is required to reduce the cost and improve the energy efficiency of carbon capture technologies.[13]

CO_2 to chemicals transformations

The chemical stability of CO_2 creates the technical challenge to its use, primarily the need for substantial energy input which must come from low carbon sources to avoid further CO_2 emissions. To address this challenge there is the need for active catalysts to promote conversions and avoid the need for high reaction temperatures and/or pressures. A range of biological and chemical technologies are available for CO_2 conversions with research and technical development required to improve conversion efficiencies and costs.

Biomass as a feedstock

Biomass process technologies

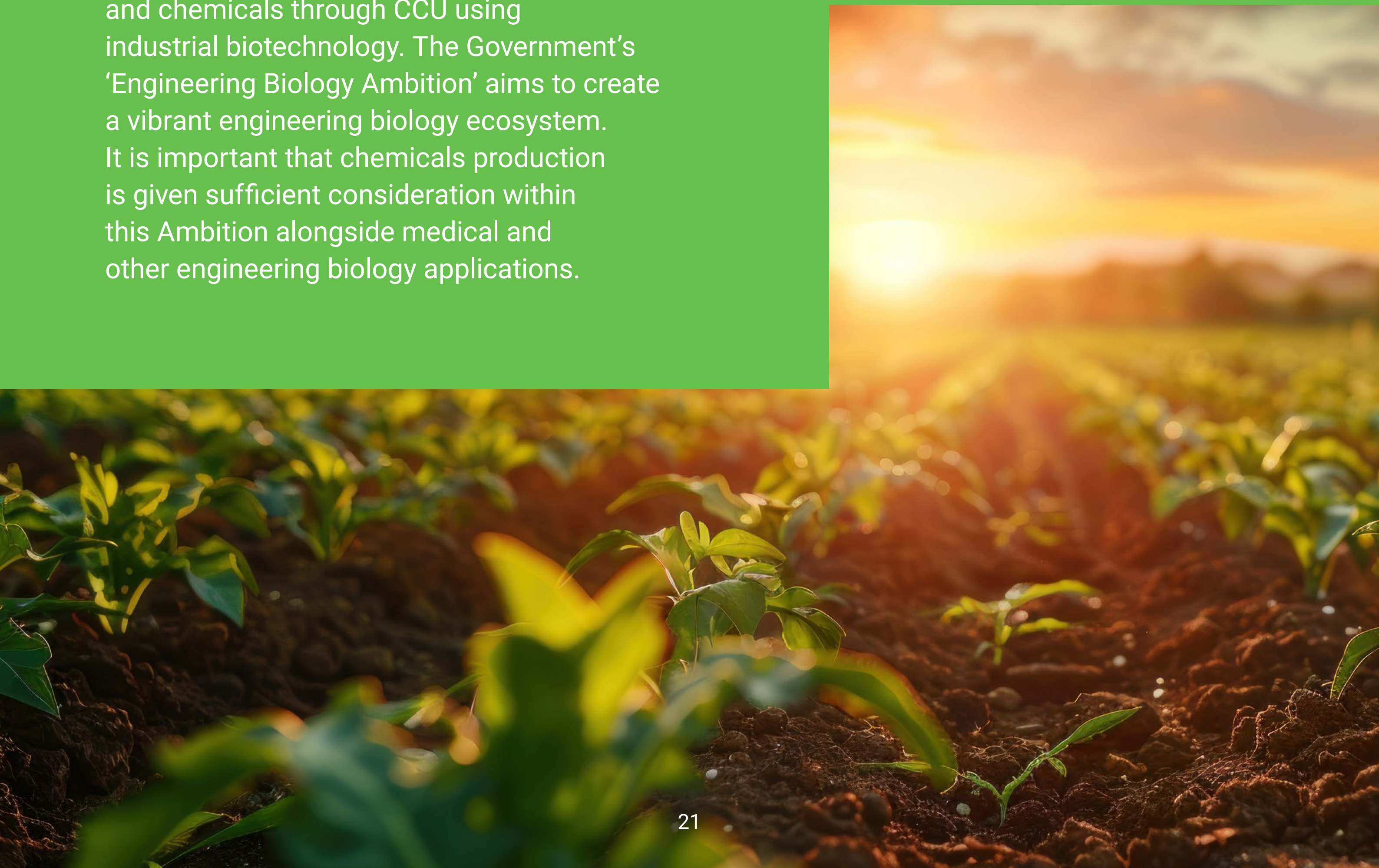
Biomass processing technologies can involve mechanical, chemical or biological processes for the fractionation, pretreatment and conversion of feedstocks into valuable components downstream. Key biomass processing technologies for the conversion of feedstock into chemicals include fermentation, pyrolysis, gasification, combustion, carbonation, thermal decomposition, and hydrothermal liquefaction technology etc.

Engineering biology for chemical production

Engineering biology has a key role to play in the production of bio-based chemicals and chemicals through CCU using industrial biotechnology. The Government's 'Engineering Biology Ambition' aims to create a vibrant engineering biology ecosystem. It is important that chemicals production is given sufficient consideration within this Ambition alongside medical and other engineering biology applications.

Low carbon agriculture

The environmental impacts of bio-based chemical production are, to a large extent, determined by the choice of biomass feedstock and how it is cultivated. Optimising the planting, cultivating and harvesting of biomass can reduce GHG emissions and reduce other environmental impacts thereby improving the sustainability of bio-based chemical production. Fertiliser use is a significant source of GHG emissions, increasing nitrogen-use efficiency in combination with the decarbonisation of fertiliser production would dramatically reduce emissions. The Biomass Feedstocks Innovation Programme represents an important initiative to support the sustainable production of biomass resources.



Recycled Carbon as a feedstock

Chemical recycling process development

Chemical recycling encompasses a range of concepts including polymer dissolution, depolymerisation to monomers and thermal treatments to chemical feedstock (e.g. naphtha and carbon monoxide) and a range of technologies (e.g. liquefaction, pyrolysis and gasification). While challenges in collecting, sorting and cleaning end of waste plastic can be common, each recycling technology has its own specific technical challenges. Technology development is required to scale chemical recycling and ensure that efficient recycling is achieved with minimal loss of resource.

Waste collection and sorting infrastructure

Implementation of advanced automated sorting systems that can accurately identify and separate different types of waste materials, such as plastics, metals, paper, and organic matter is required. It is important to utilise technologies like near-infrared (NIR) spectroscopy, X-ray fluorescence, machine learning algorithms for material identification and sorting.

Recommendations

To promote the development of a sustainable chemical industry in the UK, government support should be utilised, as highlighted in the tables below.

Biomass Recommendations

<table>
<tr><th>Short Term</th><th>Medium Term</th><th>Long Term</th></tr>
<tr><td colspan="2">Promote sustainability assessments relating to biomass feedstock use</td><td></td></tr>
<tr><td colspan="3">Utilise biomass as alternative feedstock</td></tr>
<tr><td colspan="2">Foster collaboration and partnerships across the entire value chain</td><td></td></tr>
<tr><td colspan="3">Construction of biorefineries</td></tr>
<tr><td colspan="3">Develop renewable energy infrastructure</td></tr>
</table>

<table>
<tr><th>Technology Needs</th><th>Policy Recommendations</th></tr>
<tr><td>• Electrification of heat
• Accessible renewable energy production
• Biomass process technologies
• Engineering biology for chemical production
• Low carbon agriculture
• Technoeconomic assessment of technologies</td><td>• Recognise and promote the benefits of biomass use in chemicals production. Utilise study outputs to understand the economic and climate benefits of bio-based chemicals to shape the future ambition.
• Ensure that investment in alternative feedstocks can be properly accounted for in new schemes.
• UK Emissions Trading System (ETS), installations that store biomass in products should be awarded a credit equivalent to the carbon drawn down from the atmosphere and stored in the product.
• Establish a comparable support mechanism for alternative feedstock investment and biomass to chemical conversion.
• Ensure that the energy strategy encourages the burning of biomass for energy to be a last best-case option for the use of biomass.</td></tr>
</table>

Recycled Carbon Recommendations

Short Term	Medium Term	Long Term
Improve collaboration in value chains		
Support R&D into product design & redesign		
Promote sustainability assessments relating to recycled carbon feedstock use		
Standardise definitions and concepts		
Develop industry accepted methods for the recovering and utilisation of recycled carbon		
Utilise waste as alternative feedstock		
Improve waste management logistics for the utilisation of waste feedstocks		
Develop renewable energy infrastructure		
Develop chemical recycling infrastructure		
Develop low carbon hydrogen network		

Technology Needs	Policy Recommendations
• Accessible renewable energy production • Low-carbon hydrogen production • Engineering biology for Chemical production • Chemical recycling process development • Technoeconomic assessment of technologies	• Tax subsidies for the use of at least 30% recycled content in plastic packaging. • Implement standardised system for the labelling of recycled content. • Inclusion of the waste sector in the UK ETS would provide an incentive to recycle carbon back into the economy rather than to burn it. • Establish a comparable support mechanism for alternative feedstock Investment.

Carbon Dioxide

Short Term	Medium Term	Long Term
Manage and convert existing assets to include carbon capture technology at source		
Support for R&D into CCU technology		
Develop renewable energy infrastructure		
Develop CO_2 distribution and storage infrastructure		

Technology Needs

- Electrification of heat
- Accessible renewable energy production
- Carbon capture technology
- Carbon dioxide to chemicals transformations
- Technoeconomic assessment of technologies

Policy Recommendations

- Clarity on the treatment of captured emissions used in products needed.
- Update the Low Carbon Hydrogen Standard to include permanent storage in products.
- Make CCU eligible for support under the ICC business model.
- In the UK ETS, create a whitelist of CCU products in which the carbon can be considered permanently stored. When the waste sector is included in the UK ETS there should be an incentive for them to get carbon back into the economy rather than emit it.
- Work with the ICC to consider business models to encourage the returning of captured CO_2 to the economy.
- Extend and increase support via CCUS Innovation Fund.
- Establish a comparable support mechanism for alternative feedstock investment.

Suggested next steps

As a follow on from this study, and to accelerate the UK chemical industry's transition to sustainable carbon feedstocks, we recommend the following next steps:

1. Identify existing sources of regional and national data on feedstock availability to share with industry, academia, innovators and Government around the use of sustainable carbon for chemicals, including carbon footprints and impact on environmental factors beyond carbon.
2. Review of current UK chemicals assets (in use and mothballed), and those likely to close, and plan for protecting them.
3. Establish an industry-government agreement on Best Available Carbon.
4. In-depth mapping of UK chemicals supply chains, gaps, and analysis of how supply chains could be re-built for key chemicals.
5. A desktop study which collates all available data on the state of the art and emerging technologies for capturing carbon which can be shared with industry including:
    a. The economics and overall carbon footprint of sustainable carbon feedstocks (including energy) at-scale;
    b. The capability and scalability of current and emerging technology;
    c. Horizon scanning for new low TRL technologies.
6. Study to determine the hydrogen and energy requirements to achieve the UK CHEM 2050 Ambition.
7. Bring together SMEs and Large industry players to connect across the full TRL, alongside investors, to co-create future supply chains.
8. Develop and implement an Innovate UK Business Connect Sustainable Carbon/ Chemical Industry Innovation Network.

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2. Introduction

2.1 Introduction

In September 2023 Innovate UK commissioned a 5-month independent study to provide evidence that could support a 'Sustainable Carbon for the UK Chemicals Industry Ambition' - which sets out how the UK can position itself, in the context of a net zero future, to be internationally competitive and meet the growing demand for sustainable chemical products.

NNFCC, **FREY Consulting**, and **Perspective Economics** were awarded the project in October 2023, and the study commenced in November 2023.

To create a 'Sustainable Carbon for the UK Chemicals industry Ambition' the project objectives included:

- Highlighting strategic innovation activities in the UK.
- Understanding the UK position vis-à-vis other countries, including places from which the UK could derive learning.
- Determining future scenarios, based on different technological approaches between now and 2050, that provide the greatest opportunity to leverage current UK assets and strengths in existing supply chains, R&D and innovation.
- Gaining consensus on which key new building block chemicals must be scaled to meet demand, alongside target chemical pathways. For example, biomass, CO_2, and chemical recycling as non-fossil resource feedstocks.
- Understanding the barriers to such a transition.
- Determining key steps and actions that are needed to overcome these barriers, alongside the most appropriate mechanisms to deliver the required transformation.

2.2 Methodology

The research methodology consisted of five main strands:

1. **Project Initiation:** A meeting was held with Innovate UK in October 2023 at which the research objectives and methodology was agreed. Subsequent project management meetings provided Innovate UK with an update regarding progress and methodological amendments.

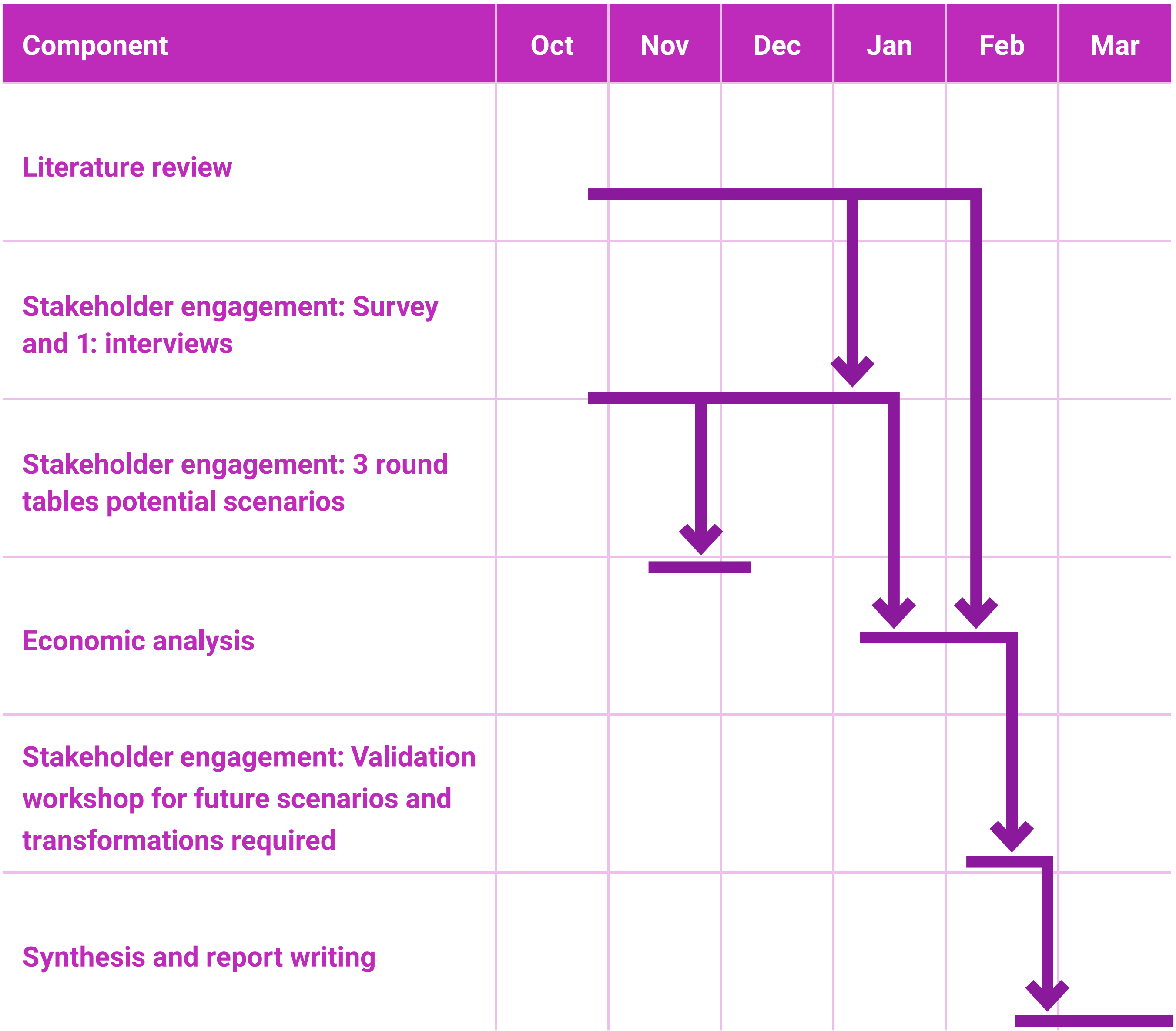
2. **Desk top literature review:** Highlighting strategic innovation activities in the UK, understanding the UK position vis-à-vis other countries, including places from which the UK could derive learning.

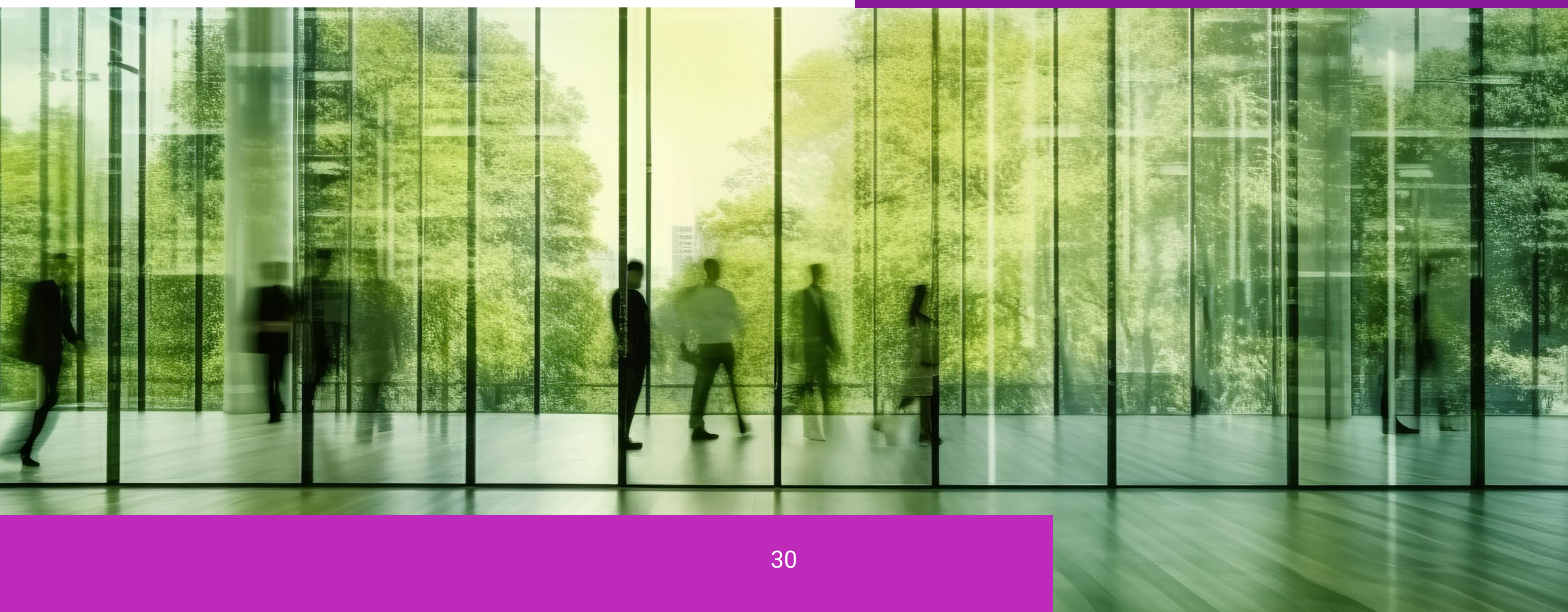
3. **Stakeholder engagement** Determining future scenarios, based on different technological approaches between now and 2050, that provide the greatest opportunity to leverage current UK assets and strengths in existing supply chains, R&D and innovation. Gaining consensus on which key new building block chemicals must be scaled to meet demand, alongside target chemical pathways, for example with biomass, CO_2 and chemical recycling as non-virgin-fossil resources as feedstocks. Understanding barriers to such a transition, determining key steps and actions that are needed to overcome these barriers, alongside the most appropriate mechanisms to deliver the required transformation.

4. **Desk top economic data analysis:** Economic analysis of UK chemical industry and technology companies, based on SIC codes. Analysing Gateway to Research[14] data to chart research funding based on key terms that are specifically relevant to sustainable chemicals research. Using Beauhurst data to analyse UK investment in relevant companies. Comparing UK to international investment in relevant companies.

5. **Evidence Synthesis and Reporting:** Synthesis of quantitative and qualitative evidence to provide clear and systematic responses to each of the project objectives, as presented in this report.

Figure 1: Study components.





2.3 Stakeholder engagement

Stakeholders were engaged via several activities throughout the study (Table 3):

1. **Online Survey -** focusing on current status and potential scenarios.
2. **Presentations and workshops**
    - Presentation to, and discussion with, Chemical Industries Association (CIA) members online – November 2023.
    - Presentation to, and discussion with, attendees at Knowledge Centre for Materials Chemistry (KCMC) Industry Steering Group meeting 'Sustainable Carbon Feedstocks for the Chemicals Industry' – London, November 2023.
    - Attendance, and stakeholder engagement, at Royal Society workshop 'Green Carbon for the Chemicals Industry' – London November 2023.
    - Presentation, and discussion with attendees, at Industrial Biotechnology Leadership Forum (IBLF) meeting, Online November 2023.
3. **1:1 Interviews –** held online between October and December 2023, focusing on the current status of the UK chemicals industry, potential future scenarios and transformation required to reach future scenarios.
4. **Three round table events –** held online in November 2023 – Focusing on sustainable carbon sources (1) biomass, (2) CO_2 and (3) recycled carbon – presenting and discussing potential scenarios for the future UK chemicals industry.
5. **Validation workshop –** held online in February 2024 – to validate final scenarios and transformation required.

Stakeholders consulted during the study included large, medium and small businesses, government officials, academics, and trade bodies, covering TRLs 1-9. In total the study has engaged with 255 individuals from over 100 organisations, including, 3 government officials, 187 from industry, 12 from RTOs, 9 from Trade associations, 16 from UKRI, and 24 academics.

Organisations were from a variety of sectors including speciality chemicals, plastics, fibres, biotechnology, consumer products, commodity chemicals, paper and coatings, bio-based chemicals and materials, composites, agrochemicals, bioplastics, agriculture, circular economy and pharmaceuticals.

Table 3: Stakeholders engaged.

Activity	Number of participants	Large organisations	SMEs	Academia	Trade Associations	Funding bodies	Government
Online survey	109	Y	Y	Y	Y	Y	Y
CIA presentation	36	Y	Y	Y	Y	N	N
KCMC workshop	56	Y	Y	Y	Y	Y	N
RSC workshop	90	Y	Y	Y	Y	Y	Y
IBLF Presentation	23	Y	Y	Y	Y	Y	Y
1:1 interview	32	Y	Y	Y	N	Y	N
Biomass round table	16	Y	Y	Y	Y	N	N
CO_2 round table	10	Y	Y	Y	Y	N	N
Recycled carbon roundtable	11	Y	Y	Y	Y	N	N
Validation round table	30	Y	Y	Y	Y	N	N

2.4 Background and context of the study

2.4.1 UK chemicals industry and climate change

Petrochemicals, and the materials and products derived from them, form an essential part of modern life. Around 96% of all manufactured goods contain petrochemical products. However, the petrochemical sector is also a significant emitter of greenhouse gas (GHG) emissions.

In 2019, UK GHG emissions totalled 551million tonnes of CO_2eq with 15% of emissions resulting from manufacturing activities (scope 1 emissions).

The manufacture of refined petroleum products, petrochemicals, glass and ceramics, cement, and iron and steel accounted for 49% of manufacturing emissions.

UK direct scope 1 emissions from the production of petrochemicals amounted to 5.9million tonnes CO_2eq in 2019. The indirect scope 2 emissions from electricity generation would add several million more tonnes of CO_2eq.[15] The assessment of industry scope 3 emissions (upstream and downstream emissions) is beyond the scope of this study but are likely to be at least equivalent to total scope 1 and 2 emissions.[16,17]

Chemicals sector decarbonisation

The chemicals sector will be a vital part of the net zero economy. A large proportion of the manufacturing sector uses chemicals to make products such as batteries, wind turbine blades and solar panels, lightweight materials for transport and fuels such as hydrogen.

Source: UK Government - Industrial Decarbonisation Strategy

Table 4: Major direct (scope 1) emission sources from UK manufacturing.

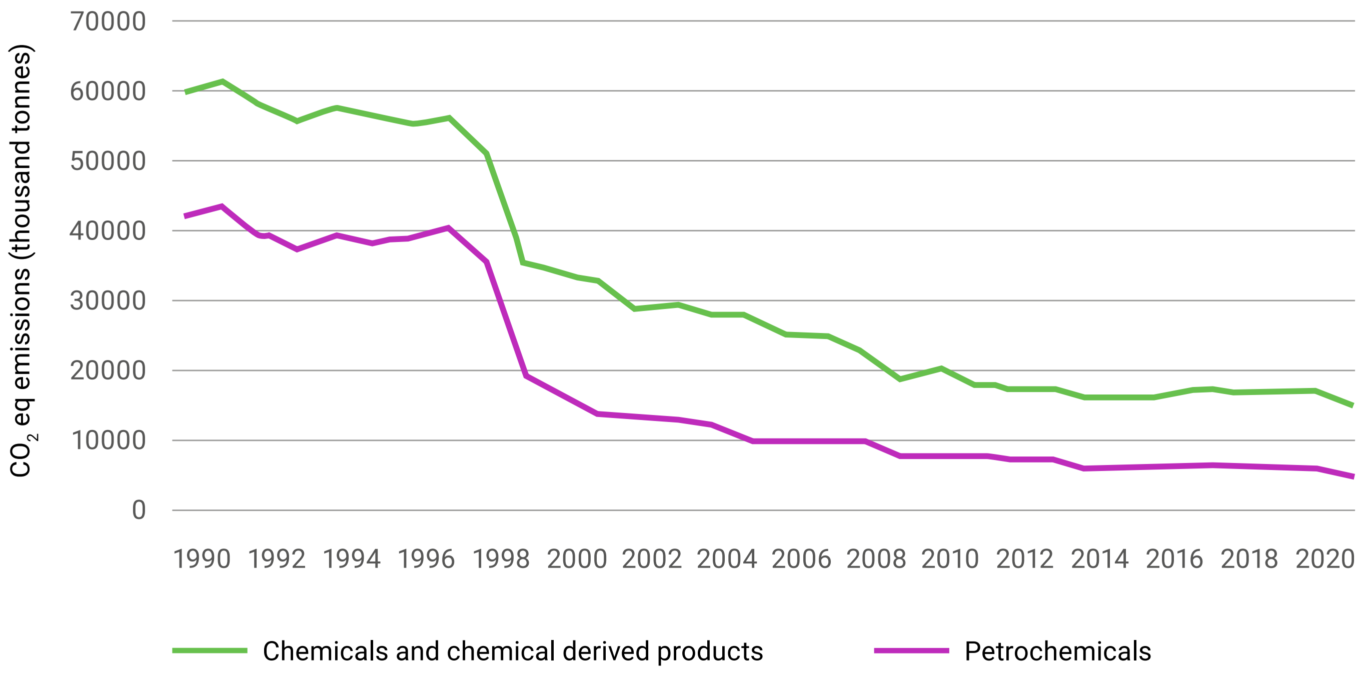
	GHG emissions Million tonnes CO_2eq (2019)	% of Manufacturing GHG emissions (2019)	% of total UK GHG emissions (2019)
Manufacture of refined petroleum products	13.0	16	2.4
Manufacture of petrochemicals	**5.9**	**7**	**1.1**
Manufacture of glass, refractory, clay, other porcelain and ceramic products, Stone, & abrasive products	3.7	4	0.7
Manufacture of cement	7.5	9	1.4
Manufacture of basic Iron & Steel	10.8	13	2.0

These manufacturing emission sources are often clustered. UK's major industrial clusters (excluding iron and steel clusters) are responsible for 26 MtCO_2eq of GHG emissions per year, with the oil and oil-derived chemical industry responsible for the majority of these emissions.[18]

Since 1990, the UK chemical industry has significantly reduced the volume of its direct GHG emissions. However, in the last decade the level of emissions has remained relatively constant. The manufacture of petrochemical products[19] results in the generation of roughly 6.1 million tonnes of CO_2eq per year (average 2012-2021). When the manufacturing of all chemicals and chemical derived products[20] is included, the related emissions increase to 16.6 million tonnes CO_2eq per year (average 2012-2021).

The large reductions in emissions seen in the late 1990's and early 2000's was a result of a small number of significant emission abatement actions and chemical plant closures.[21] These changes (described below) can be considered as the low hanging fruit for emission reductions and further reductions proved difficult to achieve.

Figure 2: UK based GHG emissions (direct) from the production of petrochemicals, and chemicals and chemical derived products.[22]



Adipic acid production produces nitrous oxide as a by-product. UK emissions associated with production of adipic acid manufacture were reduced significantly in 1999 through the installation of emissions abatement systems prior to the UK's only adipic acid plant closing in 2009.

Emissions resulting from the manufacture of HFCs and HCFCs have decreased to zero since 1990. In 1999 a thermal oxidiser was installed at the UK's only HCFC-22 plant, the plant was later closed in 2016.

Emissions have also declined due to a reduction in production capacity. For example, all UK manufacturing of methanol ceased in 2001, and installations producing carbon black and ethylene oxide closed in 2009.

Nitric oxide production is a significant producer of GHG emissions. NO emissions from nitric acid manufacture fell in the early 2000's due to the closure of 4 plants between 2000 and 2008 and the installation of abatement technology in the larger of the remaining plants in 2011.

2.4.2 Transitioning away from virgin-fossil resources

There are a multitude of actions which can be taken to improve the sustainability of petrochemical production, use and disposal. Actions range from designing better products and implementing better business models which fundamentally reduce demand, reducing emissions during production through the use of new technologies or the use of renewable energy, to adopting smarter end-of-life solutions which ensure a more circular economy. The range of options available to the chemical industry is summarised in Figure 3 with actions included to enable their delivery.

Scope 3 upstream emissions

Feedstock

Options to reduce scope 3 upstream emissions from virgin-fossil resources:

1. Reduce demand
2. Redesign to use less
3. Switch to renewable feedstock
4. Switch to recycled feedstock

Scope 1 & 2 emissions

Processing

Options to reduce scope 1 and 2 emissions from virgin-fossil resources:

1. Reduce demand
2. Redesign to use less
3. Improve process efficiency
4. Utilisation of renewable energy and electrification
5. CCU and/or CCS

Scope 3 downstream emissions

Long lived & collectable materials

End of life

Options to reduce scope 3 downstream emissions from virgin-fossil resources:

1. Reduce demand
2. Redesign to use less
3. Collect and recycle
4. Collect and sequester
5. Collect and incinerate with CCU/CCS
6. Switch to renewable feedstock
7. Switch to recycled feedstock

Biodegradable & total-loss applications

End of life

Options to reduce scope 3 downstream emissions from virgin-fossil resources:

1. Reduce demand
2. Redesign to use less
3. Switch to renewable feedstock
4. Switch to recycled feedstock

Overarching enablers: More transparent data sharing, standardised LCA methodology (level playing field), renewable energy, electrification, chemical safety and hazards, scope 4 considerations, geographical considerations for e.g. transport of feedstock

Figure 3: Ways to transition away from virgin fossil resource for the UK chemicals industry

The transition to net zero and real zero:

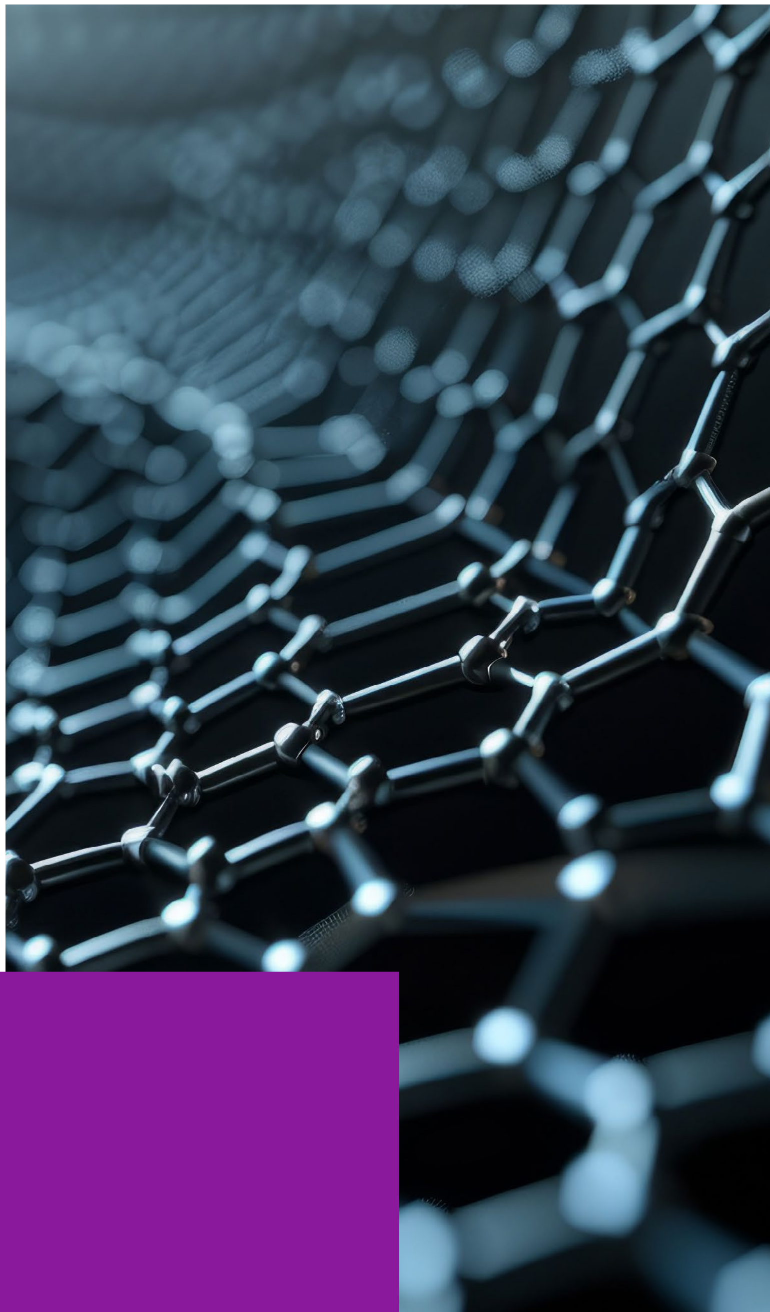
Net zero targets are designed to completely negate the amount of GHGs produced through reducing emissions and implementing methods of absorbing CO_2 from the atmosphere. This principle applies to global and national targets and can be equally applied to the chemical industry or individual chemical businesses. The net zero principle allows for continued fossil-derived GHG emissions, provided that these emissions can be off-set by GHG removals through other processes or industrial sectors. Net zero targets within the petrochemical industry can be achieved through a combination of energy decarbonisation and GHG removals. In contrast, real zero targets require the total elimination of fossil GHGs. For most industrial activities reaching real zero may be challenging but can be achieved by switching from fossil fuel to renewable energy to heat and power manufacturing processes. However, petrochemicals are fundamentally carbon based (organic) molecules, and so, their production requires carbon and inevitably results in fossil-derived production emissions which is further exacerbated through the release of embodied fossil carbon at the end of the petrochemical's life. In order to achieve real zero emissions, the petrochemical industry must transition from the use of fossil carbon to the use of more sustainable sources of carbon.

Decarbonisation of petrochemicals:

The current focus to reduce GHG emissions from petrochemical production sits in two decarbonisation areas. The first reduces emissions at source through switching to renewable fuels, particularly the electrification of heat; the second reduces emissions through the capturing of carbon emissions with the subsequent long-term storage of these emissions, otherwise known as carbon capture and storage (CCS). The electrification of heat, either via heat pumps or electric boilers for low grade heat, and in high temperature processes such as steam cracking is being increasingly researched. The development of CCS is widely regarded as essential to achieving net zero aspirations, the formation of CCS programs around industrial clusters allows petrochemicals producers to benefit from shared public/private investment in infrastructure. Decarbonisation of petrochemical production addresses scope 1 and scope 2 emissions, however it does not address the scope 3 emissions that result from the release of embedded fossil carbon at a product's end-of-life. These emissions are allocated to the waste sector or if chemical products are exported, are not considered in UK Net Zero targets.

Defossilisation of petrochemicals:

Defossilisation means transitioning away from the use of fossil resources as fuels for process energy and feedstocks for chemical production. Fortunately, alternative carbon sources exist, and alternative carbon flows can be envisaged whereby carbon is no longer mined from the geosphere and is extracted from the atmosphere, either directly or via photosynthesis into the biosphere, and then used by the chemical industry (within the technosphere) where it is then recycled within a circular economy.



2.4.3 The need for a sustainable carbon for the UK chemicals industry ambition

The sustainable chemicals space is vibrant with various organisations and institutes working on roadmaps and projects, all ultimately with the same ambition – to reduce the chemical industry's reliance on fossil resources (Table 5).

This transition, however, could be accelerated by stronger alignment between key stakeholder groups (industry, academia, and the investment community) and Government, and a shared understanding of the challenges and priority opportunities.

Table 5: Organisations and institutions working on projects focussing on the use of sustainable carbon in the UK chemical industry.

Project Title	Sponsor	Lead organisation/ Lead contact	Timeline	Key objectives / outputs
Roadmap for zero fossil resources in ingredients in FMCG by 2050	SCI	Richard Miller	TBA	Roadmap
Sustainable polymers for liquid formulations	Royal Society Chemistry	Anju Massey-Brooker	Has been ongoing for 5 years	Produced a roadmap in 2023
Green carbon for the chemicals industry	Royal Society	Royal Society	Launched May 2024	Report with policy suggestions
Roadmap for a Circular Economy of Chemicals	UKRI (CircularChem)	Newcastle University	Completed by end Q2 2024	Roadmap
Barriers for the transition to bio-based chemicals	University of Manchester	University of Manchester, Neil Dixon	End of 2024	Roadmap
National materials innovation strategy and roadmap	UKRI	Henry Royce Institute	Not known	Not known

2.5 Sustainable carbon sources and best available carbon

Sustainability shouldn't be seen as a destination - it is a journey. Therefore, the concept of sustainable carbon isn't about a concrete definition of what carbon source is the most sustainable, but rather a developing and constantly evolving view of what would be described as the 'Best Available Carbon' (BAC) for the production of chemicals and chemical derivatives.

BAC means the available carbon that could be used in manufacturing while minimising GHG emissions and any other negative impacts on the environment and maintaining the economic viability of manufacturing.

Although the focus is placed on CO_2 emissions, the careful management of carbon is required to avoid undesirable and unintended knock-on consequences in other areas of planetary health, such as water availability, air and water pollution, toxicity and biodiversity.[23]

The idea of BAC sits within the established concept of 'best available techniques' (BAT),[24] where advanced and proven techniques are used for the prevention and control of industrial emissions and the wider environmental impact caused by industrial installations. These available technologies have been developed to a scale that enables implementation under economically and technically viable conditions. In a similar way, the concept of BAC should consider the economic and technical viability of the carbon source required for a specific manufacturing process.

Carbon sustainability and 'best available carbon' builds on carbon cycles, climate change, and the need to maintain a balance of carbon (in various forms) across the planet's geosphere, biosphere, atmosphere and hydrosphere. The use of fossil resources taken from the geosphere (underground), ultimately results in the transfer of carbon in the form of CO_2 into the atmosphere and hydrosphere, which cannot then be easily returned to the geosphere (Figure 4). It is this transfer of carbon that lies at the heart of climate change, with increasing concentrations of CO_2 in the atmosphere.

Petrochemicals are critical to modern life with around 96% of all manufactured goods containing petrochemical products. It is also recognised that petrochemical products play an important role in addressing climate challenges e.g. through lightweighting transport and enabling renewable energy generation.

It is therefore unrealistic to expect any significant reduction in their use and, on the contrary, production is expected to significantly increase.

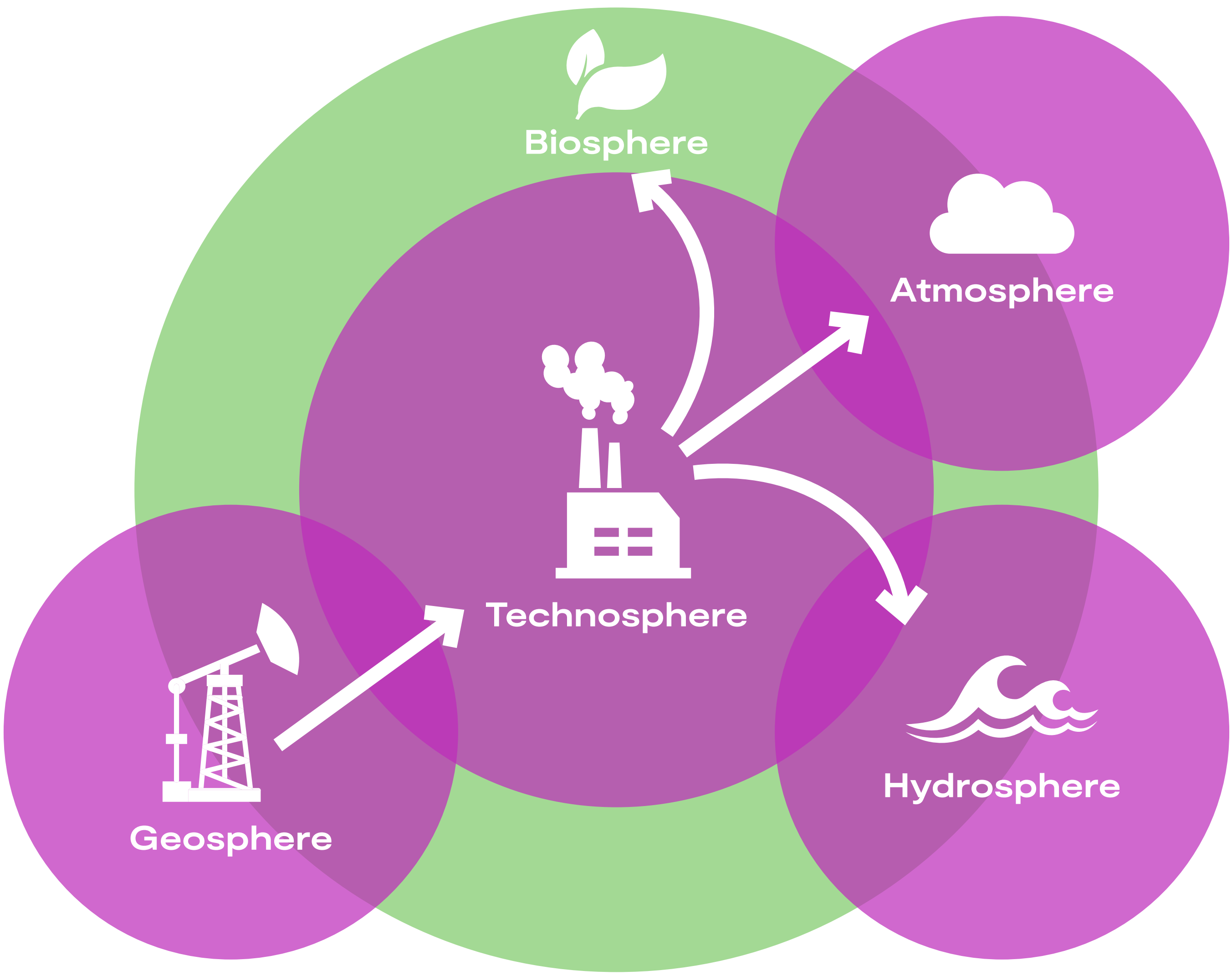


Figure 4: Illustration of the planet's carbon cycles, demonstrating how the biosphere, atmosphere, hydrosphere, geosphere, and technosphere are all interlinked.

The scale and value of petrochemical production means that any change to established processes and raw materials will inevitably be a slow one. It is, therefore, foreseeable that virgin-fossil resources will continue to be the predominant source of carbon for the manufacturing of chemicals and materials for several decades to come.[25]

Geospheric fossil carbon (GFC) in the form of crude oil, natural gas (natural gas liquids) and coal represents the predominant source (85%) of carbon used in organic chemical production.[26] The environmental impact of different sources of GFC can be considerable, as demonstrated in the GHG emissions associated with the production of methanol.

Most methanol is currently produced from natural gas, where natural gas is used both as a feedstock and as a process fuel. Natural gas-based methanol production is estimated to have a carbon footprint of around 110 g CO_2eq/MJ of methanol.[27] However, coal-based methanol production, as widely practiced in China, has emissions of close to 300 g CO_2eq/ MJ, due to considerable emissions associated with both the mining of the coal and the methanol conversion process itself.[28]

Therefore, there is a need to ensure that, where GFC resources are used or derived products are procured, the lowest impact GFC has been used. Beyond the decarbonisation of energy sources, the chemical industry has the ability and a strong interest in using CCS technologies as a means of abating its GHG emissions.[29] The development and deployment of CCS technology can, to an extent, mitigate the fossil GHG emissions resulting from petrochemical production. However, carbon leakage during CCS operations means that fossil carbon will inevitably continue to enter the atmosphere.[30]

Unlike other industries, the chemical industry uses fossil resources as both a fuel and as a feedstock for manufacturing. This means that GFC is embedded in millions of everyday products which eventually enter the waste system at their end of life. This waste needs to be treated and, if incinerated with or without energy recovery, the GFC will be released as CO_2 into the atmosphere; although incineration plants could be fitted with CCS technology which would partially mitigate emissions.[31] Additionally, not all products can be collected at their end of life and are designed to biodegrade after use, further resulting in CO_2 emissions.

The chemical sector is the largest industrial energy consumer, but only the third largest industry subsector in terms of direct CO_2 emissions. This is because around half of the chemical sector's energy input is consumed as feedstock — fuel used as a raw material input rather than as a source of energy.

Source: International Energy Agency

Fortunately, alternative carbon sources are available in the form of carbon extracted or recovered from the biosphere, atmosphere, and technosphere. These sources offer the opportunity to reduce, and even halt the extraction of GFC, preventing any additional fossil carbon derived GHGs from entering the atmosphere.

The use of biospheric carbon (BC), atmospheric carbon (AC), and technospheric carbon (TC) resources means that carbon is sourced and remains above ground, creating a circular carbon economy coming from feedstocks that can be regrown (i.e. biomass from the biosphere), recycled, captured and utilised (i.e. carbon in multiple forms from the technosphere), or extracted (i.e. CO_2 from atmosphere)(Figure 4).

Technospheric carbon (TC):

Technospheric carbon (TC) can take two forms; the carbon recovered through carbon capture and utilisation (CCU), and carbon recovered through product recycling.

CCU relates to the extraction of CO_2 from the atmosphere, followed by the utilisation of said CO_2 for the production of fuel, chemicals and downstream materials. Carbon recovered through product recycling relates to the carbon potential that already exists within the millions of tonnes of products traded and used across the economy today, with ~400 million tonnes of plastics entering the economy each year.[32]

The recycling of plastic and its embodied carbon can be achieved through mechanical and chemical recycling processes. Although mechanical recycling is preferable from a sustainability perspective, chemical recycling offers an opportunity to expand recycling to currently hard to recycle plastic materials. Chemical recycling is a broad term used to describe a range of emerging technologies which allow plastics that are difficult or uneconomic to recycle mechanically.

Emerging technologies include solvent dissolution, chemical depolymerisation, aqueous liquefaction, pyrolysis and gasification.[33] Although ideally avoided where possible, TC may be combusted or oxidised through chemical or biological processing.

The subsequent use of carbon through CCU therefore provides a way of preventing GHG emissions from entering the atmosphere and keeping carbon circulating through the economy. Each form of recycling has its own merits and disadvantages and requires systemic approaches to ensure the right methods are used for different products and materials.

Technospheric (recycled) carbon is expected to grow in importance in the future. However, despite the desire to develop circular economies[34] no recycling system can be run perpetually and the loss of some carbon via oxidation to CO_2 and escape to the atmosphere is inevitable. Recycling also requires energy input (for the recycling process and in logistics) and therefore while recycling may deliver against resource efficiency and waste avoidance objectives it may increase GHG emissions.

Additionally, not all chemical products can be collected, with large volumes of carbon lost through their use (e.g. personal care, household cleaning products and total loss lubricants). Therefore, the chemical industry will still require virgin carbon extracted from the atmosphere or derived from biomass in order to make up for these losses.

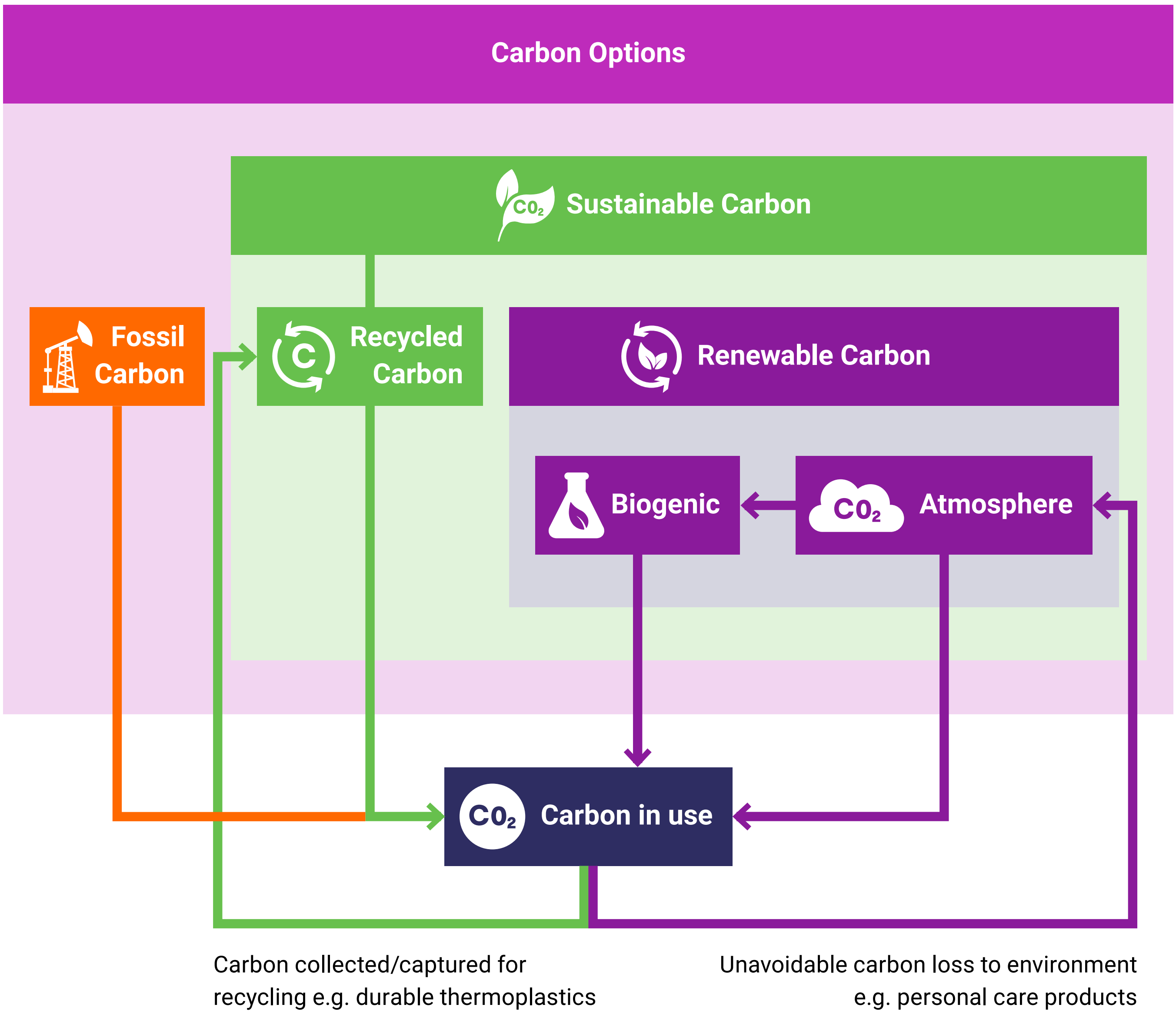
Biospheric carbon (BC)

The use of carbon contained within the biosphere predates human civilisation, with plant and animal material being used to construct shelters and provide clothing. The development of new chemistry, and in particular industrial biotechnology, results in increasing opportunities to utilise biomass for the production of biochemicals and synthetic materials. The challenge in biomass use lies in ensuring that the volumes harvested do not damage our ecosystems' ability to maintain its regulating and cultural services. Sustainably managed biospheric (biogenic) carbon constitutes an important renewable carbon source.

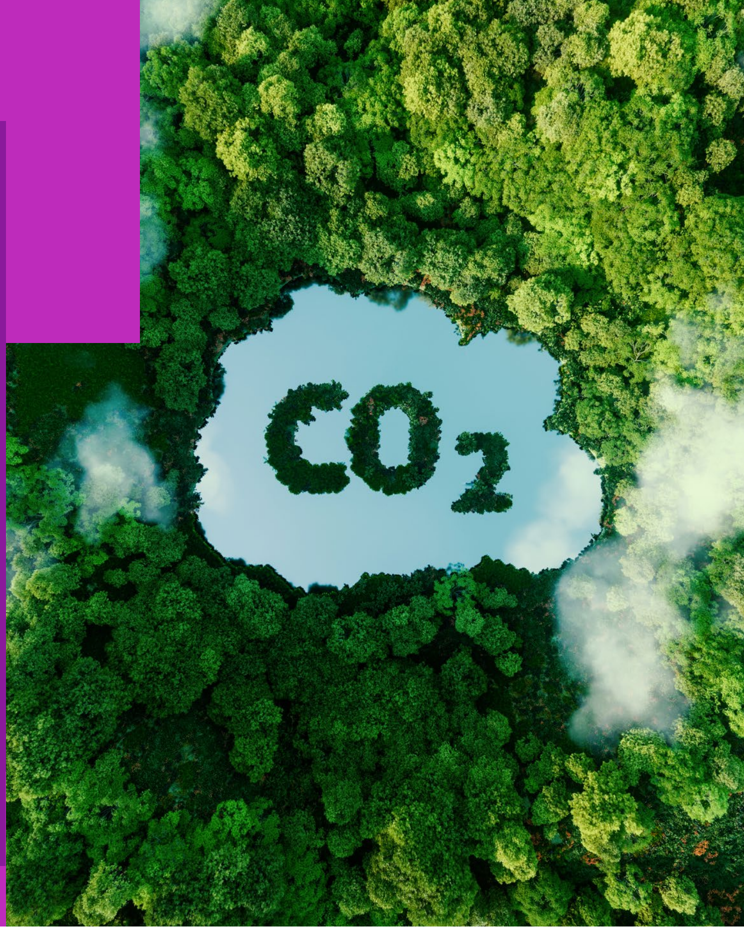
Atmospheric carbon (AC)

The final category of alternative carbon sources is atmospheric carbon (AC), where CO_2 is extracted through direct air capture (DAC). While the direct capture of atmospheric CO_2 provides an essentially unlimited supply of carbon for manufacturing, the effort, energy and financial cost of recovering such a dilute source of carbon from the atmosphere raises questions on the viability of its use. The use of CO_2 as a carbon source is, therefore, dependent on the co-development of low carbon electricity and/or low carbon hydrogen.

Figure 5: Carbon options available to the chemical industry.



2.6 Availability considerations for sustainable carbon feedstocks



Carbon is widely available and not generally considered a critical material. However, the availability of carbon, when considering economic and environmental sustainability, in the volumes required to support a global transition away from the use of fossil resources, is limited.

Competing uses and key factors influencing the availability of sustainable carbon are summarised in Figure 6.

Biogenic carbon and sustainable biomass: The production of primary biomass is primarily linked to the availability of land and how that land is used. Marine environments can provide an additional source of biomass (e.g. macroalgae) but the sustainable use of this resource is equally limited.[35] UK land is limited, and it is required for multiple functions, including the production of food, the maintenance of biodiversity, the provision of a range of ecosystem services, and the supply of biomass to produce chemicals, materials and bioenergy. Additionally, healthy ecosystems can take up and store a significant amount of carbon in soils, sediments and vegetation and therefore, biomass has an important role to play in climate mitigation.[36] The careful management of land and biomass resources is therefore required to ensure the optimal use of land and the biomass it provides, across all its potential applications.[37, 38, 39, 40]

Recycled carbon from chemical recycling: Chemical recycling is dependent on the material flow of end-of-life plastics which are difficult to treat through conventional mechanical recycling methods. The volume of material available for chemical recycling is first determined by the volume of plastic placed on the market, and then influenced by how effectively said plastic is collected and sorted within the municipal waste system.

The volume of plastic placed on the market is influenced through policies such as bans on specific single use plastic applications,[41] voluntary business commitments to reduce plastic use,[42] and consumer led decisions on the desirability of plastic products, such as plastic packaging.[43] End-of-life fates for plastics include export, incineration and landfill. Each of these competes with both mechanical and chemical recycling. It is estimated that 6 million tonnes of plastic were placed on the UK market in 2017, with around 2 million tonnes in the form of packaging. In the same year, around 3 million tonnes of plastic waste were generated, with treatment split equally between landfill, incineration and recycling. However, it is estimated that only 0.4 million tonnes of plastic recycling took place in the UK in 2017, with the remainder exported for recycling outside the UK.[44]

Recycled carbon from carbon capture: CCU is dependent on point sources of CO_2. Although not strictly competing uses, the decarbonisation of energy sources or the closure of facilities producing CO_2 will directly affect the availability of CO_2. Once captured, recycled carbon can be used in several applications which can create competition in regard to its use as a chemical feedstock. Predominant applications include the use of CO_2 in the production of mineral products[45] or in the production of renewable fuels of non-biological origin (RFNBOs),[46] and the use of recycled carbon for the production of recycled carbon fuels.[47]

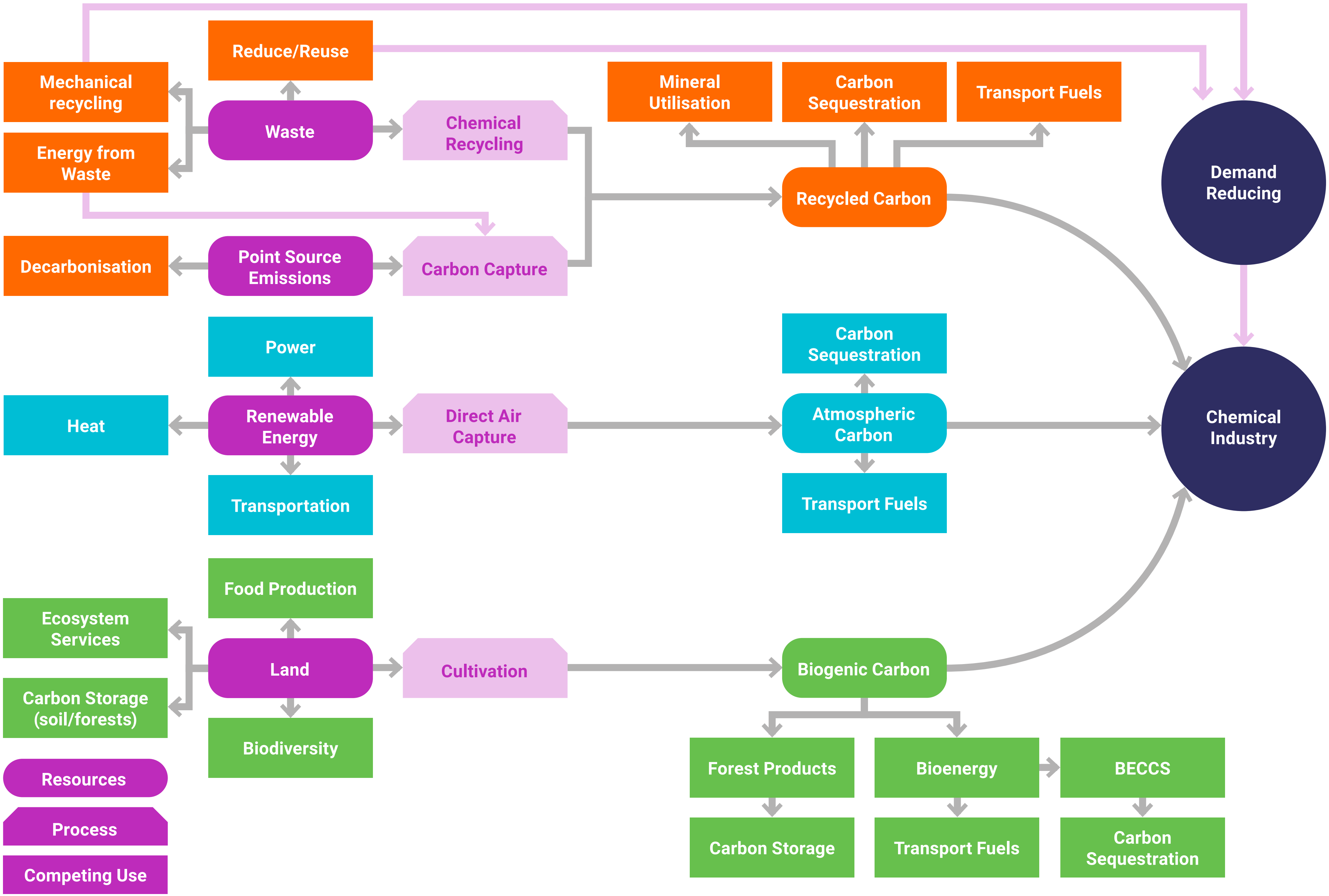


Figure 6: Factors affecting the availability of recycled carbon (orange), CO_2 derived carbon (blue), and bioderived carbon (green) for the chemical industry.

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18 HM Government, Industrial Decarbonisation Strategy, https://assets.publishing.service.gov.uk/media/6051cd04e90e07527f645f1e/Industrial_Decarbonisation_Strategy_March_2021.pdf, [accessed 22 Mar 2024]

19 Petrochemical products includes, manufacture of other organic basic chemicals (SIC Code 20.14), manufacture of plastics in primary forms (SIC Code 20.16), manufacture of synthetic rubber in primary forms (SIC Code 20.17), manufacture of man-made fibres (SIC Code 20.6)

20 Manufacture of industrial gases and non-nitrogen-based inorganic chemicals (SIC Code 20.11 & 20.13), petrochemicals (SIC Code 20.14, 20.16, 20.17 & 20.6), dyestuffs & agro-chemicals SIC Code 20.12 & 20.2), paints, varnishes & ink (SIC Code 20.3), cleaning & toilet preparations (SIC Code 20.4), basic pharmaceutical products and pharmaceutical preparations (SIC Code 21), rubber products (SIC Code 22.1), plastics products (SIC Code 22.2), fertilisers and other nitrogen compounds (SIC Code 20.15), and the manufacture of other chemical products (SIC Code 20.5).

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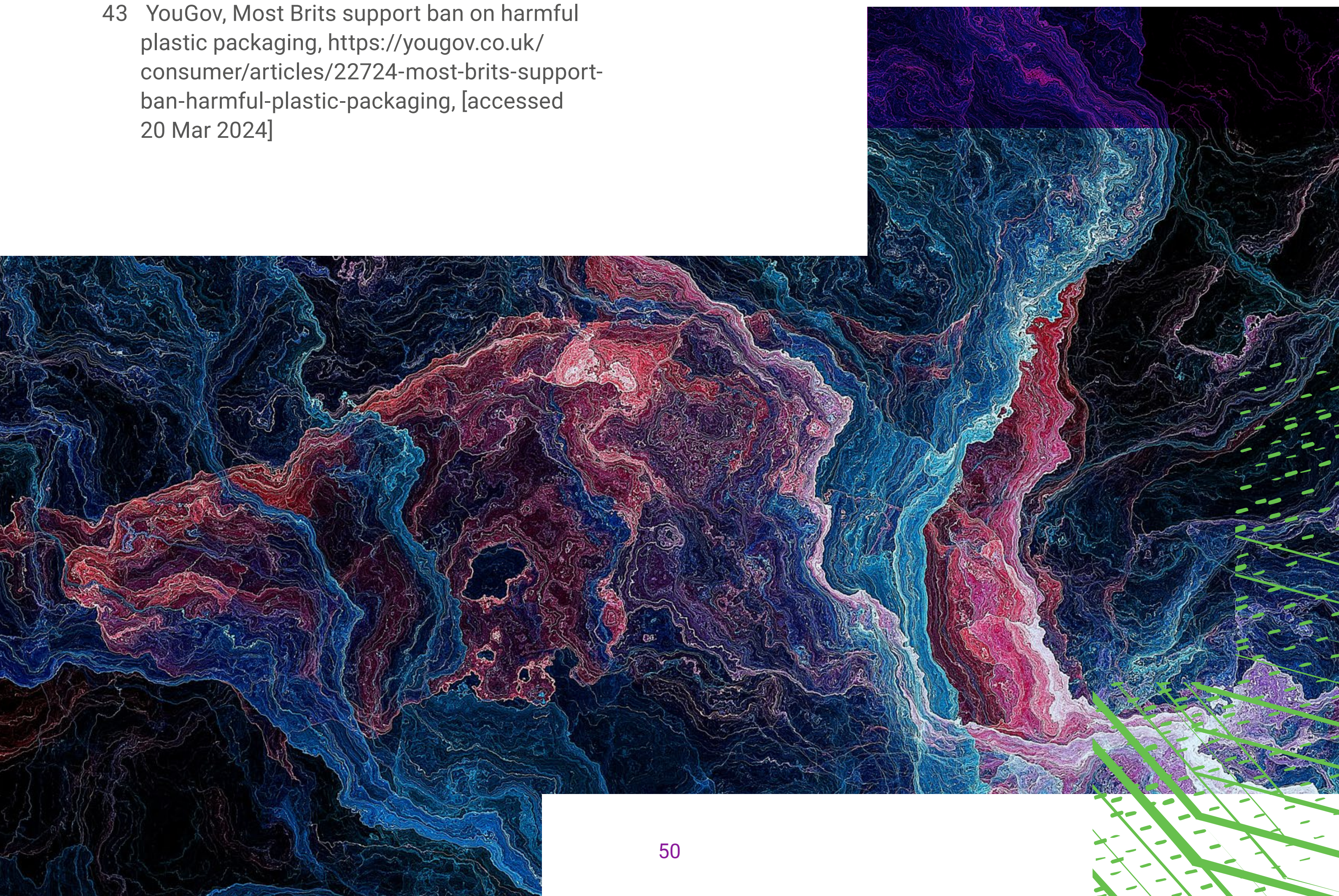


3. UK chemical industry

3.1 UK petrochemical industry

Petrochemical production takes place at scale through mature value chains inextricably linked to the refining of fossil oil and gas.

As such, the UK is predominantly positioned as a producer of added value speciality and consumer chemicals. In 2016 these two sub-sectors were responsible for 70% of chemical industry revenues, 50% of gross value add (GVA) and 67% of employment.[48] Speciality chemicals are associated with high-value and growing downstream markets, such as healthcare, agriculture, and a range of other markets. The UK has maintained a competitive advantage in innovative and high value products due to its strong academic and industrial R&D base relative to lower cost chemical producing countries such as China and the Middle East.

The UK has complex supply chain flows with the potential for multiple border crossings of intermediate products before the final end product is produced. For example, companies active in the specialty chemicals sector often source raw materials from outside the UK, which are converted to value added products before being exported.

The sector is highly competitive but also faces a number of challenges. These include.

- Increasing global competition (particularly from the United States and China)
- Very high operating costs (as an energy intensive industry facing comparatively high energy prices combined with high costs of complying with environmental regulations)
- Difficulty in attracting investment from global parent companies
- Skills shortages

These challenges are particularly relevant to the production of intermediate commodity chemicals which are produced at large scale but sold with low profit margins.

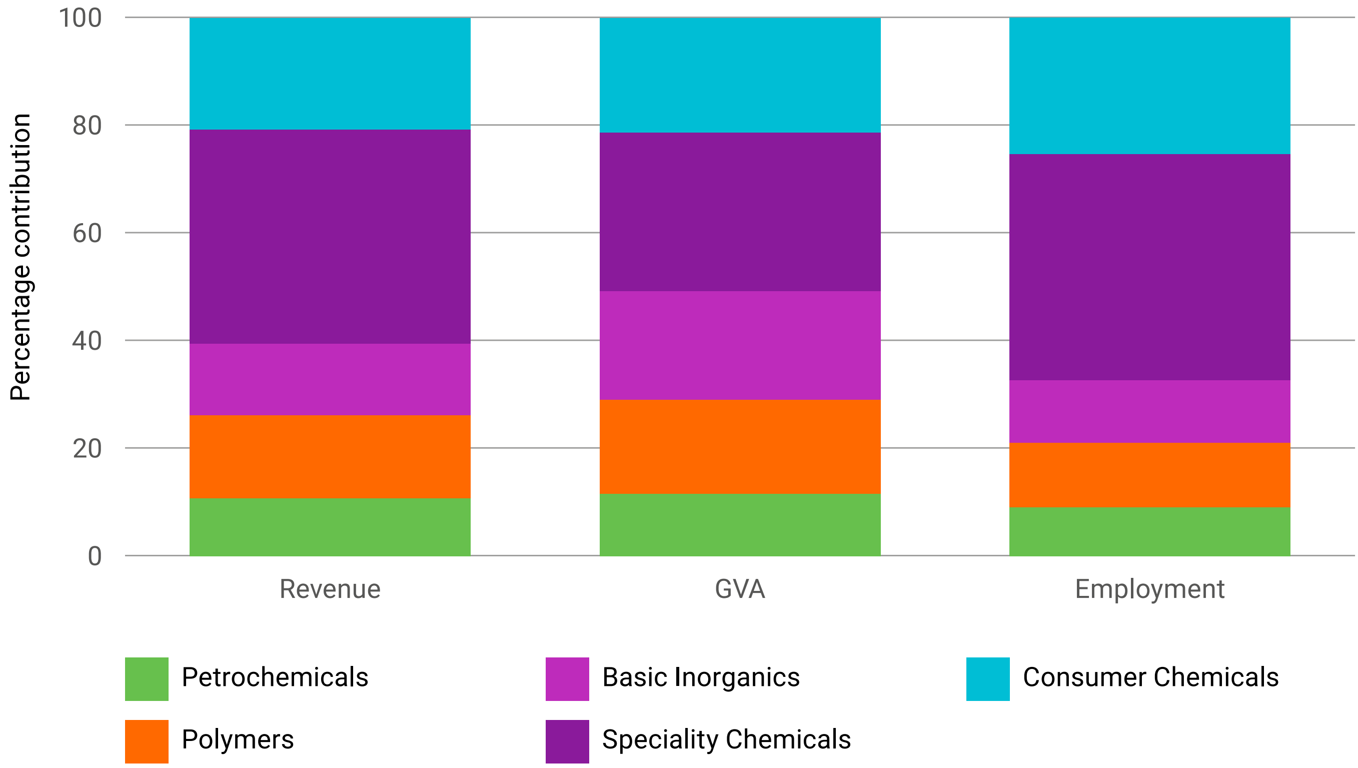


Figure 7: Contribution of UK chemical industry subsectors to revenue, GVA and employment (2016)

3.1.1 Primary chemicals and cracker products

The UK's refineries and chemical crackers produce large quantities of primary chemicals. Steam crackers at Mossmorran, Grangemouth, and Wilton produce ethylene and propylene, while Essar Oil's manufacturing complex at Stanlow produces propylene and benzene which are subsequently converted to polypropylene and ethylbenzene respectively. The ExxonMobil refinery at Fawley produces a range of chemicals including higher olefins, isobutylene and methyl ethyl ketone.

The UK's ethylene producers and core users are linked through a network of ethylene pipelines. Ethylene can be transported reversibly between the UK's key chemical production facilities at Grangemouth[49] in Scotland and Wilton in the Northeast, and from Mossmorran in Scotland to Stanlow on Merseyside. Ethylene produced at Mossmorran is transferred to the Essar manufacturing complex at Stanlow where it is used in the production of higher olefins and alcohols. Ethylene is also piped to the Saltend Chemicals Park where it is used to produce ethyl acetate and ethylene-vinyl alcohol.

3.1.2 UK chemical plant closures

Despite the UK's strengths in primary chemical production, the last 25 years have seen significant changes in the UK landscape for intermediate chemical production.

Figure 8: UK chemical plant closures

In 2010, Dow Chemical Company closed its ethylene oxide and ethylene glycol (EOEG) production facility at Wilton, Teesside. Several factors contributed to the closure of this EOEG plant, including unfavourable input costs, as well as declining demand and profit margins for the site's main outputs, particularly monoethylene glycol (MEG).[50]
In 2013, Lotte Chemical closed their pure terephthalic acid (PTA) plant based in Wilton, Teesside, which had been operating since 1981. The company blamed the move on increasing production and energy costs and a fundamental lack of competitiveness at the site. This plant produced around 500,000 tonnes of PTA for use in the manufacture of PET plastic bottles and food packaging.[51]

In 2019, INEOS announced the closure of their acrylonitrile production plant, based in Seal Sands, Middlesborough. INEOS stated that manufacturing assets need constant renewal if they are to survive, demonstrating that constant reinvestment is vital for the long-term prosperity of large-scale chemical plants. INEOS will continue to produce acrylonitrile at other sites around the world, where it is more competitive to do so.[52] In January 2021, BASF announced the closure of its hexamethylene diamine facility in Seal Sands, Middlesborough. BASF expressed concerns about the plant's profitability and competitiveness - hexamethylene diamine is primarily used to produce polymers for use in automotive components (e.g., engine seals and fuel system parts), but demand for these components had been on the decline following a turndown in the automotive industry, coupled with the effects of the Covid-19 crisis. BASF has instead transferred the production of hexamethylene diamine plastic components to a site in France.[53]

In 2023, Mitsubishi Chemical UK confirmed the closure of its methyl methacrylate (MMA) plant at Billingham, Stockton-on-Tees, a result of a significant downturn in the European economy due to high inflation. The production of methacrylates requires the consumption of large quantities of natural gas, both as an energy source and as a feedstock for the manufacturing process. Therefore, volatile gas prices have had a considerable impact on the economic sustainability of methacrylate manufacturing in the UK, making it less viable in an increasingly competitive global market. Mitsubishi Chemical Group will continue to provide a supply of methacrylate products to consumers from other sites around the world. Also in 2023, Versalis announced the closure of its rubber plant at Grangemouth. It was understood to have the capacity to produce 60,000 tonnes per year of styrene butadiene rubber (SBR), in addition to 80,000 tonnes per year of polybutadiene rubber (PBR).

Following these notable plant closures, it is evident that considerable supply chain gaps exist within the UK's current chemical processing infrastructure. Figure 9 illustrates the general petrochemical industry value chain. Primary chemicals are highlighted in blue. In the UK, intermediate commodity chemical manufacturing (highlighted in purple) is in decline. This means that the UK is increasingly reliant on import of chemical intermediates.

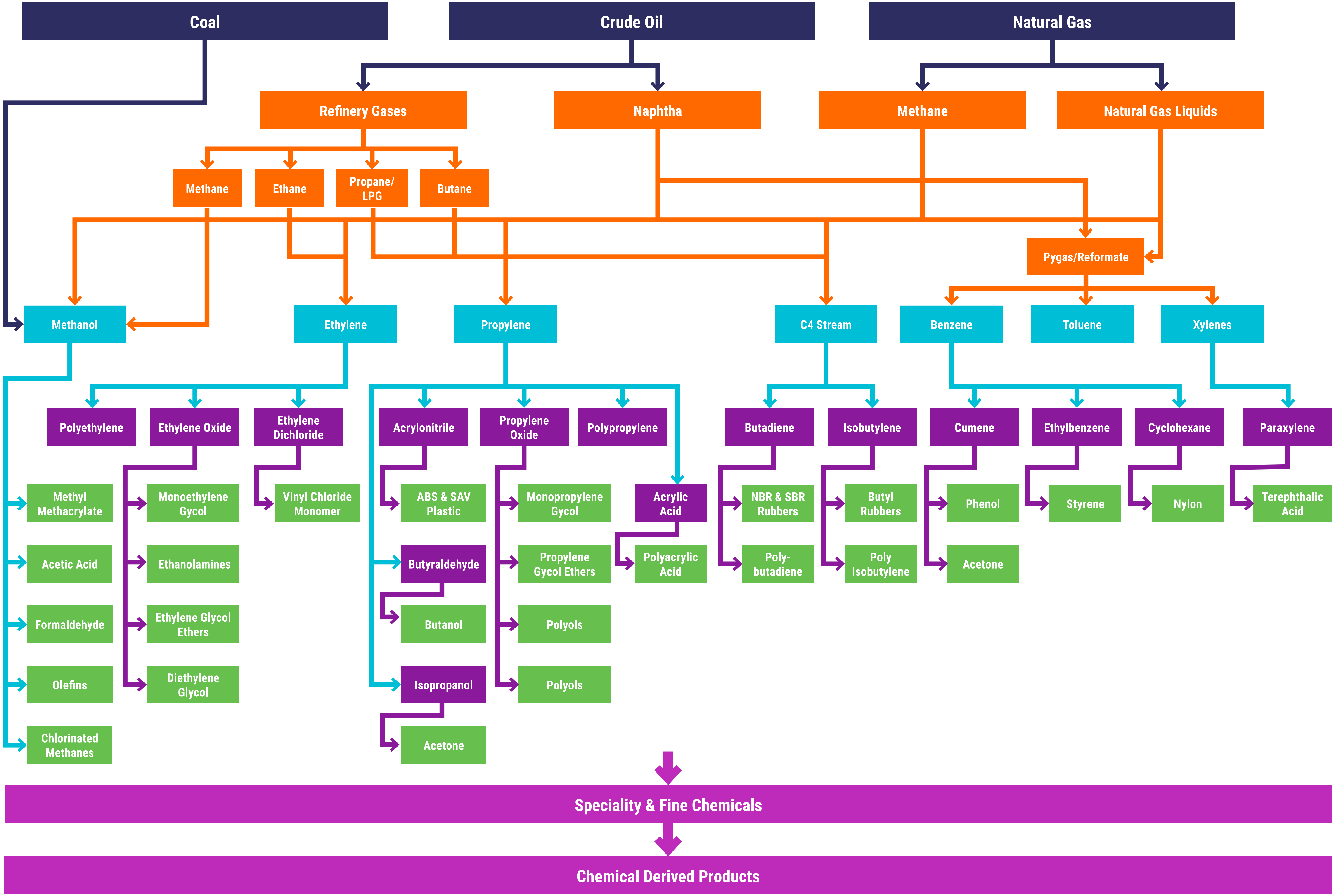


Figure 9: Petrochemical industry value chain (not intended as a comprehensive view of all industry value chains).

3.2 Economic potential of a sustainable UK chemicals industry

The chemicals industry makes a significant contribution to the UK economy. According to the Chemicals Industry Association (CIA) the UK's chemical industry comprises 4,415 businesses employing 151,000 people and supporting a further 500,000 jobs in the wider economy.[54] **It is a highly productive sector contributing an estimated £203k in Gross Value Added (GVA) per employee**, constitutes more than one sixth of total UK research and development (R&D) spend and makes up a substantive proportion of UK manufacturing exports (£54bn).

3.2.1 Chemical sector growth

Defined on the same basis as the CIA data (i.e., standard industrial classification (SIC) code 20 - Manufacture of Chemicals & Chemical Products, n=3,732) company data suggests that the UK chemical industry has seen 80% growth in revenues over the past decade.

These headline figures highlight the continued significance of the chemicals industry to the UK economy and, by extension, the major economic opportunity that could be realised were the UK to take a global lead on the development of sustainable chemicals.

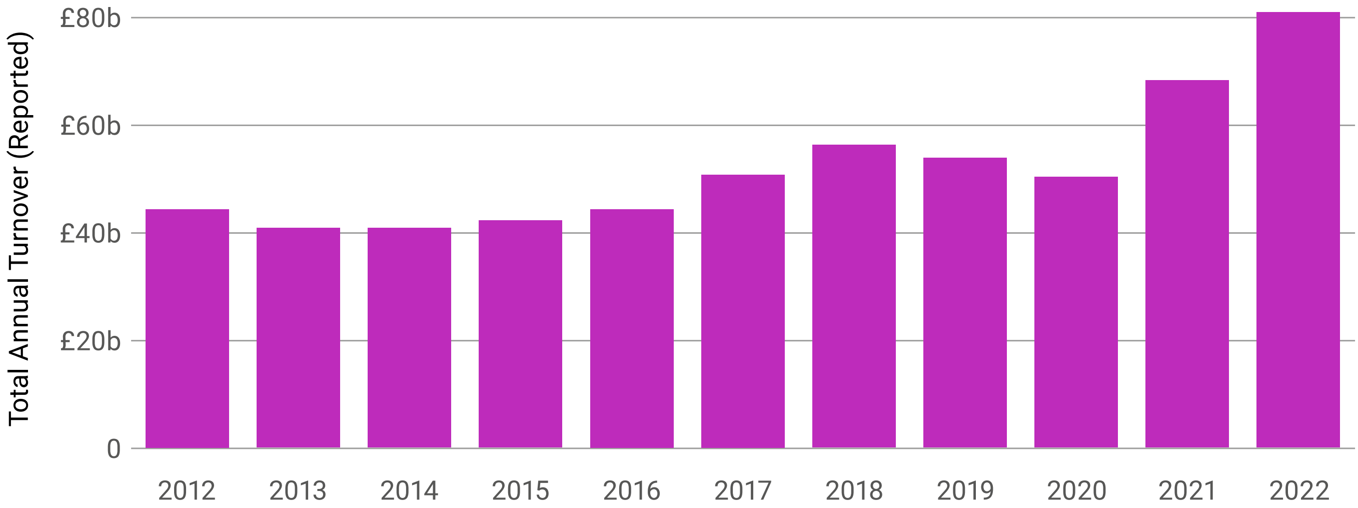


Figure 10. UK Chemical Industry Revenue Growth Source: Bureau van Dijk

Analysis of a subset of 652 companies that have full accounts data for both 2018 and 2022 shows that just 10 companies account for more than two thirds of revenue growth since 2018. This concentrated growth is due to combination of increases in chemical prices (e.g. annual reports show that all of the INEOS chemical businesses reduced volumes but increased revenues due to higher sales prices), and growth in diversified, non-chemicals activity.

3.2.2 International investment in innovative chemical companies

Data on international investment in sustainable chemicals companies suggests that the UK has a comparatively high number of innovative chemicals companies relative to other prominent European chemical manufacturing locations. However, when it comes to the scale of fundraising secured by these companies, the UK secures just a fraction of the level of investment, particularly compared to Germany, the Netherlands and Spain. Figure 11 below shows the number of chemical companies and value of fundraisings secured by chemicals companies in the UK, Germany, the Netherlands, France, Spain and Italy. The average value of fundraisings secured by innovative chemicals companies in Germany is almost 14 times the UK average. Eight of the top 20 highest investment raising chemical companies identified through the analysis are German, including the top two – Evonik and Bayer – which have secured almost $8bn in fundraisings alone.

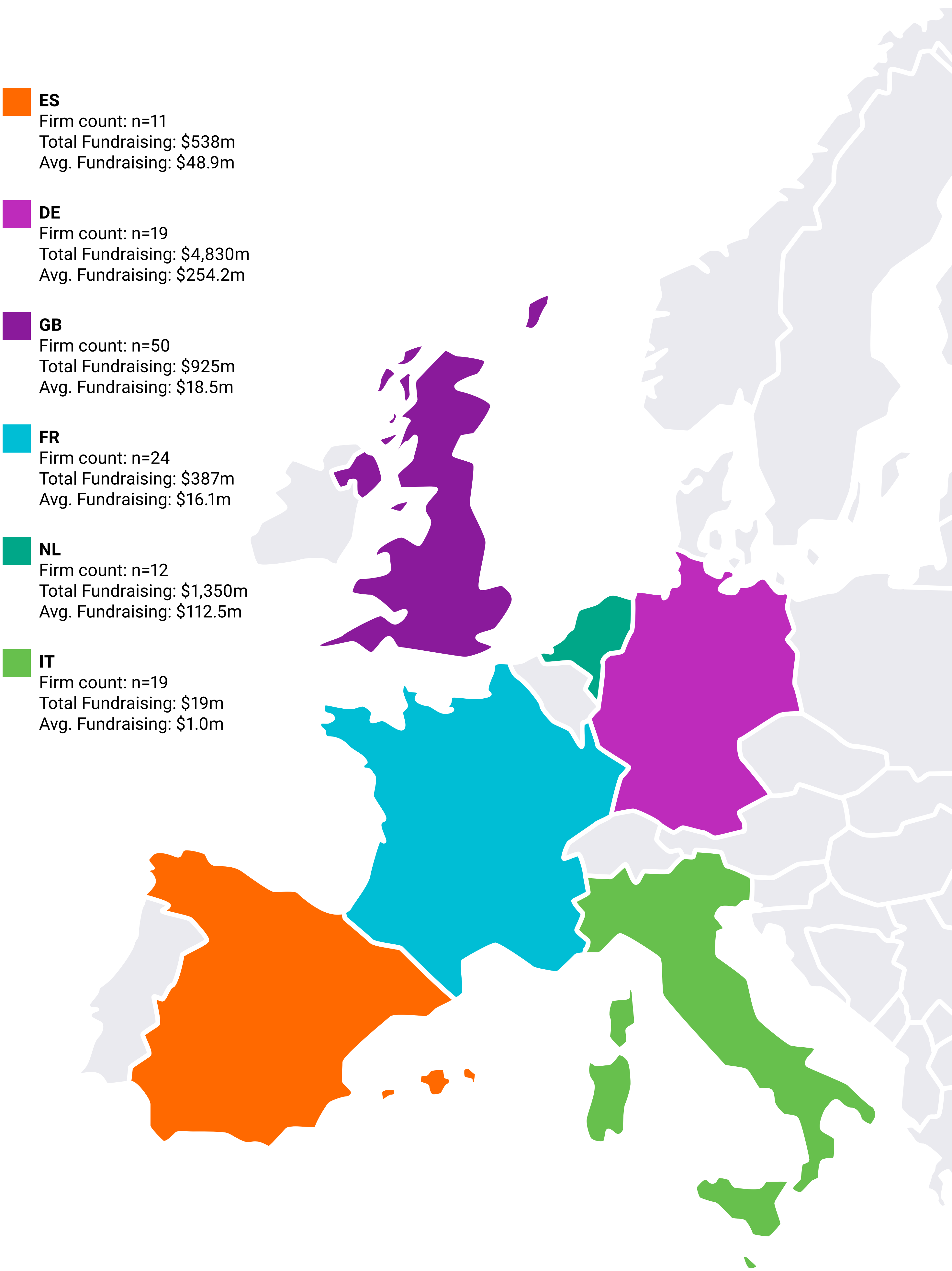


Figure 11: International Chemicals Investment **Source:** Crunchbase

Between 2012 and 2022 innovative UK chemical companies secured approximately $250m in their latest fundraisings, which represents just 16% of the total raised by companies in comparator locations (Figure 12). UK companies such as Holiferm (bio-based chemicals), C-Capture (carbon capture) and OXCCU (CO_2 conversion) have among the most substantive fundraisings.

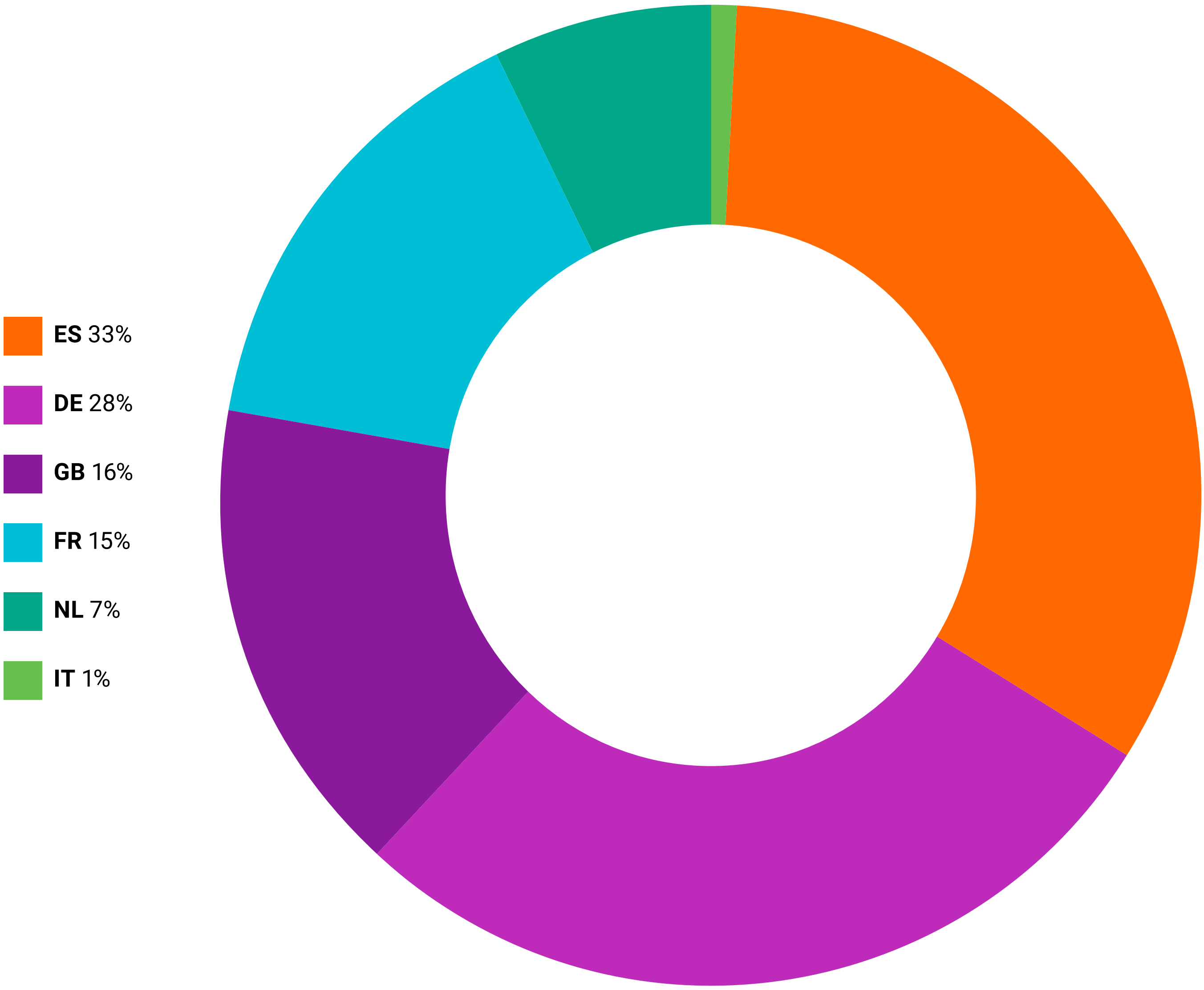


Figure 12: Share of Latest Chemicals Investment (2012 – 2022) **Source:** Crunchbase

3.3 Strategic innovation activities

3.3.1 Engineering biology

The concept of engineering biology harnesses bioscience discoveries and the understanding of biological systems to produce pharmaceuticals, food, chemicals and fuels through the application of engineering principles. Engineering Biology is seen as one of five critical technologies where the UK is well placed to take a leading global position. The Government's 'Engineering Biology Ambition' aims to create a vibrant engineering biology ecosystem that can safely develop and commercialise a broad range of opportunities including the potential to produce bio-based and recycled chemicals. To achieve its Ambition the Government has earmarked a £2 billion investment targeted at 6 key areas covering world-leading R&D, infrastructure, talent and skills, regulations and standards, take up by the broader economy, and responsible and trustworthy innovation.

3.3.2 Example UKRI programmes

Industrial Decarbonisation Challenge (IDC) (Budget = £210M, 2019–2024)

The IDC focusses on the development of low-carbon technologies and infrastructure, increasing industry competitiveness and contributing to clean growth. The challenge is split into three workstreams: deployment; cluster plans; and the Industrial Decarbonisation Research and Innovation Centre (IDRIC). The IDC is contributing to the UK's drive for clean growth by supporting the UK's six largest industrial clusters in their mission to decarbonise at scale. Together, the IDC and UK industrial partners will lay the foundation for developing at least one low-carbon industrial cluster by 2030 and the world's first net-zero industrial cluster by 2040.

Transforming Foundation Industries (TFI) (Budget = £66M, 2019–2024)

The TFI challenge aims to transform the UK's foundation industries (cement, metals, glass, paper, ceramics, chemicals) by: making them internationally competitive; securing more jobs throughout the UK; and growing the sector by 2024 in an environmentally sustainable way. TFI has helped fund companies like Holiferm (refer to page 84) and projects like Flue-2-Chem (refer to page 90).
In November 2022, Innovate UK also announced £19.5M award to the Foundation Industries Sustainability Consortium (FISC) to support scale-up of sustainable technologies for the foundation industries. This award is to run the Economic Material Innovation for Sustainable and Efficient use of Resources (ECONOMISER) programme which is developing a network of scale-up centres to support industry and academic engagement in innovation in: carbon reduction; process improvement; and product development.

Smart Sustainable Plastic Packaging (SSPP) (Budget = £60M, 2019–2025)

The Smart Sustainable Plastic Packaging Challenge (SSPP) is contributing to the UK's drive for clean growth and industrial decarbonisation by funding ground-breaking research and innovation to make plastic packaging fit for a sustainable future. It aims to: deliver a reduction in unnecessary and single-use plastic packaging; increase the viability and uptake of reuse and refill systems; and support new and improved recycling technologies and systems. SSPP has funded chemical recycling innovations like Mura Technology (refer to Figure 16).

Interdisciplinary Centre for Circular Chemical Economy (CircularChem) (2021–2025)

CircularChem is part of a £30M investment by UKRI investment in The National Interdisciplinary Circular Economy Research (NICER), a four-year programme to move the UK towards a circular economy. CircularChem aims to transform the UK chemical industry into a more resource-efficient, productive and higher value system. This means creating new pathways to recover and reuse chemicals from end-of-life products. The centre is focused primarily on a chemical group known as olefins (such as ethylene and propylene).

3.3.3 Networks in industrial biotechnology and bioenergy

In 2014, UKRI funded 13 Networks in Industrial Biotechnology and Bioenergy (NIBB) across a range of industrial biotechnology and bioenergy (IBBE) relevant areas. These networks were set up to foster collaborations between academia, industry, policy makers and non-governmental organisations (NGOs) in order to find new approaches to tackle research challenges, translate research and deliver key benefits in IBBE and also look for international opportunities.

In 2019, an additional £11 million was committed to fund six Phase II NIBBs from 2019 to 2024. The second phase builds upon the success of the first phase NIBBs and continues to build capacity and capability in the UK by supporting research and translation into sustainable bio-based manufacturing. The six Phase II NIBBs are: Algae-UK: Exploiting the algal treasure trove; BBNet: Biomass Biorefinery Network; Carbon Recycling – Converting waste derived GHG into chemicals, fuels and animal feed; E3B: Elements of Bioremediation, Biomanufacturing & Bioenergy: Metals in Biology; EBNet: Environmental Biotechnology Network; HVB: High Value Biorenewables Network.

3.3.4 Supergen

The Supergen Bioenergy Hub works with academia, industry, government and the public to develop sustainable bioenergy systems that support the UK's transition to an affordable, resilient, low-carbon energy future. The Hub's whole-system research approach encompasses all aspects of bioenergy expertise to identify pathways for delivering bioenergy with wider social, economic and environmental benefits. In this way, UK academics support policy and industry in identifying and characterising sustainable bioenergy systems.

3.4 Stakeholder perception of UK chemicals industry

3.4.1 UK chemical manufacturing landscape

In recent years the UK has lost significant amounts of its chemicals manufacturing capabilities. Stakeholders agreed that the UK does not manufacture all the key primary chemicals, and primarily imports chemical intermediates from other countries, transforming them into higher value speciality chemicals.

Key chemicals manufactured in the UK highlighted by stakeholders included: Ethylene; Ethylene derivatives; Specialty chemicals; Polyester; Surfactants, Pesticides, Acrylics, Acetic acid and Resins and coatings. Several stakeholders commented that the UK no longer makes ethylene oxide, derivatives of which we currently import in large volumes. It was noted that if these imports became unreliable, then UK industry relying on the imports may be forced to relocate abroad. Methanol was also a chemical that stakeholders noted that the UK imports significant volumes of but does not currently manufacture onshore.

Unsurprisingly, almost every stakeholder felt that the UK has significant supply chain gaps in its chemicals manufacturing – with several referring to it as being ‘hollowed out’. Whether the UK should try and plug supply chain gaps by onshoring the manufacture of the seven key primary chemicals, was not agreed upon by all stakeholders. However, there was consensus that only repairing one or two parts of a particular chemicals supply chain would not provide benefit to the UK chemical industry, and that any investment should therefore concentrate on providing full supply chains for the most important future chemicals for the UK.

3.4.2 UK chemical manufacturing sustainability

98% of all stakeholders agreed that the UK chemicals industry needs to transition to the utilisation of more sustainable carbon feedstocks (Figure 12). In order of ranking (greatest reason first), the reason for transitioning away from virgin-fossil feedstocks was to:

1. Reduce national GHG emissions
2. Support the development of novel products with improved function
3. Improve security of raw material and intermediate chemical supply
4. Protect market share and UK employment by responding to sustainability trends

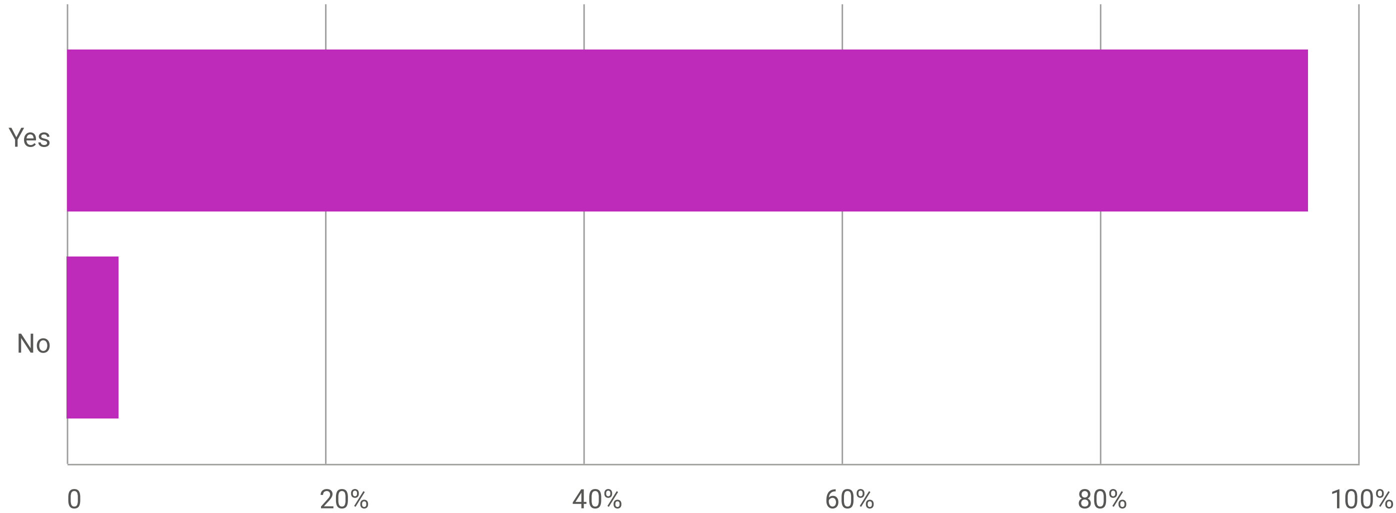
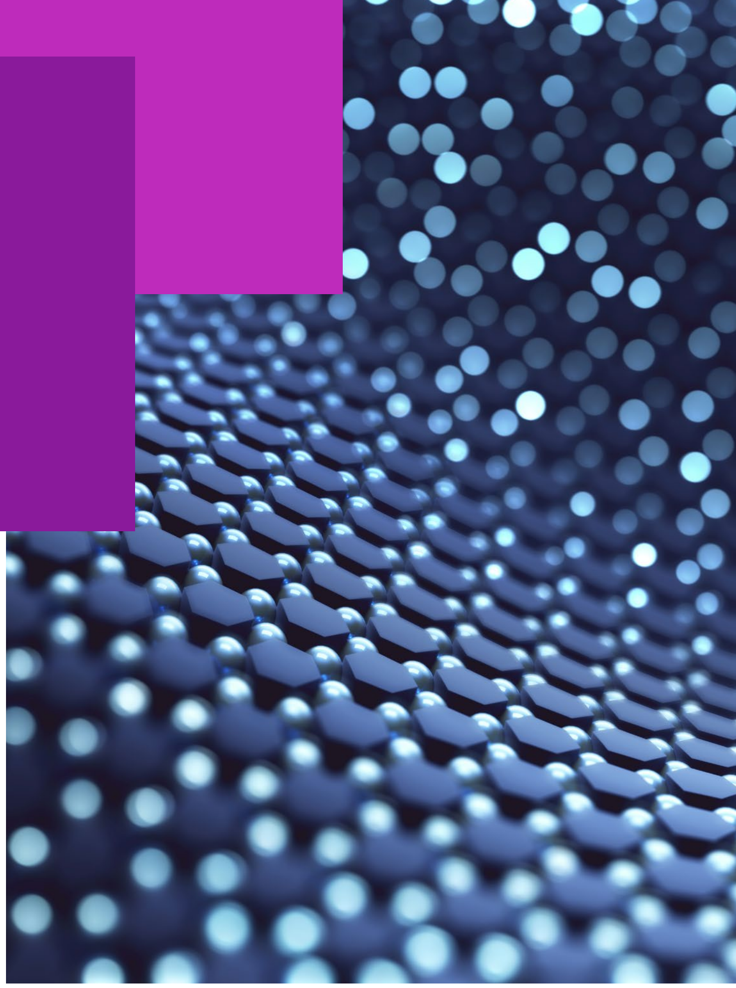


Figure 12: Stakeholder response as to whether UK chemicals industry needs to transition away from utilisation of non-virgin fossil feedstocks.

3.4.3 Impact of UK policy and regulatory landscape on a UK sustainable chemicals industry



Stakeholders were asked to rate how current UK policies and regulations impact the UK chemicals industry to become more sustainable (Figure 13):

- The Net Zero Commitment was seen as the greatest enabler for a more sustainable chemicals industry, with over 89% percent of stakeholders seeing this as either very enabling, or somewhat enabling.
- The Resources and Waste Strategy was mainly seen as enabling or very enabling by 58% of stakeholders, however, it was not understood by 18% of stakeholders, who did not know how this could affect the sector.
- The impact of Carbon Border Adjustment Mechanism (CBAM)[55] on the chemicals industry was mainly seen as enabling or very enabling by 47% of stakeholders, however, it was not understood by 44% of stakeholders, who did not know how this could affect the sector.
- The recently published Biomass Strategy was seen as also being an enabler, with over 62% percent of stakeholders seeing this as either very enabling, or somewhat enabling, but with the caveat that the role of biomass for biochemicals needs to be formally regarded in the strategy.
- The Hydrogen Business Model was seen as also being an enabler, with over 58% percent of stakeholders seeing this as either very enabling, or somewhat enabling.
- The CCUS Business Model was seen largely neither as an enabler or inhibitor, with 54% percent of stakeholders seeing this as either very enabling, or somewhat enabling.
- The Jet Zero Strategy was mainly seen as enabling or very enabling by 56% of stakeholders, with 18% seeing it as somewhat or very inhibiting and the remainder not knowing.
- The 25-year environmental policy was seen as enabling or very enabling by 47% of stakeholders, and the Resources and Waste Strategy by 61% of stakeholders.

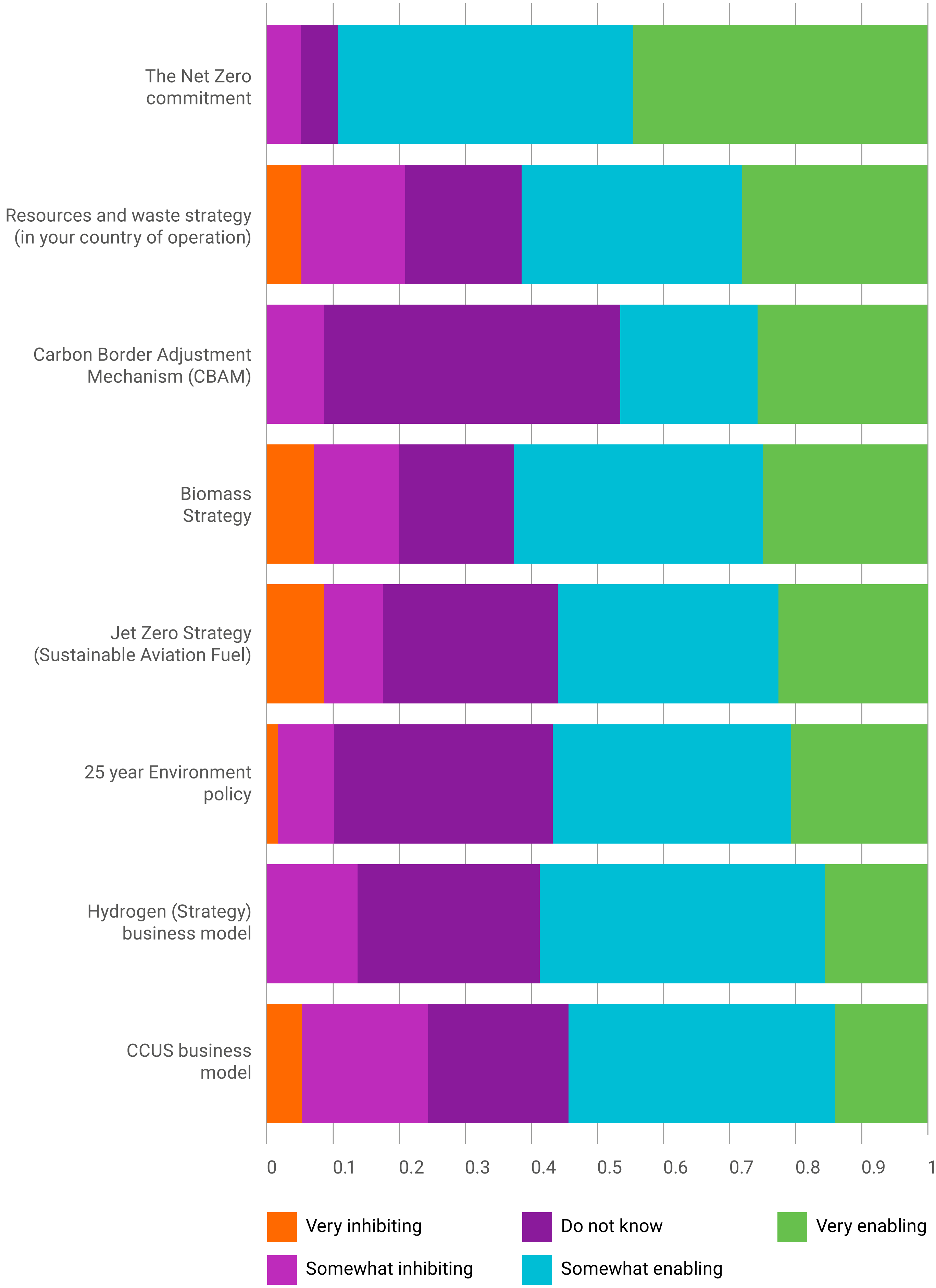


Figure 13: Stakeholder response to how current UK policies and regulations impact the UK chemicals industry to become more sustainable.

3.5 Current challenges faced by the UK chemicals industry

The UK chemicals industry has many strengths, and opportunities, but also has several weaknesses and threats, agreed by stakeholders, which are summarised below:

Strengths

- Ethane import infrastructure and three crackers able to use ethane as a feedstock
- LNG import and re-export facilities
- Several closely integrated clusters
- An extensive ethylene pipeline network
- Modern chlor-alkali and derivatives production based on membrane technology
- Strong exports to geographically diverse markets
- High resource efficiency
- Highly innovative, backed by exceptional research and university infrastructure
- Strong safety and responsibility culture and performance in production and distribution
- Able to satisfy sophisticated consumer demands
- Heightened political recognition and value driven by industry's criticality to the economy and broader society in tackling Covid-19

Weaknesses

- Ongoing disruption linked to Brexit and the medium to long-term impact on investment
- Uncertainty over the design and implementation of UK REACH
- Fragmented ownership of plants within clusters can lead to non-optimal long-term strategies
- Energy prices are globally uncompetitive, driven up by EU and UK climate policies while US, Middle East and China rivals access cheap hydrocarbons
- Mature European market: growth is faster in Asia and the US

- Scarcity of skilled craft workers because of ageing workforce and competition from other sectors
- Historic strength in some key customer industries – e.g. aerospace and automotive – now challenged by ongoing Brexit disruption and stronger growth in non-European markets
- The fact that strategic decisions are made by multinationals with fewer ties to the UK, means that there isn't always alignment on what makes sense for the company versus the country.

Opportunities

- **Research and development (R&D):** The UK has a strong research base and a history of research in the chemicals sector. By investing in R&D and promoting collaboration between industry and academia, the UK can develop new products, processes, and technologies that can give a competitive edge in high-value chemicals.
- **Sustainability and circular economy:** As the demand for sustainable and eco-friendly products grows, the UK chemicals industry can position itself as a leader in developing bio-based, biodegradable, or recycled chemicals and materials. This can open up new markets and align with global sustainability goals.
- **Advanced manufacturing and digitalisation:** Embracing advanced manufacturing techniques, such as additive manufacturing (3D printing), automation, and digital technologies, can improve efficiency, productivity, and customisation capabilities of the UK chemicals industry.
- **Specialty chemicals and high-value products:** The UK can focus on producing high-value, specialised chemicals for sectors like pharmaceuticals, electronics, and advanced materials, where expertise and innovation can command higher margins and provide a competitive advantage.
- **Export opportunities:** With its strong reputation and research capabilities, the UK chemicals industry can target export markets, particularly in emerging economies with growing demand for chemicals and related products.
- **Collaboration and industry clusters:** Fostering collaboration between companies, universities, and research institutions can create strong industry clusters, promoting knowledge sharing, innovation, and economies of scale.
- **Workforce development:** By investing in STEM education, apprenticeships, and workforce training programs, the UK can build a skilled and talented workforce to support the chemicals industry's growth and innovation.
- **Regulatory leadership:** The UK can leverage its expertise and position itself as a leader in developing and implementing effective chemical regulations, standards, and best practices, which can benefit the industry globally.

Threats

- Continued competition from lower cost production regions
- **Brexit:** The UK's departure from the European Union (EU) has created uncertainties and challenges for the chemicals industry. Potential issues include tariff and non-tariff barriers to trade, regulatory divergence, and disruptions to supply chains and workforce mobility.
- **Competition from emerging economies:** Countries like China, India, and others have rapidly developed their chemicals industries, benefiting from lower production costs and favourable government policies. This intense competition poses a threat to the UK's market share and profitability in certain chemicals segments.
- **Regulatory pressures:** The chemicals industry is subject to stringent environmental and safety regulations, both in the UK and globally. Complying with these regulations can be costly and burdensome, particularly for smaller companies. Additionally, potential changes or divergence in regulations post-Brexit can create further challenges.
- **Fluctuations in raw material costs:** The chemicals industry is heavily dependent on feedstocks derived from oil, natural gas, and other raw materials. Price volatility in these commodities can significantly impact production costs and profitability.
- **Energy costs:** The chemicals industry is energy-intensive, and high energy costs in the UK can erode competitiveness compared to regions with cheaper energy sources.
- **Skills shortage:** The industry faces challenges in attracting and retaining skilled workers, particularly in areas like engineering, research, and development. A shortage of skilled labour can hinder innovation and growth.
- **Public perception and sustainability concerns:** There is increasing public pressure and scrutiny on the chemicals industry regarding environmental impact, safety, and sustainability. Addressing these concerns and transitioning to more sustainable practices can be challenging and costly.
- **Geopolitical tensions and trade disputes:** Global trade tensions and disputes can disrupt supply chains, increase costs, and limit access to important markets for UK chemicals exports.

Stakeholders were asked what the main challenges for the UK chemicals industry were, and what barriers were preventing accelerated growth, highlighted below in Figure 14, and described in more detail below (in order of significance).

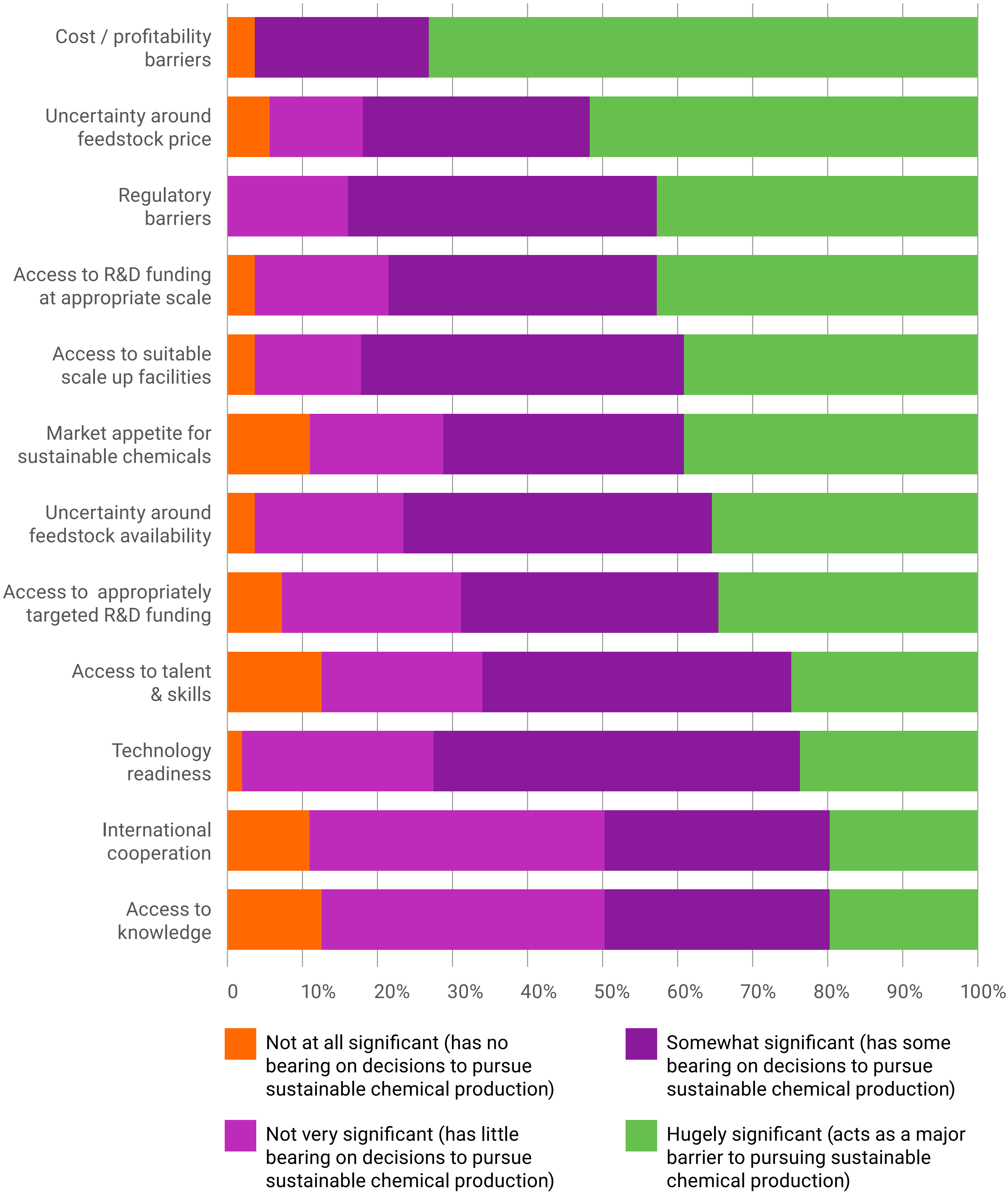


Figure 14: Challenges and barriers facing the UK chemical industry.

Cost and Profitability

The UK chemical industry is facing a number of current and long-term challenges. Data gathered from the Chemicals Industry Association membership,[56] through regular business surveys, shows that the largest current challenge is the cost of energy, specifically gas. Unlike other industries, gas is not just an energy source but is also a feedstock, this intensifies the industry's exposure to rising prices. The energy crisis, triggered by Russia's invasion of Ukraine, is currently adversely impacting the UK chemical industry, cementing the fact that other sources of sustainable carbon for feedstocks are urgently required to ensure the future of a UK chemicals industry. Fluctuating gas prices mean that the cost of chemicals production rises. It also means that, as consumers spend more on their own heating bills, disposable income to purchase products made from outputs of the chemicals industry declines.

Uncertainty around feedstock price and availability

96% of all stakeholders agree the greatest barriers to transitioning to the use of sustainable carbon is economics, since sustainable chemical manufacturing faces cost competitiveness challenges when compared to fossil-based counterparts. High capital investment costs, limited economies of scale, and the dependency on fluctuating sustainable carbon feedstock prices can make production economically unviable. Achieving cost parity or cost advantage is crucial for the commercialisation and widespread adoption of sustainable chemicals. 78% of stakeholders cite the availability and consistent supply of sustainable carbon feedstocks as a significant challenge for the industry. Access to feedstocks, at the required volume, required specification, and consistent cost was cited by 82% of stakeholders as an issue, alongside understanding future feedstock availability, which was also highlighted as a key barrier.

Policy and regulatory barriers

84% of stakeholders see the regulatory environment as a key barrier to the transition to a more sustainable chemicals industry. One particular issue that was highlighted by stakeholders was that new products manufactured from sustainable carbon feedstocks need to have the same, or better performance than their fossil resource counterparts. This requires requalification of specification – which is extremely costly, where fees to register a new chemical product with REACH, can span into the millions, making sustainable chemicals development unviable.

Table 7: Overview of current policies and their barriers to the UK chemicals industry.

Biomass

Policy	Current Policy Barrier
Energy prices	High network and policy costs related to renewables roll out, plus natural gas-to-power setting the marginal wholesale price. Pass through cost of carbon pricing from ETS and CPS.
UK Biomass Strategy	Inadequate detail on chemicals sector in the strategy.
Climate Change Agreements (CCA) scheme	The CCA scheme does not have a formal method to account for the increase in energy that a site could expect to use if it switches to alternative feedstocks.
Plastic Packaging Tax	No accepted mass balance accounting method to calculate the proportion of recycled content in plastic packaging.
Standards and labelling	No standardised system for the labelling of recycled content.
UK Emissions Trading Scheme	The UK ETS does not consider biomass used in a product as carbon stored. This means there is no incentive to use bio-feedstock over fossil feedstock.
Industrial Energy Transformation Fund	Scheme does not support alternative feedstock investment as it focuses on scope 1 emissions.
Renewable Transport Fuel Obligation	Renewable Transport Fuel Obligation encourages biomass to fuel over biomass to chemicals.
Green Gas Support Scheme	Supports biomethane injection to the grid for combustion.

Recycled Carbon

Policy	Current Policy Barrier
Energy prices	High network and policy costs related to renewables roll out, plus natural gas-to-power setting the marginal wholesale price. Pass through cost of carbon pricing from ETS and CPS.
Plastic Packaging Tax / Mass balance	No accepted mass balance accounting method to calculate the proportion of recycled content in plastic packaging.
Extended producer responsibility	Continual delays, now delayed until 2025.
Consistent collection, including collection for flexibles	Different collection practices across the UK means people often get confused about what to recycle and how to dispose of waste. Some packaging cannot be collected separately/recycled in certain parts of the UK which is a barrier to having a usable feedstock for chemical recycling purposes.
Climate Change Agreements (CCA) scheme	The CCA scheme does not have a formal method to account for the increase in energy that a site could expect to use if it switches to alternative feedstocks.
Standards and labelling	No standardised system for the labelling of recycled content.
UK Emissions Trading Scheme	CCS is supported as the emissions sent to permanent geological storage are zero-rated. CCU is only supported by the UK ETS where the carbon is stored in precipitated calcium carbonate - incentivising CCS over more valuable and circular CCU.
Industrial Energy Transformation Fund	Scheme does not support alternative feedstock investment as it focuses on scope 1 emissions.

Carbon Dioxide

Policy	Current Policy Barrier
Energy Prices	High network and policy costs related to renewables roll out, plus natural gas-to-power setting the marginal wholesale price. Pass through cost of carbon pricing from ETS and CPS.
GHG Protocol	No clarity on the treatment of captured emissions used in products.
Hydrogen Production Business Model	The Low Carbon Hydrogen Standard underpinning this subsidy requires that captured carbon is either permanently stored or is made into carbon black – incentivising CCS over more valuable and circular CCU.
Industrial Carbon Capture (ICC) business model	CCU is currently ineligible for support under the Industrial Carbon Capture (ICC) business model - incentivising CCS over more valuable and circular CCU.
UK Emissions Trading Scheme	CCS is supported as the emissions sent to permanent geological storage are zero-rated. CCU is only supported by the UK ETS where the carbon is stored in precipitated calcium carbonate -incentivising CCS over more valuable and circular CCU.
Climate Change Agreements (CCA) scheme	The CCA scheme does not have a formal method to account for the increase in energy that a site could expect to use if it switches to alternative feedstocks.
Climate Change Levy (CCL)	Although an exemption is provided for natural gas as a feedstock, HMRC's interpretation is that this would not apply where natural gas is combusted and the carbon captured for use in a product.
Bioenergy carbon capture and storage	Government support for BECCS pulls biomass out of the market and directs it towards permanent geological storage, whereas it would be more valuable and sustainable if it were returned to the economy.
Plastic Packaging Tax	No accepted mass balance accounting method to calculate the proportion of recycled content in plastic packaging.
Standards and labelling	No standardised system for the labelling of recycled content.
Industrial Energy Transformation Fund	Scheme does not support alternative feedstock investment as it focuses on scope 1 emissions.

Access to R&D funding, scale-up facilities and expertise

83% of stakeholders feel that access to scale up facilities is a significant issue for the chemicals industry, followed by 50% seeing access to expert knowledge as a barrier. Many stakeholders cited the need for affordable UK pilot and demonstration facilities to help scale up technologies and processes, alongside the need for subsidised access to such facilities for SMEs, since many organisations are currently having to take their processes to Europe to carry out scale-up. SMEs in particular noted that gaining access to academic expertise was difficult, and finding out where expertise is available was hard – not knowing which researchers or institutions specialise in the areas relevant to their needs. Industry also had concerns about intellectual property (IP) and ownership when collaborating with academia.

Market appetite for sustainable chemicals

71% of stakeholders see gaining market acceptance as a significant barrier to a transition to a sustainable chemicals industry. This is due to various factors, including cost differences, limited awareness among consumers, potential performance gaps compared to conventional chemicals, and resistance from established industries. There was a perception amongst stakeholders that the public did not consider climate change as an immediate threat, and that the UK was going to be able to mitigate any effects. Stakeholders feel that addressing these barriers requires a multi-faceted approach involving collaboration among industry, academia, policymakers, and research institutions. Investments into public awareness campaigns were also seen as vital for overcoming these barriers and promoting the widespread adoption of sustainable chemicals.

Access to appropriately targeted R&D funding

The need for long-term access to finance was seen as an issue by most stakeholders, spanning the full TRL. 69% of stakeholders see a lack of R&D funding as a significant issue. Several stakeholders also noted that the lack of longevity of funding meant that lots of great projects get to TRL 3 or 4 but never any further with 79% of stakeholders agreeing funding for scale-up is a significant issue for the chemicals industry. It was also noted that for SMEs innovate UK funding was inaccessible for some due to the need for them to fund 30% of costs themselves and have funds upfront before claiming back. In terms of investment, stakeholders felt that the UK does not support start-ups in the sustainable chemicals sector, and that most investment currently comes from abroad. For example, Holiferm has secured most of its investment from the US and EU. One stakeholder cited that Sanofi, one of the largest investors in the biochemicals space, has not made an investment in UK since Brexit.

Access to talent and skills

66% of stakeholders see a significant challenge facing the UK chemical industry is the availability of skilled staff, recruitment, and retention. A workforce with an adequate skillset has been an underlying challenge for the UK chemical industry for a number of years. The pandemic has exacerbated some of the challenges, but an unhelpful immigration policy and an ageing workforce have delivered a perfect storm of workforce related issues. Currently there are 3.6 job vacancies in the manufacturing sector per 100 jobs, significantly above the long-run trend of 1.7 and pre-pandemic peak of 2.6.[57] For bio-based chemical production, stakeholders noted the UK has a skills gap in biochemical engineers who could translate chemical processes into bio-based ones. The application of advanced technologies, such as computational modelling and data analysis, also requires specialised expertise, which the UK chemicals industry struggles to attract. A skills gap around people with Life Cycle Assessment (LCA) expertise was also noted.

Technology readiness

Over 73% of stakeholders agreed that technology readiness for sustainable carbon feedstocks production and processing is either a slightly significant or very significant barrier, with the main issue being technologies being successfully demonstrated at TRL 5 and above.

The technology readiness of chemical recycling varies depending on the specific process and application, however, stakeholders noted that significant challenges exist including technological limitations, cost competitiveness with traditional recycling methods, and the need for supportive policy frameworks. Waste classification of plastic waste was also seen as a significant barrier for chemical recycling. The technology readiness of biomass as a feedstock was seen as higher by stakeholders, and already in wide use across the UK. However, the pre-treatment of biomass in the volumes required for scaling up was seen as limiting, since the conversion of biomass into bio-based chemicals often involves complex and resource-intensive processes. Optimisation of these processes, as well as improving the yield and selectivity of target chemicals, requires ongoing research and development efforts. Stakeholders felt that the use of CO_2 either by CCU or by direct air capture (DAC) was the least advanced in terms of being a commercially viable source of sustainable carbon for the chemicals industry. By 2030 most stakeholders believe that biomass as a source of more sustainable carbon for the chemicals industry is most likely. Stakeholders believe that it is likely to be 2040 before significant amounts of sustainable carbon via recycled carbon will be available, and that it is most likely to be post 2050 when carbon capture and utilisation or direct air capture of CO_2, as a feedstock for the UK chemicals industry, will be in place in significant enough volumes to be commercially viable. Stakeholders noted that the existing infrastructure for the production, storage, and transportation of chemicals is typically designed for fossil-based chemicals. Establishing a dedicated infrastructure for sustainable chemical production, including feedstock collection, processing facilities, and distribution networks, requires significant investment. In addition, the significant investment in existing assets, which utilise fossil resources, means that organisations want to utilise these as much as possible, before making any new investments.

Access to low carbon hydrogen and renewable energy

Stakeholders all agree the need for large scale production of low carbon hydrogen and renewable energy as playing a vital role in the production of sustainable chemicals. Access to competitively priced and reliable sources of both hydrogen and energy are key. Hydrogen serves as a crucial feedstock in various chemical processes and can be combined with CO_2 captured from industrial processes or directly from the atmosphere to produce synthetic fuels or chemicals including methanol and ammonia. The potential to use hydrogen as a storable form of energy is often cited as a driver for hydrogen production. The hypothesis is that hydrogen can be produced intermittently using curtailed renewable energy produced in excess to localised electricity grid capacity. However, the economics of intermittent production are likely to be challenging.

International co-operation

Stakeholders' feelings about international co-operation was mixed, with 50% seeing it as a barrier, and 50% not. Many stakeholders cited Brexit and not being able to access EU funding for a period of time, and currently not as easily as before, as a significant barrier.

Unintended consequences

Many stakeholders highlighted the issue of ensuring that the uptake of sustainable carbon for the chemicals industry does not replace its usage elsewhere, leading to overall less sustainable practices. One example described was the use of animal fat to produce jet fuel. Airlines are under pressure to reduce their carbon emissions, which mainly comes from burning fossil-based kerosene in aircraft engines. Demand for fuel made from biomass derived animal by-products is expected to triple by 2030. But experts fear scarcity will force other industries to use more palm oil – potentially a significant generator of carbon emissions. A second example was distillery by-products, traditionally used as an animal feed, being diverted to produce bio-based chemicals, leading to farmers importing soy from Brazil to use as animal feed, which potentially generates significantly more carbon emissions.

Section References

48 Chemical Industries Association, Britain's chemical industry fuelling UK Growth – A plan for the next Government, Chemical Industries Association Launches Manifesto in Parliament | CIA, [accessed 26 Mar 2024]

49 The anticipated closure of the Grangemouth oil refinery is not expected to impact chemical production which is based on imported ethane feedstock.

50 https://www.plastemart.com/news-plastics-information/dow-to-shut-uk-ethylene-oxide-glycol-plant-by-jan-2010-end/15782

51 https://www.bbc.co.uk/news/uk-england-tees-25213602

52 https://www.ineos.com/news/shared-news/ineos-announces-launch-of-consultation-on-the-potential-closure-of-seal-sands-acrylonitrile-plant/

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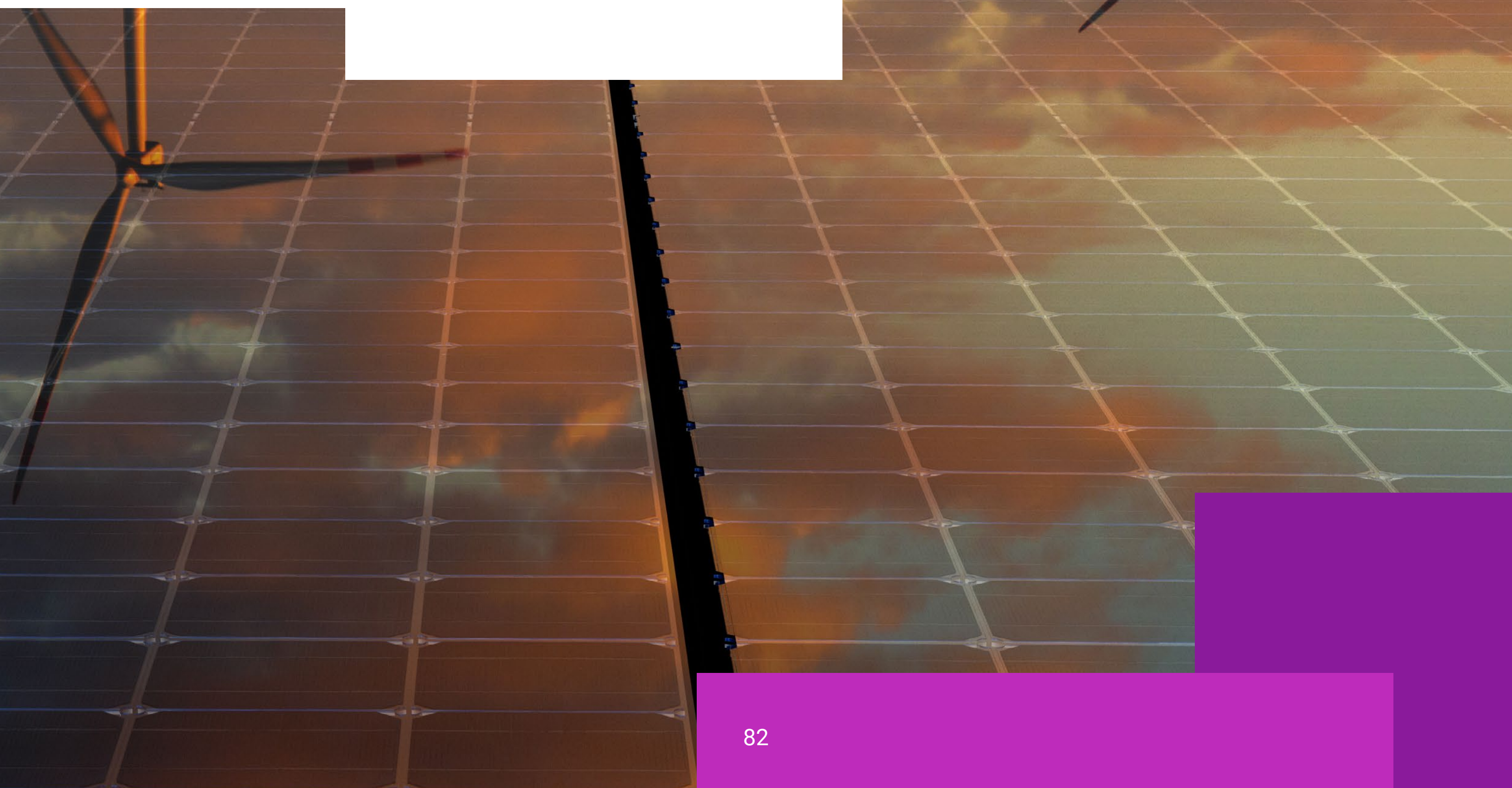
54 https://www.cia.org.uk/Portals/0/Documents/CIA%20Q4%202023%20Economic%20Report.pdf

55 However, perhaps counterintuitively, the CBAM is not targeting the kind of embodied carbon this study correlates to at present, it is targeting the scope 1 emissions released in the production of an imported good.

56 United Kingdom - cefic.org

57 Chemicals Industry Association



4. Review of transition proposals beyond the UK

4.1 Transition pathways

A wide range of policy roadmaps were reviewed to identify proposals considered by countries and authorities outside of the UK for a transition to the use of sustainable carbon feedstocks in chemical manufacturing. Timelines were typically considered in terms of short-, medium-, and long-term strategies. With immediate term actions noted in a handful of cases. Immediate term refers to 2024-2025. Short-term refers to 2026-2027. Medium-term refers to 2028-2030. Long-term refers to 2030 onwards. A summary of transition pathways for biomass, recycled carbon, and CO_2 are presented below.

Biomass feedstocks

The prospect of the UK's chemical sector becoming largely bio-based remains challenging. It will be difficult to achieve given: (i) the limited availability of sustainable primary biomass in the UK & the EU; (ii) the fierce competition for biomass resources from other sectors (in particular, the energy and transport sectors); and (iii) the sheer scale of demand. Increased pressure on biomass demand therefore requires careful assessment of trade-offs[58] by adopting biomass-use prioritisation.

Key steps acknowledged by policy roadmaps to promote the use of biomass feedstocks for chemical production in the future include:

- Standardising sustainability assessment tools (e.g. mass balance methods),
- Aligning regulations to support the use of bio-based feedstocks;
- Developing appropriate labelling to promote consumer awareness;
- Developing certification criteria;
- Economic incentives.

Table 8: Summary of short-, medium- and long-term proposals considered by countries and authorities outside of the UK for a transition to the use of biomass feedstocks in chemical manufacturing.

Biomass Feedstocks [59, 60, 61, 62, 63]	
Short Term	• Set up incentive schemes that enhance the use of biomass for materials. The mass balance approach for bioderived materials should be promoted. • Endorse trustworthy certification systems and standards for the sustainable sourcing of biomass feedstocks - clear sustainability criteria and incentives for labels. • Promote externally assured third-party certification systems to create a thriving market for sustainably sourced biomass streams. • Definitions need to be harmonised • Provide economic incentives to use sustainable biomass as feedstock - Incentivise the availability of and demand for circular feedstocks and help industry to develop recyclable products
Medium Term	• Enhance the quality and quantity of collected biomass suitable as feedstock for chemical production • Increase the efficiency and transparency of biomass supply chains. • Improve methodologies to monitor the environmental performance of biomass as a feedstock
Long Term	• Continued R&D to improve the sustainability of using biomass as feedstocks for the chemical industry. • Ensure that the use of biomass aligns with future net-zero targets in terms of emissions produced and sustainability

Case Study: Holiferm

Holiferm is a spin-out company from the University of Manchester using novel technologies for the sustainable production of biosurfactants. The company is currently producing sophorolipids at their 1,100 tonne commercial plant in Wallasey, UK. Holiferm have recently secured an £18.5 million investment to scale up to 15,000 production capacity and have plans to expand their product range to mannosylerythritol lipids (MELs) and rhamnolipid surfactants.

Recycled Carbon Feedstocks

Chemical recycling technologies (excepting solvent dissolution processes) break down the chemical structure of polymeric waste and other input materials such as plastic or textile waste into monomers and chemical building blocks. These technologies then transform the monomers and chemical building blocks into valuable secondary raw materials and dedicated and drop-in intermediates for manufacturing new products. Chemical-recycling processes each have their own requirements regarding the inputs used and result in different outputs. Processes typically involve depolymerisation, pyrolysis and gasification. These techniques offer a solution for best dealing with the deteriorating quality of polymer chains after each cycle of mechanical recycling.

To meet ambitious objectives for sustainability and circularity, increased volumes of plastic waste must be recycled, and a broad range of markets need to be served with plastics and chemical products containing higher recycled content. In the immediate term, investments in recycling infrastructure should be incentivised. Policymakers should leverage and expand Extended Producer Responsibility (EPR) schemes and other policy instruments to increase and warrant the long-term financing of collection, sorting and recycling infrastructure across the UK, with the aim to increase the quantity and quality of plastic waste collected for recycling. Furthermore, phase out of the landfilling and incineration of recyclable plastic waste should be initiated. It is recommended that policy phases in minimum landfill and incineration taxes on waste streams containing plastics – potentially increasing and going beyond €100 per tonne in 2030 - to be effective in deviating recyclable waste from landfilling or incineration and towards recycling.

Table 9: Summary of short-, medium- and long-term proposals considered by countries and authorities outside of the UK for a transition to the use of recycled carbon feedstocks in chemical manufacturing

Recycled Carbon Feedstocks [64, 65, 66]	
Short Term	• **Incentivise investments** in recycling infrastructure. • Leverage and **expand Extended Producer Responsibility (EPR) scheme** and other policy instruments to increase the long-term financing of collection, sorting and recycling infrastructure - the aim is to increase the quantity and quality of plastic waste collected for recycling. • **Phase out landfilling and incineration** of recyclable plastic waste. • **Harmonise definitions** and improve statistics for plastic waste management. • **Set targets for recycled and bio-based content** in order to stimulate demand.
Medium Term	• Make the **shipping** of sorted waste and recycled feedstock easier. • **Help the industry develop recyclable products** - put forward clear definitions and practical methodologies (e.g., at CEN or ISO level). • Improvements on **transparency** in the use of substances of concern to clean up material cycles at national level. • **Phase out the most harmful substances** from consumer products, unless they are essential for society. • **Phase in minimum landfill and incineration taxes** on all waste streams containing plastics - to be effective in deviating recyclable waste from landfilling or incineration to recycling.
Long Term	• Continued development into the design of products in such a way that they can be **easily recycled and valorised** as high-quality feedstock for the industry.

Mura Technology

Mura have developed an advanced plastic recycling process (Hydro-PRT) based on hydrothermal processing. The process uses supercritical water to crack the carbon-carbon bonds found in end of life, hard to mechanically recycle plastic, to produce a range of liquid hydrocarbons and gas, including a naphtha which can be used as alternative to virgin naphtha as a feedstock for chemical production. Mura will open its first commercial-scale plant in Teesside, UK, in Q3 2024, recycling 20,000 tonnes of post-use, mixed plastic waste every year, with a global, annual capacity target of 1.5 million tonnes in operation or development by 2032. Their process can save approximately 1.8 tonnes of CO_2 per tonne of plastic recycled compared to incineration.

CO_2 as a Chemical Feedstock

In December 2021, the European Commission adopted the Sustainable Carbon Cycles communication, which sets out an action plan on: (i) how to develop sustainable industrial solutions to increase carbon removals (using direct air capture and bio-based products with long lifetimes); and (ii) key actions to support the industrial capture, use and storage of CO_2 (CCU and CCS). Carbon capture (CCS/CCU) technologies are key technological pathways for the decarbonisation of energy-intensive industries, including the chemical industry. Their application potential has been identified as particularly high for the chemical sector (both CO_2 and CO). However, these technologies still face some challenges. The two main challenges are listed in the bullet points below.

- It is complex and costly to collect and purify CO_2 directly from the air.
- Transforming CO_2 via electrolysis for CCU requires a lot of energy, preferably from renewable sources.

The infrastructure required to capture, transport and produce the feedstock for these types of chemicals still needs to be built, and current price levels need to come down. Research in the area should continue and investment will help to scale up commercial production. For example, it is expected that carbon capture and hydrogen-based plastics will only account for 0.1 Mt in 2030, but then grow sevenfold to 0.7 Mt by 2040, and further scale up five-fold to 3.2 Mt by 2050 in Europe.[67]

A review of policies supporting the use of CO_2 as a chemical feedstock states the importance of research and development for CCU. UK policy should look to promote research and investment to scale up CCU, support the economic and technological development of CO_2 as a feedstock and formalise the CO_2 emission savings from CCU in regulation. A summary of recommendations based on policy mechanisms identified in the EU and beyond for the uptake of CO_2 as a feedstock for the chemical industry is included in the table below.

Table 10: Summary of short, medium and long-term proposals considered by countries and authorities outside of the UK for a transition to the use of recycled carbon feedstocks in chemical manufacturing

CO_2 Feedstocks [68, 69]	
Short Term	• Support **research and development** for CCU scale up • **Support the economic and technological development** of CO_2 • Invest in the development of CCU technologies. • **Research into the safe and sustainable use** of captured CO_2
Medium Term	• **Formalize CO_2 emission savings** from CCU in regulation. • Create a **transparent legal framework** harmonised across the EU market to calculate and validate the CO_2 savings from CCU. • Standardise the **regulatory framework for the transportation of CO_2** within the EU - Consider harmonising the EU regulatory framework for cross-border CO_2 transport.
Long Term	• **Build CCU infrastructure** at industrial facilities to capture flue gases. • Roll out **direct air capture technologies.** • Support scale-up to help bring costs down in the longer term

SALTEND CHEMICALS PARK

Flue2Chem

The Flue2Chem Project aims to take waste gas from foundation industries such as metal, glass, paper and chemicals, and generate an alternative source of carbon for the UK chemicals industry. The two-year £5.4m programme led by Unilever has a total of 15 partners bringing together a full value chain for the conversion of CO_2 into chemical intermediates, on to consumer chemicals and finally into formulated products. The project aims to demonstrate how the UK could cut 15-20 million tonnes of CO_2 emissions each year.

Carbon Mitigation – Saltend Chemicals Park

The Saltend Chemicals Park is one of the UK's key chemical clusters. The 370 acre site positioned on the banks of the Humber estuary is home to international chemical businesses including Ineos Acetyls, Mitsubushi and BP as well as bioethanol producers Vivergo and bio-based construction material producers Tricoya. The site has an output of 2 million tonnes of chemicals each year. The site is home to the Hydrogen to Humber Saltend (H2H Saltend) project. The project will establish the world's largest Hydrogen production plant with Carbon Capture capability and will be the starting point for a regional hydrogen and CO_2 pipeline network. The plant will allow companies such as Ineos Acetyls to switch to hydrogen fuelled energy and reduce energy emissions. The H2H Saltend project has the potential to cut GHG emissions by nearly 900,000 tonnes dioxide emissions each year.

4.2 Investment into low carbon technologies

While policies outside of the UK have been reviewed and recommendations suggested in the previous section, it is helpful to be aware of where other countries have been focusing on investment. Europe's chemical sector is heading towards the biggest transformation in its history as it looks to reduce its impact on climate change and the wider environment. Many companies active across the region are already looking to modify production sites to incorporate more sustainable, low-carbon technologies into their operations. While some are focusing on increasing their chemical and mechanical recycling capacities, others are looking towards novel hydrogen production, carbon capture solutions, or the building of entirely new bio-based chemical production facilities.

Cefic, the European Chemical Industry Council, maintains a mapping tool to illustrate the locations of low carbon technology projects, both planned and started, across Europe. The projects captured by this tool range from biochemical plant construction to chemical recycling and CCS projects. The map showcases the complexity of Europe's chemical sector and demonstrates the breadth of solutions being targeted to transform it into a more sustainable chemical industry. This map is not exhaustive and does not feature every single initiative and project planned, started and/or executed by the chemical sector. However, it does give a good feel for where industry is investing at the moment, and the types of technologies that will play an important role in decarbonising the sector in the future.

Overall, investment in Europe's chemical sector is led by renewable and low carbon electricity projects (in terms of project numbers), accounting for around one quarter (24%) of all projects incorporated into Cefic's 'Low-Carbon Technologies Projects' map. Hydrogen & derivative product manufacturing is the next largest investment area (17%), followed by chemical recycling (15%), efficiency measures (10%), waste/ biomass to energy projects (8%) and bio-based chemical manufacturing (7%).

Of the total number of projects (both planned and started) in the UK, roughly one third are concerned with the production of hydrogen and its derivative products, another third are carbon capture and storage related projects. The remainder are involved with improving process efficiencies (15%), chemical recycling (10%), renewable and low-carbon electricity (5%), and carbon capture and utilisation (5%). There are currently no UK bio-based chemical production projects registered in the database.

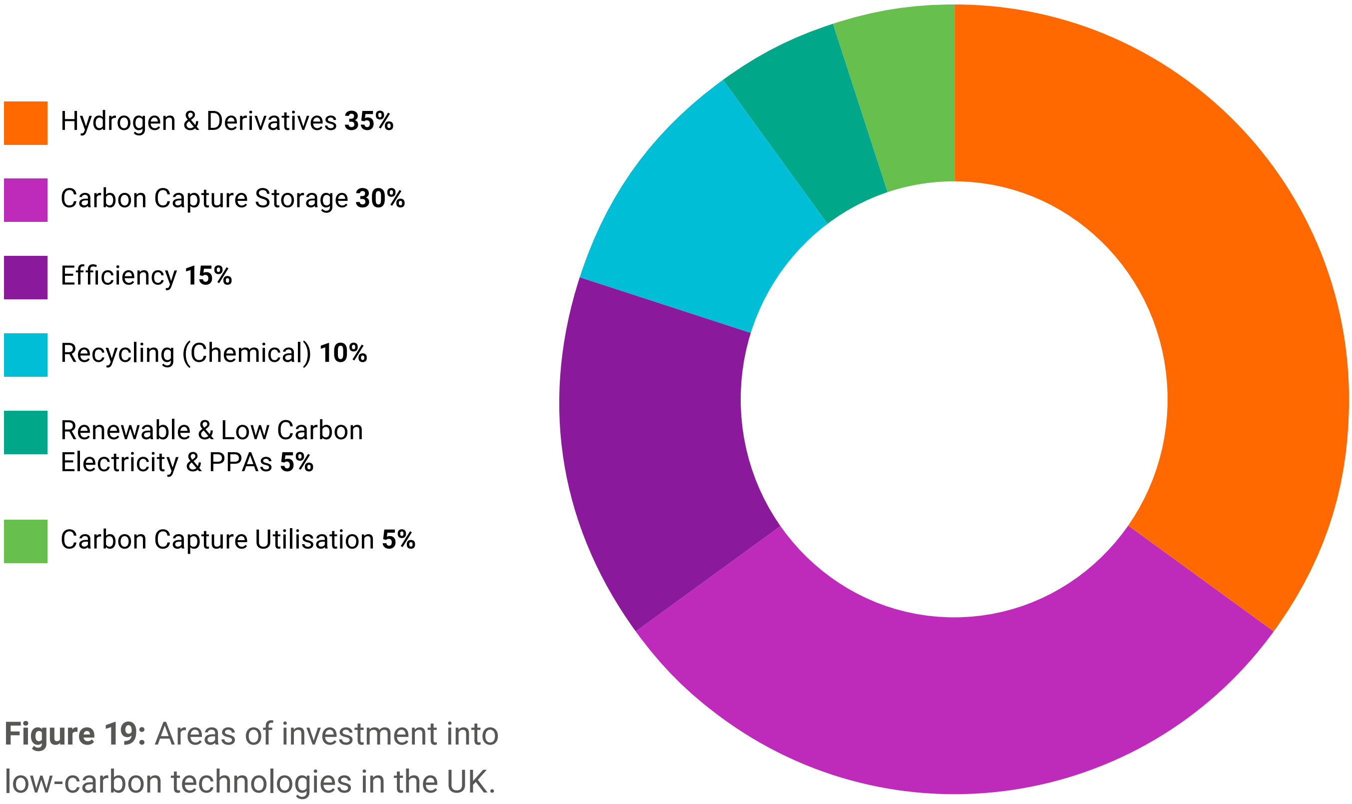


Figure 19: Areas of investment into low-carbon technologies in the UK.

In total across Europe, there are 165 low-carbon technology projects listed within Cefic's 'Low-Carbon Technologies Projects' map, including 78 planned projects and 87 started projects. The data shows that Germany is the biggest investor in low-carbon technology projects across Europe (in terms of numbers, both planned and started), followed by Belgium, the Netherlands, Spain and the UK. Total investment occurs across 16 European nations, with investment from the top 5 nations, with investment from the top 5 countries in this list representing roughly two-thirds of all projects recorded.

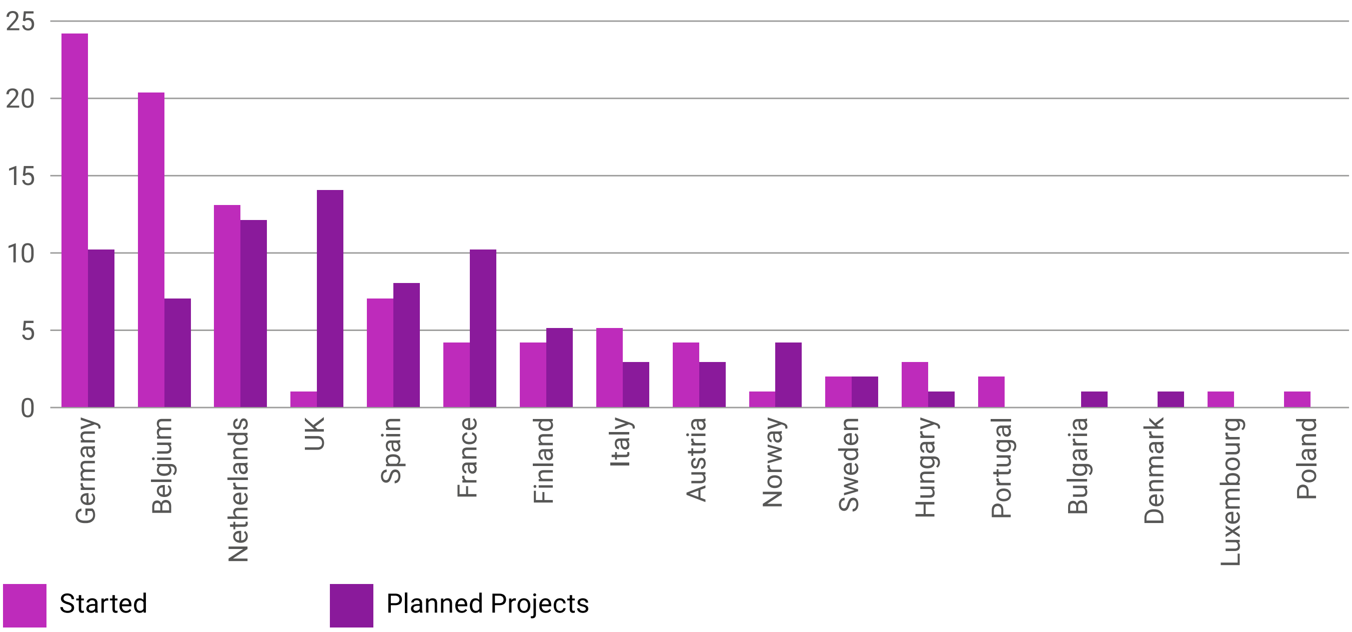


Figure 20: Countries carrying out low carbon technology projects across Europe.

4.3 Sustainable carbon projects around the world

A number of examples of sustainable hydrocarbon projects that are being scaled up around the world are included below to highlight key learnings that the UK could benefit from.

Biomass Feedstock Projects

Novamont are world leaders in the development and production of biobased plastics and biobased chemicals through the integration of chemistry, the environment and agriculture. The Novamont circular bioeconomy model is one of the most successful in Europe in terms of investments and new industry-driven technologies, with €500 million invested in plants, directly or in joint ventures, €200 million in research and development, and 600 direct and 2,000 indirect workers. Novamont's biodegradable and compostable bioplastics range "Mater-Bi®" are produced by patented technologies in the field of processing starches, vegetable oils and combinations thereof. Mater-Bi products are suitable for injection moulding, sheet and film applications, and typical applications include carrier bags, film for agricultural mulching, personal care products, catering products, food packaging. Mater-Bi® is manufactured in the Novamont Integrated Biorefinery in Terni (Italy) which has a production capacity of 120,000 tons per year for compounding, and 60,000 ton for polyesters.[70]

Furthermore, **Mater-Biotech** is a company 100% owned by Novamont and was created in order to construct the first dedicated industrial plant in the world that can produce butanediol (1,4 BDO) directly from sugars. It benefits from a partnership that links together a technology developed by Genomatica, a leader in the biotechnology industry, and Novamont's unique skills and know-how in developing low-impact processes. The plant has a 30,000 tonnes per year capacity, and reuses by-products for its own energy purposes, thus optimising the life cycle of the entire process. The plant is a key development in Novamont's biorefinery model and paves the way to the production of further chemical intermediates from renewable resources.[71]

UPM are also building a new industrial scale biorefinery which will produce renewable glycols and lignin to replace fossil-based ingredients in a wide variety of industrial applications. The Leuna Biorefinery is anticipated to be operational by the end of 2024 and will convert solid wood into next generation biochemicals, including bio-monoethylene glycol (BioMEG), lignin-based renewable functional fillers bio-monopropylene glycol (BioMPG) and industrial sugars. The plant will have a total annual capacity of 220,000 tonnes upon completion.[72]

Chemical Recycling Feedstocks

OMV have established a joint venture with **Interzero** to build and operate Europe's largest sorting facility for chemical recycling. This sorting facility, based in Germany, will be the first of its kind to produce feedstock for OMV's chemical recycling on a large industrial scale. The ReOil® technology developed and patented by OMV is a chemical recycling innovation that converts plastic waste that cannot be mechanically recycled into pyrolysis oil. The input for the sorting plant essentially involves mixed plastics that have not been recyclable until now. Interzero operates five sorting plants for lightweight packaging in Germany and sorts around one third of Germany's lightweight packaging waste in the form of over 800,000 metric tonnes per year. This means that the company has the largest sorting capacity in Europe at present. Cooperation between OMV and Interzero will ensure the supply of sustainable and high-quality feedstock for OMV's chemical recycling. The state-of-the-art sorting facility developed by Interzero will be capable of processing up to 260,000 tonnes of mixed waste plastics per year, providing the raw materials for the production of virgin polyolefins. This innovative sorting process will make it possible to recover a polyolefin-rich fraction from a waste stream that currently ends up in thermal recycling. In terms of the waste hierarchy, their focus is on waste plastics that are not suitable for mechanical recycling. This ensures that chemical recycling does not compete with mechanical recycling.[73]

CO_2 Feedstock Projects

In October 2022 **Carbon Recycling International** completed the commissioning of a new CO_2-to-methanol production facility located adjacent to a coke oven gas production facility (COG) based in Anyang city, Henan Province, China. The plant is the world's largest production plant of fuel from captured CO_2 emissions with a capacity of 110,000 tons of low-carbon intensity methanol per year. The coke-oven facility, operated by Chinese chemical company Henan Schuncheng Group, produces metallurgical coke. This coke is then used as a raw material for steel manufacturing, with coke oven gas - containing CO_2, hydrogen and methane - formed as a by-product. CRI's Emissions-to-Liquids platform (ETL) is a key addition to recover energy and create value from these by-products. Recycling 160,000 tons of CO_2 per annum, the Shunli plant greatly reduces the emissions associated with steel production and supplies local corporations with clean fuel and chemicals in the form of low-carbon intensity methanol.[74]

Technip Energies and **LanzaTech** are in a collaboration to create a new pathway to generate sustainable ethylene, utilising their combined technologies. Together LanzaTech's carbon capture and utilisation technology with Technip Energies' Hummingbird® technology will transform waste carbon into ethylene. Up to 95% of the CO_2 in the flue gas is captured from the furnaces of an ethylene cracker and mixed with hydrogen. Then LanzaTech's biorecycling technology transforms this captured waste carbon into ethanol. Technip Energies' Hummingbird® technology then dehydrates this ethanol into ethylene.[75] Ethylene is a building block for thousands of chemicals and materials, including plastics, detergents, and coatings. However, the traditional process for the production of ethylene is also one of the largest sources of CO_2 emissions in the chemical industry and remains one of the most challenging processes to decarbonise. This collaboration with Technip Energies and LanzaTech aims to tackle this challenge.

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5. Potential future scenarios

5.1 UK chemicals industry in 2050

5.1.1 The future UK chemicals industry

Stakeholders were widely consulted on what the future scenarios for the UK chemicals industry could look like, with a summary of findings highlighted below.

98%

of stakeholders believe that we need to **transition away from using fossil resources** as a feedstock for the UK chemicals industry

100%

of stakeholders agree that until fossil resources are no longer subsidised, sustainable Carbon feedstocks will not be a **commercially viable alternative**

Low carbon hydrogen and renewable energy

are **key enablers** for chemicals made from sustainable carbon

UK chemicals industry has

significant supply chain gaps

that need to be rebuilt

>90%

stakeholders believe a transition will not happen without a **long-term industrial strategy**

Ethylene and methanol

From sustainable carbon seen as **critical** for UK chemicals industry

>75%

of UK chemicals should be manufactured from green carbon sources by **2050**

Lack of communication and consumer understanding

of their daily interaction with chemicals is seen as a **barrier**

In 2030 biomass

is the most likely source of **sustainable carbon** being used

>75%

of stakeholders believe that the UK should either **build its own domestic supply**, or take advantage of the ability to **import, sustainable carbon feedstocks,** to manufacture chemicals across the full supply chain, from base chemicals to speciality

>95%

Stakeholders believe that the UK chemicals industry **needs to address scope 3 emissions**, and that off-setting should only be used during a transition to Net Zero

CO_2

will not be viable as a **sustainable Carbon** source until **2050**

Recycled carbon

will not be viable as a sustainable carbon source until **2040**

All stakeholders believe that there is a need to transition away from the use of virgin-fossil feedstocks, but only 21% believe that this is possible by 2050. A minority of stakeholders believe that the chemicals industry will never be virgin fossil resource free, due to increases in the human population, the tendency of humans to mass consume, and the lack of globally aligned policies being implemented. However, 69% of stakeholders believed that declining crude oil demand will affect the UK chemicals industry somewhat or to a great extent, meaning that the industry needs to take urgent action (Figure 22).

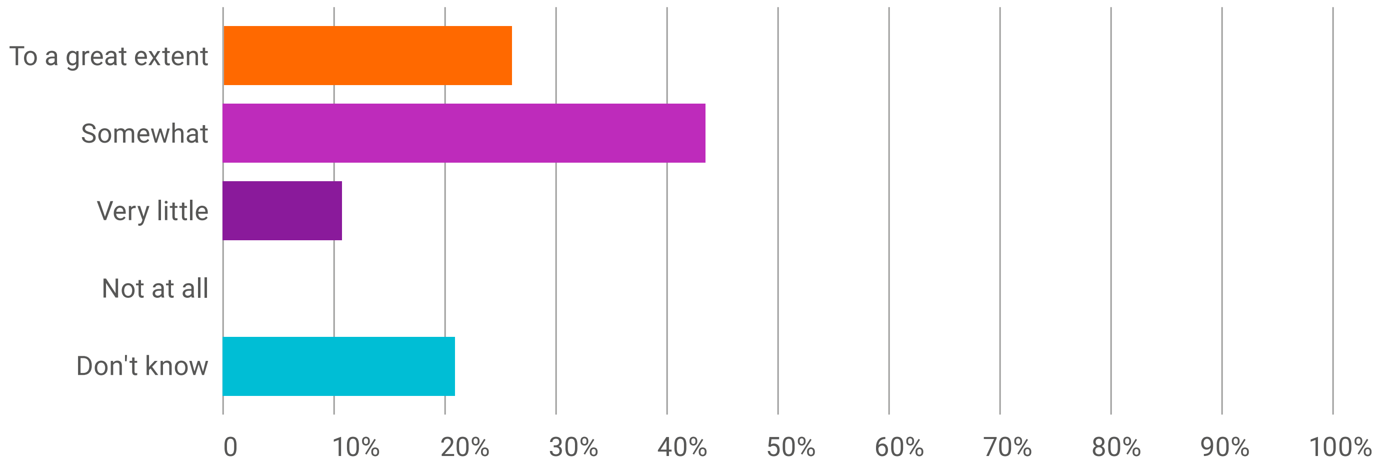


Figure 22: Stakeholder thoughts on how declining crude oil demand will affect the UK chemicals industry

In terms of the transition away from virgin-fossil resources, by 2030 most stakeholders believe between 1-25% of UK chemicals should be manufactured from sustainable carbon, by 2040 this should be 26-75%, and by 2050, between 51-100% (Figure 23).

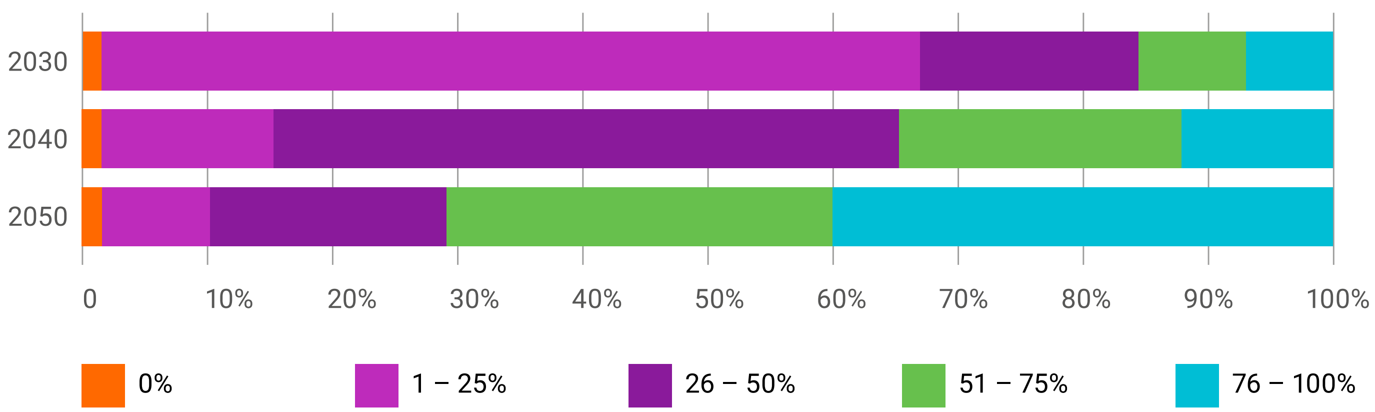


Figure 23: Percentage of chemicals stakeholders believe should be manufactured from non-fossil feedstocks

When asked whether the chemicals industry should set voluntary targets, some stakeholders believe that having voluntary targets would encourage UK chemical manufacturers to think about reducing their virgin-fossil resource usage, however, the majority of stakeholders indicated that they believe mandatory targets need to be in place to enable a transition away from fossil resources. For this to happen stakeholders agreed that regulations would need to be put in place alongside longer term strategies and policies.

Almost every stakeholder agreed that the chemicals industry should address all its GHG emissions including upstream and downstream scope three emissions – but some stakeholders felt that offsetting could be used as part of the transition towards becoming more sustainable. Several stakeholders noted that if everyone in the chemical supply chain dealt with their scope one and two emissions, this would mean that everyone's scope three emissions would automatically be dealt with, apart from the person at the very top and very end of the supply chain.

When asked how the UK should develop its sustainable carbon feedstock supply, over 55% of stakeholders believe that we should develop our own domestic supply (Figure 24). However, 21% of stakeholders agree we should take advantage of the ability to import sustainable carbon.

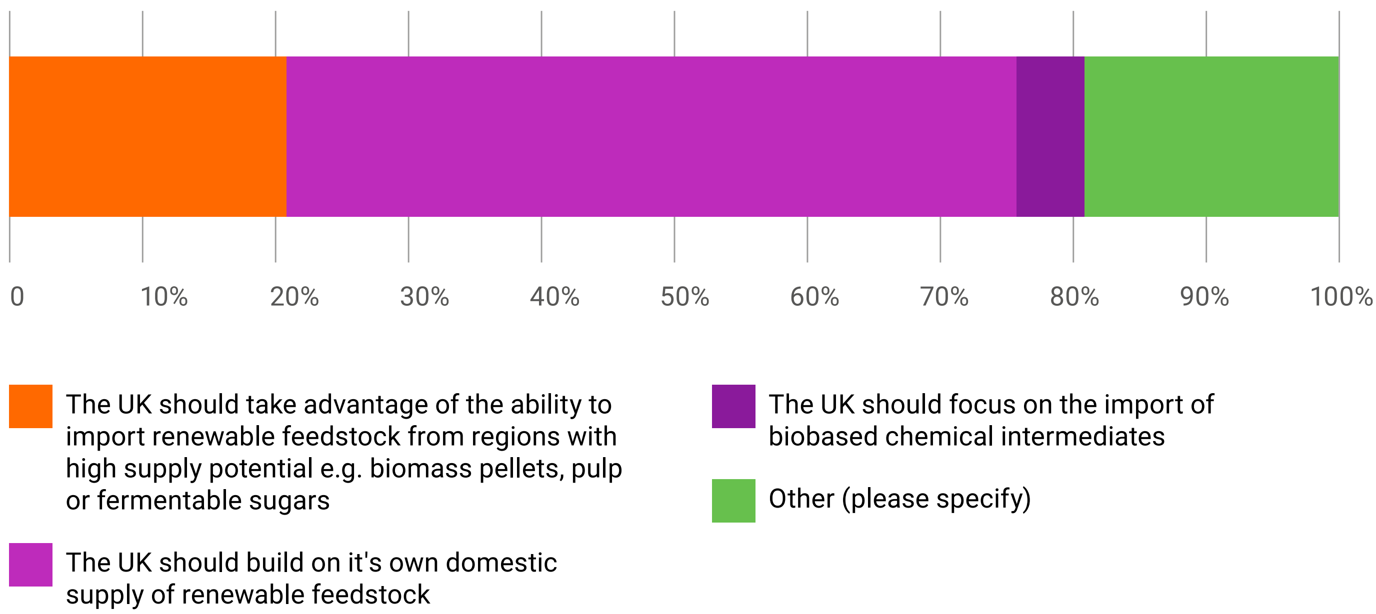


Figure 24: Stakeholder perception of how the UK should develop its sustainable carbon feedstock supply.

5.1.2 Building block chemicals of the future

When asked which chemicals we should focus on making from sustainable carbon in the future, most stakeholders agreed it would be very beneficial to the UK if we could manufacture primary chemicals from sustainable carbon sources, since these chemicals, as they worked down the supply chain would mean that intermediate and speciality chemicals would also therefore be more sustainable. However, stakeholders agreed that significant investment would need to be made into existing UK cracker assets to either retrofit them to be able to process sustainable carbon feedstocks, or entirely new infrastructure to be built.

Specific chemicals noted by stakeholders for the UK to concentrate on manufacturing from sustainable carbon included: Methanol, Ethylene, Acetic acid, Propylene, Ethanol, Butanol, Ethylene oxide, Fatty alcohols, Glycerol, Surfactants, Ammonia and Hydrocarbons (Figure 25).

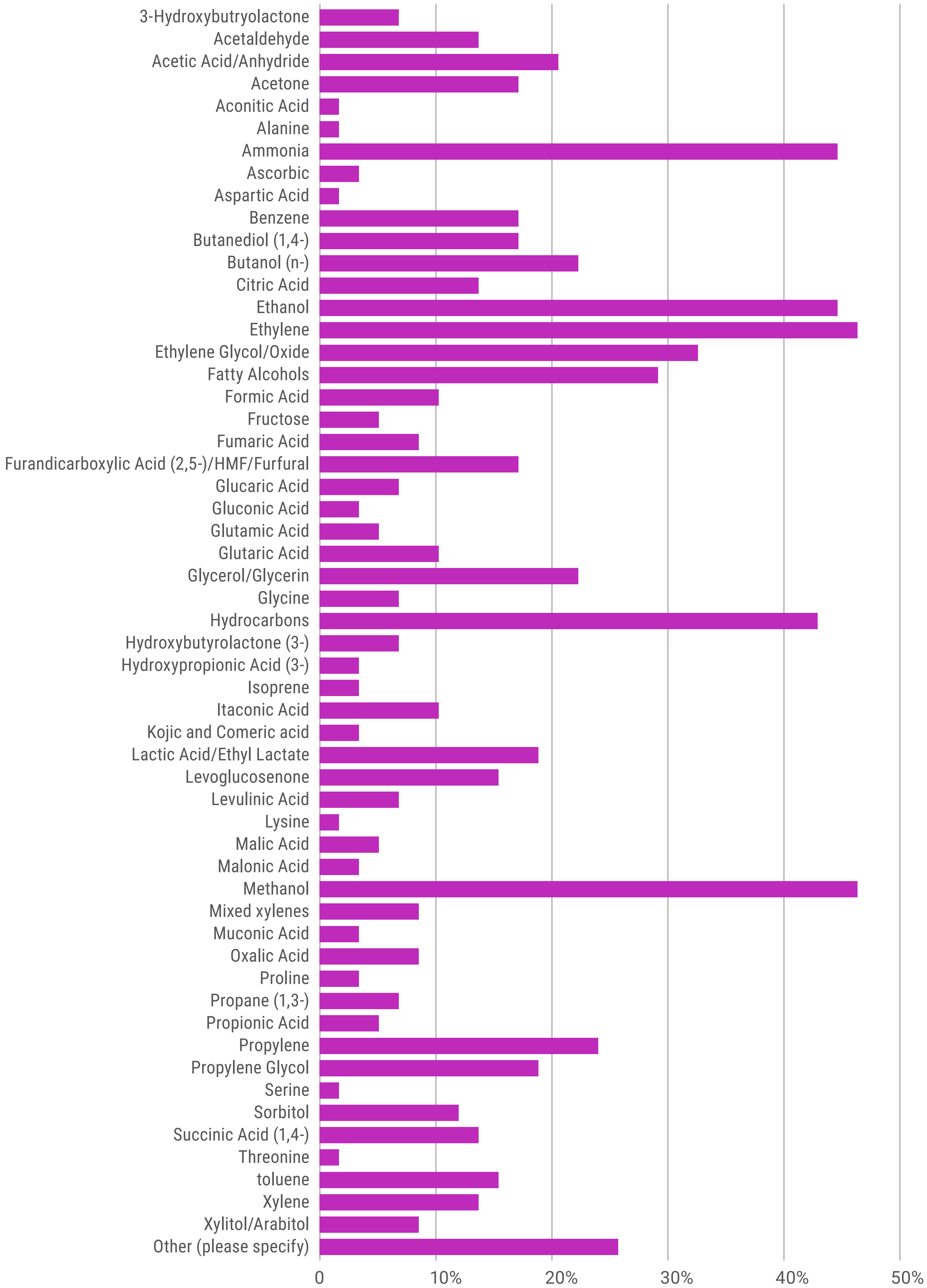


Figure 25: Stakeholder perception of which chemicals the UK should focus on making in the future from sustainable carbon.

5.1.3 Assessment of sustainable carbon sources

Stakeholders were consulted widely to enable SWOT analyses of potential sustainable carbon sources, as shown below.

Biomass Swot

Strengths

- Industrial base of bio-based chemical production from which to grow
- Mature supply chains for agricultural and forestry biomass

Weaknesses

- Production economics uncompetitive with fossil processes
- Must acknowledge energy requirements across the entire life cycle for the processing of biomass
- Loss of biodiversity due to increased crop cultivation, intensive agriculture or other unsustainable practices
- Ecosystem stress from water use or pollution
- Potential for increased food prices

Opportunities

- Supply expansion through the use of biomass crops or lignocellulosic residues
- Expansion, and more efficient production, of chemical targets through biotechnology
- Co-production of products and energy within biorefineries
- Negative emissions when adopted in conjunction with CCS

Threats

- Competition for biomass from bioenergy applications
- Reduced crop yields due to climate change
- Low oil price

Recycled Carbon Swot

Strengths

- Hydrocarbon feedstock supply familiar to the chemical industry

Opportunities

- Emerging technology and potential for technology improvement

Weaknesses

- Integration with existing UK chemical industry is challenging
- Feedstock economics uncompetitive with geospheric fossil feedstocks
- There are significant concerns around the toxicity of chemically recycled feedstocks and whether these will be feasible for use in the chemicals industry

Threats

- Optimal development of a circular economy would reduce feedstock volumes
- Competition from energy from waste facilities
- Low oil price

CO_2 Swot

Strengths

- Large volumes theoretically available
- Strong sustainability credentials

Opportunities

- Negative emissions when biogenic or atmospheric CO_2 is adopted in conjunction with CCS
- Expansion, and more efficient production, of chemical targets through biotechnology

Weaknesses

- Production economics uncompetitive with fossil processes
- Large energy requirements

Threats

- Insufficient or high cost of renewable energy prevents low-carbon hydrogen production

5.1.4 Utilisation of sustainable carbon sources in the UK

The carbon available to the chemical industry comes in various forms which points to where it may be most effectively used by the chemical industry.

The existing petrochemical industry is built on a platform of seven base chemicals, methanol, ammonia and so-called high value chemicals, ethylene, propylene, benzene, toluene and mixed xylenes. These platform chemicals are then transformed into a range of intermediate chemicals including oxygenated derivatives such as ethylene glycol and propylene glycol.

Chemical recycling of plastics produces hydrocarbon mixtures suited to the production of the high value chemical platforms.

Conversely, biomass is an oxygenated feedstock, producing hydrocarbons from biomass requires deoxygenation and therefore results in more mass balance and atom inefficiency. However, the presence of oxygen means it is well placed for conversion directly to oxygenated intermediate chemicals such as ethylene glycol and many other alcohols, acids and esters.

Biomass presents itself in a range of forms which influences the choice of process technology. Simplistically, biomass with relatively low moisture content, grains, crop residues, wood etc can be processed through a range of chemical or biotechnological technologies. However high moisture biomass forms such as agricultural slurries and some food waste which is often heterogeneous in nature is better suited to processing through anaerobic digestion to produce methane which can then be used as an alternative feedstock to natural gas.

CO_2 is a fully oxidised one carbon molecule, methanol is the most readily accessible chemical from CO_2 and can be used directly or as a platform for chemical production, often referred to as the methanol economy.[76]

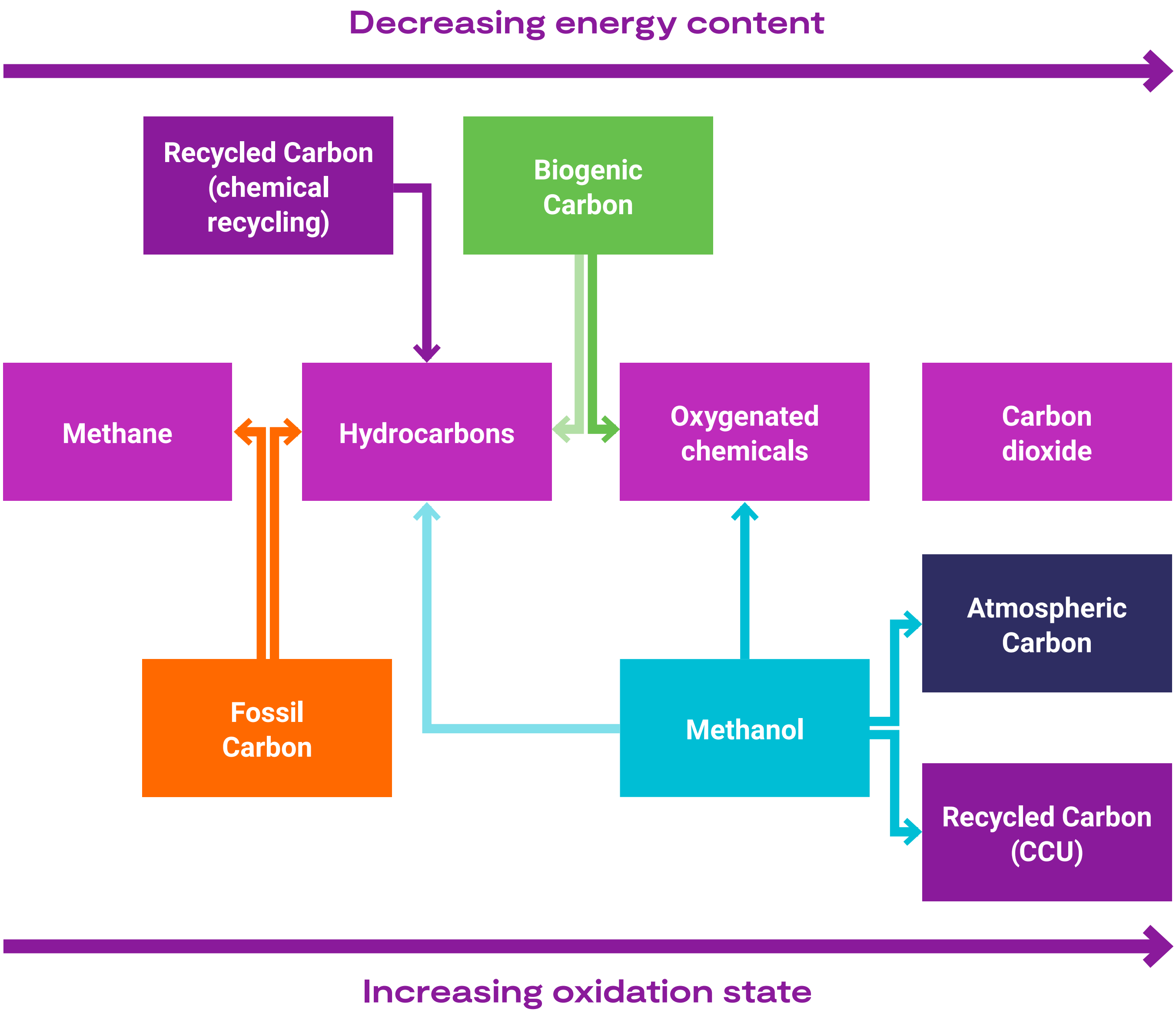


Figure 26: Simplified representation of carbon source integration for chemical production

Based on stakeholder feedback, and evidence described above, the best use of sustainable carbon sources is show below in Table 14.

Feedstocks		
Virgin Fossil	Oil, coal, gas	All chemicals and materials
Biomass	Food / feed crops	All chemicals
	Biomass Crops non-food/feed	All chemicals
	Virgin Wood and Forestry Residues	All chemicals
	Waste wood	All chemicals
	Biogenic fraction of MSW	All chemicals
	Agricultural slurries and sewage sludge	Biomethane derived products
	Agri-food by-products and Food waste	Biomethane derived products and fermentation products
Recycled Carbon	Mechanically recycled plastic	PET, HDPE
	Chemically recycled polymers	Ethylene, propylene, butane, BTX Methanol
CO_2	Direct air capture	Methanol
	CCU	Methanol

Table 14: Suggested best use of sustainable carbon sources.

5.2 Potential future scenarios

5.2.1 Developing the scenarios

Stakeholders we engaged to determine future scenarios, based on different technological approaches between now and 2050, that provide the greatest opportunity to leverage current UK assets and strengths in existing supply chains, R&D and innovation.

Key aspects of stakeholder insight that helped to shape the potential future scenarios include:

- Stakeholders feel that a business-as-usual scenario should be included in the final list of scenarios. In this scenario virgin fossil resource would account for 88% of feedstock to the chemicals industry in 2050
- Stakeholders felt that a scenario should be considered where fossil resources continue rising for the next 20 years and then begin to decrease
- Stakeholders are skeptical about the recycling of waste chemicals and polymers reaching over 30% by 2050. For example, how do you collect and recycle paints, adhesives and coatings
- Stakeholders were very skeptic about enough low-carbon hydrogen being available to manufacture significant amounts of chemicals from CO_2. The amount of energy that would also be required for this is enormous and stakeholders questioned whether it was feasible
- Stakeholders questioned whether a potential future scenario could be that the chemical industries continue to manufacture all chemicals from fossil resources as there will be more available with the move to electrification. However, in this scenario the UK would need more oil refineries
- Stakeholders think that chemical recycling is unlikely to be commercially viable in significant numbers until 2035

5.2.2 Predicted UK sustainable carbon 2050

In order to determine the validity of any future potential scenarios, a calculation of the potential amounts of each sustainable carbon feedstock that will be available by 2050 is required, as shown in Table 15.

Sustainable Carbon Type	Feedstock Type	Million Tonnes
Carbon available from Biomass[1]	Food / feed crops	1.0
	Biomass Crops non-food/feed	6.1
	Virgin Wood and Forestry Residues	1.4
	Waste wood	1.4
	Biogenic fraction of MSW	1.2
	Agricultural slurries and sewage sludge	3.3
	Agri-food by-products and Food waste	1.0
	Total carbon in biomass	**15.4**
Recycled plastic available (proxy carbon)[2]	Mechanically recycled plastic	3.4
	Chemically recycled polymers	
	Total recycled carbon	**3.4**
Carbon available from CO_2[3]	Direct air capture	Unlimited
	CCU	20
	Total carbon from CO_2	**Unlimited**

Table 15: Amounts of sustainable carbon feedstocks that are estimated to be available by 2050

1 –Biomass carbon availability based Ricardo AEA, DESNZ UK Biomass Availability Model

2 – BPF Recycling Roadmap, with waste volumes extrapolated at 2.5% CAGR, assumes 75% recycling rate

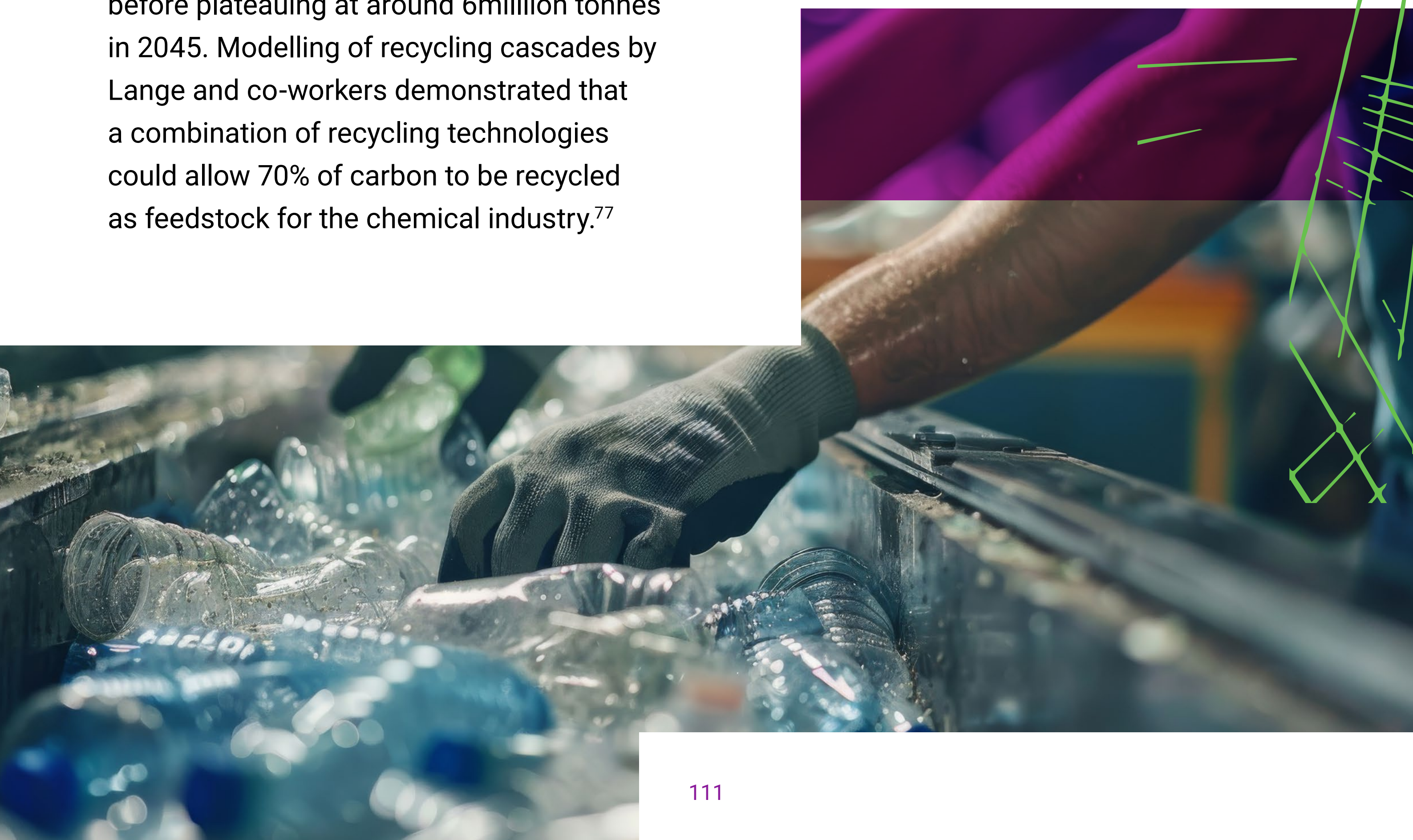
3 – CO_2 point source (currently 10% of UK emissions). Assumes 100% CO_2 captured

Recycled plastic availability

An analysis of UK plastic flows by Serrenho and coworkers concluded that in 2017 the UK had an annual plastic demand of 6million tonnes. Demand was shown to be dominated by plastic packaging (2million tonnes) and consumer products (1.9million tonnes) with the remainder of demand resulting from vehicles, construction, textiles and agriculture (2.1million tonnes). The study also concluded that the UK plastic demand had reached a saturation point. While UK plastic demand may have peaked this does not feed through to plastic waste generation in the near and medium term. A large volume of plastic containing products have multi-year lifetimes which creates a large stock of plastic within the UK economy. As these products reach their end-of-life, waste plastic is generated which requires treatment. Serrenho and coworkers estimate the volume of plastic currently in-use to be around 42million tonnes. Projections out to 2050 show plastic wastes volume growing before plateauing at around 6milllion tonnes in 2045. Modelling of recycling cascades by Lange and co-workers demonstrated that a combination of recycling technologies could allow 70% of carbon to be recycled as feedstock for the chemical industry.[77]

CO_2 availability

The UK's industrial sector produces 72 Mt CO_2eq per year representing 16% of UK emissions. The Industrial decarbonisation strategy sets out how industry can decarbonise in line with net zero while remaining competitive. It includes plans to support deployment of CCUS on industrial sites in clusters to capture and store around 3 MtCO_2 per year by 2030. Scenarios produced by the Climate Change Committee (CCC) for reducing UK emissions to net zero by 2050 include a minimum of 44 million tonnes of biogenic CO_2 captured per year. Analysis for the Government's 2021 Net Zero Strategy showed the requirement to deploy 75 and 81 MtCO_2 per year of engineered CO_2 removals to help compensate residual emissions.



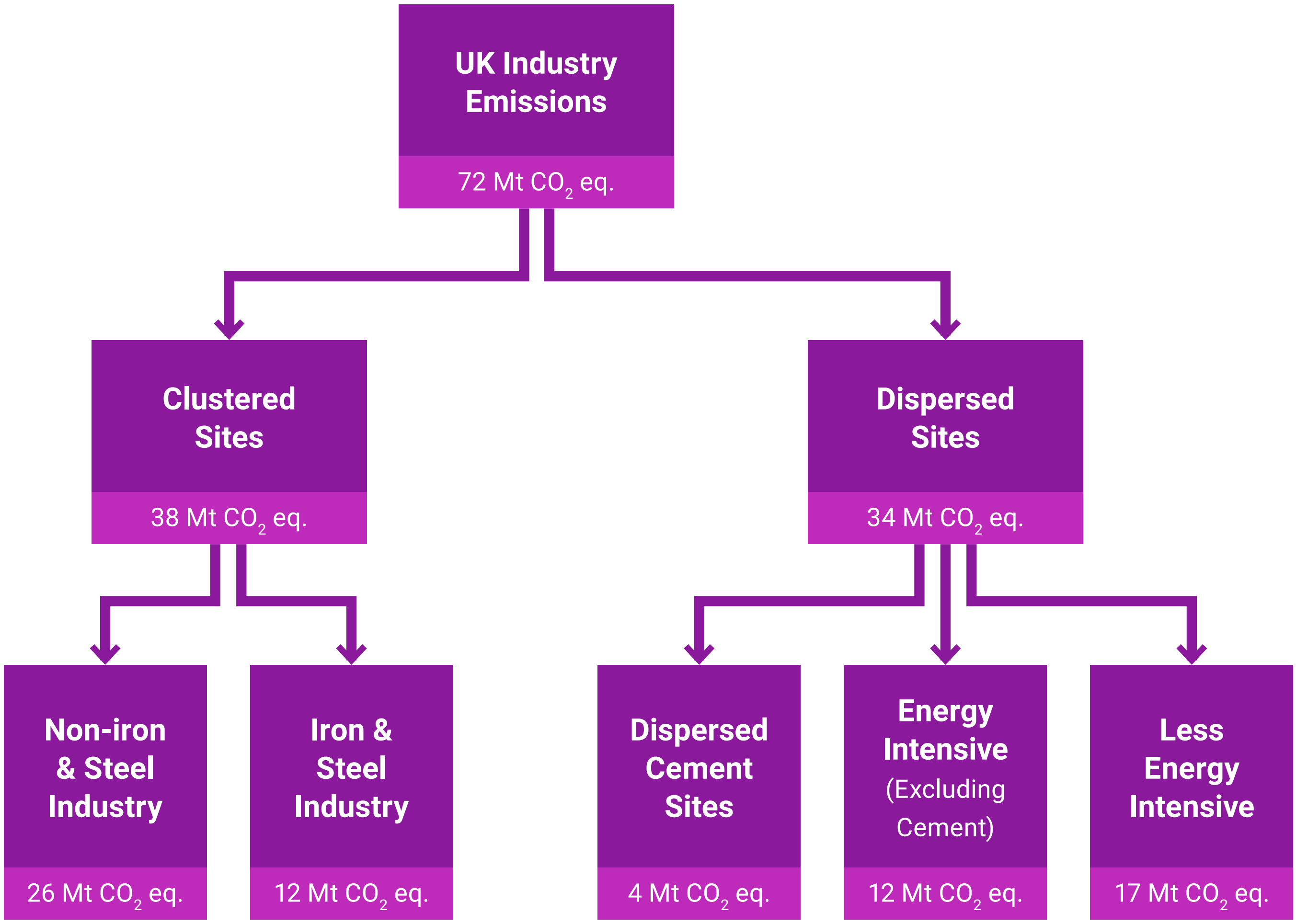


Figure 27: UK industrial emissions[78]

The UK's largest CCU facility is operated by Tata Chemicals Europe. The facility has the capacity to capture up to 40,000 tonnes of CO_2 which can be purified to food and pharmaceutical grade and is being used as a raw material in the manufacture of sodium bicarbonate.[79]

DRAX power station emits 12million tonnes of biogenic CO_2 annually and has plans to capture around 8 million tonnes.

Producing chemicals from CO_2 requires both hydrogen and renewable energy to be available. As an example, the requirement to produce 1 million tonnes of light olefins is considered.

Producing 1 million tonnes of light olefins requires 2.7million tonnes of methanol which in turn would require 0.5 million tonnes of low carbon hydrogen and 3.7 million tonnes of CO_2. Following the World Bank "1-10-20-30 rule", 0.5 million tonnes of hydrogen requires 5 gigawatts of electrolysers, 10 gigawatts of renewable power generation, and $15 (£12) billion in investment.[80] The cost of producing olefins through this route is considered a major barrier to production.[81] To put this level of production in context the UK's steam cracker fleet has a capacity of over 2.5 million tonnes of ethylene per year.

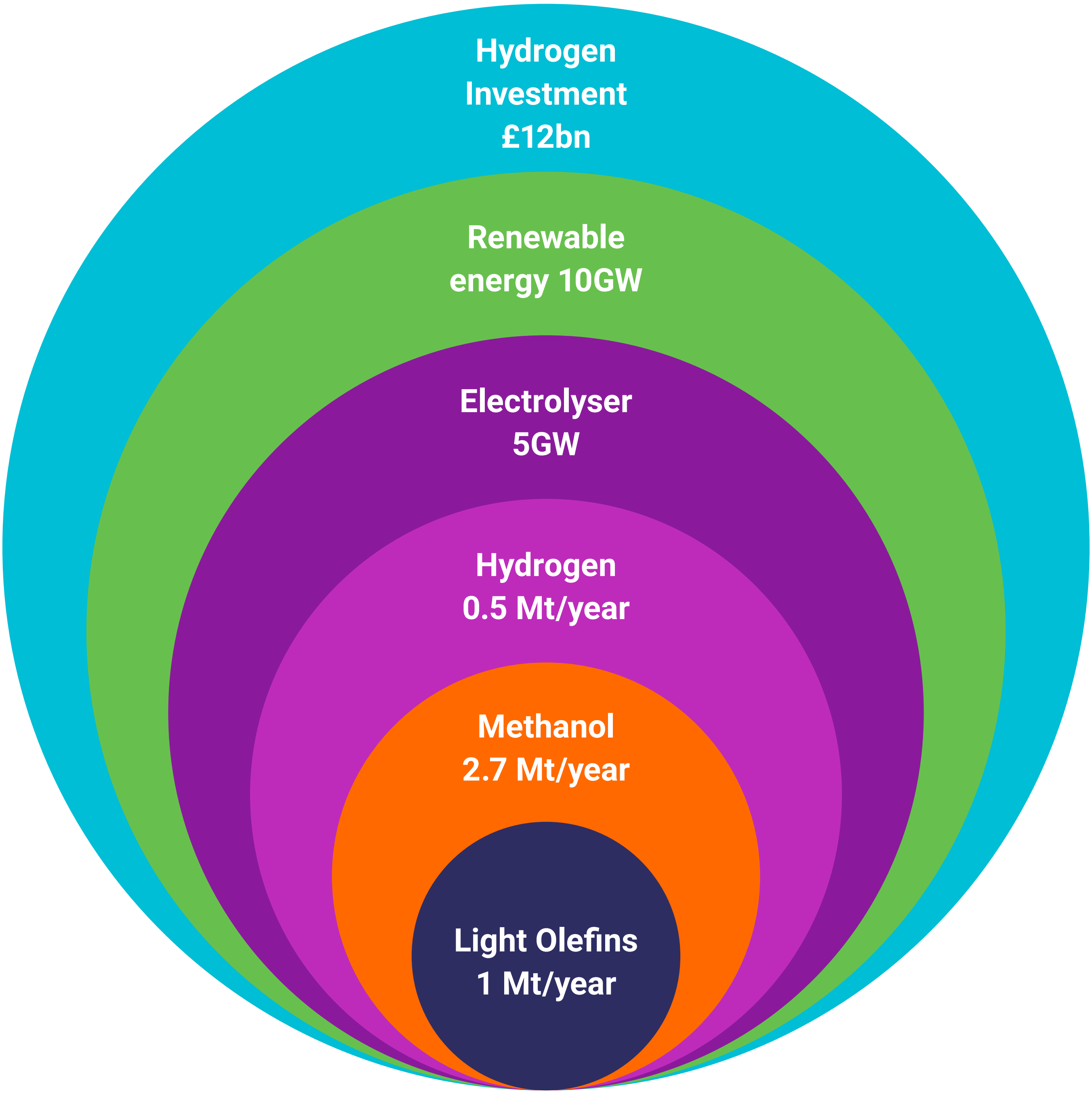


Figure 28: Hydrogen and investment requirements for the production of light olefines from CO_2.

5.2.3 Scenario assumptions

For all scenarios, a CAGR 2.5% (Nova Institute_2024) is assumed. It is also assumed that the UK requires 1% of total global carbon demand (Green Alliance). Therefore, the total carbon demand for the UK has been determined as per Nova Institute_2023, adjusted for UK (and confirmed by Oxford Economics, 2019 and Digest of UK Energy Statistics (DUKES), shown in Table 16. The UK carbon demand assumption is further validated through the capacity of the UK steam cracker fleet (3million tonnes), the import of organic chemicals (5 million tonnes in 2019) plus an additional volume of UK oil refinery produced chemicals (e.g. ethyl benzene and isobutylene).

Carbon required (million tonnes)	2020	2030	2040	2050
Carbon required (million tonnes)	550.0	704.0	901.2	1153.7
UK 1% Nova institute total global Carbon	5.5	7.0	9.0	11.5

Table 16: Total carbon demand for the UK.

5.3 Exploration of future scenarios

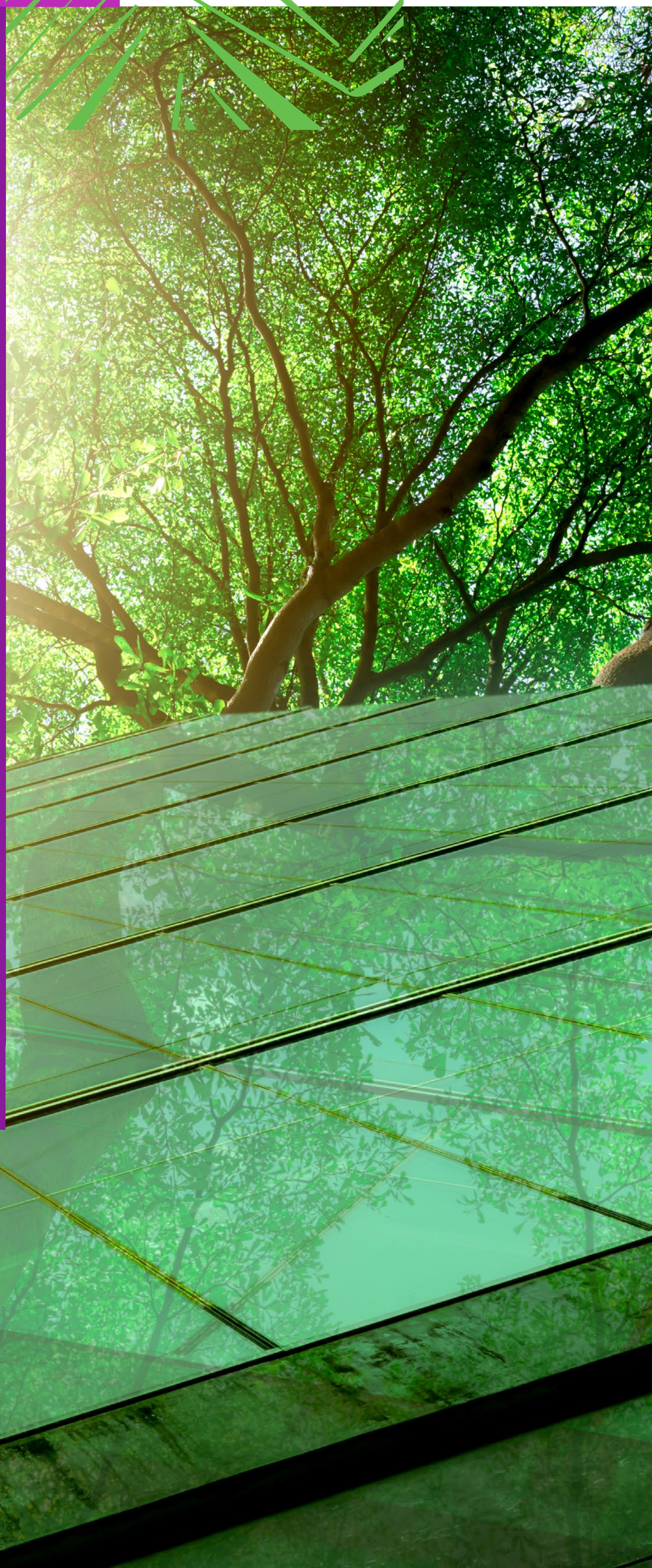
Based on all stakeholder feedback and the in-depth literature review, four potential future scenarios for the UK chemicals industry are proposed (Table 17):

1. **Do Nothing**
   Where carbon feedstock percentages remain the same as they are today.

2. **Green Growth**
   Where virgin-fossil feedstock volumes remain the same as today, with any industry growth being from sustainable carbon.

3. **Stakeholder Ambition**
   Virgin-fossil feedstocks reduce to 20% by 2050

4. **Zero Fossil**
   UK chemicals industry has fully transitioned to sustainable carbon feedstocks



Carbon requirement in 2050 (% of total requirement)								
		Disruption / alterations to current UK assets	Virgin-fossil	Biomass	Recycled carbon	CO_2	Assumptions
1	Do nothing	None	88	8	4	0.03	• The percentage contribution of individual carbon feedstocks stays the same as today • Fossil resource is still economically viable
2	Green growth	None	42	18	23	17	• Virgin-fossil volume stays same as today • Any growth is via green carbon • 65% recycling rate achieved
3	Stakeholder ambition	Significant	20	30	30	20	• Virgin-fossil reduces to 20% by 2050 • Chemical recycling viable post 2030 • CO_2 viable post 2040 • 65% recycling rate achieved
4	Zero fossil	Highly significant	0	20	55	25	• Virgin-fossil resource no longer required by 2050 • 65% recycling rate achieved • Biomass capped at 20%

Table 17: Summary of the four potential future scenarios for the UK chemicals industry

5.3.1 Scenario 1 — Do nothing

In this scenario, there are no interventions made, and growth of the chemicals industry continues in line with the proportions of different carbon feedstocks as today (Figure 29).

Based on this, by 2050, the UK's reliance on virgin-fossil feedstocks will have more than doubled, from a current requirement of 4.8million tonnes, to over 10.1 million tonnes.

In terms of theoretically available carbon in 2050, this equates to 6.6% of carbon available from biomass, 13.6% of carbon available from recycled carbon, and 0.015% of carbon available from CO_2.

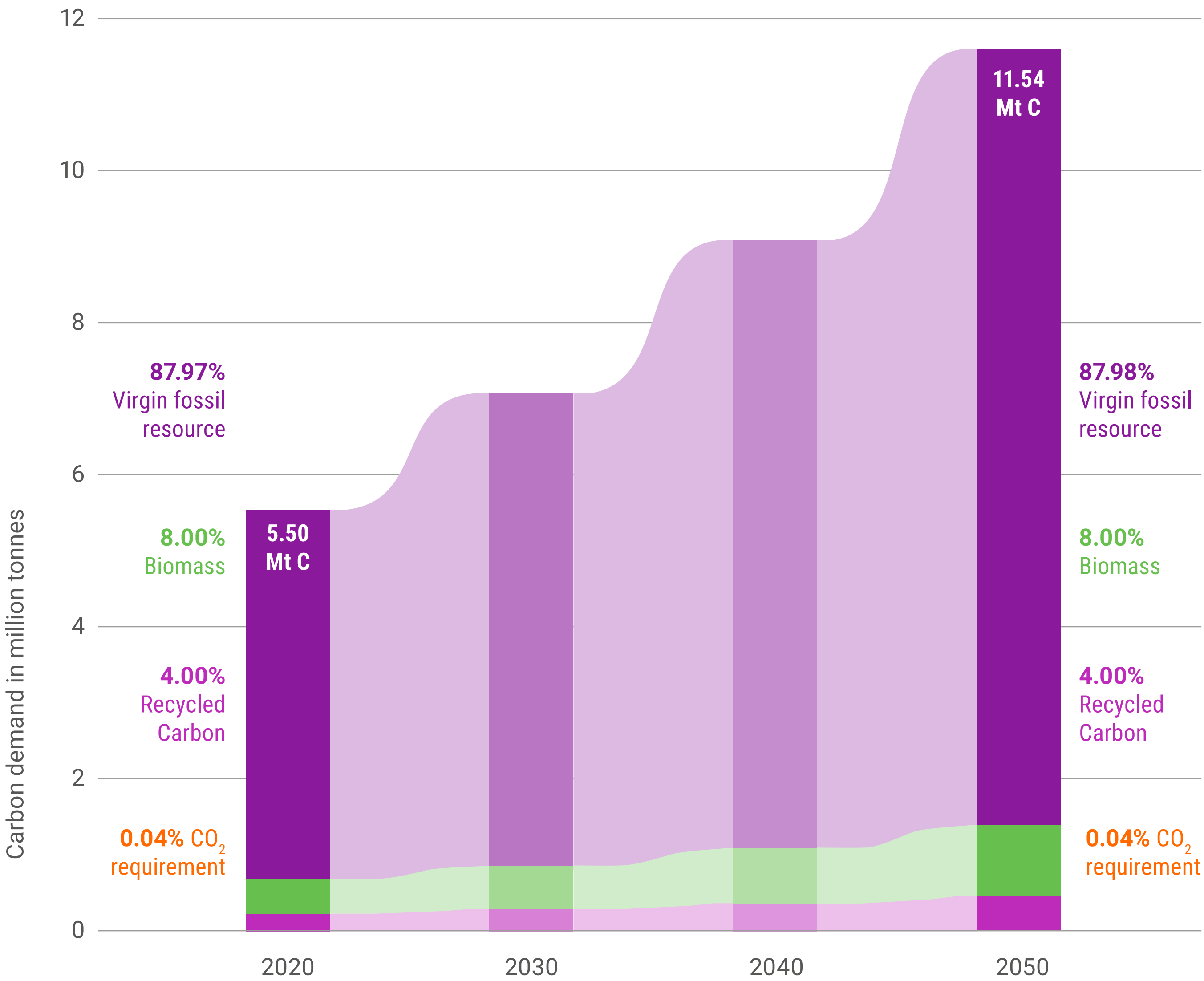


Figure 29: Visualisation of scenario 1, from 2020 through to 2050.

Table 18: Projected carbon tonnage required from 2020 to 2050 for scenario 1.

Carbon source (million tonnes)					
	2020	2030	2040	2050	% of total theoretically available carbon in 2050
UK chemical industry total requirement	4.840	6.196	7.931	10.152	-
Virgin-fossil	4.259	5.452	6.979	8.933	-
Biomass	0.440	0.563	0.721	0.923	6.6% of available biomass
Recycled Carbon	0.220	0.282	0.360	0.461	13.6% of available recycled carbon
CO_2	0.002	0.002	0.003	0.003	0.015% of available CO_2 from CCU

This scenario places a large emphasis on CCS to avoid a growth in process-based carbon emissions. Significant fossil carbon emissions will result from end-of-life waste disposal, which in the absence of significant recycling efforts, will be through treatment at energy from waste facilities (EfW). The addition of CCS technology at EfW facilities could abate emissions but in this scenario the opportunity for negative emissions through the capture and storage of renewable carbon is minimal.

5.3.2 Scenario 2 — Green growth

In this scenario, any growth of the UK chemicals industry is via sustainable carbon feedstocks (Figure 30).

Based on this, by 2050, our reliance on virgin-fossil feedstocks will be the same as our current requirement of 4.8 million tonnes per annum, our reliance on biomass will have increased 4-fold from 0.44 tonnes to 2 million tonnes per annum, reliance on recycled carbon will have increased over 10-fold from 0.2 tonnes to 2.7 million tonnes per annum, and reliance on CO_2 have increased 1000-fold from 0.002 tonnes to 2 million tonnes per annum.

In terms of theoretically available carbon in 2050, this equates to 15% of carbon available from biomass, 79.8% of carbon available from recycled carbon, and 10.1% of carbon available from CO_2.

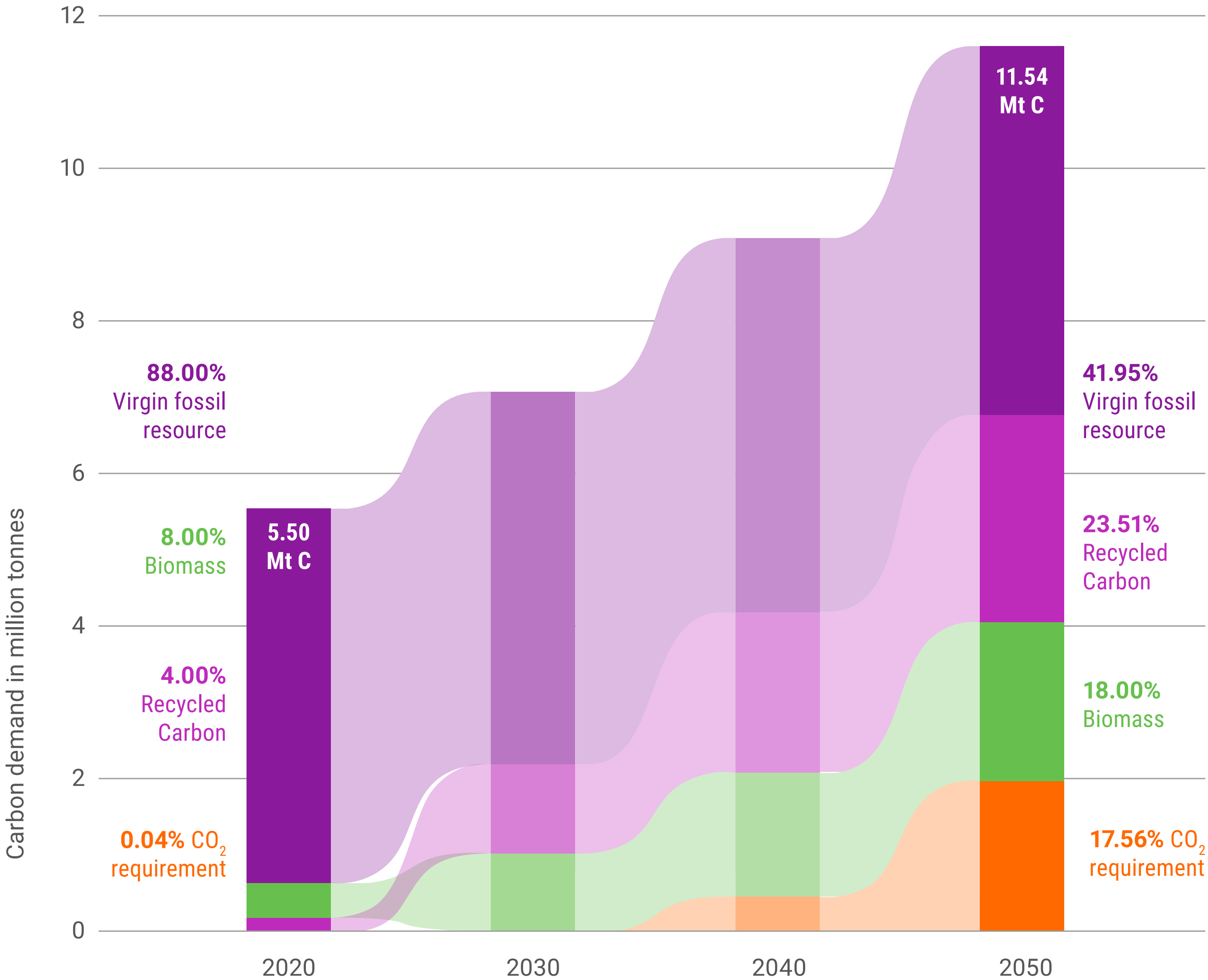


Figure 30: Visualisation of scenario 2, from 2020 through to 2050.

Table 19: Projected carbon tonnage required from 2020 to 2050 for scenario 2.

Carbon source (million tonnes)					
	2020	2030	2040	2050	% of total theoretically available carbon in 2050
UK chemical industry total requirement	5.500	7.040	9.012	11.537	-
Virgin-fossil	4.840	4.840	4.840	4.840	-
Biomass	0.440	1.056	1.622	2.077	15% of available biomass
Recycled Carbon	0.220	1.155	2.107	2.712	79.8% of available recycled carbon
CO_2	0.002	0.025	0.512	2.026	10.1% of available CO_2 from CCU

This scenario places an emphasis on recycling in line with policies to increase both mechanical and chemical recycling. The required volume of each type of sustainable carbon is available although the volume of recycled carbon relies on 65% collection rates.

5.3.3 Stakeholder ambition

In this scenario, utilisation of virgin-fossil resources reduces to 20% by 2050, CO_2 increases to 20%, and biomass and recycled carbon increase to 30% (Figure 31).

Based on this, by 2050, our reliance on virgin-fossil feedstocks will have halved, from a current requirement of 4.8 million tonnes, to less than 2.3 million tonnes per annum.

In terms of theoretically available carbon in 2050, this equates 24% of carbon available from biomass, 101.7% of carbon available from recycled carbon, and 11.5% of carbon available from CO_2.

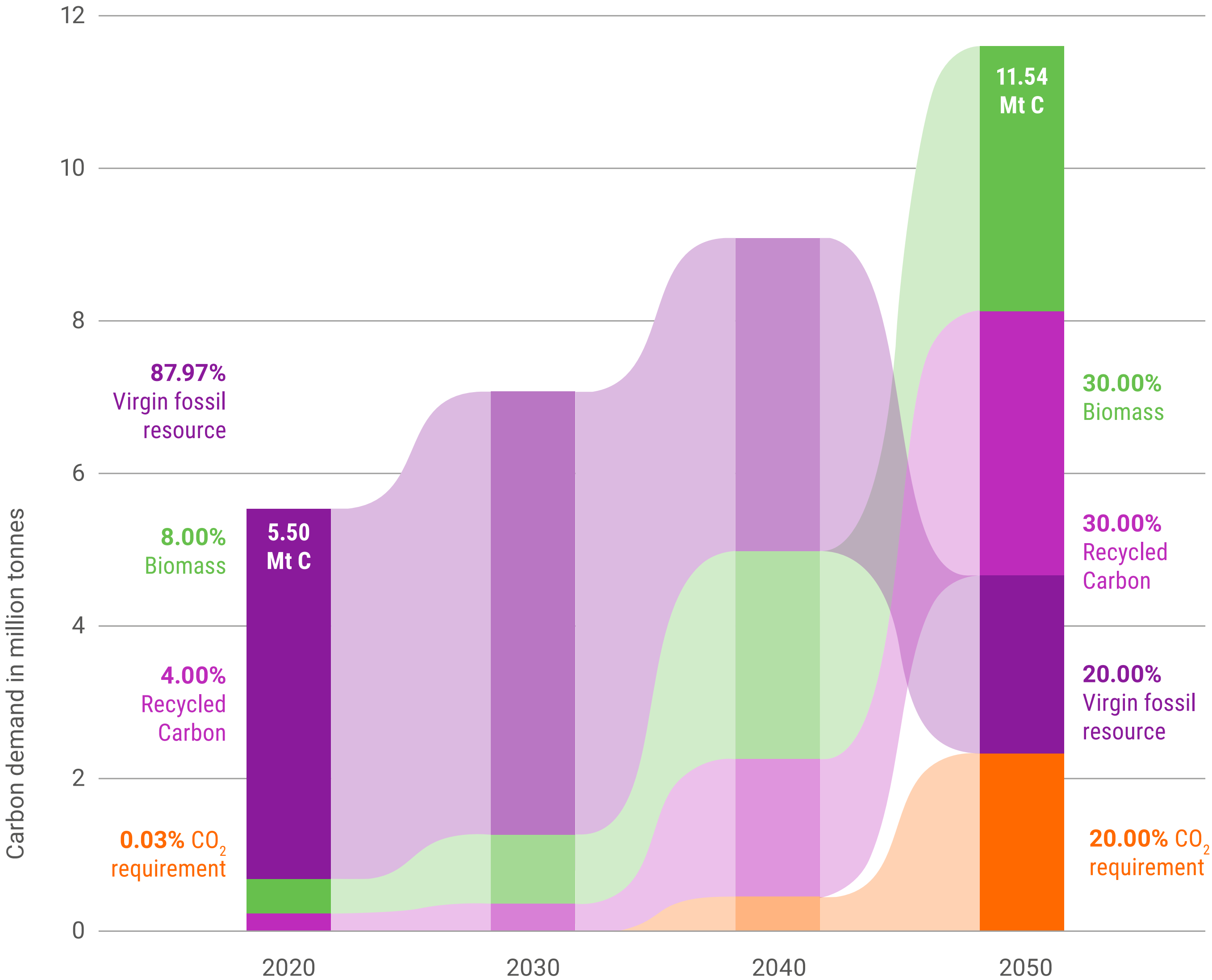


Figure 31: Visualisation of scenario 3, from 2020 through to 2050

Table 20: Projected carbon tonnage required from 2020 to 2050 for scenario 3.

Carbon source (million tonnes)					
	2020	2030	2040	2050	% of total theoretically available carbon in 2050
UK chemical industry total requirement	5.500	7.040	9.012	11.537	-
Virgin-fossil	4.840	5.773	4.056	2.307	-
Biomass	0.440	0.915	2.704	3.461	24% of available biomass
Recycled Carbon	0.220	0.352	1.802	3.461	101.7% of available recycled carbon
CO_2	0.002	0.002	0.451	2.307	11.5 % of available CO_2 from CCU

In this scenario the demand for recycled carbon reaches 101.7% of the lower estimate of UK availability and therefore could be challenging to achieve, and likely requiring imports of recycled carbon. The volume of biomass required does appear limiting although the spatial and compositional variability of biomass means a deeper analysis is required to match biomass volumes to specific processes and production locations. The availability of CO_2 is not considered a constraint in this scenario and would only be a concern should CCS policies prevent the development of CCU technologies.

5.3.4 Zero Fossil

In this scenario, by 2050 there is no virgin-fossil feedstock utilised by the UK chemicals industry (Figure 32).

Based on this, by 2050, our reliance on virgin-fossil feedstocks will be zero. We will require a 4-fold increase in biomass from 0.4 to 2.3 million tonnes per annum, a 29-fold increase in recycled carbon from 0.22 to 6.35 million tonnes per annum, and a 14,400-fold increase in CO_2 from 0.002 to 2.88 million tonnes per annum.

In terms of theoretically available carbon in 2050, this equates to 17% of carbon available from biomass, 186.6% of carbon available from recycled carbon, and 14.4% of carbon available from CO_2.

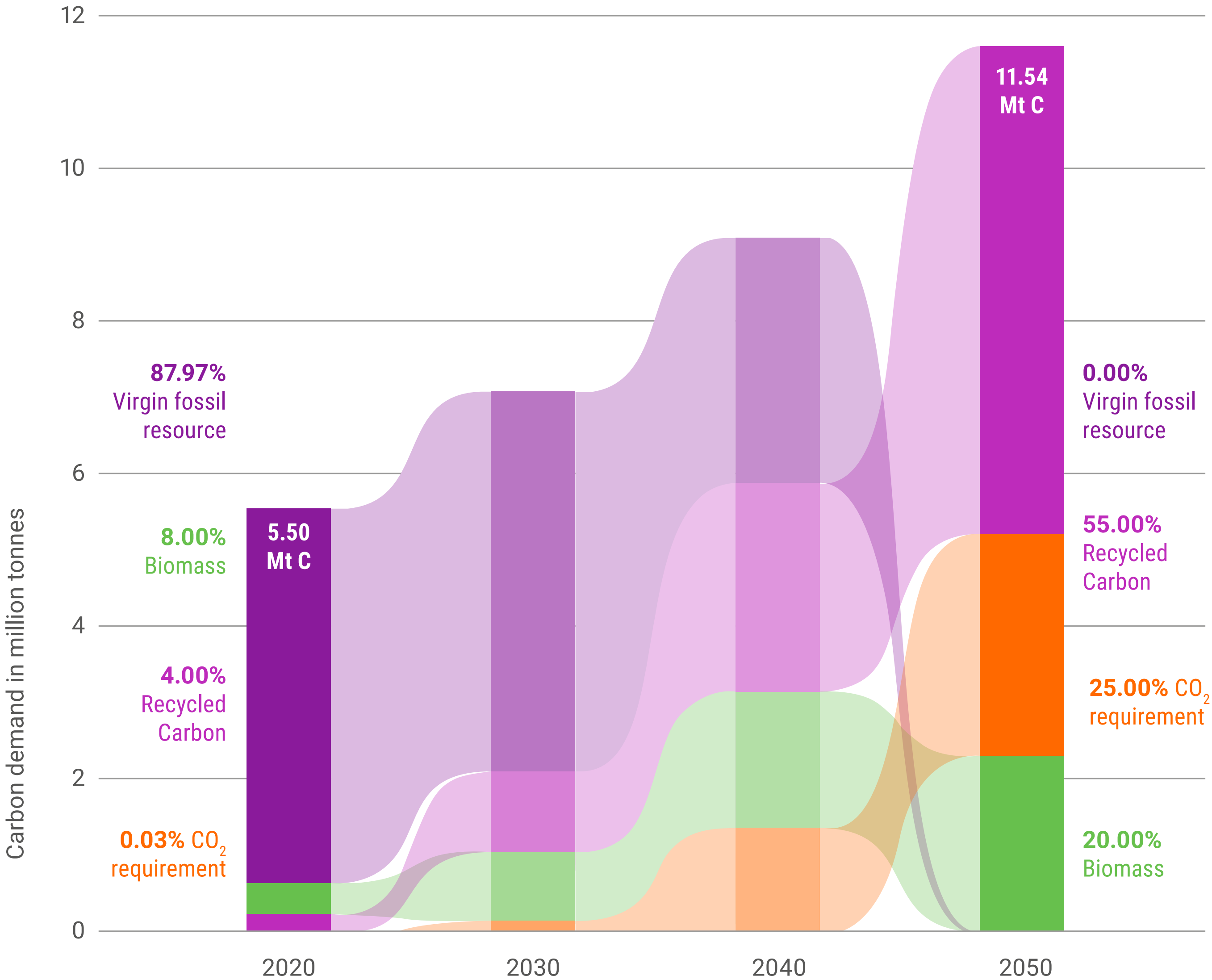


Figure 32: Visualisation of scenario 4, from 2020 through to 2050.

Table 21: Projected carbon tonnage required from 2020 to 2050 for scenario 4.

Carbon source (million tonnes)					
	2020	2030	2040	2050	% of total theoretically available carbon in 2050
UK chemical industry total requirement	4.840	6.196	7.931	10.152	-
Virgin-fossil	4.840	4.928	3.154	0.000	-
Biomass	0.440	0.915	1.801	2.307	17% of available biomass
Recycled Carbon	0.220	1.056	2.703	6.345	186.6% of available recycled carbon
CO_2	0.002	0.1408	1.351	2.884	14.4% of available CO_2 from CCU

The feasibility of this scenario relies on the continued growth of plastic consumption. The volume of biomass required does appear limiting although the spatial and compositional variability of biomass means a deeper analysis is required to match biomass volumes to specific processes and production locations. The availability of CO_2 is not considered a constraint in this scenario and would only be a concern should CCS policies prevent the development of CCU technologies.

5.4 The challenge ahead: Scenarios in real terms

The four potential scenarios all require a significant increase in all four carbon sources; virgin-fossil, biomass, recycled carbon and CO_2, with the scale of the challenge highlighted in Table 22.

In particular, the scale of the challenge for increase in utilisation of recycled carbon and CO_2 is evident in all scenarios.

Scenario		Volume of carbon required in 2050, compared to 2020 volume			
		Virgin-fossil	Biomass	Recycled carbon	CO_2
1	Do nothing	200%	200%	200%	200%
2	Green growth	100%	477%	1232%	122,757%
3	Stakeholder ambition	50%	709%	1573%	236,000%
4	Zero fossil	0%	520%	28,000%	288,000%

Table 22: Scenarios summary

Table 23: Increases in utilisation for the stakeholder ambition scenario relies on several interdependencies

	% Growth in feedstock utilisation	Interdependencies
Biomass	709%	• Regenerative sustainable farming practices. • Cheap renewable energy
Recycled Carbon	1573%	• 65% recycling rates • Cheap renewable energy
CO_2	236,000%	• 8% off all point source emissions captured • Low-carbon hydrogen availability • Cheap renewable energy

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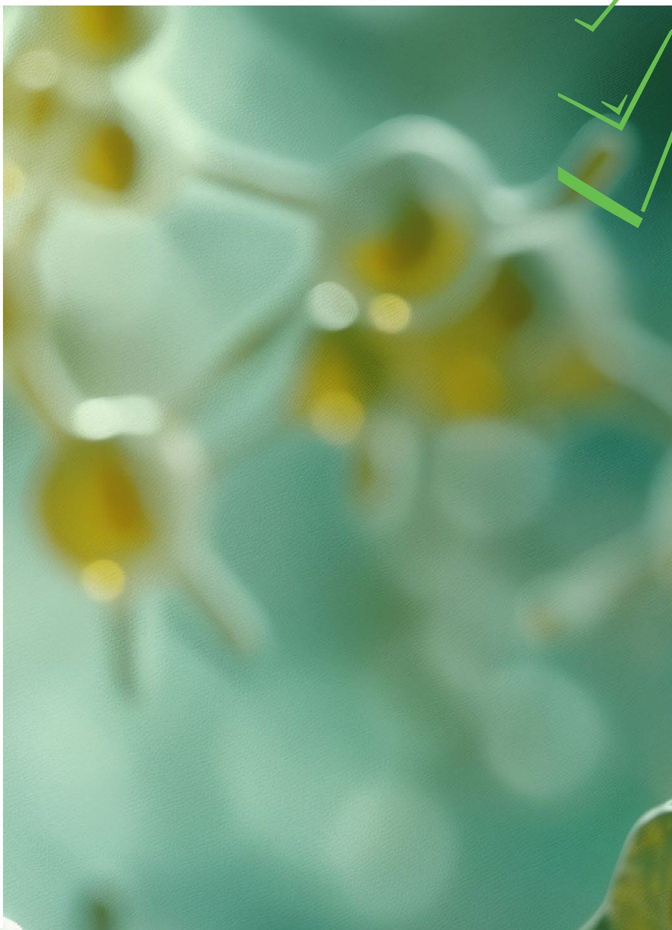


6. UK CHEM 2050 ambition and transition

6.1 UK CHEM 2050 Ambition

By 2050 the UK chemicals industry will have doubled economic output, but significantly lowered it GHG emissions, sourcing 80% of its carbon requirements from non-virgin fossil, sustainable carbon sources.

6.2 Are we investing in the right things?

6.2.1 Public Investment in Sustainable Chemicals Research

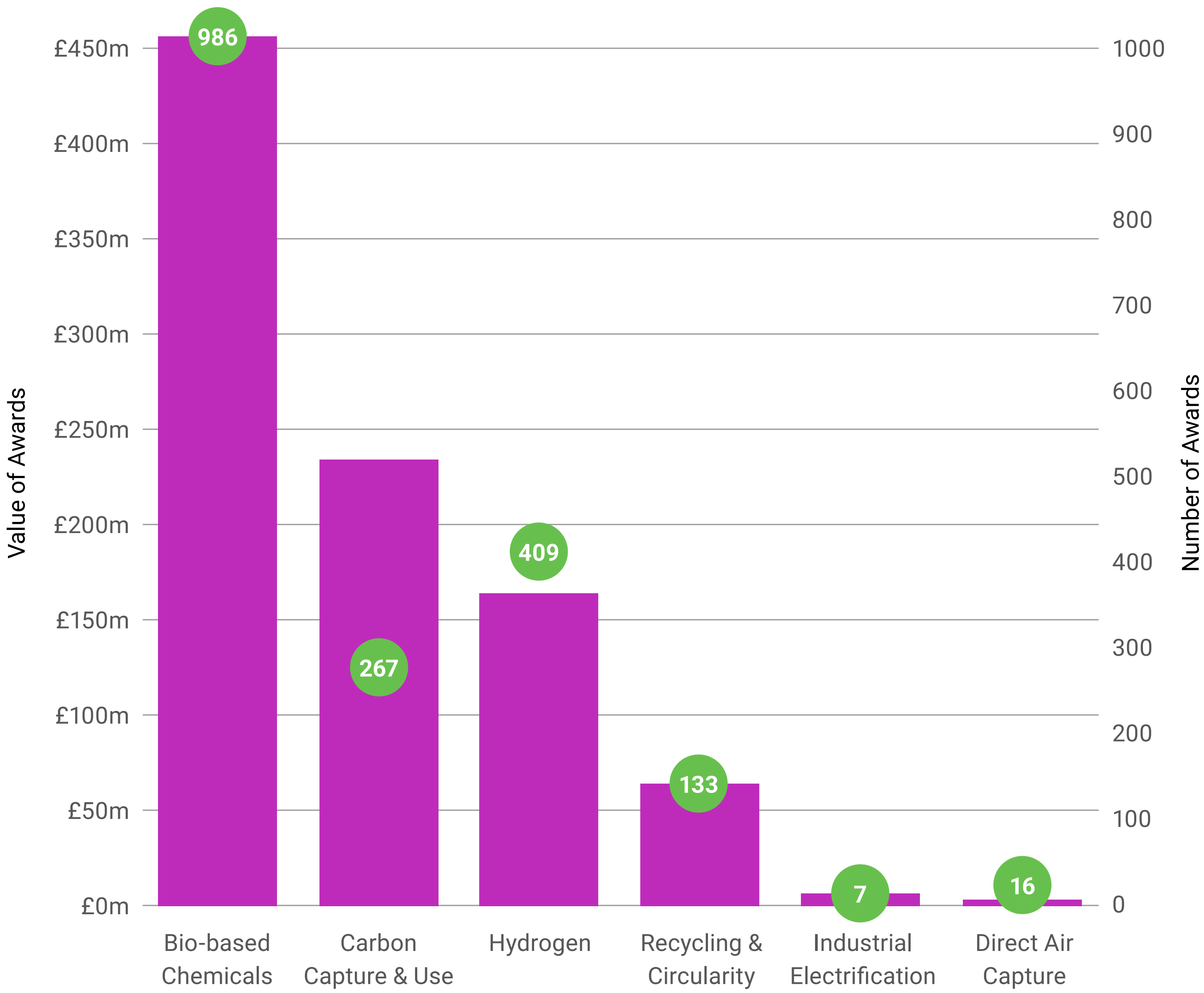
The study gathered data for approximately 6,000 research projects recorded on UKRI's Gateway to Research that contained terms deemed relevant to sustainable chemicals research and innovation, including:

- **Sustainable chemicals**
- **Bio-based**
- **Biobased**
- **Biochemicals**
- **Chemical recycling**
- **Recycled carbon**
- **Carbon capture**
- **Green chemistry**
- **Mechanical recycling**
- **Biogenic carbon**
- **Bioplastic**
- **Biopolymer**
- **Industrial biotechnology**
- **Synthetic biology**
- **Engineering biology**
- **Direct air capture**
- **Point source CO_2**
- **Atmospheric CO_2**
- **Hydrogen**

Project abstracts were used to identify a sample of 2,252 research projects deemed to be of particular relevance to this study. These projects have received a total of £920m in public funding since 2013.

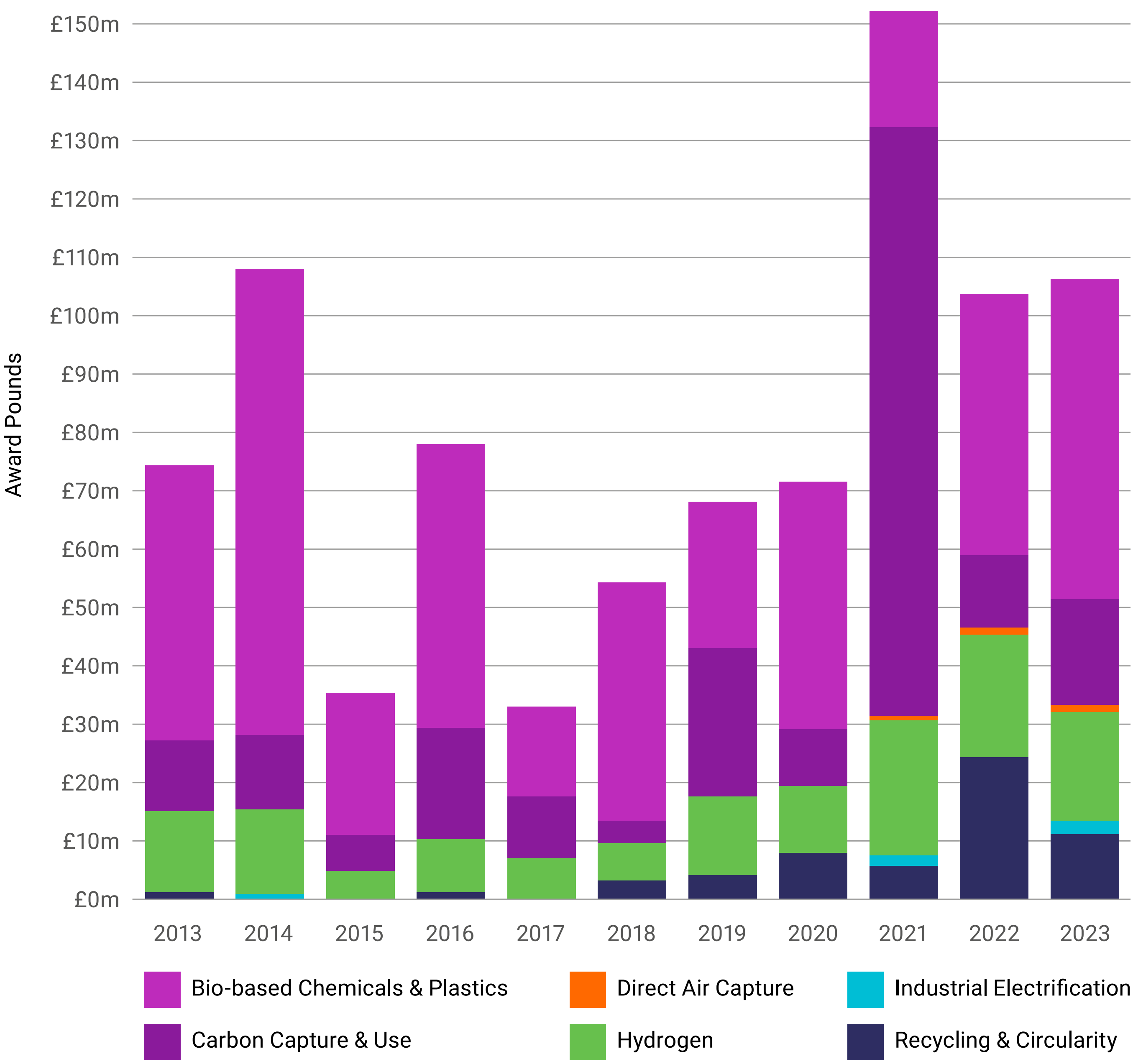
Research into biobased chemicals accounts for most projects, and the highest value of awards. Carbon capture accounts for the second highest share of research funding but for comparatively fewer research projects, pointing to higher average award values for carbon capture projects.

Figure 33: Public Investment in Research (2013 – 2023 Totals) **Source:** Gateway to Research



Analysis of funding over time for in-scope technologies suggests average investment of c.£81m each year. Investment in bio-based chemical technology development has remained relatively constant. Funding for hydrogen and recycling / circularity research have shown modest increases in recent years. In addition, since 2018 DESNZ (formerly BEIS) has invested c.£50m into Carbon Capture, Utilisation and Storage via the CCUS Innovation Programme (not shown due to different source data).[82]

Figure 34: Public Investment in Research (2013 – 2023 by Year) **Source:** Gateway to Research



More than three hundred commercial entities have been involved in relevant research projects, including private sector businesses such as Phillips 66, Johnson Matthey and Mitsubishi Chemicals, and research organisations such as the John Innes Centre and the Centre for Process Innovation (CPI).

Ten percent of the companies identified are large (250 employees or more). Fifty-two percent of the companies involved in collaborative research around sustainable chemicals are micro-sized entities (fewer than 9 employees), 27% are small (between 10 and 49 employees) and 12% are medium-sized (between 50 and 249 employees).

BP, RWE, VPI and SSE have secured the highest value of research funding, all for carbon capture utilisation and storage projects. Ingenza, Biome Technologies, the John Innes Centre Xampla and Unilever have delivered the highest number of research projects, primarily for bio-based chemical research.

6.2.2 Private investment in sustainable chemicals innovation

Data for 170 companies classified by Beauhurst as operating within the 'CleanTech' sector and using relevant key terms within company descriptions suggests that a total of £1.6bn of private investment has gone into companies involved in in-scope technology areas. The highest share of private investment in these CleanTech companies has gone towards bio-based chemicals and plastics activity (32%, £517m) followed by CCUS, recycling and circularity and hydrogen respectively (Figure 35).

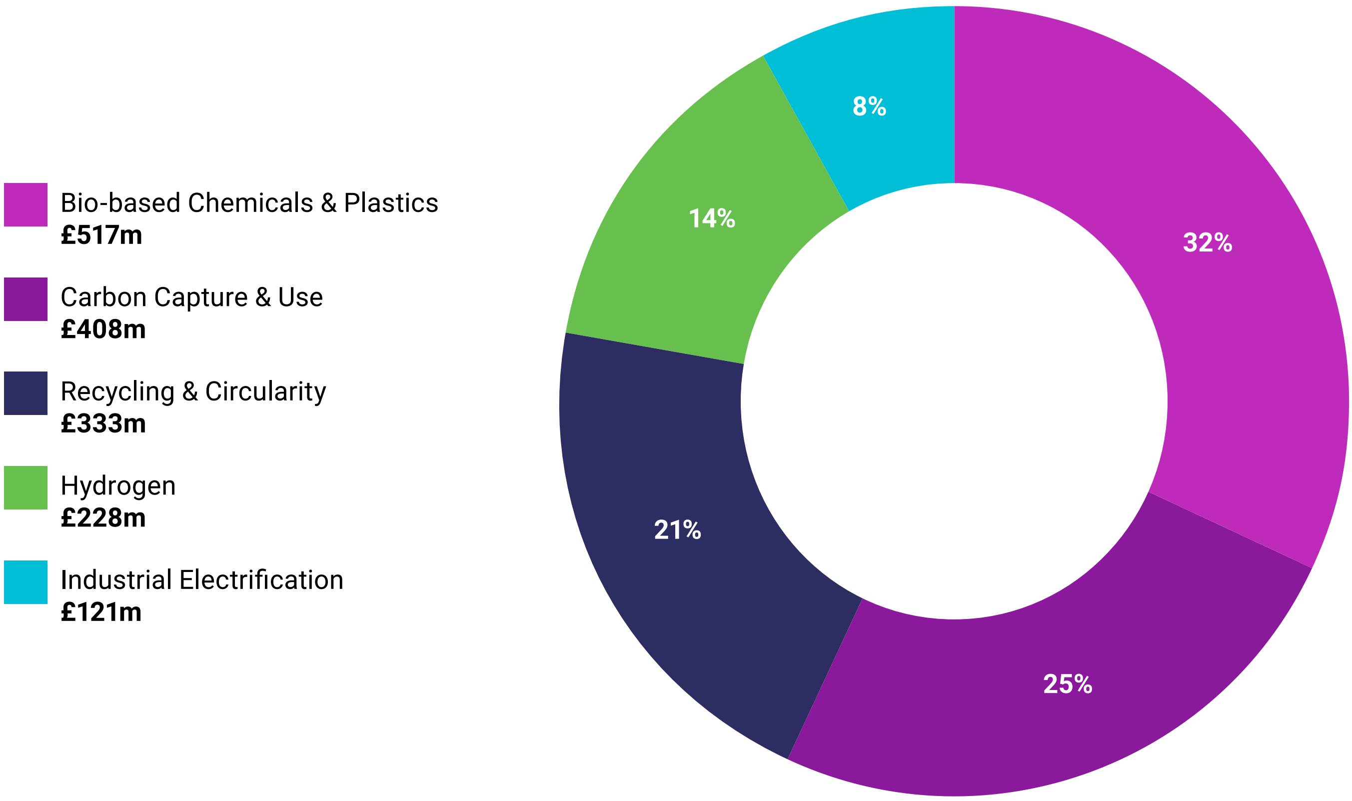


Figure 35: Private Investment in In-Scope Technologies (2001 – 2023 Totals) **Source:** Beauhurst

Companies such as Plastic Energy (plastics recycling), Carbon Clean (carbon capture) and Mura Technology (hydrothermal recycling) have received among the highest value of investment.

To achieve the UK CHEM 2050 ambitious Ambition, significant investment into key technologies is required to increase sustainable carbon feedstock utilisation - by 709% for biomass, 1573% for recycled carbon, and 236,000% for CO_2.

The data above suggests that the areas of chemical recycling and CCU and DAC require substantial funding, which has not been seen to date, to enable the rapid scale up of these technologies.

6.3 UK CHEM 2050: Transition pathway

Although stakeholders indicated a preference for a transition to sustainable carbon, it was generally recognised that the transition would stetch beyond 2050 and that fossil feedstocks would play a significant role in chemical production in the medium and long term.

Four critical observations underpin the 2050 Ambition.

1. No one form of sustainable carbon is available in sufficient quantities and at acceptable prices.
2. There are considerable uncertainties around the availability of all forms of sustainable carbon.
3. Although stakeholders indicated a preference for a transition to sustainable carbon, there was no clear stakeholder view of which carbon source would be preferred.
4. Each carbon source has critical limitations:
    a. Abated fossil carbon does not fully address end of life emissions;
    b. Biogenic carbon is limited by ecosystem and social impact concerns;
    c. Recycled carbon is limited by collection rates and delays rather than eliminates fossil carbon emissions;
    d. Atmospheric carbon is limited by renewable energy requirements and extraction costs.

These observations indicate the need to support a four-pronged approach in the transition to a UK chemical industry built upon the use of sustainable carbon.

1. **Protecting and abating** current key petrochemical assets such as the UK's three steam crackers. Focus on electrification, the use of low carbon hydrogen, and carbon capture technologies. This targets hydrocarbon production.

2. **Targeting and developing** specific bio-based chemicals. Focus on biomass sustainability and increasing availability, supporting process innovation through engineering biology. This targets oxygenated chemical intermediates, such as alcohols, acids, and esters.

3. **Establishing** a chemical recycling industry as part of a wider circular economy. This targets the production of basic chemical hydrocarbon feedstocks.

4. **Preparing** for carbon capture and utilisation (CCU). Focuses on ensuring plans for carbon capture and storage (CCS) includes flexibility for utilisation and the establishment of a low-carbon hydrogen industry. This targets the production of methanol direct chemical or fuel use or as a chemical intermediate. Also, it is worth noting that there is potential to use chemicals to store renewable energy that cannot be used at the direct point of generation.

Table 26: Based on the critical observations and four-pronged transition approach, the following 12 technology needs are required.

Overarching for UK Net Zero

Electrification of heat

Fuel switching via electrification is technically possible for a wide range of applications and has been identified as key component of the UK's plan for industrial decarbonisation.[83] The suitability of a process for electrification depends on the temperature of the heat required, the chemical industry has multiple temperature needs and differing electrification challenges across steam generation, steam cracking, steam methane reforming and for cracking furnaces.Low temperature applications are technically easy to electrify and technologies such as boilers and heaters, are commercially available. However high temperature applications, particularly for processes greater than 1000°C, are technically challenging and require further research or development. Active projects include DOW and Shell developed electric cracking technology,[84] the construction of a large-scale demonstration electrically heated steam cracker furnace by BASF, Sabic and Linde,[85] and LyondellBasell/ Chevron and Technip are also working on an electric steam cracker.[86]

Renewable Energy

The supply of low cost and low carbon renewable energy underpins both the production of sustainable carbon feedstock and the transformation of feedstock into primary chemicals, chemical intermediates and end products. The development for renewable power generation, storage and distribution technology is a key enabler of sustainable chemical production.

Low-carbon hydrogen production

Hydrogen is considered a critical low carbon solution in the UK's transition to net zero. As part of a deeply decarbonised and renewable energy system, low carbon hydrogen could be a versatile replacement for high-carbon fuels. Although low carbon hydrogen may find use as a fuel in the chemical industry it is additionally required for the production of chemicals from CO_2. It is important that the needs of the chemical industry and role of low carbon hydrogen in the production of chemicals via CCU technology is considered in the UK's hydrogen strategy.

Artificial intelligence (AI)

The use of artificial intelligence offers the potential for increased productivity, accelerated innovation, improved decision-making, and stronger customer relations. Chemical production, particularly at integrated sites, is complicated with modelling and the creation of digital twins results in large data sets, AI can be used to optimise processes, improve yields and optimise utility usage. All of which serve to optimise carbon efficiency and reduce GHG emissions. Industrial decarbonisation through AI is supported through the AI for Decarbonisation Innovation Programme, although a number of process industry projects have been funded the programme is yet to support research in the chemical industry which is an opportunity to be encouraged.

Technoeconomic and lifecycle assessment

Successful technology development is underpinned by continuous and systematic technology assessment. Assessing novel technology from its initial development allows the early identification of economic and environmental challenges which can then be targeted in subsequent phases of research. Technoeconomic (TEA) and lifecycle assessment (LCA) are common assessment tools widely used to determine the economic viability and environmental sustainability of a process or product. The wider adoption and harmonisation of approaches to TEA and LCA has an important role in ensuring that new technology is both economically viable and environmentally sustainable.

CO_2 as a feedstock

Carbon capture technology

The current global demand for CO_2 is around 230 Mt of CO_2 per year.[87] It is mainly used in the fertiliser industry for urea manufacturing (~130 Mt) and for enhanced oil recovery (~80 Mt). The development of technology for capturing carbon dioxide from industrial emissions at a purity suitable for chemical conversions and at viable costs is a key challenge in the adoption of CO_2 derived chemicals. More research is required to reduce the cost and improve the energy efficiency of carbon capture technologies.[88]

CO_2 to chemicals transformations

The chemical stability of CO_2 creates the technical challenge to its use, primarily the need for substantial energy input which must come from low carbon sources to avoid further CO_2 emissions. To address this challenge there is the need for active catalysts to promote conversions and avoid the need for high reaction temperatures and/or pressures. A range of biological and chemical technologies are available for CO_2 conversions with research and technical development required to improve conversion efficiencies and costs.

Biomass as a feedstock

Biomass process technologies

Biomass processing technologies can involve mechanical, chemical or biological processes for the fractionation, pre-treatment and conversion of feedstocks into valuable components downstream. Key biomass processing technologies for the conversion of feedstock into chemicals include: fermentation, pyrolysis, gasification, combustion, carbonation, thermal decomposition, and hydrothermal liquefaction technology etc.

Engineering biology for chemical production

Engineering biology has a key role to play in the production of bio-based chemicals and chemicals through CCU using industrial biotechnology. The Government's 'Engineering Biology Ambition' aims to create a vibrant engineering biology ecosystem. It is important that chemicals production is given sufficient considered within this Ambition alongside medical and other engineering biology applications.

Low carbon agriculture

The environmental impacts of bio-based chemical production are to a large extent determined by the choice of biomass feedstock and how it is cultivated. Optimising the planting, cultivating and harvesting of biomass can reduce GHG emissions and reduce other environmental impacts thereby improving the sustainability of bio-based chemical production. Fertiliser use is a significant source of GHG emissions, increasing nitrogen-use efficiency in combination with the decarbonisation of fertiliser production would dramatically reduce emissions. The Biomass Feedstocks Innovation Programme represents an important initiative to support the sustainable production of biomass resources.

Recycled Carbon as a feedstock

Chemical recycling process development

Chemical recycling encompasses a range of concepts including polymer dissolution, depolymerisation to monomers and thermal treatments to chemical feedstock (e.g. naphtha and carbon monoxide) and a range of technologies (e.g. liquefaction, pyrolysis and gasification). While challenges in collecting, sorting and cleaning end of waste plastic can be common many technologies each recycling technology has its own specific technical challenges. Technology development is required to scale chemical recycling and ensure that efficient recycling is achieved with minimal loss of resource.

Waste collection and sorting infrastructure

Implementation of advanced automated sorting systems that can accurately identify and separate different types of waste materials, such as plastics, metals, paper, and organic matter is required. It is important to utilise technologies like near-infrared (NIR) spectroscopy, X-ray fluorescence, and machine learning algorithms for material identification and sorting.

6.4 Recommendations

To promote the development of a sustainable chemical industry in the UK, government support should be utilised, as highlighted in the tables below.

Biomass Recommendations

<table>
<tr><th>Short Term</th><th>Medium Term</th><th>Long Term</th></tr>
<tr><td colspan="2">Promote sustainability assessments relating to biomass feedstock use</td><td></td></tr>
<tr><td colspan="3">Utilise biomass as alternative feedstock</td></tr>
<tr><td colspan="2">Foster collaboration and partnerships across the entire value chain</td><td></td></tr>
<tr><td colspan="3">Construction of biorefineries</td></tr>
<tr><td colspan="3">Develop renewable energy infrastructure</td></tr>
</table>

<table>
<tr><th>Technology Needs</th><th>Policy Recommendations</th></tr>
<tr><td>
• Electrification of heat
• Accessible renewable energy production
• Biomass process technologies
• Engineering biology for chemical production
• Low carbon agriculture
• Technoeconomic assessment of technologies
</td><td>
• Recognise and promote the benefits of biomass use in chemicals production. Utilise study outputs to understand the economic and climate benefits of bio-based chemicals to shape the future ambition.
• Ensure that investment in alternative feedstocks can be properly accounted for in new schemes.
• UK ETS installations that store biomass in products should be awarded a credit equivalent to the carbon drawn down from the atmosphere and stored in the product.
• Establish a comparable support mechanism for alternative feedstock investment and biomass to chemical conversion.
• Ensure that the energy strategy encourages the burning of biomass for energy to be a last best-case option for the use of biomass.
</td></tr>
</table>

Recycled Carbon Recommendations

Short Term	Medium Term	Long Term
Improve collaboration in value chains		
Support R&D into product design & redesign		
Promote sustainability assessments relating to recycled carbon feedstock use		
Standardise definitions and concepts		
Develop industry accepted methods for the recovering and utilisation of recycled carbon		
Utilise waste as alternative feedstock		
Improve waste management logistics for the utilisation of waste feedstocks		
Develop renewable energy infrastructure		
Develop chemical recycling infrastructure		
Develop low carbon hydrogen network		

Technology Needs	Policy Recommendations
• Accessible renewable energy production • Low-carbon hydrogen production • Engineering biology for Chemical production • Chemical recycling process development • Technoeconomic assessment of technologies	• Tax subsidies for the use of at least 30% recycled content in plastic packaging. • Implement standardised system for the labelling of recycled content. • Inclusion of the waste sector in the UK ETS would provide an incentive to recycle carbon back into the economy rather than to burn it. • Establish a comparable support mechanism for alternative feedstock Investment.

Carbon Dioxide

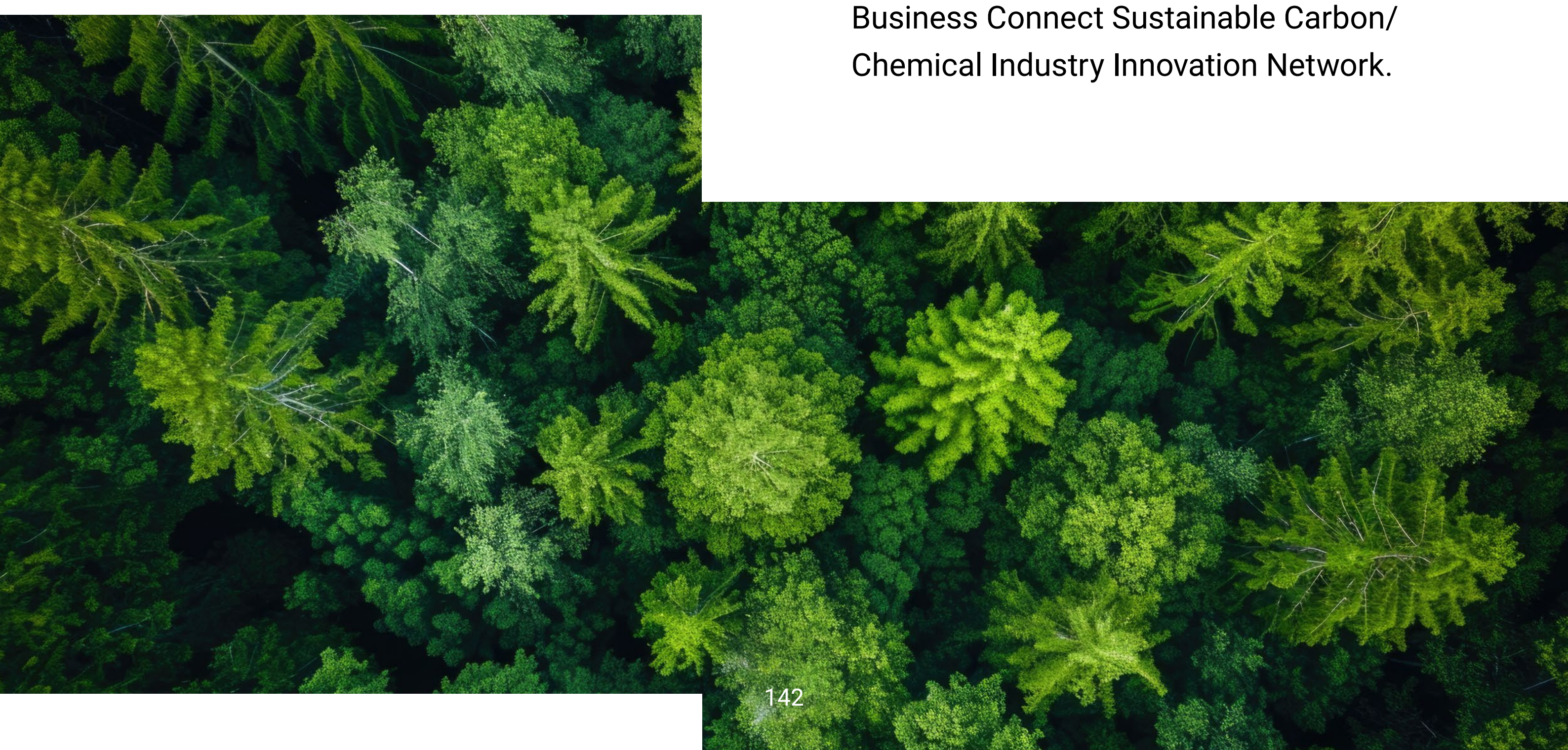
<table>
<tr><th>Short Term</th><th>Medium Term</th><th>Long Term</th></tr>
<tr><td colspan="3">Manage and convert existing assets to include carbon capture technology at source</td></tr>
<tr><td colspan="2">Support for R&D into CCU technology</td><td></td></tr>
<tr><td colspan="3">Develop renewable energy infrastructure</td></tr>
<tr><td colspan="3">Develop CO_2 distribution and storage infrastructure</td></tr>
</table>

Technology Needs	Policy Recommendations
• Electrification of heat • Accessible renewable energy production • Carbon capture technology • Carbon dioxide to chemicals transformations • Technoeconomic assessment of technologies	• Clarity on the treatment of captured emissions used in products needed. • Update the Low Carbon Hydrogen Standard to include permanent storage in products. • Make CCU eligible for support under the ICC business model. • In the UK ETS, create a whitelist of CCU products in which the carbon can be considered permanently stored. When the waste sector is included in the UK ETS there should be an incentive for them to get carbon back into the economy rather than emit it. • Work with the ICC to consider business models to encourage the returning of captured CO2 to the economy. • Extend and increase support via CCUS Innovation Fund. • Establish a comparable support mechanism for alternative feedstock investment.

Suggested next steps

As a follow on from this study, and to accelerate the UK chemical industry's transition to sustainable carbon feedstocks, we recommend the following next steps:

1. Identify existing sources of regional and national data on feedstock availability to share with industry, academia, innovators and Government around the use of sustainable carbon for chemicals, including carbon footprints and impact on environmental factors beyond carbon.
2. Review of current UK chemicals assets (in use and mothballed), and those likely to close, and plan for protecting them.
3. Establish an industry-government agreement on Best Available Carbon.
4. In-depth mapping of UK chemicals supply chains, gaps, and analysis of how supply chains could be re-built for key chemicals
5. A desktop study which collates all available data on the state of the art and emerging technologies for capturing carbon which can be shared with industry including:
    a. The economics and overall carbon footprint of sustainable carbon feedstocks (including energy) at-scale;
    b. The capability and scalability of current and emerging technology;
    c. Horizon scanning for new low TRL technologies.
6. Study to determine the hydrogen and energy requirements to achieve the UK CHEM 2050 Ambition.
7. Bring together SMEs and Large industry players to connect across the full TRL, alongside investors to co-create future supply chains
8. Develop and implement an Innovate UK Business Connect Sustainable Carbon/ Chemical Industry Innovation Network.



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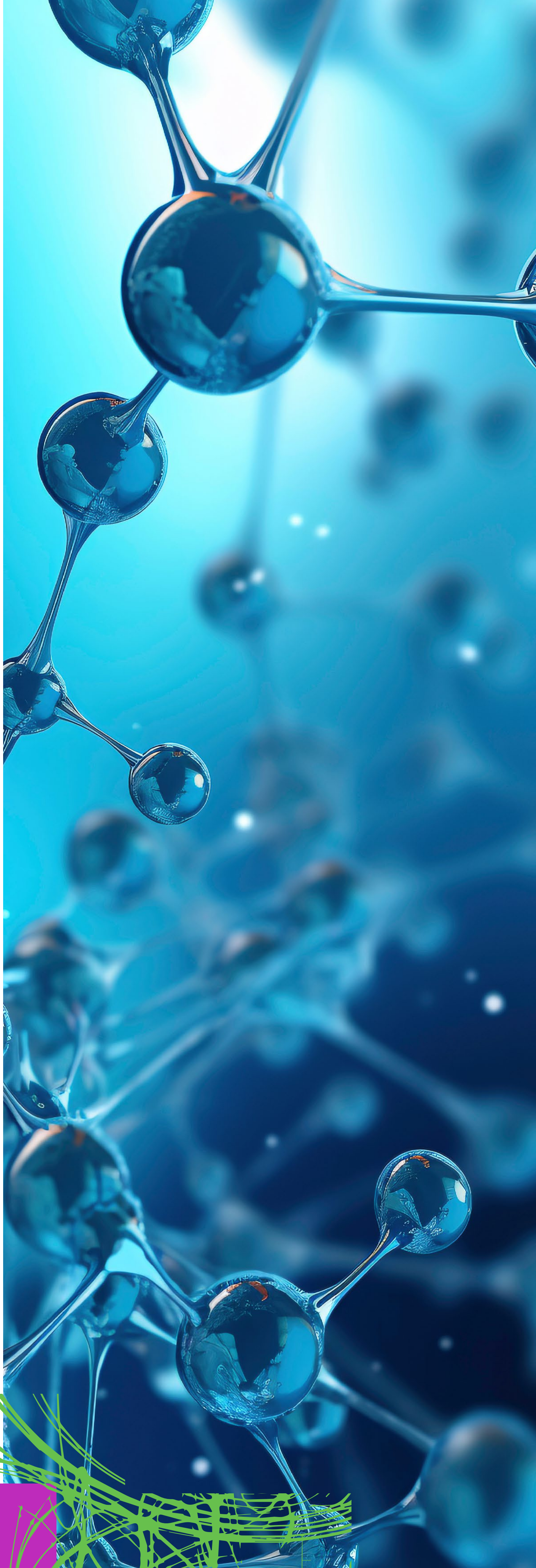

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