ARUP

An independent report commissioned by Offshore Energies UK

Carbon Capture & Storage in the UK: Accelerating Towards the Merchant Model

Nine steps to unleash a commercially self-sustaining CCS industry in the UK

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OEUK Executive Summary

The UK's Carbon Capture and Storage (CCS) sector is at a pivotal moment. After several false starts, progress has been made with the East Coast Cluster becoming the first to reach final investment decision (FID) and the first CO_2 storage permit awarded to the Endurance store. This represents the beginning of the UK's CCS industry, a crucial step for the global CCS sector. This achievement would not have been possible without the close coordination between industry and government. Momentum must be maintained, as we anticipate the HyNet cluster to reach FID soon.

However, we will fail if we don't go beyond Track-1 clusters. The entire project pipeline must be realised to ensure the UK is on track to meet its Net Zero commitments. Track-2 clusters are vital to establishing a robust CCS sector, and a firm commitment to support these projects is urgently required. Additionally, transportation and storage systems and emitters outside the cluster sequencing process must have clear routes to market.

This independent report, commissioned from Arup, outlines a pathway to creating a self-sustaining CCS sector in the UK. The report's modelling demonstrates a feasible path to achieving this, which will be dependent on three factors: (1) cost reductions enabled through technological advancements, competition and collaboration (2) a supportive, transparent policy framework which provides a clear route to market, enables additional revenue streams and the development of a Pan-European CO_2 market with the UK as an indispensable part of it (3) an agile planning system and a willing public supportive of CCS. The alternative is a UK CCS sector that never develops at scale with high costs, international misalignment and public opposition.

The path forward is clear, and industry will continue to play its part in building a robust CCS sector. OEUK members are already making substantial capital investments across the value chain, including millions in front-end engineering and design (FEED) work, carbon store appraisals, the first test injection of CO_2 in a depleted gas field and supply chain engagement voluntarily maximising UK content.

The UK is uniquely positioned to become a global leader in CCS, with significant advantages including Europe's largest offshore CO_2 storage capacity, and a strong supply chain. Over 120 of OEUK's 400 members are already active in the UK's CCS sector, demonstrating the strong transferability of skills and capabilities from the oil and gas industry to CCS.

These factors are key to building a sustainable industry that can thrive without long-term government financial support. This is a once in a lifetime opportunity for the UK to become a global leader in a sector which is essential for Net Zero.

We extend our thanks to our members, including developers of CO_2 transportation and storage systems, and emitters, whose valuable input helped shape the recommendations in this report.

David Whitehouse

Chief Executive Officer, Offshore Energies UK

The Pathway to the UK's Merchant Model for Carbon Capture, Utilisation and Storage

The UK has shown fantastic leadership in CCS, and we have a lot to celebrate. We have a growing consensus behind the idea of a new carbon capture and storage industry in our country. We are recognised around the world for the creation of the first public-private risk sharing model for CO_2 transport and storage, which has been downloaded and copied by officials in countries ranging from Italy to Indonesia and Belgium to Brunei.

Over nearly 20 years, we have developed a resilient model for the sharing of costs and management of public risk in the initial CO_2 systems. Our major developers understand CO_2 management and storage, and have good data on the capacity and potential of our reservoirs to store CO_2. Major global corporates have taken investment decisions in UK CCS, committing thousands of global shareholders to UK CCS development.

However, we no longer have time on our side. In the preparation of this report, we have examined the latest policy landscape for UK and relevant international CCS, including both existing legal agreements, and statements of intent. We have reviewed the economic proposition for investors and developers in UK CCS in the round, and weighed the possible revenues achievable against costs both now and in the light of future economies of scale. Building on this analysis, we have interviewed leading representatives of the UK's energy industry across the centrally supported Track projects, and unsupported post-Track projects, to understand the barriers they face.

We have cross-examined the barriers and the enablers before us in UK CCS; economic, policy and regulatory. Our investigation included detailed cost modelling considering expected savings which the CCS value chain can expect as the technologies enter deployment in the 2030s in the UK.

These price trajectories are then compared to the UK government's figures on a carbon pricing trajectory to support Net Zero ambitions. Based on positive outlooks for the UK (EU-aligned) carbon price, our analysis indicates that we can look forward to a self-sustaining market in CCS from the mid-2030s across all major applications (gas-fired power, cement, waste to energy and hydrogen production).

We have identified nine steps to ensuring a competitive and self-sustaining UK CO_2 market. These steps are all fully executable, and fully in the capacity of our own industry, our investors and our Government representatives jointly to deliver. With the completion of these steps, we envisage not only taxpayer-supported CO_2 capture and storage, but also the beginning of an organically growing and self-sustaining, fully commercial global CCS system.

Our Nine Recommendations are listed here in 3 categories:

- Get the basics in place
- Engage the public
- Enable the market

Get the basics in place

1. The UK must leverage its position of having the largest offshore storage capacity in Europe to become the leading provider of CO_2 storage services in the region. OEUK has identified two sets of barriers that need to be addressed urgently to achieve this:

    a. Misalignment between the UK and ETS, and London Protocol regulations.

    b. Potential discrepancies in CO_2 standards, infrastructure, and liability coordination. While these challenges are not insurmountable, coordinated action is crucial, and time is of the essence.

2. Support the growth of UK ETS system with the ambition of it tracking the values required for the Net Zero pathway and align to the EU ETS so that the UK can accept EU CO_2 for storage.

3. Establish world-leading CO_2 safety practices for CO_2 as a joint effort between all relevant developers and UK authorities. This must be centrally funded so that the UK develops world-leading safety regulations for the management of CO_2 onshore and offshore, and sets international standards in this regard for onshore as well as offshore infrastructure, in close collaboration with the NSTA and its emerging guidance on MMV.

Engage the public

4. The UK's energy sector, and public sector, must engage the UK public in the establishment of a world-leading CCS sector, raising the positive profile of CCS across the UK, and generating a shared conviction in the CCS mission, and not only in the regions directly impacted.

5. UK companies and public sector decision makers must specify the use of CCS-enabled products such as CCS-enabled cement, concrete, aggregates and steel in major construction projects, CCS-enabled power, CCS-enabled power from waste, and CCS-enabled fertilisers and other chemicals.

6. CO_2 networks (rail and marine): central decarbonisation funds are well placed to come together to enable development of a UK-wide network for CO_2 transport, targeting a range of UK entities including:

    a. Refineries with ports and storage capacity, where CO_2 can be held prior to storage.

    b. Fabrication yards which are likely to be major points of assembly and storage of amine columns, pipeline steels and other capture infrastructure.

    c. Vessel (tank) manufacturers which are equipped to assemble and supply vessels for compressed CO_2 storage, including rail and marine tanks.

    d. Marine and logistics companies and infrastructure owners which can facilitate pressurised transport of CO_2 by both rail and maritime routes.

7. Planning Authorities must be informed, involved and equipped with necessary information and skills to manage developments in their areas related to safe and non-disruptive CO_2 transmission, capture and/or storage.

Enable the market

8. A range of capture technologies must be supported to mature and reach scale. Amine-based capture is not the only means of CO_2 separation, it results in a toxic sludge which requires incineration and is unlikely to be the best technical option for all industrial contexts. A wide range of technologies are available, some of which are fully recyclable and all of which vary in energy requirement. A sustainable and competitive CCS industry requires a range of options to be on the table.

   Having emphasised amine-based capture to date, the UK government must now support rapid scaling of the least environmentally damaging and most readily scalable of all capture technologies. Decarbonisation funding should be deployed to invite companies with innovative capture technology addressing energy and residual waste challenges to set up R&D facilities in the UK.

9. The UK should look to receive landing of the first major CO_2 trunkline from mainland Europe. Plans are in development for this new infrastructure. One main route will be developed from refineries in Belgium, and it makes most economic sense for this to land near our largest stores, at Bacton.

Abbreviations and Acronyms

The following abbreviations and acronyms are used throughout this document:

ABP	:	Associated British Ports
ACT	:	Advanced Conversion Technology
AI	:	Artificial Intelligence
ATT	:	Advanced Thermal Treatment
AVR	:	Accreditation and Verification Regulation
BAT	:	Best Available Techniques
BAU	:	Business as Usual
BECCS	:	Bioenergy with Carbon Capture and Storage
BEIS	:	Department for Business Energy and Industrial Strategy
BM	:	Business Model
CaaS	:	Carbon Capture as a Service
CAPEX	:	Capital Expenditure
CBAM	:	Carbon Border Adjustment Mechanisms
CCC	:	Climate Change Committee
CCS	:	Carbon Capture and Storage
CCSA	:	Carbon Capture and Storage Association
CCUS	:	Carbon Capture, Utilisation and Storage
CESAR	:	Chemical Emissions Safety and Risk Assessment
CfD	:	Contract for Difference
CfDc	:	Contract for Difference for Carbon
CHP	:	Combined Heat and Power
CNPC	:	China National Petroleum Corporation
CO_2	:	Carbon Dioxide
COP21	:	The 21st session of the Conference of the Parties
CSLR1		Carbon Storage License Round 1
DAC	:	Direct Air Capture
DACCS	:	Direct Air Carbon Capture and Storage
DESNZ	:	Department for Energy Security and Net Zero
DOE	:	Department of Energy
DPA	:	Dispatchable Power Agreement
EA	:	Environmental Agency
EEA	:	European Economic Area
EEMPA	:	(Ethylamino)ethanol
EfW	:	Energy from Waste
EOR	:	Enhanced Oil Recovery
ERM	:	Environmental Resources Management
ETS	:	Emissions Trading Scheme
FID	:	Final Investment Decision
FOAK	:	First-of-a-kind
GGR	:	Greenhouse Gas Removals
GHG	:	Greenhouse Gas
Gt	:	Gigatonne
HEFA	:	Hydroprocessed Esters and Fatty Acids
HM	:	His Majesty's
HPBM	:	Hydrogen Production Business Model
HSE	:	Health, Safety, and Environment
ICC	:	Industrial Carbon Capture

IEA	:	International Energy Agency
IEEFA	:	Institute for Energy Economics and Financial Analysis
IGET	:	Immingham Green Energy Terminal
IMO	:	International Maritime Organisation
IOGP	:	International Association of Oil and Gas Producers
kg	:	Kilogramme
km	:	Kilometre
kWh	:	Kilowatt-hour
LCCC	:	Low Carbon Contracts Company
LCO_2	:	Liquid Carbon Dioxide
LNG	:	Liquefied Natural Gas
MEA	:	Monoethanolamine
MMV	:	Measurement, Monitoring and Verification
MOF	:	Metal-Organic Framework
MoU	:	Memorandum of Understanding
MRR	:	Monitoring and Reporting Regulation
Mt	:	Megatonne
$MtCO_2e$	:	Million Tonnes of Carbon Dioxide Equivalent
MtJ	:	Methanol to Jet
Mtpa	:	Megatonne Per Annum
MWh	:	Megawatt-hour
NDRC	:	National Development and Reform Commission
NOAK	:	Nth-of-a-kind
NPT	:	Non-Pipeline Transport
NSTA	:	North Sea Transition Authority
Ofgem	:	Office of Gas and Electricity Markets
OGA	:	Oil and Gas Authority
OPEX	:	Operational Expenditure
PCC	:	Post Combustion Carbon Capture
PtL	:	Power to Liquid
PV	:	Photovoltaic
R&D	:	Research and Development
RAB	:	Regulated Asset Base
RCF	:	Recycled Carbon Fuel
RFNBO	:	Renewable Fuel of Non-Biological Origin
RTFC	:	Renewable Transport Fuel Certificate
RTFO	:	Renewable Transport Fuel Obligation
SAF	:	Sustainable Aviation Fuel
SDE++	:	Sustainable Energy Production and Climate Transition Incentive Scheme
SEAA	:	Storage Exploration and Appraisal Agreement
SOE	:	State-Owned Enterprise
SWIC	:	South Wales Industrial Cluster
T&S	:	Transport and Storage
T&SCo	:	Transport and Storage Company
TCA	:	Trade and Cooperation Agreement
TRI	:	Transport and Storage Regulatory Investment Model
UK	:	United Kingdom
UKCS	:	United Kingdom Continental Shelf
UKIB	:	United Kingdom Infrastructure Bank
UNCLOS	:	United Nations Convention on the Law of Sea
US	:	United States
VCM	:	Voluntary Carbon Market

1. Introduction

1.1 Purpose and Scope of the Report

To ensure a long-term and self–sustaining industry, the UK public and private sector now need to collaborate to develop a CCS industry which can cover its own costs. This report examines the transition scenarios for this market to be realised from 2035, and identifies the actions which are critical now, to ensure that a safe and permanent capture and storage of CO_2 can become a profitable industry in its own right.

The first 4 CCS clusters in the UK are targeted to be in service by 2030. The capacity of these projects will not meet the UK's ambitions for storage, and it is envisaged additional stores will be commercial ventures in a viable market. This is on a timeline of a transition period from a subsidised regime from 2030 through to 2035, with a self-sustaining CCS market from 2035 to meet Net Zero in 2050 [1].

This report examines the current state of the CCS value chain and the wider environment that it operates in. It models the expected costs of the industry moving forwards against potential revenues. The report will then provide analysis and recommendations on how to meet the target of an independent commercial market operating from 2035.

The key areas the report examines are:

1. Reducing the costs of CCS across the value chain.
2. Increasing revenue in the CCS market place.
3. Modelled trajectory of these costs and revenues.
4. Market-enabling actions (private sector)
5. Market-enabling actions (public sector)

1.2 Overview of CCS

1.2.1 The Role of CCS in Decarbonisation

CCS is a cornerstone of efforts to achieve Net Zero emissions, both in the UK and globally. The UK's Climate Change Committee (CCC) has described CCS as a "necessity, not an option," [2] highlighting its indispensable role in reducing emissions across critical sectors such as industry, electricity generation, and fuel supply. At the global level, the International Energy Agency (IEA) underscores the importance of CCS in meeting climate goals, estimating that 1 billion tonnes of CO_2 must be captured and stored annually by 2030 to limit global warming to 1.5 °C. With a highly developed oil and gas sector, the UK has technical and regulatory expertise to deliver CCS services to European emitters. The geology and location of the UK make it uniquely positioned to provide large scale storage solutions for nations without storage capacity throughout the region.

For industries with process emissions, such as glass, cement, steel, and chemicals, CCS remains the only scalable pathway to deep decarbonisation. These industries produce materials essential to modern economies, and CCS ensures their continued viability while reducing their environmental impact. Furthermore, the technology is central to producing low-carbon hydrogen and sustainable fuels, such as sustainable aviation fuel and low carbon maritime fuels, which are critical to decarbonising transportation and other hard-to-abate sectors.

CCS also strengthens energy security by enabling the development of clean gas-fired and bioenergy power plants equipped with carbon capture (BECCS). These facilities provide reliable, dispatchable power that complements renewable energy sources, ensuring a stable energy supply while aligning with Net Zero ambitions. CCS also plays a role in managing emissions from the residual waste sector, capturing carbon from energy generation processes that would otherwise release CO_2 into the atmosphere.

Globally, emerging negative emissions technologies, particularly Direct Air Capture (DAC), will be critical in addressing residual emissions and removing CO_2 directly from the atmosphere. These technologies, alongside CCS infrastructure, are essential to achieving Net Zero. The UK is well-positioned to lead in this space by developing advanced CO_2 transport and storage networks, enabling emissions from multiple sectors to be safely and permanently stored in geological formations. Such systems provide a scalable model for global adoption.

In summary, CCS is essential to both UK and global decarbonisation strategies. It offers practical solutions for reducing industrial emissions, supports the transition to clean energy systems, facilitates the production of sustainable fuels, and underpins the deployment of negative emissions technologies. By integrating CCS at scale, the UK and the global community can advance toward a sustainable, Net Zero future with greater resilience and energy security.

1.2.2 Applications in Power Generation and Industry

CCS is a critical technology for decarbonising power generation and certain industrial processes, including some of the largest contributors to global CO_2 emissions. By deploying CCS in power generation and industry, economies can maintain their competitiveness and sustain jobs in sectors that are traditionally hard to decarbonise. The technology also supports the development of CO_2 transport and storage infrastructure, which can serve multiple facilities, creating an interconnected network for emissions reduction.

Power Generation

In the power sector, CCS is pivotal for transitioning to a low-carbon energy system to meet the UK's Clean Power 2030 targets. While renewable energy sources like wind and solar are central to decarbonisation, they are intermittent and require complementary solutions to ensure grid stability. CCS allows gas-fired power plants and bioenergy facilities equipped with carbon capture technology (e.g., BECCS) to deliver reliable, clean, dispatchable power. These plants can act as a consistent energy source, particularly during periods of low renewable energy generation, while capturing and storing the CO_2.

Gas-fired power plants equipped with CCS also support energy security by providing flexibility to meet peak electricity demand, enabling a smooth transition from fossil fuels to a renewable-dominated grid. BECCS, on the other hand, plays a dual role by generating energy while achieving negative emissions, essential for offsetting residual emissions from other sectors.

Industry

Industries such as cement, steel, and chemicals are responsible for significant CO_2 emissions due to the high-temperature processes and chemical reactions inherent in their production. For example, cement production releases CO_2 not only from energy use but also from the chemical breakdown of limestone. Similarly, steel production involves emissions from blast furnaces, while the chemicals industry produces CO_2 as a byproduct of manufacturing processes, and also deploys CO_2 as a feedstock.

CCS enables these industries to capture CO_2 emissions at their source and store, or utilise, them safely, ensuring continued production of essential materials while significantly reducing their carbon footprint. This is particularly important for sectors where electrification or alternative technologies are not yet feasible at scale. Furthermore, CCS can be integrated into hydrogen production processes, creating low-carbon hydrogen that can serve as a clean energy source for industrial applications.

It is worth noting that a key concept in the industrial application of CCS is the establishment of industrial clusters. These clusters are geographic hubs where multiple industrial facilities can share CO_2 transport and storage infrastructure. By connecting emitters to shared pipelines and geological storage sites, clusters enable economies of scale and significantly lower the cost of deploying CCS. The largest 6 industrial clusters in the UK based on their annual cumulative emissions output are South Wales, Solent, Humber, Teesside, North West and Grangemouth, with deployment projects such as HyNet, South Wales Industrial Cluster, and Solent Cluster. These projects aim to bring together emitters to create integrated carbon capture networks that accelerate decarbonisation efforts. The cluster model also encourages innovation and collaboration between industries, creating opportunities to integrate CCS with hydrogen production and the development of low-carbon fuels.

Hydrogen

Carbon capture is crucial in low carbon hydrogen production. This production method is sometimes referred to as "blue hydrogen." Blue hydrogen is produced from natural gas through a process called steam methane reforming (SMR), which generates CO_2 as a byproduct. By capturing and storing this CO_2, the carbon intensity of the hydrogen energy vector is significantly reduced. While “green hydrogen”, where hydrogen is produced from electricity and water, is not reliant on hydrocarbons, the energy requirement for this method limits its widespread adoption.

1.3 Global CCS Ambitions

The Paris Agreement is a legally binding international treaty on climate change. Signed at the UN Climate Change Conference (COP21) in Paris, December 2015, it commits all 196 signatories to limit global warming to 1.5 ^{o}C above pre-industrial levels. A limit which requires a reduction of greenhouse gas emissions of 43% by 2030 [3]. CCS is the 4th largest contributor to emissions savings accounting for 15% of all emissions and 25% within the energy sector [4].

1.3.1 Key Projections and Targets

i. **Global Capacity Growth**: To meet current net-zero targets, global CCS capacity needs to increase over 100 times from current levels, reaching between 4 to 6 gigatons (Gt) of CO_2 captured annually by 2050. This would help decarbonise around 15 to 20 percent of today's energy-related emissions[1] [5].

ii. **Sectoral Contributions**: CCS is expected to play a crucial role in decarbonising hard-to-abate sectors such as cement, steel, and chemicals. It will also be essential for retrofitting existing fossil fuel-based power and industrial plants [4].

iii. **Technological Integration**: The focus will shift towards integrating CCS with bioenergy (BECCS) and direct air capture (DAC) technologies. These methods not only capture CO_2 but also help in producing climate-neutral fuels and materials [4].

iv. **Policy and Investment**: Achieving these ambitious targets will require significant policy support and investment. Governments and the private sector need to collaborate to create favourable regulatory frameworks and financial incentives to accelerate the deployment of CCS technologies.

[1] Noting here the estimates vary between the IEA and McKinsey by 5%.

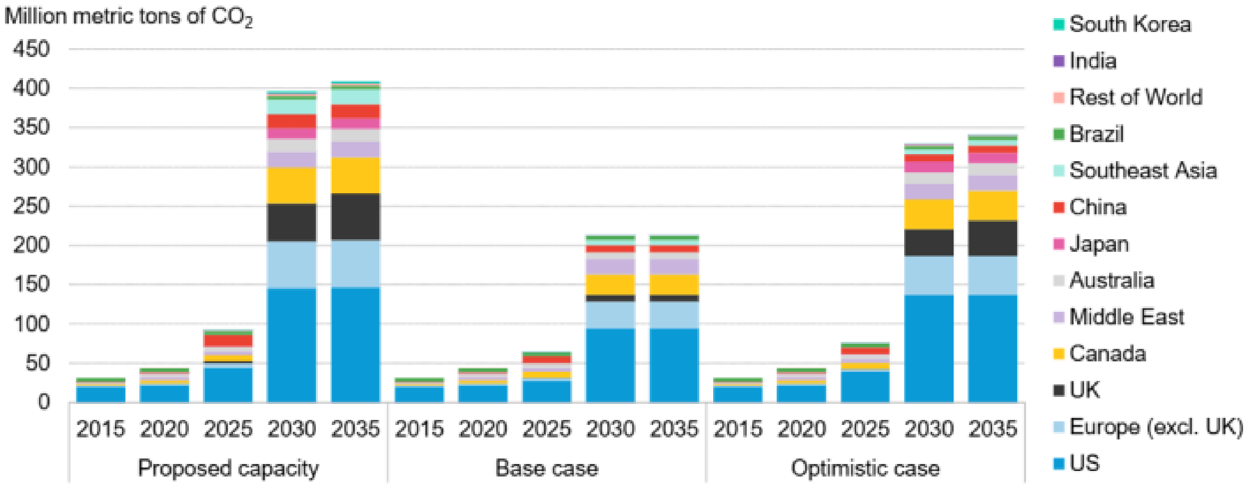

Figure 1: Annual carbon capture capacity forecast, by market and commissioning year (including EOR), BloombergNEF 2024 [6]

1.4 The Value to the UK

The UK has clear CCS targets set out in the *'Carbon Capture, Usage and Storage: a vision to establish a competitive market'*, policy paper, published in December 2023 [1]. The goals of this are:

- Market creation: Getting to 20 to 30 megatonnes per annum (Mtpa) CO_2 by 2030 across 4 clusters.
- Market transition: The emergence of a commercial and competitive market.
- A self-sustaining CCS market: with the UK economy meeting Net Zero by 2050.
- Creation of 50,000 jobs in the CCS sector.
- Domestic content of the UK CCS supply chain of greater than 50%.
- The CO_2 stored each year should increase by 6 MTPA from 2031.

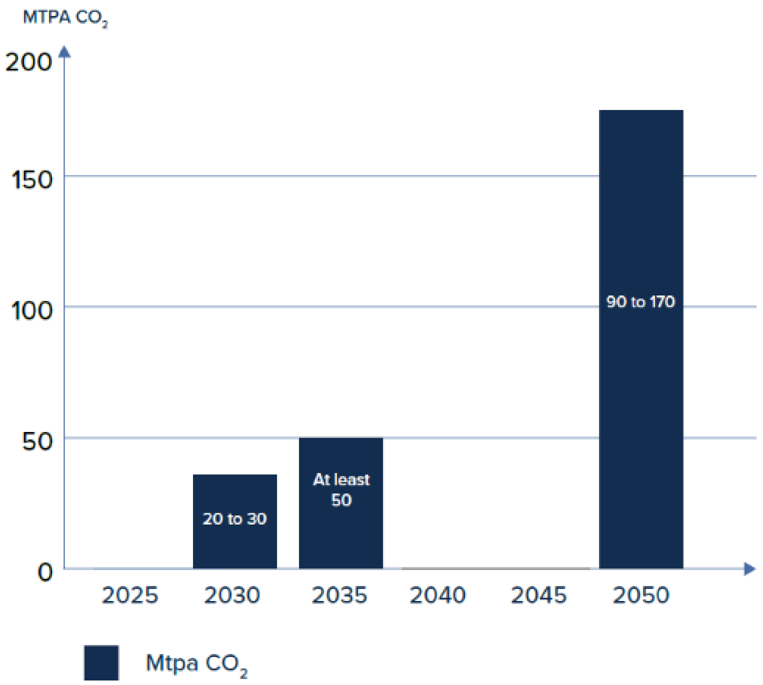

Figure 2: UK Government CCS Roll Out Range of Ambitions. [1]

1.5 UK's CO_2 Storage Capacity

The UK has one of the largest potential subsurface storage capacities for CO_2 in Europe, positioning it to take a leading role globally in providing CO_2 transport and storage services. The UK's CO_2 storage database, compiled by the BGS, identifies over 500 potential sites across the UK Continental Shelf (UKCS) for geological CO_2 storage, with an estimated 78 billion tonnes of theoretical storage capacity. This capacity is found in deep saline aquifers and depleted oil and gas fields. For the selected Track-1 clusters, including HyNet and the East Coast Cluster, CO_2 will be injected into depleted oil and gas fields and saline aquifers, respectively.

Offshore CO_2 storage is a safe, well-established method backed by extensive industry experience and thorough academic research. OEUK supports prioritising offshore storage over onshore options, as offshore sites in the UK offer up to 78 Gt of capacity, significantly more than potential onshore sites.

Offshore storage technology is underpinned by robust monitoring processes and is considered a crucial component of achieving decarbonisation goals. Projects such as the Sleipner field in the North Sea, which has been operational since 1996, demonstrate the feasibility and safety of offshore CO_2 storage. This project alone stores approximately 1 million tonnes of CO_2 annually, providing valuable insights into the long-term behaviour of stored carbon. CO_2 is stored in deep geological formations, such as depleted hydrocarbon reservoirs and saline aquifers, which are selected for their capacity to securely contain CO_2, with caprocks acting as impermeable seals. For well decommissioning, the principle is restoration of the caprock, and zones capable of flow are isolated from the surface. Two permanent barriers are typically required for any zone that can flow, and for zones that could flow if charged with CO_2. These barriers include cement plugs and, in some cases, the sealing properties of certain geological formations.

This substantial storage capacity means that the UK is well-positioned to support large-scale CCS projects. The ability to store vast amounts of CO_2 offshore makes the UK a key player in global efforts to reduce greenhouse gas emissions and combat climate change.

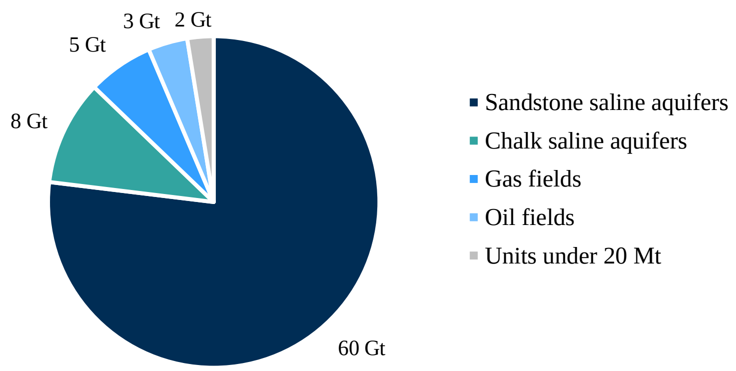

Figure 3: Overall UK CO_2 Storage Capacity (estimated at 78 Gt) in Offshore Geological Formations by Type of Store [1]

1.6 The Cost of Offshore Storage

Estimating the costs of offshore storage provides a challenge due to the number of variables and unique nature of each storage complex. IEAGHG (2021) estimate that costs could be in the range of €1-7/tonne for onshore storage in a depleted oil and gas fields, and €6-20/ tonne for offshore storage in saline aquifers[2] [8], with compression and transport. This could rise to an estimated cost of €10/tonne [9]. Reported figures from the Track-1 clusters, indicate that a T&S cost of £40/tonne may be expected at the start of operations. Further

[2] ZEP in 'The cost of subsurface storage of CO_2' are broadly in agreement with estimates of €4-20/tonne and €13-20/tonne for a deplete oil and gas example.

analysis shows that the UK is in a prime position to leverage its geology to drive towards the lower ends of these estimates [10].

Over the lifetime of the project significant OPEX savings can also be expected as stores scale in capacity and monitoring overheads reduce with increased confidence in store integrity and plume of injected CO_2 conforming to modelled behaviour [11]. The increased confidence can be used as grounds for reducing expensive monitoring, such as 4D seismic modelling, on the basis that conformance has been proven. These savings are captured in the models as part of the holistic process cost improvements.

2. A Merchant Model for CCS

2.1 Characteristics of a Merchant Model

The merchant model describes a market-based framework that can transition the CCS industry from reliance on subsidies and other Government support mechanisms to self-sustaining operations where costs and risks of operation can be recovered by the revenue generated. When achieved, this model implies a sustainable ecosystem where revenues are generated through a range of sources related to CCS, including such as selling carbon capture, storage and transportation services to emitters, trading carbon credits in compliance with market frameworks (e.g., EU or UK ETS), and by trading CCS-enabled H_2, power, cement and other products at a premium. In this scenario, a sufficient multiplicity of capture technologies, trading or transmission routes, demand sources for CCS mean that competition exists and the market is increasing in liquidity, facilitating further price-suppressing competitive market behaviours.

The chart below highlights the six focus areas integral to the development of a merchant model, which include:

i. Network interconnectivity;
ii. Cluster and dispersed site network development;
iii. Market framework;
iv. CCS-enabled products;
v. Technology advancements; and
vi. Value chain integration.

These areas together enable technological, infrastructural, regulatory, and economic factors required for a successful transition. The target areas emphasise specific action points ranging from network interconnectivity, such as CO_2 shipping and transport, to enabling CCS-based products like low-carbon cement and steel. This ensures a comprehensive strategy for transforming the UK CCS industry into a sustainable and profitable venture.

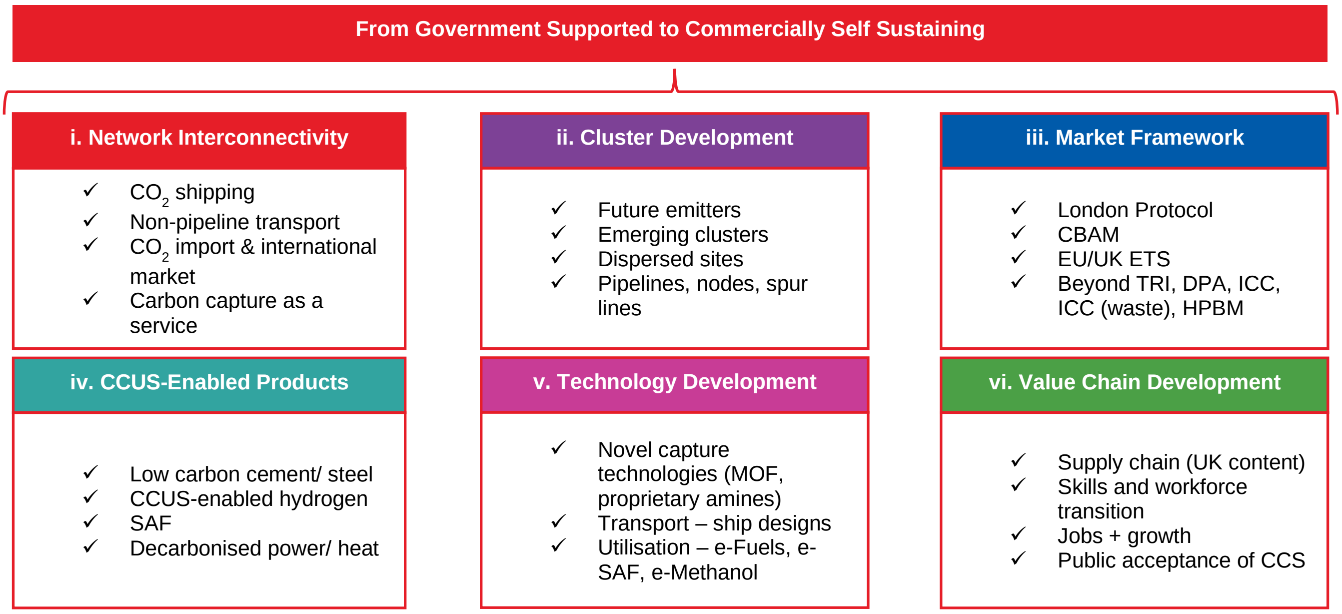

Figure 4: Focus Areas – Merchant Model Development

Table 1: Six Key Focus Areas Discussed in Detail

i. Network Interconnectivity	**CO_2 shipping**	CO_2 shipping enables the bulk transport of captured CO_2 across long distances, especially for emitters that are geographically distant from storage locations. This is critical for connecting small or isolated emitters to centralised clusters and large-scale storage sites like undersea reservoirs.
	Non-pipeline transport	For emitters not connected to pipeline networks, road, rail or barge transport solutions offer flexibility. For example, CO_2 containers that can be loaded onto trucks or trains can deliver captured CO_2 to storage hubs or port terminals. This approach supports dispersed emitters in remote areas and avoids high building costs of pipeline infrastructure.
	CO_2 import & international market	Expanding the scope of CCS beyond national borders, CO_2 import and export can support regions with limited storage capacity by allowing them to send captured CO_2 to countries with underutilised storage sites, offering European countries a chance to optimise shared infrastructure and create an international CCS market.
	Carbon capture as a service	Emitters can outsource their CO_2 capture operations to specialised providers. By paying for capture, transport, and storage as a service, small emitters lacking technical expertise can adopt CCS without large capital investments, creating a new revenue stream for CCS operators and encouraging broader participation.

ii. Cluster Development	**Future emitters**	CCS networks must anticipate future demand by designing infrastructure that can be expanded to accommodate new emitters. Pipeline capacity needs to ensure that growing industries can connect seamlessly to the CCS network, reducing costs and delays in the future.
	Emerging clusters	New industrial zones, particularly those expanding energy-intensive industrial regions, can become CCS hubs. The development of carbon capture in emerging clusters can allow these clusters to align with global decarbonisation goals while benefiting from shared infrastructure. Clusters will need close coordination to manage CO_2 stream impurities and attribution of arising issues.
	Dispersed sites	Connecting isolated emitters, such as factories in rural areas or remote industrial areas, requires innovative approaches. Non-pipeline transport can enable integration of these dispersed sites into the CCS network and prevents emissions from being stranded simply due to location.
	Pipelines, nodes, spur lines	Developing a dense network of pipelines, along with strategically located nodes and spur lines can ensure efficient CO_2 transport within clusters. Central collection points, such as Teesside, can connect multiple industries and storage sites through an interconnected network.

iii. Market Framework	**London Protocol**	The London Protocol can facilitate international cooperation on the cross-border transport of CO_2, provided international agreements are aligned. It can allow countries to transport CO_2 to shared storage reservoirs, ensuring compliance with environmental standards and encouraging global CCS collaboration.
	CBAM	CBAM imposes tariffs on imported goods based on their carbon intensity. For example, a steel manufacturer using CCS could remain competitive despite higher production costs as imported steel would face equivalent carbon pricing at the border. This is designed to ensure fair competition for domestic industries that adopt CCS.
	EU/ UK ETS[3]	The ETS sets a price on carbon emissions, incentivising industries to adopt CCS by making it more cost-effective than paying for emissions. Therefore, systems like the ETS can facilitate the creation of a market-based incentive for adoption of CCS.
	Beyond TRI[4], DPA, ICC, ICC (waste), HPBM	Expanding beyond existing regulatory frameworks ensures comprehensive policy coverage for CCS. For example, the development of DPA for CCS-equipped power plants ensures revenue stability while supporting flexible power generation that align with renewable energy supply.

iv. CCS-Enabled Products	**Low-carbon cement/ steel**	Integrating CCS into cement and steel production can support the "greening" of energy intensive industries. The low-carbon cement and steel can be marketed as a sustainable alternative in construction projects which addresses emissions from chemical reactions in addition to energy use.
	CCS-enabled hydrogen	Hydrogen production using natural gas emits significant CO_2, but CCS allows this CO_2 to be captured, creating "blue hydrogen". This low-carbon hydrogen can be used in transport, heating, and industrial processes, aligning with clean energy targets while maintaining affordability.
	SAF	CO_2 captured from industrial processes can be used as a feedstock to create SAF, reducing reliance on fossil fuels in aviation. A refinery using CCS can produce SAF by combining captured CO_2 with renewable energy source, helping decarbonise the aviation sector which has limited alternatives to liquid fuels.
	Decarbonised power/ heat	Power plants and industrial facilities equipped with CCS can deliver low carbon energy. For instance, a natural gas power plant with CCS can capture a great amount of its emissions and provide decarbonised electricity and heat for local communities while maintaining grid reliability.

[3] Emissions Trading Scheme

[4] Transport and Storage Regulatory Investment, Dispatchable Power Agreement, Industrial Carbon Capture (and Waste), Hydrogen Production Business Model.

v. Technology Development	**Novel capture technologies (MOF, proprietary amines)**	Metal-organic frameworks (MOFs) and proprietary amines can offer breakthroughs in CO_2 capture efficiency and cost reduction. MOFs have extremely high surface areas, allowing them to capture CO_2 more effectively at lower pressures, and this can make them suitable for smaller emitters with fluctuating emissions.
	Transport – ship design	Specialised CO_2 transport ships can be designed to safely carry large quantities of compressed or liquified CO_2. Accompanied by refined shipping routes, specialised ships can maintain CO_2 at ultra-low temperature and enable long-distance transport between emitters and offshore storage sites far away from source.
	Utilisation – e-fuels, e-SAF, e-methanol	Technologies that convert CO_2 into e-fuels like e-methanol and e-SAF can help decarbonise sectors like shipping and aviation. For example, e-methanol can be used in marine engines which helps reduce emissions from international shipping.

vi. Value Chain Development	**Supply chain (UK content)**	Prioritising UK-based suppliers ensures domestic economic benefits from CCS projects. Sourcing materials within the UK can not only support local jobs but also promote the long-term growth of UK manufacturing capability.
	Skills and workforce transition	Developing training programmes and upskilling initiatives prepares workers for careers in CCS. This is essential in transferring skills of engineers traditionally working in the oil and gas industry to ensure that their expertise is retained while aligning with clean energy goals.
	Jobs + growth	CCS projects stimulate job creation across multiple sectors, from construction and engineering to long-term operations. During the process of deploying CCS technologies, jobs can be created during pipeline network construction, with permanent jobs in maintenance and operations afterwards.
	Public acceptance of CCS	Engaging communities through transparent communication and tangible benefits such as local job creation and reduced emissions can foster public support. However, educational campaigns are still needed to address concerns about safety and demonstrate the environmental significance of CCS.

2.2 Merchant Model Development – Transition Scenarios

2.2.1 Emergence of a Commercial and Competitive Market

The Government's goal is to establish four CCS clusters across the UK by 2030, with public support. Beyond 2030, a substantial increase in CCS deployment beyond these 4 clusters is essential to decarbonise key industries, contributing to the UK's Carbon Budget and meeting the mid-2030s target. By the mid-2030s, the amount of CO_2 annually stored may need to increase to at least 50 Mtpa.

Achieving this will require expanding the capacity of the CCS sector, including an increase in CO_2 storage by at least 6 Mtpa by the mid-2030s. Delivering this increase will necessitate an evolving strategy focused on speed and scalability, moving away from the approach used for the initial four clusters, while still ensuring affordability and value for money. Reduced government intervention will be needed for the development and expansion of new CO_2 transport networks, meaning that industry must collaborate closely to synchronise the timing of capture projects with the development of transport and storage networks.

During this transition, international CO_2 transport networks and storage assessments will be prioritised. This will allow for greater growth in CCS technology confidence, especially through coordination with the existing CO_2 storage infrastructure in the UK's four clusters. As the sector matures, government support will focus on scaling up projects while balancing the demand for emissions reduction and market viability.

Enabling these changes will require fostering competition and reducing costs. The Government's efforts, alongside industry advancements, will contribute to building a multi-phase, multi-stage CCS market, requiring collaboration between the public and private sectors to ensure long-term success.

2.2.2 Reducing Costs for CCS

As the CCS market grows in the UK and globally, the cost of capturing, transporting, and storing CO_2 is expected to decrease. This trend follows the experience of other industries that have seen costs drop with increased investment and market confidence. Technical and market innovations will further reduce costs, including next-generation capture technologies, advances in compression and liquefaction, modular capture plants, and improved CO_2 transport network utilisation.

The UK Government anticipates continued leadership in CCS research, development, and innovation. The 2023 CCS Vision [11] recommends the establishment of an industry working group to identify and adopt cost reduction opportunities. A market-driven approach to allocating capture projects will encourage lower-cost solutions and improve CO_2 transport networks, ultimately reducing the cost of CO_2 storage and transportation. The creation of a CO_2 import market will also lower costs, due to scale and competition, and reduce reliance on government support, making it more affordable in the 2030s.

3. CCS Policy Enablers

3.1 Key Messages

- ✓ UK Government should articulate a clear vision for the UK ETS beyond 2030 to establish long-term policy clarity and international alignment
- ✓ Ongoing and open CO_2 transport mode innovation can enable exponential increases in cost savings via competition and widespread development of CCS and a liquid, commoditised market for CO_2.
- ✓ Strengthening the Industrial Carbon Capture framework can be achieved by aligning the ICC business model with the UK ETS
- ✓ A comprehensive strategy needed to establish UK supply chain manufacturing base avoiding supply chain bottlenecks and reducing lead times for CCS deployment.

3.2 Revised UK ETS

The UK Emissions Trading Scheme (UK ETS) has undergone significant revisions to enhance its effectiveness in achieving net-zero targets and mitigating carbon leakage. These revisions, informed by the July 2023 consultation and the July 2024 Climate Change Committee (CCC) progress report [12], encompass several key areas including:

- **Net-Zero Consistent Gap**: The UK ETS Authority has implemented a Net Zero consistent emissions cap which started in January 2024. This guides emissions reduction and reduced the cap from 92 $MtCO_2e$ in 2024 to 49 $MtCO_2e$ in 2030, aligning with the UK's Carbon Budgets and nationally determined contributions.
- **Market Stability Mechanisms**: To ensure market stability, the Government is considering reforms such as a carbon price floor and demand-side mechanisms, to protect against demand shocks.
- **Expanded Scope**: The UK ETS is expanding to include additional sectors, significantly enhancing its coverage. This includes maritime (from 2026), waste incineration (from 2028), and engineered greenhouse gas removals. The inclusion of non-pipeline transport (NPT) in the UK ETS allows CCS projects to subtract CO_2 sent to permanent storage via NPT from their reportable emissions. This expansion further encompasses CO_2 shipping, multi-journey transport via intermodal facilities, and intermediate CO_2 storage. CCS projects are incentivised by earning allowances for sequestered CO_2, which can be sold in the ETS market.
- **Reduced Free Allowances**: The UK ETS cap aligns with the net-zero trajectory, leading to a reduction in free allowances over time.

Despite these positive developments, there are concerns remaining regarding the efficiency and effectiveness of the UK ETS and its readiness for upcoming commitments. The December 2023 report "Evaluation of the UK Emissions Trading Scheme" [13] to the UK ETS Authority incorporated quantitative and qualitative data from surveys and interviews, and key concerns and recommendations are detailed below:

1. **Inefficient and Ineffective Processes**: While overall satisfaction with UK ETS processes was high, significant dissatisfaction existed regarding free allocation and the UK ETS Registry. The report noted lower satisfaction with free allocation amongst high-emission operators and time-consuming registry processes, particularly for those outside the UK. It is quoted that "Operators were least satisfied with the approach to free allocation (44% satisfied, n=104) and, for installation operators, the process of submitting activity level reports (52% satisfied, n=77)."

   Recommendations:

   - <u>Free Allocation</u>: The UK ETS Authority should review the free allocation methodology, ensuring transparency and fairness, especially for high-emission sectors. Consideration should be given to aligning allocation methods with international best practices and ensuring consistent application across all regulatory bodies.

- UK ETS Registry: The Authority should streamline the UK ETS Registry's processes, particularly for registration and changes to authorised representatives and develop user-friendly online sources and improve communication channels to support international and domestic operators. In addition, it is also recommended to invest in resources to ensure efficient response times to user queries.

2. **Market Liquidity and Volatility**: Although secondary market data showed reasonable market quality of the UK ETS, qualitative research revealed considerable trader concern, particularly regarding liquidity and volatility. The relatively small size of the UK ETS market compared to the EU ETS might have contributed to this volatility and uncertainty.

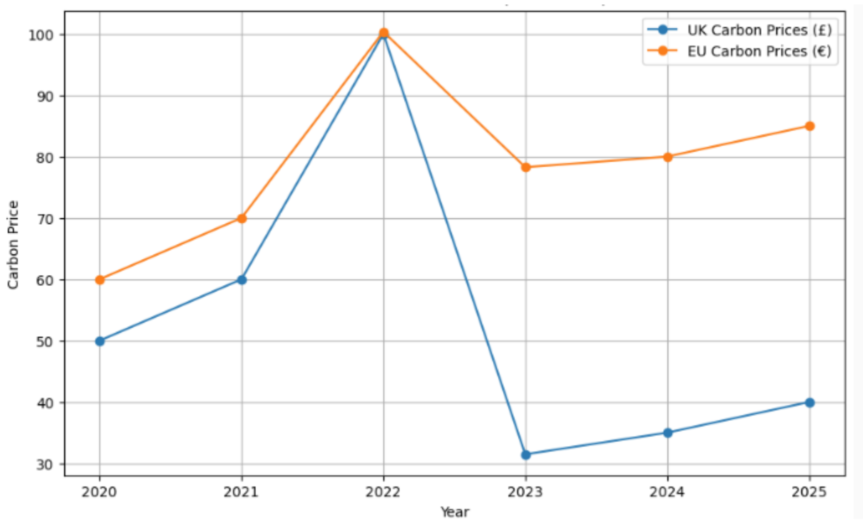

Figure 5: EU and UK carbon prices 2020-2025

Recommendations:

- Increase Market Size: The UK should aim to pursue alignment in standards with the EU ETS to increase the UK ETS market's size and liquidity. This could also improve price stability and efficiency.
- Improve Market Design: The UK ETS Authority should explore options to enhance market liquidity and actively consider measures to address traders' concerns about volatility. This could involve increased auction frequency, attracting more market makers, creating transparent and standardised trading mechanisms.

3. **Lack of Policy Certainty**: The uncertainty surrounding the UK ETS's long-term direction beyond 2026 and the mechanisms for achieving net-zero creates a significant barrier to long-term decarbonisation investment. Stakeholders consistently expressed a need for improved communication, collaboration, and cross-party agreement on policy direction to foster confidence and encourage strategic investment.

Recommendations:

- Long-Term Policy Clarity: The UK Government should clearly articulate a long-term vision for the UK ETS beyond 2026, fostering greater predictability for investors and businesses. This should incorporate mechanisms for a just transition.
- International Alignment: The strongest call from stakeholders was for closer alignment between the UK ETS and the EU ETS. Where operators were considering major investments, including future decarbonisation investments, they saw alignment between the UK ETS and EU ETS as providing more certainty and hence supporting their investment decisions. This was particularly an issue for organisations with international parent companies.

3.2.1 UK Carbon Border Adjustment Mechanism

In the UK, the implementation of the Carbon Border Adjustment Mechanism (CBAM) alongside revisions to the ETS is designed to effectively mitigate carbon leakage. This mechanism aims to discourage the transfer of carbon-intensive production to nations with less stringent climate regulations. By the year 2027, the CBAM will impose a carbon price on imports known for their high emissions, such as aluminium, cement, and steel. This pricing model will be determined by the emissions intensity of these goods and the difference in carbon pricing between the exporting country and the UK. The liability is calculated as:

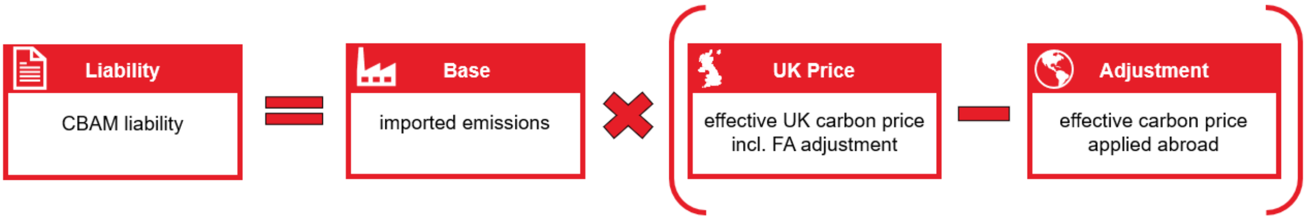

Figure 6: CBAM Liability Calculation

The primary objective of the CBAM is to ensure that imported goods are subject to carbon costs that are comparable to those borne by domestic products, thereby creating a fair competitive landscape for UK industries. This approach not only aligns with the European Union's own CBAM, which impacts UK exports to EU member states, but also reinforces the UK's commitment to climate action.

The CBAM is expected to bolster the UK's CCS sector, as it provides a competitive advantage to domestic industries that utilise CCS technologies. By imposing a carbon price on higher-emission imports, UK-produced goods that employ these methods will become more competitive. As a result, industries reliant on high-emission imports may face increased costs.

Key features of the CBAM include a carbon price equalisation mechanism, ensuring that imported products incur a carbon cost similar to that of domestically manufactured goods. Additionally, the CBAM will incorporate an emissions assessment framework to evaluate the greenhouse gas emissions intensity of imported products, encompassing both direct emissions from production and indirect emissions associated with upstream processes.

3.3 Principles of UK CCS Business Models

Overview

In Summer 2019, BEIS published their first consultation on business models for CCS [14]. Significant progress has been made since, with Government publishing the latest guidance in April 2024 for Track-1 business models across emitters and T&S [15]. In October and December 2023, HyNet and East Coast Cluster respectively, agreed Heads of Terms with Government on a regulated asset base business model on the T&S network [16], [17]. Track-1 emitter projects are currently in negotiations with Government. Moreover, guidance has also been published on post Track-1 business models across Greenhouse Gas Removals and Power BECCS, noting the Government's ambition to capture and store 5 Mtpa of carbon from GGRs by 2030 [15].

DESNZ has developed tailored business models for Track-1, outlining risk-sharing between the Government and private sector and detailing financial support for projects. These arrangements are being finalised through ongoing negotiations. Ofgem and the Low Carbon Contracts Company will collect, monitor, and verify data to ensure accurate recording of key metrics like power generated and carbon captured. The current purpose of the business models is crucial for the effective operation of the CCS programme and ensuring appropriate financial support for carbon capture projects.

History of regulatory structures referred to by the UK Government as ‘business models’ for CCS

It is unlikely that CCS would develop in the UK without Government business model support. The cost of capture is currently too great and the levelised cost of abatement exceeds any current incentivisation through carbon pricing. CCS would not be cost-competitive without subsidy support and the requirement of economies of scale and high CO_2 volumes as essential levers need Government intervention to co-ordinate the development approach. The business models look to recreate the success of Contracts for Difference (CfDs) in launching the clean generation energy sector[5] in the UK. These provides guaranteed revenue for produced electricity, allowing companies to make the private investment against the assurance of government contracts.

Government is developing two broad approaches to business models with individual subcategories; these include contract for difference mechanisms and a regulated asset base [14], [15].

The management of cross-chain risk and dependency on others (i.e. transport and storage to emitters, and vice-versa) is also governed by the business models. These are an extremely complex network of interdependencies and creates *de facto* regulations.

Contract for Difference (CfD)

The UK CCS and hydrogen business models are based on the CfD principles. A CfD is a contract between an emitter and the UK Government in which an agreement is reached on price for an asset (i.e. a unit of electricity). DESNZ will pay the emitter the difference between the current value of the CO_2 and the agreed price (‘strike price’). If the difference is negative the payment flows the other way. This is designed to make up the difference between business-as-usual (BAU) activity and CCS enabled activity to make the latter commercially viable.

CfD type agreements have been adapted across 4 categories to incorporate costs incurred by emitters across specific emitter sectors. These are:

- Dispatchable Power Agreement (DPA) [18]
- Hydrogen Production [19]
- Industrial Carbon Capture (ICC) [20]
- Waste to Heat Industrial Carbon Capture (Waste ICC) [20]

The CCS business models are necessarily more complex than the CfD. The Government ‘topping up’ the electricity price to the premium strike-price for clean energy, while using established infrastructure in the national grid is a simple concept. As CCS is effectively a waste disposal activity, the business models need to be extremely careful in how they attribute subsidy to realised benefit across the CCS applications.

Regulated Asset Base (RAB)

The regulated asset base (RAB) business model (called Transport and Storage ('TRI', Transport and Storage Regulatory Investment Model)) is designed to regulate public and private sector interests in the naturally monopolistic infrastructure of the CO_2 T&S system [21]. The ‘operator’ of the asset, (which must be an ‘end-to-end’ system including both the onshore and offshore legs) will receive a licence from DESNZ. A regulated price (‘allowed revenue’) is set for users (CO_2 emitters) in exchange for provision and use of the T&S infrastructure.

This prevents the T&Soperator creating prices that are not financially viable for users of the network and allows pre-agreed revenue for developers and owners of the networks. This is based on an agreed return on investment negotiated between DESNZ and the transport and storage company.

3.3.1 Dispatchable Power Agreement (DPA)

This bespoke CfD framework allows the intermittent nature of conventional power generation with CCS to compliment renewable generation. Subsidy is based on:

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[5] Largely offshore wind and solar, with examples of onshore wind and tidal energy.

- **Availability** – downtime but the plant must be available. This flat payment is irrespective of electricity production and is designed to control additional OPEX and CAPEX costs associated with the CCS plant.
- **Variability** – payment per unit of electricity when plant is turned on-line and is prioritised ahead of unabated alternatives. Additional payment paid as a premium for decarbonised power.

3.3.2 Industrial Carbon Capture (ICC)

This CfD mechanism follows a conventional approach as a payment per tonne of carbon abated against a reference price, taken from ETS carbon prices. The subsidy is designed to incentivise CCS installation instead of paying carbon tax. Moreover, the ICC business model accounts for capital costs of installing the equipment at the facility. An example of ICC scope would be cement manufacture with carbon capture.

3.3.3 Waste (Waste ICC)

This follows the ICC model but is specific for new waste management facilities. The details of the agreement are designed, like the DPA, to target additional costs associated with intermittency with Carbon Capture plants, since incinerators face significant interruption risk and downtime requirements. This model will be increasingly relevant as planned waste and waste incineration inclusion in the UK ETS takes effect, with full participation expected by 2028.

3.3.4 Hydrogen Production (HPBM)

This CfD is based on the premise that low-carbon (blue) hydrogen[6] is more expensive than unabated (grey) production and subsidy makes up the difference. This includes:

A variable premium – based on the variable market costs of the unabated reference. This is paid to a producer for selling blue hydrogen.

Price discovery incentive – encourages the sale of blue hydrogen based on the natural gas price.

Sliding scale top-up – when the demand for hydrogen drops, and the producer is given subsidy based on the circumstances as an amount per unit hydrogen sold to compensate the producer.

3.3.5 Beyond Track-1

DESNZ is identifying additional carbon capture projects to link with the HyNet and East Coast Clusters, aiming for operation before 2030. These projects serve as alternatives to initial Track-1 projects if contract issues arise or if some projects offer poor value for money. The expansion aims to enhance the value of Track-1 investments by better utilising existing infrastructure. While applications for Track-1 expansion at HyNet began in December 2023, DESNZ has not set a timeline for the East Coast Cluster.

The Track-2 process plans to have two additional carbon capture clusters, Acorn in northern Scotland and Viking on the Humber, operational by 2030. Announced in July 2023, DESNZ requested initial anchor carbon capture projects in early 2024. DESNZ is assessing the scope, timeline, and cost of Track-2, with high-level cost estimates provided to HM Treasury, but has not finalised the process.

The CCS Vision outlines a plan for creating a self-sustaining, competitive CCS market in the UK, supporting net-zero goals and job creation. CCS exports could add £4-5 billion annually to the economy by 2050. To achieve a self-sustaining market by 2035, DESNZ plans three phases: establishing the market (up to 2030), transitioning (2030–2035), and maintaining it (from 2035 onwards). The Government is also working with industry to integrate dispersed sites into the CCS programme.

[6] The production of 'green' hydrogen from electrolysis is also covered in this business model, but is outside of this report's scope of interest.

3.4 Evolution of CCS Business Models

This section discusses the evolution of CCS business models beyond their design for Track-1. It discusses evolution that will help the development of a merchant model and alignment with carbon markets. In some cases, it will help projects decide whether a business model is the correct route or whether they could operate outside the business model, accepting market risk but also greater opportunity to benefit from carbon market rewards.

Industrial Carbon Capture (ICC BM)

Recommendations (ICC evolution beyond Track-1):

Align ICC BM with UK ETS

- Adoption of a variable reference price based on the emitter's carbon price exposure, creates a fairer market position. A variable reference price enables a longer-term market-based business case based on ETS with greater payment opportunity but underpayment risk.
- The emitter should bear the risk of two-way payment when the reference price drops below the strike price (ETS tracking) **-** i.e. the emitter paying the difference to the contracting counterparty (LCCC). Importantly, in a future scenario, an emitter can choose whether to enter into the ICC contract or invest in carbon capture outside the contract and avoid exposure to two-way payments. Currently DESNZ don't allow asymmetric payments and the emitter can't incur this risk.
- Phasing out free allowance volume protection at the end of the 10-year ICC period exposes the emitter to ETS fluctuation. Doing this earlier in the 10-year period alongside a variable reference price aligns with ETS earlier meaning the emitter must adapt to carbon markets exposure to be competitive.

Provision for 'Carbon-Capture-as-a-Service' Within the ICC

- This **broadens the reach of the ICC business model** beyond the major emitters able to afford CCS. By managing the costs of operating and owning carbon capture facilities, Carbon Capture as a Service (CaaS) can help smaller emitters decarbonise. A CaaS aggregator brings technical knowledge of CCS & local industries to enable the technical co-ordination of CaaS projects. However, current business model incentives and structures do not sufficiently accommodate small emitters.
- In the early stages, CaaS exhibits many traits of a high-risk investment. To secure the necessary funding, investors will need support in grasping the business case before committing.

DESNZ and Environment Agency Alignment on Minimum Capture Rate

- DESNZ stipulates a minimum capture rate of 85% in the ICC, however the Environment Agency require projects to use 'Best Available Techniques'. Capture rates can be as high as 95% however this isn't reflected in the ICC. **Incentivisation to achieve better capture efficiencies** will drive innovation and improve capture techniques.

Reference Price

Initially the Track-1 business model for the purpose of contract negotiation is based on a fixed trajectory carbon market reference price (providing investor stability in the early market stages). DESNZ are considering whether this should evolve into a variable reference price linked to the emitter's carbon price exposure. This matches the UK ETS market and means that compensation won't be skewed (fixed price presents danger of under-compensation based on ETS value). Asymmetric payments during the initial 10-year term of the ICC means that no payment will be owed by the emitter to the ICC counterparty (LCCC). This overcomes the problem of two-way payments if the reference price is above the strike price, with the emitter paying the difference to the LCCC.

In the evolution of the ICC business model, the risk could be borne by the emitter and a two-way payment structure based on the carbon price and the emitter competing in an international market. Emitters would not face this risk if they invested in carbon capture outside the ICC contract, incentivising this move away from business models. The security of one-way payments is accepted by DESNZ in the initial stages (initial 10-year period) as continued exposure to the carbon price within the ICC contract may adversely affect investment in carbon capture in the early stages.

Free ETS Allowances

This principle aligns with other international carbon based CfD schemes including the Dutch model. It will align better with the UK CBAM due to be introduced in 2027. It also allows for future revisions of ETS policy.

Carbon-Capture-as-a-Service (CaaS)

Carbon-capture-as-a-service offers a practical solution for companies that might struggle with the on-site complexities of CCS on their own. Through aggregation of emitters and economies of scale, CaaS can make CCS more accessible and cost-effective, especially for smaller emitters or those located in a collection but outside major industrial clusters.

CaaS is noted as a capture route in the Track-1 expansion HyNet guidance for the ICC business model through development of CaaS Groups and CaaSCo. The establishment of this route is essential to broaden the reach of CCS beyond the major emissions sites able to afford the expensive capture process. The inclusion of non-pipeline transport along with CaaS may be needed to connect CaaS groups.

By managing the costs of operating and owning carbon capture facilities, Carbon Capture as a Service (CaaS) can help smaller emitters decarbonise. However, current business model incentives and structures do not sufficiently accommodate these small emitters. The closeness of emitters to one another and to shared infrastructure greatly influences the complexity and cost of CaaS. Each prospective Carbon Capture as a Service (CaaS) system has a unique deployment context, presenting distinct technical and commercial integration challenges that become more complex as the system's complexity increases.

The growth of the international Carbon Capture as a Service (CaaS) market will greatly impact the UK market, leading to ongoing competition for skills, resources, and customers throughout the value chain. There is the opportunity for the UK to become a major CaaS export player.

ICC (Waste) BM

Recommendations:

Align the Waste ICC with UK ETS

- Establish a clear distinction between captured fossil and biogenic CO_2. Certain biogenic CO_2 emissions have a zero rating under the UK ETS and no associated carbon price.

Ensure the Waste ICC is Delivering as per Original Design to Enable Future Evolution

- Establish a clear distinction between captured fossil and biogenic CO_2, ensures the waste ICC is delivering as per original design. This means projects aren't able to take advantage of biogenic emissions and the potential for negative ETS credits when instead they should be operating through the BECCS business model

Generating Revenues from Negative Emissions is also a Way in Which Costs of CCS Could, in the Future, be Supported Beyond Contract Holders

- The sale of negative emissions during the term (to the extent allowed by the counterparty in accordance with the terms of the Waste ICC Contract) could help to stimulate a market for negative emissions, which could help sustain CCS after contracts end.

Align the Waste ICC with the Government's 'Biomass Strategy'

- As per the strategy, it's important the Waste ICC doesn't create incentives for unsustainably sourced biomass. The distinction between sustainable and unsustainable biomass is key as the latter is not zero-rated under ETS and the OPEX payment should reflect this. Unsustainable biomass should be exposed to the carbon price.

Biogenic vs Fossil Emissions

Track-1 HyNet projects need to demonstrate that they plan to process feedstock composition that will generate less than 90% biogenic CO_2. Using high proportions of biogenic waste is beneficial as it generates negative emissions and higher-value ETS credits. It's important to ensure the business model operates as intended.

DESNZ proposes adjusting payments for projects that generate 90% or more biogenic CO_2. Contractual provision may be included in the Waste ICC contract controlling this.

Projects that primarily use biogenic waste and aim to generate negative emissions might find the Greenhouse Gas Removals (GGR) business model more suitable. This model is intended to attract investment in projects that primarily deliver net negative emissions.

Certain biogenic CO_2 emissions have a zero rating under the UK ETS and no associated carbon price, it's essential to align the Waste ICC with ETS enabling cross-over. The Waste ICC contract should align with ETS and should also be zero rated under the Waste ICC contract. ETS expansion to include Energy from Waste eligibility from 2028 was announced following consultation in July 2023. This enables a variable reference price to align with the carbon market price. The inclusion of a variable reference price also aligns with above recommendations for the ICC.

Monitoring Framework

The Waste ICC contract must include a monitoring framework to track the biogenic content of the captured emissions with greater GHG reduction potential. This ensures revenue support payments are accurate and reflect the variable content of the waste and alignment with ETS. Carbon-14 analysis is expected to be used to assess a monthly composite sample to provide a monthly biogenic/ fossil CO_2 percentage that is representative of the CO_2 captured for the entire month. The inclusion of a monitoring, reporting and verification framework that measures the biogenic/ fossil CO_2 split of captured emissions is essential.

Dispatchable Power Agreement (DPA)

Recommendations:

Participation in a Capacity Market Once the DPA has Ended to Encourage Investment

- Allowing CCS facilities to participate in a capacity market can provide a revenue stream independent of energy market fluctuations. This stability is vital given the capital-intensive nature of CCS projects and the uncertainties surrounding carbon pricing and energy demand. CCS installations can also deliver flexible generation in an evolving energy mix, providing reliable resources especially during times of high demand or supply challenges. Therefore, expanding capacity market participation for CCS facilities is crucial for integrating these technologies into the broader energy landscape.

- However, there is currently uncertainty surrounding future capacity market participation for CCS projects post DPA and further work examining the potential for future interaction between DPA and the capacity market scheme is still underway. It is strongly recommended that the Government establish a clear pathway for future CCS capacity market participation and develop a roadmap outlining the criteria and timeline for such participation. The roadmap should clarify the transition mechanisms, eligibility requirements, and potential modifications to existing capacity market regulations to accommodate CCS technologies. By doing such, investor confidence can be enhanced and thus reduce reliance on long-term government support.

Transformations in the Energy Mix Could Affect Dispatchability

- While flexible gas-fired power plants with CCS play a valuable role in the UK energy mix, there are some potential challenges around how significant transformations in the energy mix could substantially affect the dispatchability of power CCS facilities. The increasing penetration of intermittent renewable energy sources could alter the electricity market's demand profile and merit order. This shift could reduce the need for flexible, dispatchable power generation from CCS plants and impact their profitability and the effectiveness of the current DPA business model which relies on a combination of availability payment and variability payment.

- Therefore, it is recommended that the current DPA model be enhanced to more accurately capture the full value of dispatchability and to include the value of CCS plants' flexibility in providing ancillary services. In addition, any future merit order interaction with new forms of dispatchable power, for example hydrogen power, should also be considered. The DPA should consider including a provision to cover risks associated with the potential for fuel supply of a power CCS facility to include a portion of hydrogen in the future. These approaches can create a robust and flexible business model well-suited to the dynamic energy landscape and enhance the market viability of CCS projects.

Alignment with the Review of Electricity Market Arrangements Consultation

- Aligning the DPA with the Review of Electricity Market Arrangements would be a critical step toward making the CCS business model more market driven. The underlying principle is to ensure the DPA does not inadvertently create market distortions or hinder the efficient operation of the electricity system. The alignment should aim to ensure the DPA operates efficiently within the broader electricity market framework, promoting fair competition and reducing long-term reliance on direct government subsidies. For example, the design and mechanisms of DPA should ensure that CCS plants are properly integrated into the existing electricity dispatch and ancillary service markets, and that payments reflect market dynamics and the value provided by CCS plants to the overall electricity system.

Incorporation of the Gain Share Mechanism

- Both project and sale gain share mechanism in the DPA are set to be retained. With respect to either a corresponding gain share mechanism, or a 'cap and floor' approach, either approach could be construed as a form of minimum revenue guarantee, which would be inconsistent with the fiscal rule under which the DPA has been developed. In addition, such an approach would disincentivise the efficient operation of plants in receipt of a DPA and increases the risk of gaming of a complex sharing system to push more risk and cost onto consumers. Instead, the gain sharing mechanism can align the incentives of investors with consumer protection goals, while promoting efficient market behaviours.

- The gain share mechanism ensures that while investors have the opportunity to achieve returns from successful projects, they also share some of those gains with consumers. This balance encourages investors to pursue efficiency and innovative strategies that align with market outcomes, rather than relying solely on subsidies. By incorporating gain sharing, projects are incentivised to achieve market competitiveness. Generators will be motivated to optimise costs and performance, and thus driving market efficiency. Gain sharing also acts as a safeguard against excessive profits derived from unforeseen market advantages, thereby ensuring a fairer price distribution. This mechanism reassures consumers that they will benefit from projects' success, keeping the market tempered and equitable. Therefore, incorporating the gain sharing mechanism serves as a helpful tool in transitioning to a market-driven model by balancing commercial incentives with consumer protection, encouraging competition, and stimulating innovative investments.

Transport and Storage Regulatory Investment Model (TRI)

Recommendations:

Introduction of an Investment Grade Issuer Credit Rating

- A mechanism for the future assessment of the T&SCo by the introduction of an investment grade issuer credit rating. It will be for the T&SCo to obtain and maintain that credit rating. With a future interconnected network, a credit rating gives emitters choice over T&SCo moving away from monopolistic nature of the RAB model. It also drives standards and encourages investment in infrastructure ensuring the T&SCo is operating best-in-class storage provision.

- The credit rating also drives standards when attracting investment and helps demonstrate which networks are performing best in a free market.

Include Provision for both New Unsupported Projects and 'End-of-Contract' Unsupported Projects in the TRI

- Track-1 expansion HyNet included provision for 'unsupported projects' i.e. the connection of projects without a business model, however at this stage, these connections are unlikely. With the evolution of business models and opportunities to benefit out of contract taking advantage of the fluctuating carbon price, future emitters may decide not to enter into a contract.

- The TRI model is designed to cover the long-term operational lifespan of the infrastructure, this can vary but is expected around 25 years. The duration of CfD business models is 10-15 years. Mismatch in agreements means at the end of contract the project will become a de facto unsupported project.

- The TRI business model needs to accommodate more 'unsupported project' opportunities. These opportunities become more attractive as the sector matures.

Development of a Framework for both the Onshore and Offshore Decommissioning Obligations on T&SCo

- This means infrastructure where required is new build and able to cope with the demands of dense phase CO_2. This is for situations where repurposed infrastructure may not be able to safely transport CO_2 due to the unacceptable risk of failure due to material or mechanical incompatibility. Through sector maturation, the option for projects to proceed without needing business model support becomes more attractive.

Ofgem to Support the Evolution of Business Models to Create a More Flexible and Innovative Approach

- Currently there is a substantial regulatory oversight on transport and storage companies preventing the monopolistic effects of early market movement.
- Through its current regulatory oversight role, Ofgem will oversee the implementation of the TRI business model, ensuring it aligns with regulatory standards and promotes fair competition.
- Ofgem, along with the Low Carbon Contracts Company, will be responsible for collecting, monitoring, and verifying data related to power generation and carbon capture. This ensures accurate reporting and accountability.
- Ofgem will play an important role in supporting innovation and evolution of the TRI business model but must also ensure consumer protection consumer protection isn't compromised. This allows the benefits of new business models are realised without compromising service quality (this also applies to the DPA where energy consumers will support power-CCS).
- Ofgem is also involved in the development of the Future System Operator, which will play a key role in planning and managing the UK's energy networks, including CCS infrastructure.

Role of Ofgem

Part 1 of the Energy Act 2023 creates a framework for the economic licensing and regulation of carbon dioxide transport and storage activities. It designates Ofgem as the independent economic regulator and outlines its statutory mandate, duties, and functions for CO_2 transport and storage.

The receipt of an economic licence means the T&S company will be operating under the regulatory regime enshrined in the Energy Act 2023 and subject to the conditions of the economic licence granted under the provisions of the Act which will be regulated by Ofgem.

Ofgem is responsible for establishing and overseeing the regulatory framework that governs CCS networks. This includes setting the rules and guidelines for the operation and development of CCS infrastructure. Ofgem works to create a stable investment environment for CCS projects. This includes providing clarity on funding mechanisms and ensuring that there are incentives for private investment in CCS infrastructure. It ensures that the economic aspects of CCS projects are managed effectively. This involves setting price controls and ensuring that the costs of CCS projects are fair and transparent.

Greenhouse Gas Removals (GGR) BM and Power Bioenergy with Carbon Capture and Storage (Power BECCS) BM

Recommendations:

Set of Reference Price Based on Achieved Sales Price

- For both GGR and Power BECCS, the Government proposes using the achieved sales price (i.e. the actual price achieved by the developer) of negative emission credits in approved markets as the reference price in the design of the GGR business model and the contract for difference for carbon (CfDc) element of the Power BECCS business model. This approach is a significant departure from fixed subsidies as it directly links payments to actual market value. A combined use with a Price Discovery Incentive, which incentivises developers to seek the highest possible sales price, further amplifies this market-drive approach. This is a key aspect of the business model to encourage market engagement, reduce the difference payment, and prevent poor value-for-money outcomes. Without these provisions, the Government could face low sales price and an overreliance on the difference payment to achieve the required strike price.

- Therefore, it is recommended that the developers and market participants actively engaged in market activities to achieve competitive sales prices and leverage the Price Discovery Incentive to optimise revenue and ensure alignment with market values. At the same time, policy makers need to continue to refine the reference pricing model by monitoring market trends and adjusting incentives to maintain a balance between market-driven payments and financial viability for GGR and Power BECCS projects.

Development of High-Integrity Voluntary Carbon Markets (VCMs)

- The UK Government is actively promoting the development of high-integrity VCMs to stimulate private investment in GGR projects. Despite the relatively small size of the global GGR sector, there is clear evidence of a rapid growth in voluntary demand for high-durability carbon removal credits, driven by large corporate commitments (e.g., Microsoft, JPMorgan Chase, Amazon) and initiatives like the Frontier initiative. This demonstrates a growing private sector valuation of engineered removals exceeding that of traditional carbon offsets and some compliance markets.

- To foster this market development, the Government is committed to take steps to maximise the potential of VCMs to channel private finance into GGR projects while ensuring that carbon credits issued under negative emissions business models meet high standards of integrity. Key approaches include [22]:
    - **Rigorous Credit Issuance and Tracking**: All government supported GGR credits will be issued using approved standards and methodologies, subject to independent third-party verification. An approved registry will publicly track each credit from issuance to retirement.
    - **Market Interaction and Interoperability**: The Government is exploring how VCMs can best interact with existing regulatory frameworks like the UK ETS, aiming for efficient credit fungibility and interoperability between markets. This is crucial to creating a more seamless and effective carbon credit system.
    - **Conditional Support Instead of Price Guarantees**: Government support for GGR projects will be conditional on the successful sale of credits in the market. This approach moves away from direct subsidies towards market-driven incentives, fostering project viability and minimising government financial exposure. While acknowledging that initial government support may be necessary to boost market liquidity, Government are explicit in their intent to not provide support if credits are not sold in the market. The intention is to transition towards a more market-driven system.
    - **Additionality**: The Government addresses the crucial issue of additionality, emphasising that support would only go to projects where carbon removals from the project would not have occurred in the absence of the incentive created by carbon credit revenues. A variety of approaches including investment analysis, barrier analysis, market penetration assessments and standardised approaches (e.g. positive lists) will be used to demonstrate this, confirming that only genuinely additional carbon removal will be supported.

- Therefore, project developers should focus on meeting additionality criteria through comprehensive investment and market analysis to ensure that projects are genuine and have a positive environmental impact. The Government should keep implementing clear guidelines and verification processes for rigorous credit issuance and tracking, ensure that all VCM-related activities are transparent, enforce accurate registry practices, and encourage high-quality credit standards. It is also important that the private sector (e.g. corporations like Microsoft, JPMorgan Chase, and Amazon) increases commitments towards purchasing high-integrity carbon credits to further stimulate private investment in GGR projects.

3.5 Risk to Track-1 Developments

DESNZ's current goal is to have Track-1 projects operational by the end of 2027. To achieve this, DESNZ must maintain effective oversight throughout both the construction and operational phases to identify risks that could affect the successful delivery of the CCS programme's objectives. The organisation needs to manage a range of risks, including technological risks (due to reliance on unproven technologies), construction risks (typical of large infrastructure projects), and financial risks (since it is financing many elements of the programme).

Infrastructure Risks

Delays in the construction of emitter or transport and storage projects would affect DESNZ's carbon capture goals and, in turn, its overall Net Zero strategy. Government major projects often experience overoptimism in their scheduling, with the drive to meet ambitious targets sometimes overshadowing a realistic assessment of growing risks. There is also a possibility that unforeseen increases in construction costs could make carbon capture projects financially unfeasible without additional revenue from the Government or consumers.

The CCS programme faces a significant risk due to the technology being untested at the planned scale, as well as the reliance on specialised expertise and equipment. For instance, one of the Track-1 emitter projects aims to build a gas-fired power station with carbon capture, which would be 40 times larger than any existing examples globally. Additionally, as many countries around the world are also pursuing CCS, there is a risk that global supply constraints could lead to unforeseen cost increases or delays.

Financial Risks

The Track-1 projects must secure adequate financing to support project construction. The private sector will need to provide most of the capital required to build and install carbon capture equipment, pipelines, and storage infrastructure. The National Wealth Fund (NWF) estimates that the HyNet and East Coast Clusters alone will need between £8 billion and £10 billion in private finance between 2024 and 2025 [23]. However, there is a risk that the transport and storage companies, as well as the carbon capture projects, may struggle to secure enough funding to complete construction. The NWF has developed various methods to support capital investment, such as providing debt, but this may expose the Government to financial risk, as these financial products essentially underwrite private sector investments.

The budget for the later stages of the CCS programme remains uncertain, which could present risks like those that led to the failure of the previous government's competition. HM Treasury and government ministers will ultimately decide the level of financial support for the programme, balancing government and consumer contributions. While up to £21.7 billion in funding has been announced for the current CCS programme, it is unlikely to meet the Government's 2030 CCS deployment targets. Although DESNZ has provided high-level cost estimates, HM Treasury has yet to commit further funding. The lack of certainty about long-term funding was a key issue in the failure of the previous attempt to launch CCS in the UK. This uncertainty also poses risks for potential investors, who may be reluctant to invest without clear government backing. HM Treasury hopes that securing government support for Track-1 will provide industry with greater confidence in the long-term commitment to CCS, and both DESNZ and HM Treasury plan to agree on funding in stages.

3.6 Cross Border CO_2 Transport in Europe

3.6.1 Cross-Border Transport Opportunities

The transition to a low-carbon economy in Europe presents significant opportunities for cross-border CO_2 transport and storage collaboration between the EU and the UK. With 119 commercial-scale CCS facilities at various stages of development across Europe, there is substantial potential for cooperative ventures in CO_2 transport and storage [24]. Support from the EU is robust, with the Innovation Fund, the Connecting Europe Facility - Energy, and Horizon Europe providing funding for CCS developers. These initiatives are critical under the EU's broader frameworks like the Fit for 55 package and the Green Deal Industrial Plan. At a national level, the revised Climate Energy and Environmental State Aid Guidelines empower member states to tailor their CCS strategies, enhancing regional development, and has resulted in notable support in Denmark and Netherlands.

The economics of CCS are also becoming increasingly appealing, driven by the EU ETS where the price of emissions soared to a record high of €100 per tonne in February 2023 [25]. This pricing development strengthens the business case for CCS, encouraging sectors heavily reliant on carbon to invest in sustainable technologies. Countries such as France, Germany, and the Netherlands are relying on forthcoming Contracts for Difference (CfDs) to stabilise and support CCS investments, ensuring economic viability in fluctuating market conditions, and positioning the UK as a strategic partner in managing the EU's industrial carbon emissions.

Establishing cross-border CO_2 transport between the EU/EEA and the UK is therefore a crucial move towards providing European industrial emitters with cost-effective and nearby storage solutions. By enabling the efficient movement of captured CO_2 from emitters in mainland Europe to the UK's storage sites, industrial emitters could significantly reduce the costs associated with long-term CO_2 sequestration. Shorter transport distances to the UK's Southern North Sea compared to other options, such as Denmark or Norway, not only reduce costs but also minimise the environmental impact of transportation infrastructure and operations.

3.6.2 CO_2 shipping in Europe

CO_2 shipping as an essential component of CCS deployment in Europe has not only been endorsed at the EU level within frameworks like the European Taxonomy for Sustainable Activities and the EU Emissions Trading System (ETS) Directive but has also been supported by various national programmes [26]. CO_2 shipping enables efficient and flexible storage solutions, allowing for captured carbon to be transported to optimal storage locations across Europe. Noteworthy examples include Total's Bifrost project in Denmark, Project Castillo in Ravenna, Italy, and Energeans' Prinos storage project in Greece [27]. These examples illustrate the potential of CO_2 shipping to link emissions sources with storage sites, promoting integrated cross-border solutions. Additionally, the Gdansk CO_2 shipping terminal, featured on the 5th Projects of Common Interest list, exemplifies the critical infrastructure developments facilitating these linkages.

Collaborations in CO_2 shipping among European countries present opportunities for enhanced connectivity and shared technologies, fostering a coalition that can meet the EU's ambitious decarbonisation goals. The UK can capitalise on its proximity to the North Sea and align with EU efforts, crafting a cohesive approach to managing CO_2 emissions and enhancing carbon management strategies.

3.6.3 The UK as a CO_2 Import Hub

The UK's Southern North Sea is the largest and most critical CO_2 storage resource in Europe, and therefore, can serve as the primary basin for North-Western Europe. With its well-characterised geology, developed through decades of oil and gas exploration, the Southern North Sea offers an abundance of depleted hydrocarbon reservoirs and saline aquifers ideal for CO_2 transport and storage. This unique combination of resources positions the UK's Southern North Sea, with its 78 billion tonnes of storage capacity – almost one third of Europe's geological CO_2 storage capacity, as a cornerstone of Europe's decarbonisation efforts.

The European Commission, through its Industrial Carbon Management Strategy, has expressed a willingness to explore CO_2 storage in third-party countries, provided robust standards ensure safe and permanent storage. The Southern North Sea, with many licensed sites located closer to EU emitters than alternatives in the Northern North Sea, offers a significant cost advantage as reduced transport distances translate into lower overall costs for emitters.

Unlocking EU/EEA-UK cross-border CO_2 transport and storage would enhance resilience and flexibility for European decarbonisation efforts, providing emitters with cost-efficient and reliable storage options. However, delays in establishing these cross-border connections risk limiting future access to the Southern North Sea. Early infrastructure developments will shape the configuration of pipeline networks, potentially locking EU emitters into less optimal and more expensive storage pathways. Therefore, to capitalise on this shared resource and ensure the lowest cost pathway to decarbonisation, timely collaboration between the UK, EU, and member states is essential.

3.6.4 Current Policy Misalignment

Despite its technical feasibility and clear economic benefits, cross-border CO_2 transport remains hindered by policy barriers. Current regulatory frameworks, such as the EU Emissions Trading System (ETS), fail to recognise CO_2 stored in the UK, resulting in emitters being penalised with double liability, which is a clear disincentive for cross-border collaboration. This misalignment between EU and UK policies limits the ability of emitters to access the most cost-effective and geographically advantageous storage sites, undermining the potential for an integrated European CO_2 transport and storage market.

To address these barriers, robust policy alignment is essential. Establishing mutual recognition of storage sites and permitting regimes under a bilateral agreement could streamline processes and reduce regulatory complexity. This alignment would not only unlock access to existing storage capacity but also pave the way for developing a resilient, interconnected infrastructure network across Europe.

3.6.5 UK – EU Alignment

Under the EU Emissions Trading System (ETS), CO_2 emissions that are captured, transported, and stored in permanent geological storage within the EU are considered as not having been emitted. The emitter will therefore not incur a legal obligation to surrender EU emission allowances for those emissions.

However, this exemption does not extend to CO_2 emissions captured in the EU and transported for storage in third-party countries, such as the UK, outside the EU and EEA. The EU ETS Directive only recognises storage facilities permitted under the Carbon Capture and Storage (CCS) Directive, which applies exclusively to facilities within the EU and EEA. Similarly, under the UK ETS, emitters can deduct CO_2 emissions captured and permanently stored within UK-licensed facilities, but this recognition does not apply to storage in other countries, including those within the EU.

As a result, emitters in both the EU and the UK who wish to utilise storage facilities in a third-party country remain liable under their respective ETS frameworks to surrender allowances for the stored CO_2, effectively negating the benefits of cross-border storage.

The root of this barrier lies in the limited scope of the EU's CCS permitting regime, which governs safe geological storage of CO_2 and is the basis for the EU ETS exemption. The EU CCS Directive, which also underpins the UK's CCS permitting framework, was transposed into UK law before Brexit and remains largely consistent with EU standards. Despite this alignment, the lack of mutual recognition between the two regimes prevents cross-border storage from being acknowledged under either ETS, posing significant obstacle to the development of an integrated CO_2 transport and storage market.

The London Protocol

The London Protocol is an international treaty designed to protect the marine environment and has historically posed a barrier to cross-border CO_2 transport and storage, as Article 6 of the protocol prohibits the export of waste, including CO_2, for disposal in the marine environment. In 2009, an amendment was introduced to allow cross-border CO_2 transfers between contracting countries for permanent geological storage, provided specific conditions outlined in the Article 6 Amendment are met. In 2019, Norway and the Netherlands proposed a resolution to allow provisional application of the 2009 Amendment to Article 6 citing the Vienna Convention. This effectively states that if countries have both applied provisionally for an Amendment before its entry into force can proceed, then there is an agreement between the nations.

As the EU is not a party to the London Protocol, individual member states must decide independently whether to progress with the Article 6 Amendment. To date, nine countries - the UK, Norway, the Netherlands, Denmark, South Korea, Belgium, Sweden, Switzerland, and Australia - have formally declared their provisional application of the Article 6 Amendment with the IMO. Several European countries, not including the UK, have established bilateral agreements, often in the form of Memorandums of Understanding (MoUs). There is no fixed timeline for concluding such agreements, as this depends largely on the time needed to achieve political alignment. Bilateral agreements formalising the UK's adherence to this protocol are a key precursor to the UK's competitiveness in the international CCS market.

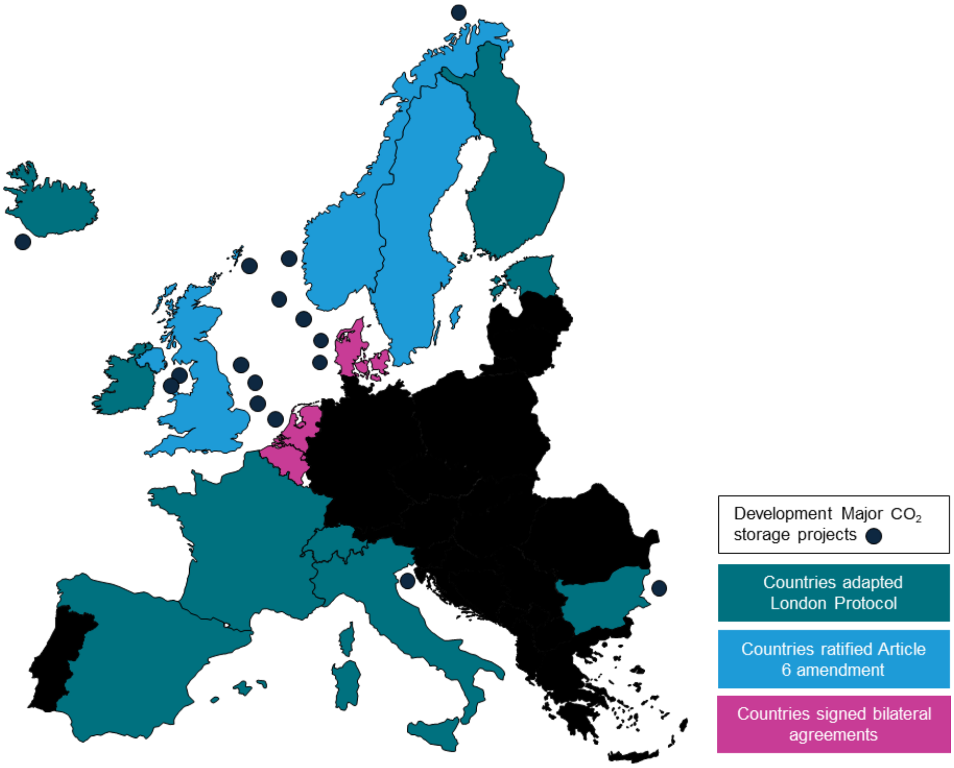


Figure 7: Adoption of International Agreements in European Countries

3.6.6 Cross-Border Transport Recommendations

To fully unlock the potential of cross-border CO_2 transport and storage, the UK and EU must align regulatory and legislative frameworks to ensure mutual recognition of CO_2 storage, exempt emitters from surrendering allowances, and create an integrated CO_2 market. Below are the key recommendations to achieve this. By acting swiftly on these recommendations, the UK and the EU can eliminate key barriers to cross-border CO_2 storage and unlock economic and environmental benefits.

Amend the EU ETS Directive

Effective alignment between the EU and the UK is essential for optimising cross-border transport of CO_2, particularly within the framework of ETS. The current provisions outlined in Article 12 of the ETS Directive are central to addressing this alignment.

Article 12 governs the transfer, surrender, and cancellation of EU ETS allowances and importantly exempts facilities from allowances for CO_2 that has been captured, transported, and geologically stored. This provision indicates that CO_2 which is properly handled and stored should not count as an emission, thereby incentivising emitters to adopt carbon capture technologies. However, it is worth noting that this exemption currently applies only to CO_2 stored within the EU. Specifically, Article 12(3a) clarifies that an obligation to surrender EU allowances does not apply to emissions that are verified as captured and transported for permanent storage at a facility holding a valid permit under the CCS Directive. This is a crucial point for facilitating climate-friendly practices in the EU.

However, the CCS Directive, as outlined in Article 2(1), restricts its application to the geological storage of CO_2 solely within the territories of EU Member States, their exclusive economic zones, and continental shelves as defined by the United Nations Convention on the Law of Sea (UNCLOS). Consequently, the scope of the CCS Directive does not extend to third counties, which creates a barrier for recognising CCS activities that occur in the UK. Moreover, the permitting process specified in the CCS Directive is designed so that only sites located within the EU can fulfil the requisite conditions, further complicating cross-border cooperation.

In light of these limitations, it is recommended that Article 12(3a) of the ETS Directive be amended to incorporate provisions that recognise permits issued under the CCS permitting regime as part of an international agreement between the EU and the UK. This amendment would establish a framework for recognising CCS activities conducted in the UK, thereby fostering collaboration and alignment between the two systems. By facilitating this alignment, both the EU and UK can enhance their CCS efforts and contribute to global climate goals more effectively, allowing for a comprehensive approach to managing carbon emissions that cross jurisdictional boundaries. This strategic adjustment will not only benefit the respective ETS but also support broader environmental objectives by ensuring that captured carbon is managed in a way that aligns with both jurisdictions' emissions reduction commitments.

Amend the EU ETS Monitoring and Reporting Regulation

To enhance the effectiveness of the EU ETS in facilitating CCS, it is essential to amend the Monitoring and Reporting Regulation (MRR). Current provisions, particularly Article 49(1), dictate when captured CO_2 is considered transferred for storage and therefore not emitted. However, these regulations primarily pertain to storage within the EU, creating barriers for operations that involve cross-border CO_2 transport and storage, especially concerning third countries like the UK. Article 49(1) currently allows operators under the EU ETS to subtract certain amounts of captured CO_2 from their overall emissions, provided the CO_2 is transferred to approved facilities. These facilities must be permitted under the CCS Directive, which only applies to storage sites within the EU. This limitation hinders the ability to recognise and incentivise captured emissions intended for storage in third countries.

To address these limitations, the following amendments to the MRR are recommended:

- **Recognition of international agreements**: Amend Article 49(1) to include a provision that covers capture installations, transport networks, and storage sites permitted under the CCS permitting regime recognised in international agreements between the EU and the UK. This change would ensure that CO_2 captured for storage in the UK could be subtracted from the emissions liability of operators within the EU.
- **Clarification on transportation methods**: Modify Article 49(1) to clarify that the transportation of CO_2 by methods other than pipelines, such as shipping, does not affect the ability of emitters to subtract captured and permanently stored CO_2 from their EU ETS liabilities. This amendment would specifically recognise non-pipeline transportation methods, thus broadening the operational flexibility for CO_2 transport.
- **Update identification methods**: Revise Annex I(7)(d) to introduce a different method of identification for receiving installations located in the UK. This change would ensure that both EU and UK installations can seamlessly track and report CO_2 transfers, facilitating better regulatory alignment.
- **Approval and information sharing mechanism**: Adjust Article 48(3) to specify which entity should be responsible for approving adjustments in cases where discrepancies arise between the transferring and receiving installations, especially when the receiving installation is based in the UK. This amendment should also define the framework for sharing information between EU and UK authorities, ensuring efficient communication and regulatory compliance.

Amend the EU ETS Accreditation and Verification Regulation

To enhance the consistency and effectiveness of the verification process within the EU ETS, it is crucial to amend the Accreditation and Verification Regulation (AVR). Currently, Article 17(4) stipulates that verifiers must ensure that the procedures outlined in Article 48(3) of the MRR are properly followed when assessing an installation's annual emissions report. As the regulatory landscape evolves, especially with anticipated changes to Article 48(3) of the MRR, it is essential to ensure that the AVR is aligned with these updates. This alignment will create a cohesive framework for verifying emissions reports across both regulations, thereby improving the reliability and integrity of data reported by installations.

Therefore, it is recommended that Article 17(4) of the AVR be amended to incorporate the updated procedures and requirements established in the revised Article 48(3) of the MRR. This amendment will ensure that verifiers are operating under the most current guidelines, reflecting any new protocols or adjustments made to the MRR.

Amend UK Legislation to Accommodate Changes in the above EU Legislation

To ensure that the UK's CCS framework remains fully compatible with evolving EU regulations, it is necessary to amend UK legislation in response to any changes made to the corresponding EU legislation. These amendments will largely depend on the minimum criteria established through international agreements on storage permit recognition between the UK and the EU. Given the existing high degree of alignment between the UK CCS permitting regime and the EU CCS Directive, any required changes are expected to be minimal and will primarily reflect significant alterations in EU law.

Assuming a mutual recognition framework between the UK and the EU for their respective CCS permitting regimes, it is crucial to amend paragraph 23(a)(ii) of Schedule 4 of the Greenhouse Gas Emissions Trading Scheme Order 2020. This amendment would reinstate references to the EU CCS Directive alongside those of the UK CCS permitting regime. Doing so would allow UK CO_2 emitters to subtract from their annual emissions reports any CO_2 transferred to capture installations, transport networks, or storage sites that are permitted under either regulatory framework.

Since the UK's departure from the EU, both the AVR and the MRR have undergone amendments. As such, it is essential to evaluate these changes and any future modifications to determine their material impact on UK legislation. Any adjustments to Article 48(3) of the MRR and Article 17(4) of the AVR, as discussed before, should also be mirrored in the relevant UK legislative provisions.

Establish a Bilateral Agreement Under the Trade and Cooperation Agreement (TCA)

Currently, there is no recognition or equivalence system between the EU ETS and the UK ETS. Nonetheless, both the European Commission and the UK Government have acknowledged the importance of including CCS in their discussions under the TCA.

Addressing CCS issues through the TCA could eliminate barriers between the EU/EEA and UK ETS. This could establish a degree of equivalence or recognition of CCS permitting regimes, without requiring full linkage of the two ETSs and could leverage the TCA's existing governance framework to enhance trade and cooperation for climate change mitigation, avoiding the need for entirely new treaties. The agreement should:

- Define minimum criteria that all CCS systems must meet
- Include a governance body to oversee implementation and address changes
- Establish a dispute resolution mechanism
- Ensure CCS contributes to overall CO_2 reductions and does not increase hydrocarbon recovery
- Provide mechanisms for sharing information on cross-border CO_2 transport and its inclusion in national greenhouse gas inventories.

Make Agreements under the London Protocol Provision

While the 2009 amendment to Article 6 has not yet been ratified, provisional application of the Article 6 Amendment was permitted in 2019. This means that the London Protocol no longer acts as a barrier to EU/EEA-UK cross-border CO_2 transport and storage. It is now a procedural formality requiring adherence to the following requirements:

- **Formal Declaration**: The signatory must submit a formal declaration to International Maritime Organisation (IMO) of their intent to provisionally apply the Article 6 Amendment.
- **Agreements Between Parties:** Contracting parties must establish agreements or arrangements with importing countries to permit cross-border CO_2 storage.
- **Notification**: Such agreements or arrangements must be officially notified to the International Maritime Organisation (IMO).

The provision has provided a legal foundation for countries to engage in cross-border CO_2 transport and storage activities. The bilateral agreement between Belgium and the Netherlands has also demonstrated the feasibility of this approach. Therefore, it is recommended that UK and more countries in the EU make notifications and agreements or arrangements under the provision to enable cross-border CO_2 transport and storage. By implementing this, the London Protocol can be more effectively utilised to facilitate cross-border CO_2 transport, ultimately contributing to the global transition towards more sustainable carbon management practices.

Develop CO_2 Stream Specification and CO_2 Metering Standards

To facilitate the effective transportation and storage of CO_2 across Europe, it is essential to establish uniform standards for CO_2 specifications and metering practices. The introduction of minimum CO_2 specification standards is crucial for ensuring compatibility across various transportation methods, both pipeline and non-pipeline. These standards should define acceptable impurity limits for CO_2 streams without being overly restrictive, thereby enhancing flexibility in choosing storage sites. While certain transport and storage facilities may require CO_2 specifications that exceed the minimum standards, establishing a baseline standard is essential for the industry to operate efficiently and effectively.

In addition to CO_2 specifications, it is vital to develop standardised methodologies for CO_2 metering across the entire value chain, from capture to storage. Implementing accepted metering standards will enhance compatibility for both domestic and imported CO_2 streams. High accuracy in CO_2 metering is also crucial for ensuring compliance with ETS requirements, as it allows for timely and precise assessment of data related to emissions.

Align Third-Party Access Principles in the TRI Business Model

To create a conducive environment for CO_2 stream transport and storage businesses, it is essential to standardise and align third-party access principles across Europe. Such alignment would facilitate smoother operations and enhance competitiveness within the market.

The UK is currently undertaking a review of the third-party access principle established in its 2010 CO_2 storage legislation. This review is part of the Transport and Storage Regulatory Investment (TRI) business model, aimed at developing a cohesive regulatory framework that balances access to pipeline infrastructure, shipping routes, and the handling of imported CO_2 streams. This review is anticipated to be finalised by 2025, setting the stage for a more integrated approach to CO_2 transport and storage.

In parallel, the EU is also working on establishing a regulatory framework that addresses how third-party access is codified in network regulations across Europe. This initiative will help to harmonise standards and practices, enabling easier access to transport and storage facilities, which is vital for the movement of CO_2 across borders.

A crucial aspect of this initiative is the solicitation of a UK-wide network code that aligns with European standards. Developing a network code that encompasses both the UK and EU frameworks would enhance interoperability between the two regions, ensuring that CO_2 transport and storage operations can seamlessly integrate across borders. This collaborative approach would provide clarity and consistency in regulatory requirements, further encouraging investment in CO_2 infrastructure and facilitating the efficient movement of CO_2 across the continent.

Start Developing Supporting Fit-for-Purpose Infrastructure and Facilities

The long-term nature of planning and permitting for large-scale infrastructure projects, such as port terminal facilities for CO_2 transport, presents significant challenges. Additionally, the global supply chain disruptions experienced in recent years further complicate the timely development of such infrastructure. If development work does not commence immediately, there is a substantial risk that the necessary facilities will not be ready in time to take advantage of emerging market opportunities.

To mitigate these risks, stakeholders in both the UK and EU must prioritise the investment and planning of essential infrastructure. This includes not only developing port terminals and transport networks but also ensuring that they are strategically coordinated across countries.

Moreover, engaging with relevant stakeholders early in the planning process will facilitate smoother permitting and implementation, ensuring that infrastructure projects align with market needs and regulatory requirements. By fostering collaboration between countries and sectors, the transition to a Europe-wide CO_2 market can be accelerated.

3.6.7 Environmental Agency Alignment

The alignment between the Environment Agency and industry practices is essential for the successful implementation of carbon capture projects, particularly those Track-1 projects. To evaluate potential environmental impacts, particularly concerning air quality and local habitats, the Environment Agency mandates that operators provide comprehensive details about all solvent components and any by-products during the permit application process. This requirement is underpinned by the Environment Agency's legal obligation to ensure transparency concerning emission-related data, which must be made publicly accessible.

However, despite these mandates, many operators express reluctance to disclose information about proprietary solvents, leading them to submit permit applications using a more generic solvent designation. This practice could inadvertently compromise the accuracy of environmental impact assessments and limit the Agency's ability to assess the true risks associated with the proposed projects. Moreover, this lack of transparency may hinder the overall efficiency of carbon capture efforts, as operators might face the need to modify their permits post-final investment decision (FID) if they decide to transition to proprietary solvents later in the process.

Recognising the potential implications of this issue, DESNZ is actively collaborating with the Environment Agency to navigate the complexities surrounding proprietary solvent disclosure. Their goal is to balance the need for comprehensive environmental assessments with the legitimate concerns of operators. Through this collaboration, they aim to foster an environment of compliance and transparency while addressing the industry's hesitance to fully disclose solvent details. By ensuring that operators meet their legal disclosure requirements, DESNZ and the Environment Agency can enhance the credibility of CCS initiatives and safeguard environmental interests.

3.6.8 Further CO_2 Storage Beyond Carbon Storage License Round 1 (CSLR1)

In 2023, the North Sea Transition Authority (NSTA) conducted its first Carbon Storage License Round, granting 21 licenses to 14 different companies. These licensed areas have the potential to store up to 30 Mtpa of CO_2 at sites located off the coasts of Teesside, Liverpool, Norfolk, and Aberdeen. Looking ahead, additional storage capacity will be necessary beyond what was allocated in the initial licensing round. To meet its net-zero targets, the UK is anticipated to expand its carbon storage capabilities significantly. The NSTA has suggested that multiple future licensing rounds will be crucial, with projections indicating that the country may require up to 100 CO_2 storage sites by the year 2050. Future licensing efforts are expected to concentrate on regions that exhibit suitable geological formations, are in close proximity to existing infrastructure, and have established connections to industrial clusters. This strategic focus will be vital for accommodating the growing volumes of CO_2 captured from industrial activities, ensuring that the UK can efficiently manage its carbon storage needs as it works towards its climate objectives.

3.7 Supply Chain Opportunity

Global Opportunities

The growing global CCS market offers the UK an opportunity to establish itself as a sector leader. With international commitments to net-zero increasing, many nations are exploring CCS to decarbonise industries, providing a lucrative opportunity for UK companies. By building a competitive and technologically advanced domestic supply chain, the UK can position itself to export CCS technology, services, and expertise supplying this nascent but rapidly developing global market.

In addition, the UK's early adoption of CCS gives it a strategic advantage in influencing global standards and technological innovation. UK companies can export high-value components, such as carbon capture equipment, and create a larger footprint in the emerging CCS market, benefiting the national economy. Early estimations from the UK Government are the global CCS market could be worth £260bn by 2050 and the UK has the potential to capture £200bn of that market.

UK Content

The CCS Supply Chain Strategy sets an ambitious goal of achieving at least 50% UK content by 2030 across both CCS products and services. This means increasing reliance on domestic manufacturers, fabricators, and service providers for major CCS projects. Achieving this goal requires the active involvement of government which must provide financial support, clear timelines for project allocations, and flexibility in bilateral negotiations to secure UK content in the supply chain. The approach not only focuses on expanding domestic capabilities but also targets the long-term growth of UK manufacturing capacity. The push for higher UK content aligns with the broader net-zero goals by ensuring that a substantial share of the economic benefits from CCS projects stays within the country. This will result in job creation, skills development, and local investment, which will strengthen the overall UK economy. Industries that support CCS projects are encouraged to invest in new technologies and innovate within their manufacturing processes to increase the UK's market share in the global CCS landscape.

High-Value Opportunities

Several high-value opportunities exist within the CCS supply chain, particularly in the areas of engineering design, column assembly, and heat exchanger production. Engineering design is a critical service with significant potential for UK companies, given the UK's strengths in high-value technical design, particularly in onshore and offshore energy sectors. Column assembly and heat exchanger manufacturing are also vital for the successful operation of CCS facilities, and there is currently a shortage of domestic capacity to produce them, consequently, by investing in expansion of UK manufacturing capabilities in these areas could significantly reduce reliance from overseas

3.8 Enhancing Public Perceptions

3.8.1 Enhancing Public Perceptions

The public must be aware of the opportunities CCS can bring to local communities, jobs and regional prosperity. They must have confidence in the integrity of transport systems (pipelines and other methods) and the robustness of offshore storage, as a safe technique for storing large volumes of CO_2 under the seabed. This is key for a successful CCS deployment.

Scepticism and varying levels of awareness must be addressed to help inform the public and highlight the opportunities it brings to local communities like job creation, and economic stimulus. Recent reports have demonstrated enthusiasm growing when projects include local training and high-skill employment opportunities **[29] [30]**. However, challenges include the limited awareness of CCS and its role in achieving Net Zero targets and misunderstandings about its benefits and safety concerns around CO_2 storage and possibility of leaks. Trust issues, particularly around transparency and equitable distribution of benefits, also hinder acceptance. There are concerns about greenwashing by enabling the oil industry to continue and the misperceptions that CCS is just a way to keep oil companies in business. Scepticism remains about whether CCS is a temporary fix delaying more sustainable solutions like renewable energy.

Accessible, balanced information from trusted sources is crucial. Highlighting tangible benefits, such as job creation and emission reductions, can foster acceptance. Linking CCS to just transition strategies for industrial communities is effective but addressing concerns about prioritising corporate profits over local or environmental benefits - essential building trust and engagement. Examples of public opinion are given in the following table. This summaries the outputs of a study by Leeds University which addressed the public perceptions of CCS. It includes both areas of support and concern.

Table 2: Public Perceptions Around CCS [30]

Areas for CCS to support	Key public concerns and barriers
Broad public support exists for actions addressing climate change and decarbonisation initiatives.	Limited awareness of CCS technologies and their role in achieving Net Zero targets.
Positive perceptions of CCS when associated with local benefits, such as job creation and emission reduction.	Concerns about the safety and long-term reliability of CO_2 storage sites.
Increased knowledge and understanding of technical aspects enhance public acceptance.	Misperceptions about the benefits of CCS, such as assumptions about cleaner air and lower energy costs.
Significant support for linking CCS development with local training programmes and youth education.	Distrust of government and industries, particularly regarding transparency and equitable benefits.
Public hopeful for high-skill job opportunities and economic regeneration in industrial areas.	Scepticism about whether Net Zero targets can realistically be achieved or if CCS delays other solutions.
Opportunity to frame CCS as a key component of just transition strategies for industrial communities.	Concerns that CCS might prioritise corporate profits over local or environmental benefits.
Desire for balanced, accessible information about both the risks and benefits of CCS.	Perception that CCS is a short-term fix rather than a comprehensive solution to climate challenges.

4. International Comparison

4.1 Case Studies of International CCS Business Models

Different nations have adopted various business models to implement CCS, reflecting their unique economic, regulatory, and environmental contexts.

4.1.1 USA

The USA has adopted a diverse and market-driven approach to CCS, leveraging tax incentives, public-private partnerships, and a strong energy sector.

Policy and Incentives: The primary driver for CCS deployment in the U.S. is the 45Q tax credit, which provides financial incentives for CO_2 capture and storage. Companies can claim up to $85 per metric ton for CO_2 stored geologically and $60 per metric ton for CO_2 utilised in Enhanced Oil Recovery (EOR) or other applications (U.S. Department of Energy [DOE], 2023).

Business Models:

- **EOR-Based CCS:** The U.S. has integrated CCS with EOR, where captured CO_2 is injected into oil fields to increase extraction efficiency. This model comodifies CO_2 by generating revenue from both oil production and tax credits (Global CCS Institute, 2022).
- **Clustered Infrastructure:** Regional CCS hubs, such as the Illinois Basin and the Houston CCS Innovation Zone, are being developed to share transport and storage infrastructure, reducing costs (DOE, 2023).
- **Private Sector Role:** Major energy companies, such as ExxonMobil and Chevron, are heavily involved, often in collaboration with smaller technology firms and academic institutions. Public funding from the DOE supports large-scale demonstration projects.

Dependencies

- **Government Policy Stability**: The effectiveness of the 45Q tax credit and other incentives depends on consistent government support and policy stability. Changes in administration or policy can impact the availability and attractiveness of these incentives.
- **Private Sector Investment**: Successful CCS projects require significant investment from private companies. This dependency means that economic conditions and corporate priorities can influence the pace and scale of CCS deployment.

4.1.2 China

China's CCS strategy is shaped by its reliance on coal and industrial emissions, as well as its centralised planning approach.

Policy and Incentives: The Chinese Government has included CCS in its national Carbon Neutrality Roadmap. It provides funding for pilot projects and supports technology development through its Five-Year Plans (China National Development and Reform Commission [NDRC], 2022).

Business Models:

- **State-Led Projects:** Most CCS initiatives in China are led by State-Owned Enterprises (SOEs) like Sinopec and China National Petroleum Corporation (CNPC), ensuring alignment with national goals (Global CCS Institute, 2022).
- **Industrial Clusters:** Projects like the Yanchang Integrated CCS Demonstration focus on capturing emissions from coal-to-chemical plants and other industrial sources, with shared infrastructure.
- **Challenges:** Despite significant investments, the cost of CCS remains a barrier. The lack of a robust carbon pricing mechanism limits economic incentives for widespread adoption (NDRC, 2022).

Dependencies

- **State-Owned Enterprises (SOEs)**: China's CCS efforts are largely driven by SOEs, which means the success of projects depends on the financial health and strategic priorities of these enterprises.

- **Government R&D Support**: Continuous government support for research and development is essential for advancing CCS technologies and reducing costs. Changes in R&D funding can affect the pace of technological innovation.

4.1.3 Norway

Norway has positioned itself as a global leader in CCS, leveraging its expertise in offshore oil and gas.

Policy and Incentives: The Norwegian Government has committed substantial funding to CCS, including the "Longship" project, which represents a full-scale CCS value chain supported by public and private investment (Norwegian Ministry of Petroleum and Energy, 2023).

Business Models:

- **Government-Driven Frameworks:** The Longship project includes CO_2 capture from industrial facilities and transport to an offshore storage site, operated by the Northern Lights project—a joint venture between Equinor, Shell, and TotalEnergies.
- **Carbon Pricing:** Norway's carbon tax, among the highest globally, provides additional financial motivation for industries to adopt CCS (Global CCS Institute, 2022).
- **Export Potential:** Norway is positioning itself as a CCS service provider for Europe, offering CO_2 storage capacity to other countries (Norwegian Ministry of Petroleum and Energy, 2023).

Dependencies

- **Government Funding**: Norway's CCS projects are heavily dependent on government funding and support. Any changes in government priorities or budget constraints can impact the continuity of funding.
- **Carbon Tax Policy**: The carbon tax on offshore operations is a key driver for CCS investment. Stability and predictability of this tax are crucial for long-term planning and investment.

4.1.4 The European Union

The European Union's commitment to achieving climate neutrality by 2050 is underscored by the implementation of the Net Zero Industry Act (NZIA). This legislation aims to bolster the EU's manufacturing capacity for clean technologies, ensuring that at least 40% of the EU's annual deployment needs are met by 2030.

A key component of the NZIA is the establishment of a single market for CCS, with a target of developing 50 million tonnes of CO_2 storage capacity across the EU by 2030. In line with these objectives, the NZIA mandates that oil and gas producers contribute to the CO_2 storage capacity based on their production levels from 2020 to 2023

Policy and Incentives: CCS is supported under the EU Green Deal and the Innovation Fund, which allocates revenues from the ETS to finance low-carbon technologies (European Commission, 2023).

Business Models:

- **Regional Hubs:** Projects like Porthos in the Netherlands focus on shared transport and storage infrastructure for industrial clusters (Global CCS Institute, 2022).
- **Public-Private Partnerships:** The EU fosters collaboration between governments, industry, and research institutions to drive CCS innovation.
- **Challenges:** While the EU has made progress, regulatory hurdles and public opposition to onshore storage have slowed deployment in some member states (European Commission, 2023).

Dependencies

- **Carbon Market Stability**: The EU ETS relies on a stable and predictable carbon market. Fluctuations in carbon prices can affect the financial viability of CCS projects.
- **Regulatory Framework**: The success of CCS in the EU depends on a clear and supportive regulatory framework that encourages investment and innovation. Complex regulations can pose challenges for project developers.

4.1.5 Canada

Canada's CCS business model builds on its vast natural resources and commitment to reducing emissions from energy-intensive industries.

Policy and Incentives: The Federal Government's carbon pricing system, alongside provincial initiatives like Alberta's Carbon Capture and Storage Fund, provides financial support for CCS projects (Canadian Government, 2023).

Business Models:

- **Oil Sands Integration:** CCS is used to reduce emissions from oil sands operations, as seen in the Quest project by Shell and the Alberta Carbon Trunk Line (Global CCS Institute, 2022).
- **Hub Models:** Similar to the USA, Canada is developing regional CCS hubs to share infrastructure, particularly in Alberta and Saskatchewan.
- **Indigenous Partnerships:** Some CCS projects involve collaboration with Indigenous communities, integrating local knowledge and ensuring equitable benefits (Canadian Government, 2023).

Dependencies

- **Government Policy and Funding**: Consistent federal and provincial support is essential.
- **Industry Collaboration**: Partnerships with industry are crucial for project success.

4.1.6 Australia

Australia's CCS approach is closely tied to its energy sector, particularly natural gas and liquefied natural gas (LNG) exports.

Policy and Incentives: The Federal Government supports CCS through the Emissions Reduction Fund and grants for pilot projects. However, critics argue that stronger policies are needed to drive large-scale adoption (Australian Government, 2023).

Business Models:

- **Natural Gas Applications:** The Gorgon CCS project in Western Australia captures CO_2 from LNG production for geological storage, showcasing integration with the gas sector (Global CCS Institute, 2022).
- **Private Sector Leadership:** Companies like Chevron and Santos are key players, often leveraging government grants to offset costs.
- **Challenges:** High costs, limited public funding, and concerns over environmental risks have slowed the rollout of CCS in Australia (Australian Government, 2023).

Dependencies

- **Oil Market Conditions**: The use of CO_2 for enhanced oil recovery (EOR) is influenced by oil market conditions. Fluctuations in oil prices can impact the economic viability of EOR-based CCS projects.
- **Government Grants**: The availability of government grants and funding programs is crucial for supporting CCS projects. Changes in government policy or budget allocations can affect the availability of these funds.

4.1.7 The Netherlands

The Netherlands has emerged as a leader in CCS within Europe, focusing on industrial decarbonisation and leveraging its dense industrial clusters.

Policy and Incentives: The Dutch Government provides significant funding through its SDE++ subsidy scheme, which supports low-carbon technologies, including CCS. The Netherlands also benefits from EU funding through the Innovation Fund (European Commission, 2023).

Business Models:

- **Industrial Hubs:** The Porthos project is a flagship initiative, capturing CO_2 from Rotterdam's industrial area and storing it in depleted gas fields in the North Sea. This shared infrastructure reduces costs for participating industries (Global CCS Institute, 2022).

- **Public-Private Collaboration:** The Government collaborates with major companies such as Shell, ExxonMobil, and Air Liquide to ensure project viability and cost-sharing.
- **Challenges:** Public acceptance and regulatory delays remain obstacles, particularly for onshore storage projects. However, offshore storage has gained broader support (Dutch Ministry of Economic Affairs and Climate Policy, 2023).

Dependencies

- **Market Prices**: The SDE++ scheme provides subsidies based on the difference between production costs and market prices. Stability in energy market prices is important for the predictability of subsidies.
- **Competitive Application Process**: The success of projects under the SDE++ scheme depends on the ability to secure funding through a competitive application process. This requires thorough planning and strong project proposals.

4.2 Gap Analysis - Comparative Analysis of UK Plans and Global Practices

All nations with CCS ambitions have **Government Funding** through either direct funding, tax relief or guaranteed income. Tax relief and direct funding both have benefits in terms of simplicity of administration (over CfD arrangements), with the USA and Canadian models further providing income for CCS operators by commoditising the captured CO_2 by allowing it's use for EOR. The Dutch SDE++ model manages the complexity of the UK's business model system by awarding funding agnostic to the application but based on the most cost-effective strike price bid made by an applicant at allocation rounds [31].

The UK benefits from high levels of **Regulatory Clarity** relative to many countries. Clear and supportive regulatory frameworks are supported by a Government and civil service who are motivated to develop a CCS industry, with plenty of legacy expertise from a mature oil and gas industry.

Industry Collaboration is promoted through the UK's cluster models. The use of shared infrastructure based around the country's established industrial bases brings together the CCS value chain. The cross-chain risk is managed through the business models. These provide mechanisms to manage the risk of stranded assets but are likely to lack commercial confidence until tested.

Table 3: Comparative analysis of national CCS initiatives, including the UK

Country/Region	Policy Drivers	Business Models	Benefits	Challenges
United States	Tax incentives (45Q+), DOE funding	EOR-based CCS, regional hubs	Strong financial incentives, encourages private investment	High upfront costs, regulatory complexity, dependency on sustained government support
China	Centralised planning, pilot funding	State-led projects, industrial clusters	Large-scale projects, significant government backing	High costs, limited carbon pricing, Limited private sector involvement, regulatory and bureaucratic hurdles
Norway	Carbon tax, public funding	Full-scale value chains, export services	Strong government support, long-term stability	High dependency on government support
European Union	ETS revenues, Innovation Fund	Regional hubs, public-private partnerships	Market-driven, integrates with broader climate policies	Public acceptance issues, complex regulatory environment, fluctuating carbon prices
Canada	Carbon pricing, provincial funds	Oil sands integration, CCS hubs	Strong government support, established CCS projects	Geographic limitations, high costs
Australia	Emissions Reduction Fund, grants	Gas sector integration, private sector-led	Economic benefits from EOR, government support	Limited policy ambition, high costs
Netherlands	SDE++ subsidies, EU Innovation Fund	Industrial hubs, public-private collaboration	Broad technology support, long-term financial stability. Funding focused on most cost efficient methodologies	Public acceptance, regulatory delays, Competitive application process, dependency on market prices may encourage non-strategic investment
Indonesia	Becoming a regional leader in CCS through enabling policy to support industry and carbon imports	Carbon storage as a service, EOR	A highly developed regulatory framework to maintain output while meeting climate commitments	High costs and public acceptance
United Kingdom	Industrial clusters, government funding, and regulatory frameworks	Industrial clusters, CCS Infrastructure Fund, Contracts for Difference (CfDs)	Focus on industrial clusters, strong government support, clear regulatory framework	High initial costs, complex coordination among stakeholders

4.3 Lessons Learned from Leading Nations

The potential of Enhanced Oil Recovery

The only major utilisation application of CO_2 that is not deployed in the UK is EOR. EOR has enabled a mature CO_2 market, widespread infrastructure and skill base in the US. The legal status of combined storage-EOR operations lacks clarity but isn't explicitly banned [21] [32]. Around 20% of global oil production is from EOR[7], with each barrel requiring 300-600kg of CO_2 and each barrel producing approximately 500kg of CO_2 throughout production and combustion. This leads to the possibility that EOR could be carbon neutral or even negative [33]. A 2016 report for the then Oil and Gas Authority[8] estimates that CO_2 injection has the potential to recover 5,700 million stock tank barrels on the UKCS[9] [34]. The potential of an EOR market to encourage CCS is suggested in the OGA report, based on findings by the Energy Research Partnership [35] and is supported separately by the IEA [33]. Water injection is usually preferred once primary recovery from a reservoir is complete due to costs and complexity. Given the benefits of CO_2 injection in stimulating the CCS industry, the concept of supporting this methodology should be further investigated.

Application agnostic subsidies

The Dutch SDE++ model provides subsidies on the most cost-efficient carbon removal projects. This contrasts with the UK model which has different business models for applications. By focussing spending on the most cost-effective solutions at an early stage enables rapid scaling of infrastructure and value chains. The caution of this approach is that it may encourage non-strategic investment. A compromise on this may be found in the Delegated Regulation 2023/2537 principles applied by the hypothetical European CCS Bank proposed by the IOGP [36], whereby strategic benefits are recognised as part of an open bid system (rather than individual application pots).

[7] Noting that strictly EOR is tertiary recovery (i.e. using CO_2), but most sources do not distinguish between this and secondary recovery via water or polymer injection.

[8] Now NSTA.

[9] Of 6000 mmstb recoverable by all forms of secondary/tertiary EOR.

4.4 UK Government Identified Gaps

The 2023 UK Government's vision [1] to establish a competitive market identifies the following gaps.

Table 4: Status of DESNZ identified actions to establish a competitive UK CCS market

Issue	Description	Status	Comments
Establishment of a new process for the allocation of economic licences for CO_2 transport and storage	The ability to grant licences transferred to Ofgem, as provided for by the Energy Act 2023. Ofgem will carry out its functions in relation to the regulation of CO_2 transport and storage in line with its principal objectives and statutory duties established in the Energy Act. This will allow for the efficient and economical expansion of CO_2 transport networks, ensuring the interests of both current and future users of the networks are protected, and having regard to statutory carbon budgets and targets across the UK.	Powers were transferred under the 2023 Energy Act.	Nil
Capture contracts to be allocated through a more competitive process	To accelerate the pace and scale of deployment and incentivise cost reduction. Regular scheduled allocation rounds, with the initial round expected around 2027.	The vision document states a consultation will be launched in 2024 on future market frameworks. Identifies 'The new market framework is likely to require further legislation, establishment of an allocation body and setting up of a new delivery framework'	The most recent framework consultation is dated 2022 [37]. This recognises a need for a competitive allocation process which is shared by the respondents. The first allocation round under this process would be in 2027. An update from HMG on the progress and considerations outlined in 4.3 would be desirable.
New economic models for transport and storage to emerge	Familiarisation with onshore and offshore CO_2 transport networks and increased competition in segments of the CO_2 transport and storage chain will allow **new economic**	Heads of terms for T&S published in December 2023 [38]	The T&S business model is now in development to support the tracked clusters and other business models. Clarity should be sought from the Government over the timeline implementation.

	models for transport and storage to emerge, resulting in the evolution of the economic regulation of CO_2 transport and storage.		
Existing business models for transport and storage and for carbon capture projects will continue to evolve	To reflect a more market-led approach and the increased role that the private sector will play in managing cross chain risks.	'Industry is expected to play a major role by identifying and adopting new and innovative low-cost solutions across the value chain.'	A review of the T&S codes, interaction of the cost dynamics, import opportunities and non-pipeline transport would be desirable, with a projection of this working in a commercial environment.
Increasingly streamlined leasing, licensing and permitting processes across regulatory bodies will be developed, with the aim of accelerating subsurface storage appraisal	This will support the pace and scale of carbon storage appraisal required.	The implementation of the Storage Exploration and Appraisal Agreement (SEAA) allows developers to take the initial steps of site appraisal on a lower level of commitment than the previous licensing regime.	The Crown Estate is well engaged with developers and the SEAA allows earlier engagement. Currently 37 stores hoping to be online by 2035 with a further 25 by 2050. [39]
Non-pipeline transport (NPT) will be operational	Both onshore and offshore, **linking emission sources with permanent geological storage**. The Government has been engaging closely with industry on the potential options for NPT and how these might be integrated into the wider CCS landscape. To support industry in their work, the Government will shortly publish a call for evidence on how it envisages NPT to be delivered in the UK. We anticipate that NPT projects will be eligible for selection as capture projects from 2025 onwards.	Non-pipeline transport and cross-border CO_2 networks - call for evidence issued May 2024 (for July 2024).	Reponses were published in November 2024 [40] A full NPT consultation will be launched in 2025.

Consideration of the strategic direction for CO_2 transport networks	Including developing an understanding of the degree of strategic co-ordination needed and any potential role for the Future System Operator.	Heads of terms for T&S published in December 2023	The future of CO_2 transport networks will be closely aligned with the interaction of NPT, including import facilities. This would benefit from being considered concurrently with any review of the T&S business models.
The import of CO_2	Enabling **the import of CO_2**, to allow the UK to benefit from its strategic advantages, helping to lower costs to UK CO_2 transport network users and stimulating growth of Transport & Storage (T&S) infrastructure, which in turn will provide critical support for meeting our domestic CO_2 storage targets. The Government will also explore the potential role of CO_2 exports in providing increased resilience in the UK CCS sector.	Included in call for evidence [40]	The value of importing CO_2 to support UK storage development is strongly recognised across industry and government. Practicalities about this are captured in the wider discussions about NPT, while goes into some depth on the legislative issues.
Increasing market maturity will reduce the need for government support.	Growing confidence in the T&S business means that the need for support packages currently offered as part of the Cluster Sequencing process will diminish as the market matures and the availability and depth of CCS commercial insurance products increases. All stakeholders have a common interest in establishing a successful merchant market model for the acquisition of new customers and network expansion as rapidly as possible.	Many leading providers are now offering CCS products for operators.	While several large insurance houses are launching flagship CCS insurance programmes there is paucity of information. A detailed review and assessment of the policies is suggested in their ability to provide cover for supported and unsupported full chain CCS operations.

Innovation and cost reductions	Facilitated by the development of the global CCS sector, the development of UK ETS and increasing ability for costs to be recovered by businesses, **will reduce the amount of government/ consumer funding required for capture projects**. The Government will also continue to explore policy options (such as carbon take back obligations or carbon storage obligations) to increase investment apetite of CCS and reduce the need for government support.	Cost reductions are closely linked to increasing confidence in the CCS sector.	This refers to a strong innovation focus on reducing the CAPEX and OPEX of CCS. This will be supported by increasing revenue streams.
Review of the existing regulations regarding third party access to CO_2 transport and storage infrastructure	To ensure they are fit for purpose.	This is closely aligned to the wider NPT and T&S issues.	DESNZ have stated they will undertake a review of these. An update on this from HMG should be requested.

5. Enabling Transport Opportunities

5.1 Network Interconnectivity

5.1.1 CO_2 Shipping

The UK Government is exploring new ways to transport captured CO_2 to offshore storage sites, including by ship, to support the adoption of carbon capture technology across the country. The largest UK industrial cluster by emissions is South Wales Industrial Cluster (SWIC), however this doesn't have direct access to geological storage. The establishment of a viable CO_2 shipping industry is essential to decarbonise some of the largest emission sites in the UK.

Associated British Ports are playing a key role in the development of CO_2 shipping terminals. The most advanced project is their collaboration with Viking CCS in the Humber Cluster, where the port of Immingham will act as an import terminal where connection will enable CO_2 to be stored safely in the Victor and Viking fields in the North Sea. CO_2 shipping will open interconnectivity routes between UK clusters and enable access to the international market where the UK could act as a CO_2 import hub.

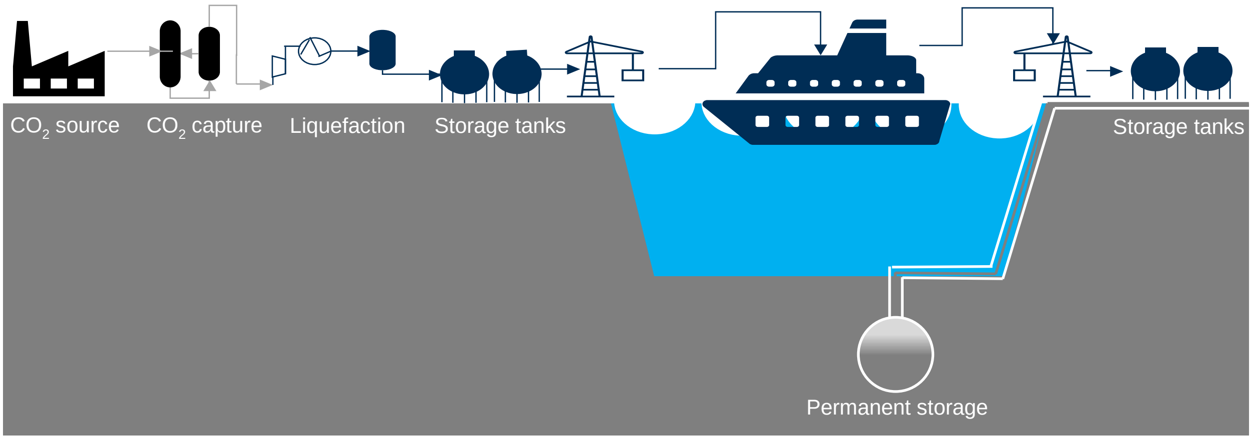


Figure 8: CO_2 Shipping from Source to Store

5.1.2 Network Interconnectivity

Table 5: Key Benefits of Interconnected Networks of pipeline and non-pipeline CO_2 transmission

Key benefits of interconnected networks over point-to-point pipelines include:	
1	**Resilience**: Interconnected networks enable industrial clusters to access alternative hydrogen supply or storage, reducing risks from disruptions in the early stages when infrastructure is limited.
2	**Cost Reduction through Competition**: A shared network fosters competition among sellers, leading to a single price for access and use, which helps offset the higher costs of building a larger, integrated network.
3	**Flexibility in Location**: Hydrogen production sites can be located away from users, reducing pressure on local resources like water supply.
4	**Enhanced Storage Access**: Networks connect more storage locations, offering greater capacity and flexibility, especially for hubs without nearby storage options.
5	**Support for Power Generation**: Networks create opportunities to transition existing gas-fired power generation sites to hydrogen or CCS, leveraging their access to electricity grids and cooling water.

Table 6: Key Recommendations for supporting investment in existing subsidy-enabled CCS ecosystem

The uncertainty surrounding the scale and location of demand for hydrogen and CCS networks creates high risk for private developers, discouraging investment. To mitigate this, the Government should play a key role in providing support, reducing risk, and encouraging the adoption of low-carbon energy sources. Key recommendations for achieving this include:	
1	**Focus on Core Networks**: Prioritise development in areas with the least demand uncertainty to minimise the risk of underused or stranded assets. Enable interconnection between core networks and international emitters.
2	**Development Expenditure**: Fund front-end engineering design studies to bring projects to the consent application stage. The National Wealth Fund can play a key role in providing development finance.
3	**Finalising Business Models**: Implement business models such as regulated asset bases (RAB) for CCS and hydrogen pipelines and revenue floors for hydrogen storage to address revenue risks. Competitive processes should be used for awarding contracts to ensure value for money. Enable merchant model interconnection to RAB-funded T&S infrastructure.
4	**Regulatory and Governance Framework**: Establish codes, standards, and governance systems to ensure compatibility and interoperability of networks, avoiding isolated development.
5	**Designate an independent system operator** for each network to efficiently manage operations and plan for future network expansion.
6	**Target Timeline**: Deliver the core networks by 2035.

The Government should ensure that hydrogen and carbon capture networks under development are viable, with confirmed users at both ends before committing funds or support. The estimated cost of building core networks ranges between £12-22 billion, depending on development costs and the potential reuse of existing natural gas pipelines.

Key recommendations include:

1. **Assurance at Each Stage**: Verify the presence of users at both ends of the network before awarding development expenditure or offering support via business models.
2. **Adaptive Planning**: Plan for future stages of the network alongside the core development to address uncertainties and use an adaptive approach to enable quick decisions for network expansion as demand evolves.
3. **Vision and Policies**: Set out a clear vision for core networks and supporting policies by the end of 2024 to guide development and expansion.
4. **Future Expansion**: Expand networks to include:
    - Imports and exports of hydrogen.
    - Connections to additional industrial areas like the Medway.
    - Carbon capture and storage for dispersed sites.
    - Increased demand from hydrogen-fired power generation.
    - Support for new hydrogen storage facilities.

The development of the core carbon pipeline and storage networks should be guided by these principles:

1. **Prioritising Large Emitters**: Focus on industries where CCS is the most viable decarbonisation solution, such as cement and lime production, CCS-enabled hydrogen, petrochemicals, and parts of the chemicals industry.

2. **Fixed Industry Locations**: Recognise that key industries are often restricted to certain locations due to reliance on specific local inputs (e.g., cement plants near lime and silica sources), zoning and planning laws, or supporting infrastructure.
3. **Planning for Long-Term Changes**: Consider that some industries, such as fuel production and oil refining, may reduce output or phase out as the economy transitions to net-zero, potentially decreasing their future need for CCS.
4. **Pipeline Transport**: Use pipelines as the optimal method for transporting large carbon volumes from capture sites to storage facilities due to efficiency and scalability.
5. **Offshore Carbon Storage**: Take captured carbon to storage sites located offshore on the east and west coasts.

Other recommendations include:

1. CCS infrastructure should be located near the core network
2. Energy-from-waste plants, due to their dispersed locations, may not be economically feasible for pipeline transport. Alternatives such as road, rail, or ship transport will be viable, and the core network should accommodate these non-pipeline carbon transport methods.

Based on the above, the core network should connect key industrial hubs, including Grangemouth, North East Scotland, Teesside, Humberside, Merseyside, the Peak District, and Southampton, maximising opportunities to link:

- **Dispersed Cement and Lime Plants**: These industries require CCS for decarbonisation, with significant emissions outside core industrial hubs.
- **Gas-Fired Electricity Generation**: Existing sites can be retrofitted with CCS or repurposed for new carbon-neutral generation projects.

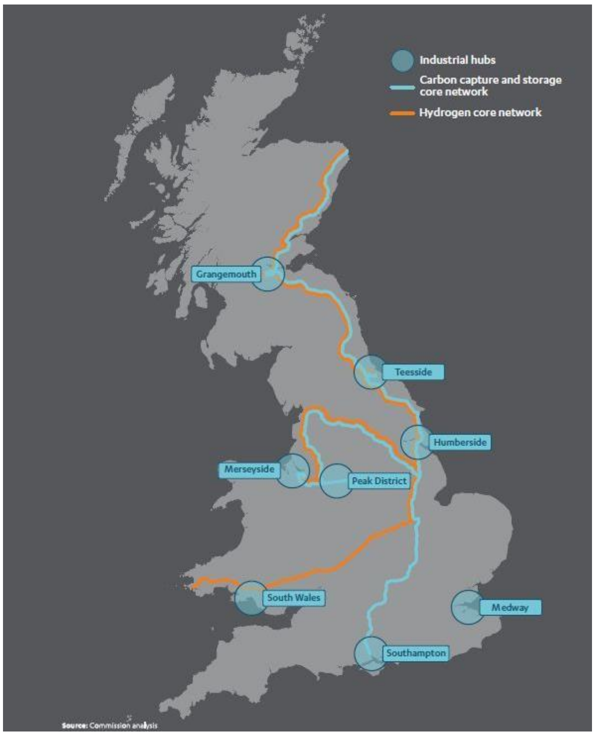


Figure 9: Cluster Interconnectivity [41]

5.1.3 Ports Infrastructure

The construction of port infrastructure for CCS involves building facilities to receive, store, and handle liquid CO_2 transported by ships from various industrial sources across Europe. These facilities include storage tanks, loading and unloading systems, pipelines, and comprehensive safety systems. The introduction of CO_2 into existing networks must comply with Network Code on entry temperature/ pressure conditions and impurity levels.

Offering new CCS services, including CO_2 handling infrastructure and bunkering services for e-fuels like e-methanol, presents significant revenue opportunities for ports, allowing them to expand their operations and become key players in the future maritime sector. The development of CCS infrastructure can also stimulate opportunities for economic growth and job creation as well as technology innovation.

Key ports infrastructure recommendations:

1) Ports should focus on developing strategic locations to serve as onshore CO_2 receiving terminals, leveraging their proximity to industrial CO_2 sources, offshore storage sites, and maritime transportation routes.

2) Collaboration between ports and strategic landowners across the UK as well as internationally is crucial for knowledge sharing, best practice implementation, and the optimisation of CCS receiving infrastructure design - potentially employing modular construction to reduce costs and accelerate development. This collaborative approach will maximise the potential of CO_2 shipping and participation in the future carbon trading market.

5.2 Development of Non-Pipeline CO_2 Transport Solutions

Non-Pipeline Transport (NPT)

NPT plays a critical role in the UK's CCS strategy. By leveraging various modes of transport, including road, rail, barge, and shipping, NPT provides a flexible alternative to fixed pipeline systems, enabling decarbonisation in locations without direct pipeline access. This flexibility is vital for unlocking CCS potential in areas outside industrial clusters and ensuring that capture projects can connect to storage infrastructure. NPT currently sits outside of any T&S RAB support structure, but it will need to interact with RAB assets as NPT would reasonably look to use the nearest, or indeed cheapest available point of entry to a storage network.

5.2.1 NPT Flexibility

NPT distinguishes itself from traditional pipeline transport through its ability to adapt to diverse logistical and geographical needs. Unlike pipelines, which provide a fixed and direct route from CO_2 emitters to storage facilities, NPT employs a network of intermodal facilities, transport modes, and storage options. This approach enables flexibility in transport routes and storage locations, as highlighted in the figure below, where NPT solutions connect users to multiple storage facilities via different transport modes.

Piped T&S Solution: Fixed Transportation of CO_2 to Store:

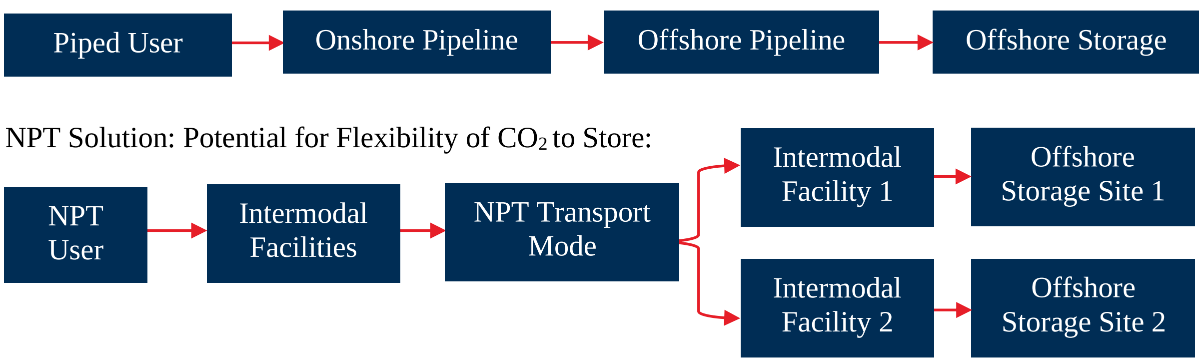


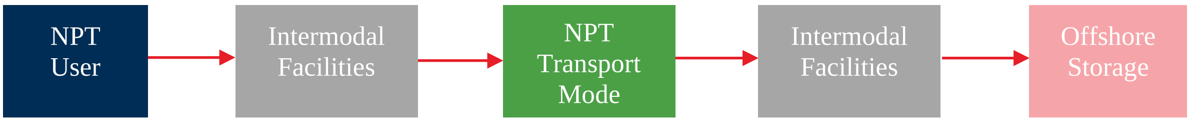
Figure 10: Comparison of Piped T&S Solution vs. NPT Solution

The flexibility of NPT lies in its ability to accommodate:

- **Geographical Diversity**: NPT can connect CO_2 emitters located in areas outside existing pipeline networks, unlocking decarbonisation opportunities for remote or dispersed industries.
- **Scalability**: NPT solutions can handle varying volumes of CO_2, from small-scale capture projects to large industrial operations.
- **Transport Modes**: By utilising road, rail, barge, and shipping, NPT offers multi-modal solutions that can switch between modes as needed, optimising transport efficiency based on distance and geography.

The ability to use both single-mode and multi-modal transport chains further enhances NPT flexibility. In a single-mode solution, CO_2 is transported using one method, such as road or rail, from the user to the storage site. Multi-modal solutions, on the other hand, involve the use of multiple transport methods at different stages of the chain, as demonstrated in the below figure. For example, CO_2 could be moved by road to an intermodal facility, transferred to rail for long-distance transport, and finally delivered to storage by ship.

Single Mode NPT Solution:



Multi-modal NPT Solution:

Figure 11: Comparison of Single Mode and Multi-modal NPT Chain

Multi-modal NPT is particularly advantageous in scenarios where technical or economic constraints make pipelines or single-mode solutions unviable. This adaptability ensures that CCS projects in complex logistical environments can still access storage, supporting broader decarbonisation goals.

Operational Flexibility

Operational flexibility is a defining feature of NPT, enabling dynamic responses to changing market and network conditions. NPT provides resilience by serving as a physical link between capture projects and storage facilities, even in the absence of direct pipelines. This operational flexibility has several key implications:

- **Resilience to Disruptions**: NPT can redirect CO_2 to alternative storage facilities in the event of pipeline outages or capacity constraints. This reduces dependency on a single storage option and ensures continuous operation of CCS projects.
- **Maximising Utilisation**: NPT enhances the utilisation of storage facilities by matching excess capacity with CO_2 volumes from multiple emitters. For example, during periods of underutilisation in a piped network, NPT providers can transport CO_2 to fill the gap, optimising storage usage.
- **Dynamic Pricing Structures**: As the CCS market evolves, NPT could support flexible pricing mechanisms, allowing users to select storage sites based on cost and availability. This would create a responsive and competitive marketplace for CO_2 storage.

5.2.2 Interconnectivity in NPT

The flexibility of NPT can strengthen network interconnectivity by linking multiple emitters, intermodal facilities, and storage sites. The more CCS clusters that are NPT enabled, the greater the potential benefits. With each cluster having NPT connectivity, further flexibility between clusters, NPT users, and stores can be unlocked. This web of interconnected NPT users and stores could then connect fixed piped T&S networks. Such connectivity is essential for:

- **Supporting Cross-Border Transport**: NPT enables international emitters to access the UK's extensive offshore storage capacity via shipping, fostering collaboration and expanding the market for CCS.
- **Complementing Pipeline Networks**: NPT serves as a feeder system to pipelines, bridging gaps in areas without pipeline access and expanding the reach of the CCS network.
- **Facilitating Redundancy**: By providing alternative routes for CO_2 transport, NPT enhances the overall resilience and reliability of the CCS infrastructure.

In conclusion, NPT is essential for achieving the UK's CCS objectives. By enabling adaptable, scalable, and multi-modal solutions, NPT addresses the needs of a diverse range of emitters and geographic locations. Its operational flexibility ensures resilience and maximises the utilisation of CO_2 storage infrastructure, while its ability to integrate with pipeline networks and support cross-border transport strengthens network interconnectivity.

Ways to Develop NPT

The development of NPT represents a critical evolution in the CCS landscape, offering innovative solutions to overcome the limitations of traditional pipeline infrastructure. By fostering competition and embracing self-organisation within the value chain, NPT systems are poised to drive growth, enhance efficiency, and expand market participation. With a focus on flexibility, scalability, and adaptability, NPT can enable cost-effective and efficient CO_2 transport and support the creation of a dynamic ecosystem. Through competitive service markets, diverse delivery archetypes, and multi-modal transport solutions, NPT is set to play a pivotal role in achieving the UK's decarbonisation objectives.

Fostering Competition to Drive Growth

The development of NPT is closely tied to the creation of a competitive service market. Unlike pipeline transportation, which often operates under a regulated monopoly model, NPT services are expected to thrive in a competitive environment. The Government anticipates that market competition among NPT providers will lead to cost reductions and drive innovation. Service providers competing to offer lower-cost solutions can incentivise new participants to enter the CCS market, creating a self-sustaining ecosystem.

Shipping solutions, in particular, present unique opportunities for enabling direct-to-wellhead CO_2 injection, especially at storage sites without a local user base. This reduces transportation costs and distances for cross-border users, further supporting market expansion. Additionally, the increased demand for geological storage driven by NPT and cross-border users can incentivise storage exploration and appraisal activities, enhancing the overall CCS value chain.

5.2.3 Self-Organisation

The NPT value chain is expected to evolve through self-organisation, where market participants independently design and implement their operational and commercial structures. This approach allows for technical and operational variability across different NPT chains, including variations in transport modes (road, rail, barge, or shipping), scale, and intermodal storage requirements. By allowing flexibility in organisational arrangements, self-organisation maximises the potential for innovation and efficiency in delivering NPT solutions.

The Government identifies three main archetypes for NPT service delivery: store led, capture led, and intermediary led models. Each archetype reflects different market dynamics and technical arrangements, enabling stakeholders to align their capabilities with specific requirements of the NPT chain. This flexibility ensures that the value chain can adapt to evolving market conditions and technical challenges.

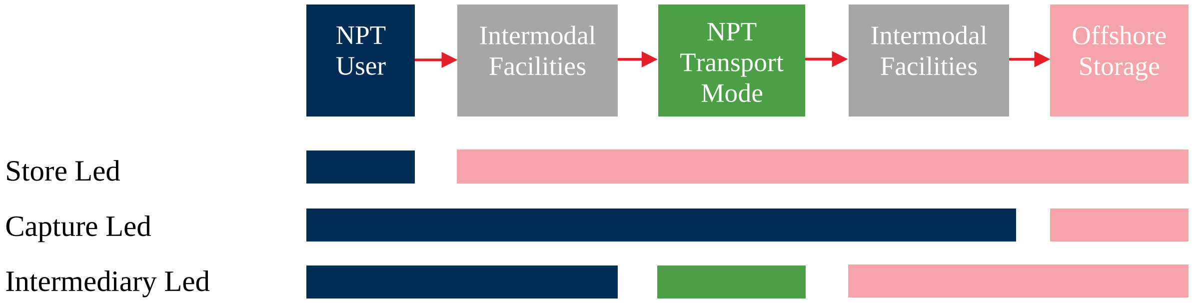


Figure 12: NPT Delivery Archetypes

1. **Store Led Model**

In this model, the storage facility takes primary responsibility for collecting CO_2. The store led approach mimics the role of pipelines in the CCS ecosystem, with intermodal receiving and transport services acting as conduits for CO_2 collection. While this model offers simplicity, its inflexibility in linking NPT users to specific storage sites may limit its broader application. However, it could serve as a transitional approach while multi-cluster NPT networks mature.

2. **Capture-Led Model**

The capture led approach places responsibility for CO_2 delivery on the capture project itself. This model allows emitters greater flexibility to choose storage sites and transport modes, ensuring an optimised match between their requirements and available storage options. The capture led model aligns well with the existing pipeline infrastructure and offers significant potential for scalability and adaptability.

3. **Intermediary-Led Model**

In the intermediary led model, third-party entities manage the connection between CO_2 emitters and storage facilities. These intermediaries act as bridges, coordinating the efficient transfer of CO_2 across different modes and facilities. This model is expected to gain prominence as the NPT market matures, providing a flexible and scalable solution for managing complex value chains.

In conclusion, the development of NPT is essential for creating a resilient and inclusive CCS network that extends beyond the constraints of pipeline systems. By fostering competition, enabling self-organisation, and adopting flexible delivery models, NPT can couple its adaptability with its ability to integrate multi-modal solutions and unlock significant opportunities for decarbonisation across diverse regions and industries.

6. Cost Improvement Opportunities

6.1 Cost Factors

The biggest barriers to the transition from supported models to an independent commercial market of CCS in the UK is economic feasibility and uncertainty in investment frameworks. This section of the report analyses the cost factors of CCS and explores those which are likely to yield reductions in cost. To accompany this analysis we have undertaken a high-level modelling of CCS costs with the purpose of establishing an approximate time frame for when CCS is likely to become economically viable based on our educated assumptions. This modelling will be based on 3 scenarios, high, low and base. We will discuss the model further in section 7.6 of this report.

At present, the CSS value chain consists of **high capital and operational costs**, and **limited income streams**. The CCS value chain presents substantial opportunities for cost reductions, particularly as many of its applications are still in the early stages of commercialisation. As CCS projects scale up, economies of scale and operational expertise will contribute to reductions in costs. This aligns with historic patterns in renewable technologies such as wind and solar which have achieved significant cost reductions over the past few decades, 80% for solar modules since 2010 [42] and 54% for wind since 2011 [43]. As industries expand, innovations improve efficiency, and financial mechanisms become more favourable.

Large scale CCS initiatives have already began to demonstrate progress in cost optimisation in the value chain. For example, CO_2 capture costs in power generation, which is also the largest carbon emitting sector in the UK, have decreased by **35%** from the first to the second large-scale CCS facility [44]. As the market matures and adoption accelerates, cost reductions are expected to continue and strengthen the commercial and investment appeal of the sector.

The cost factors for CCS according to the CCS value chain, for our report, are highlighted in below. It is important to note that the cost of each of the components and subcomponents varies significantly from project to project primarily due to difference in the size and location of the facility, and the characteristics of the source CO_2.

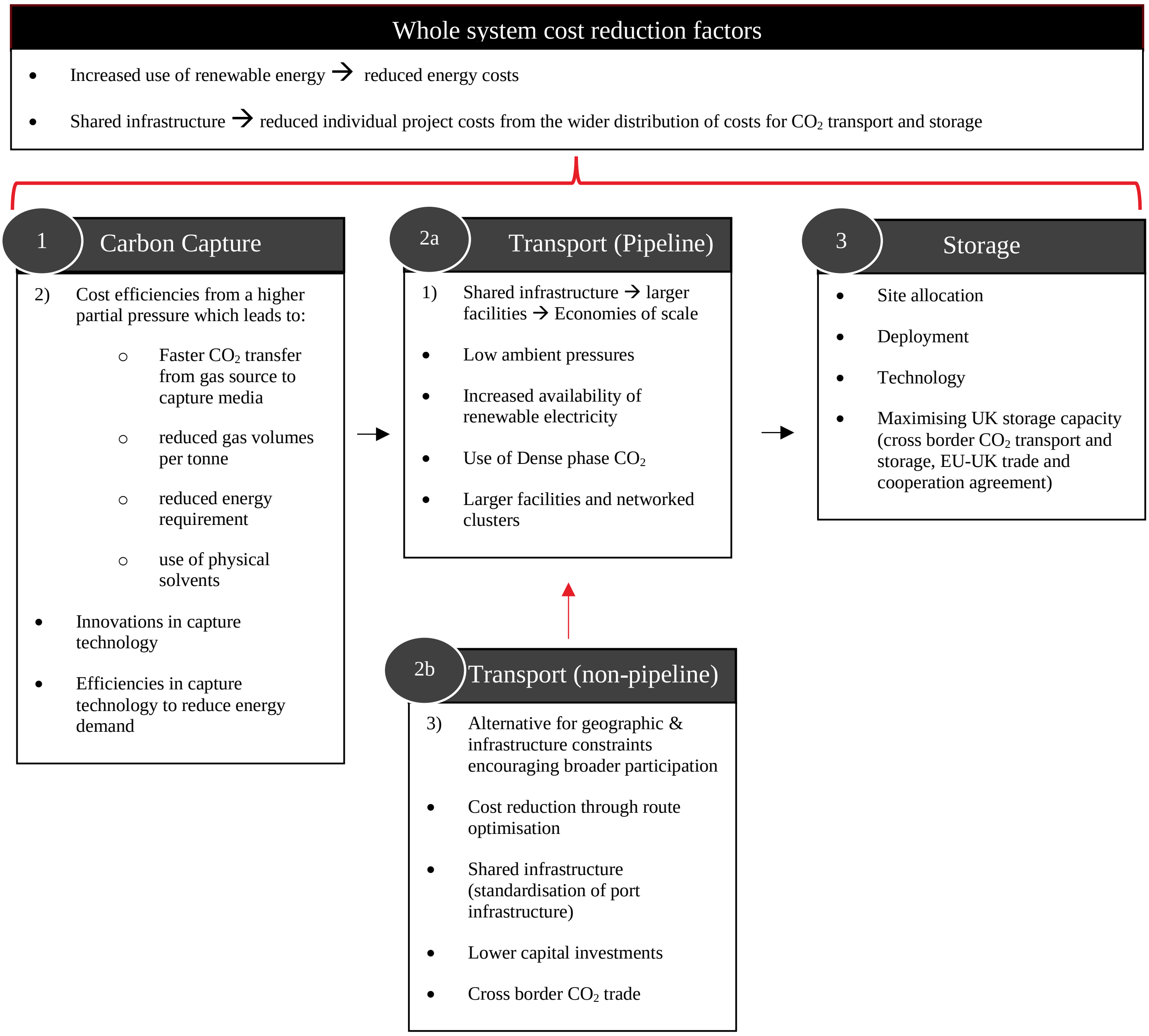


Figure 13: Cost Reduction Factors across the Carbon Capture Value Chain

6.1.1 Capital and operational costs

Stage 1- Carbon capture:

The cost of carbon capture varies greatly by CO_2 source, depending on the purity/concentration of the CO_2. Industrial processes producing "pure" or highly concentrated CO_2 streams, such as energy-from-waste, enables cheaper carbon capture. For processes with "dilute" gas streams, such as cement production and power generation, carbon capture is more expensive. **The cost reductions available in the early UK deployments will be based on technologies that are already widely used at large scale, and that can be invested in with confidence and manageable risk.** Further benefits from 'learning curve' effects, technology innovation, improved construction techniques, supply chain competition and the like will reduce costs further in the later 2020s and early 2030s.

Partial Pressure

The relationship between the partial pressure of carbon dioxide, gas volume, and equipment size is a fundamental driver of cost-efficiency in carbon capture systems. Higher partial pressures lead to greater reduction in carbon capture costs through several means. Higher partial pressure leads to faster CO_2 transfer from the gas source to the capture medium, allowing for physically smaller capture equipment. Additionally, Higher partial pressures mean a reduced volume of gas relative to the amount of CO_2 present, which again leads to smaller equipment requirements. The reduction in equipment size translates to lower capital investment. Furthermore, higher CO_2 partial pressure makes the separation process less energy intensive, thus reducing the amount of energy needed to capture CO_2 from the gas stream, resulting in lower operational costs. Similarly, partial pressure determines the type of technology that can be used for carbon capture. At higher partial pressures, physical solvents become a viable option.

From an economic perspective, off-gases with higher CO_2 partial pressure are significantly more advantageous for carbon capture and storage. Higher partial pressures reduce both the complexity and cost of the capture process, making CCS a more attractive option for industries with such gas streams. Conversely, low partial pressure sources face substantial cost barriers, often rendering CCS uneconomical.

However, it is important to note that while partial pressure is a critical determinant of economic viability, it is inherently dictated by the concentration of CO_2 at the source, and understanding the dynamics of CO_2 partial pressure is essential for identifying economically viable CCS opportunities. By targeting high partial pressure sources or exploring innovative solutions for aggregating low-pressure streams, stakeholders can optimise both the economic and environmental benefits of carbon capture technologies.

Reductions in cost from innovations in capture technologies are discussed in section 7.2 (Reduction of Capture Technology Costs).

6.1.2 Stage 2a- Pipeline Transportation

Compression

Two key factors drive compression costs: the capital cost and efficiency of compression equipment, and the energy cost to power the system. Compression operating costs do not benefit from economies of scale because the energy required for compression is directly proportional to the volume of CO_2 processed. However, capital costs do experience economies of scale to a degree, with larger facilities reducing the cost per tonne of CO_2 compressed. Again making the case for shared infrastructure as a cost reduction method for the adoption of CCS in the UK. Although it should be noted that these benefits diminish as facility size increases beyond certain thresholds. Compression technology is mature and significant cost reductions are unlikely. Future savings may arise from the increasing availability of cheaper renewable electricity.

Pipeline Transport

The cost of transport varies according to the scale/volume of the CO_2, and the distance the gas needs to be transported. The UK's relatively small geographic size and concentrated industrial clusters (e.g., Humber, Teesside) make pipeline networks feasible and practical for connecting emitters to nearby storage sites. In addition, the proximity to offshore storage sites in the North Sea further supports the suitability of pipelines, as they can efficiently link onshore emitters with offshore reservoirs. Based on these variables **dense-phase CO_2 by pipeline would be the most cost-efficient method for carbon transportation in the UK.**

In this phase, CO_2 has a high density and low viscosity, which minimises pipeline diameter requirements and friction loses, and simplifies its integration with storage sites. Meaning it is more energy efficient over long distances resulting in cost savings and it allows for optimal utilisation of geological storage volumes and facilitates accurate monitoring of CO_2 movement leading to long-term cost benefits. In addition, this optimal pipeline design, along with the strategic formation of industrial clusters, will enhance scalability, reducing overall costs as the network grows [45] .

The planned UK clusters aim to reach dense phase CO_2 with the increase in volumes of flowing CO_2 as the system expands and more emitters join the network. Once dense phase is achieved, operational energy requirements will decrease significantly, leading to long-term cost benefits. Furthermore, as CCS deployment scales up globally the demand for compressors and related equipment increases, which will reduce per-unit costs through bulk manufacturing and procurement efficiencies. Large scale projects like HyNet and the East Coast Cluster contribute to this by encouraging standardisation.

6.1.3 Stage 2b - Shipping and non-pipeline transport (NPT):

NPT can support the development of CCS in the UK, whilst minimising logistical and economic barriers by providing an alternative solution for regions with geographic or infrastructure constraints which will enable broader participation in CCS efforts. In addition to the cost benefits, NPT allows greater flexibility and resilience, allowing emitters to transport CO_2 to multiple storage sites, which provides redundancy and resilience in the market in case of storage disruptions or outages. If emitters have more flexibility over their chosen storage site this will foster a more competitive environment. A result of this will be higher quality and innovation which will drive technological advancements, and efficient resource allocation as competitive environments encourage firms to use resources efficiently to minimise cost, and subsequently drive down the cost. Furthermore, the use of NPT facilities intermodal transport chains, which combine road, rail, ship and pipeline transportation methods, minimising the cost for emitters and again allowing small and dispersed emitters to enter broader storage networks.

Ship-based transport of CO_2 has gained traction for early CCS deployment due to its lower capital investment requirements and suitability for long distances and smaller volumes. Projects like Norway's Northern Lights are leading the way in cross-border liquefied CO_2 transport, demonstrating its potential for regions with dispersed storage reservoirs, and showcasing the feasibility of NPT for large-scale CCS deployment. Similar developments are already being planned for UK clusters such as the South Wales Industrial cluster and Viking CCS, where shipping and rail are integral to CO_2 transport strategies.

Cost reduction strategies for CO_2 transportation via shipping are critical in the emerging CCS industry. One effective approach is the development of standardised port infrastructure for loading and unloading liquid CO_2 (LCO_2). This standardisation can significantly reduce port handling costs, which constitute a major expense, especially on shorter shipping routes [46]. Shipping can function as complementary method for CO_2 transport for smaller or remote emissions sources and offering cost-effective deployment and flexibility where pipeline infrastructure is impractical. On the other hand, some assessments of shipping and pipeline transportation costs for CO_2 fall within a similar range, estimating both at £5-30 per tonne. This makes them direct substitutes, with the optimal choice depending on factors such as scale, location, and deployment timelines. Shipping is particularly advantageous for transporting large volumes over distances exceeding 300 km. Medium-pressure ships, which are already in widespread use, can provide cost-efficient solutions for major CCS projects [47] . These cost reduction variables, as well as cost reductions from other factors such as economies of scale, energy savings etc., are summarised in Table 7 below. These variables will form the base of our cost reduction assumptions in our cost model.

Intermodal transport chains

Combining multiple transport methods such as rail or road to ports for shipping, minimises the costs for emitters far from storage sites and allows small and dispersed emitters to enter broader storage networks. This will also increase utilisation of the storage facilities, increase cost efficiencies. Rail is suitable for inland transport, and rail is suitable for smaller scale operations.

As highlighted above the development of clusters and shared infrastructure is a major factor for the reduction in CCS cost. However, for emitters located outside pipeline connection regions, NPT will provide an essential link, ensuring access to storage facilities without costly infrastructure development.

NPT is not without its challenges. Shipping and rail transport of CO_2 will require significant infrastructure at ports and rail hubs. There are limited port and rail network capacities pose logistical challenges for the adoption of NPT in the UK, establishing these facilities can be capital-intensive. The use of multiple transport modes can also increase logistical complexity. There is a need for a streamlined regulatory process to expedite NPT deployment [47] . DESNZ are currently looking at paying for NPT through the capture business models. This is consistent with projects that are directly connected to a pipeline and are trying to determine how NPT fees should interact with existing payments including the strike price and T&S charges.

Economic Viability of Transport Modes

In the UK, pipelines remain the most economically viable option for large-scale CCS projects due to their efficiency and the country's geological suitability for CO_2 storage. For example, the East Coast Cluster and HyNet are focussing on pipeline infrastructure, taking advantage of suitable onshore and offshore geology for storage. Existing natural gas pipelines can often be retrofitted for CO_2 transport, further reducing capital costs, although more recent studies have shown that it is only a very small proportion (approximately 25%) of the

UK's existing pipelines would be reusable for CO_2 transportation in the dense phase with the current standards [48] . Refrigeration and NPT transport methods are expected to play niche roles in specific contexts, such as international collaborations or small-scale projects. The use of shipping for the transportation of CO_2 from longer distances will allow the UK to utilise its abundant storage from other regions, contributing to the overall economic viability of carbon capture for the UK, by reducing storage costs. Shipping comes with the need to have marine CO_2 import facilities developed and owned by storage operators. The associated British Ports (ABP), for example, is seeking to construct, operate and maintain the Immingham Green Energy Terminal (IGET) which has the potential to develop an associated CO_2 import facility, again allowing the UK to leverage its storage capacity for international emitters.

As more emitters connect to a centralised CCS network, shared infrastructure will enable significant cost efficiencies. Shared infrastructure will allow for the costs of transport infrastructure to be distributed across multiple users, lowering costs for participants. As the CCS sector continues to expand, advancements in technology and increasing economies of scale will drive cost efficiencies across both transport methods. While pipeline infrastructure will dominate the UK's CCS landscape, the flexibility and adaptability of refrigeration and shipping ensure these methods will remain critical for a comprehensive CCS strategy. Doubling or halving capture costs has a significant impact on total system affordability but does not drastically alter infrastructure design. This underscores the need to prioritise cost reductions in capture technologies. For additional details on non-pipeline transport, refer to section 7.3 of the report.

Key Recommendations for cost improvement opportunities in transport:

Pipeline Transportation

- UK Government should prioritise funding and policy support for the development of shared pipeline infrastructure in industrial clusters like Humber and Teesside to maximise economies of scale. Promote dense-phase CO_2 transport by setting volume thresholds and supporting emitters in achieving them to reduce operational energy requirements.

Shipping and Non-Pipeline Transport (NPT)

UK Government should:

- Support the development of standardised port infrastructure for liquid CO_2 loading and unloading to reduce costs and encourage competition among storage operators. Facilitate intermodal transport chains (e.g., rail and road to ports) by subsidising key infrastructure projects in geographically isolated areas.
- Facilitate cross-border collaborations by supporting projects like the South Wales Industrial Cluster and Viking CCS, which integrate shipping into their transport strategies.

Industry should:

- invest in modular and scalable NPT solutions, and develop partnerships with rail, shipping, and port operators to streamline supply chains.
- Partner with international emitters to explore opportunities for CO_2 imports, using shipping as a flexible transport mode, and invest in marine infrastructure to capture emerging markets for cross-border CO_2 transport and storage, positioning the UK as a leader in global CCS solutions.

Standardisation and Innovation

- **UK Government:** Establish technical and operational standards for CO_2 transport infrastructure, including pipelines, ships, and ports, to enable cost-effective scaling and reduce project risks.
- **Private Companies:** can drive standardisation efforts by adopting uniform design and operational practices for CO_2 transport infrastructure.

Table 7: Cost Reduction Variables

Cost reduction factor	Cost reduction variables	Unit	Description
Shipping	10 – 25	£/tonne of CO_2	Depending on distance, ship size and operational efficiency.
Liquefaction	6.5	£/tonne of CO_2	Assuming electricity costs of £0.10/kWh, liquefaction consumes around 65 KWh of CO_2 with energy costs varying on electricity price.
Shipping (Economies of scale)	10 – 15	£/tonne of CO_2	Economies of scale can bring shipping costs down. For routes around 300km.
Storage (onsite buffer storage for NPT)	2-4	£/tonne of CO_2	Onsite buffer storage requirements for NPT modes add to CAPEX but are shared across multiple emitters in cluster configurations. Costs for buffer storage vary based on capacity but are estimated to be around this value.
Technology improvements and process optimisation	Below 50	£/tonne of CO_2	Innovations in capture technology such as advanced solvents or process intensification, are expected to reduce capture costs from the current £60-£80 per tonne to below £50 per tonne as new methods become commercially viable.
Cluster Development	10 – 15	£/tonne of CO_2	Estimated cost reduction range when leveraging shared infrastructure compared to stand alone facilities.
Micro-Networks for Small emitter	20-30	% per tonne	By forming "micro-networks," smaller emitters can pool resources and share operational costs, reducing barriers to participation in carbon capture services. Dependent on the level of integration and proximity to storage sites.
Integration with Non-Pipeline Transport (Shipping):	10-25	£/tonne of CO_2	Non-pipeline transport options, such as shipping or rail, provide flexible and scalable alternatives for emitters far from major pipeline networks.
Integration with existing infrastructure	5 -10	£/tonne of CO_2	Using existing pipelines or storage facilities particularly in regions with mature oil and gas infrastructure like the North Sea.
Economies of scale and Cluster development	20-30	% per tonne of CO_2	Reduction in cost of CO_2 capture and storage depending on the size and efficiency of the cluster.
Advancements in capture technologies	40-50	£/tonne of CO_2	Drop from £60-80 per tonne as capture technologies mature.
Energy Efficiency improvements	5-8	£/tonne of CO_2	Reducing energy consumption during capture and regeneration could save this much per tonne of CO_2 capture. Process innovations such as heat recovery in capture systems reduces the overall energy demand.
Utilising existing infrastructure	5-15	£/tonne of CO_2	Repurposing existing oil and gas infrastructure for CO_2 transport and storage avoids significant capital expenditure on infrastructure.
Standardisation and modularisation	5-10	£/tonne of CO_2	Could save within that range, particularly in regions adopting uniform specifications across emitters. Standardising components like CO_2 compressors and absorbers, as well as modularising designs reduces custom engineering costs and shortens timelines.
Shared infrastructure savings	10-15	£/tonne of CO_2	A reduction of this amount is anticipated as shared infrastructure savings for shared pipelines and compressor systems within industrial clusters.
Integrated Heat Recovery	5-8	£/tonne of CO_2	Waste heat recovery from high-temperature flue gases can save approximately this much per tonne of CO_2 in steam costs for solvent regeneration.
Flue Gas Blower	15	% of Total OPEX	Positioning blowers downstream of pre-treatment cooling systems reduces their size and power demand, achieving up to 15% OPEX savings.
Non-pipeline transport (shipping)	5 – 30	£/tonne of CO_2	NPT options like shipping, road, and rail provide flexibility and cost advantages for small or remote sources not connected to pipeline networks.
Modular Technologies for small Emitters	20-30	% per tonne of CO_2	Essential for small and remote emitters. The cost reduction % varies depending on deployment scale.

Sources: Arup analysis across multiple sources

6.1.4 Stage 3 - Storage

The preparation and selection of storage sites play a critical role in determining overall costs. The lowest-cost CCS strategies typically combine large-scale storage facilities with shared infrastructure and well-established, low-risk technologies. Onshore storage in high-quality reservoirs is generally less expensive than offshore storage due to the additional infrastructure and operational complexities required for offshore sites. The UK however has significant offshore storage potential and geological suitability and is expected to prioritise these offshore geological formations for carbon storage. In addition, the UK has a third of Europe's potential carbon storage, meaning we can leverage domestic carbon storage potential not only for domestically captured carbon, but also for carbon captured elsewhere in Europe. Hosting captured carbon from other countries will increase use of our storage facilities which will subsequently reduce the cost of storage.

Onshore storage in the UK

Offshore geographical storage is the primary storage solution for the UK currently. However onshore geographical storage does presents positive opportunities to reduce CO_2 transport costs by reducing CO_2 transport distances, and decarbonise dispersed point sources for small and medium sized emitters outside industrial clusters by providing localised storage solutions for dispersed industrial sites which are not well-served by offshore transport and storage networks. Despite these positive opportunities there are challenges that come with onshore storage. There is limited data on the storage capacity, injectivity and containment security of onshore sites in comparison to offshore. In addition, the UK lacks a licensing or permitting framework for onshore storage in comparison the well-defined system for offshore storage governed by the North Sea Transition Authority (NSTA), and onshore storage faces significant public opposition due to concerns over safety, and negative perceptions of subsurface technologies like fracking, have created additional resistance to onshore storage. These challenges make it unlikely that onshore storage becomes a dominant storage solution for the UK, but onshore storage could play a supplementary role in the carbon storage environment.

Lessons on carbon storage from other nations

As illustrated in Table 8, different countries have different approaches regarding carbon storage. There are several lessons we can translate from the approaches of other nations and apply to the UK, that could lead to cost reductions in our approach to storage. For example, both China and Canada emphasise clustering emitters around targeted storage sites to reduce costs for transportation and simultaneously increase storage use, which will lead to a reduction in cost per unit of storage over time. If we expand the UK's existing industrial clusters (Humber and Teesside) with dedicated CO_2 pipelines and offshore hubs we could replicate their cost efficiency of this approach.

Another common theme we observe across the selected countries, is the use of EOR. Using EOR lowers the cost of storage by generating revenue from oil recovery, and its adoption in the countries above demonstrates that value can be found in EOR for cost recovery. However, currently the exploration of EOR in the UK, and other methods of utilisation that facilitate business-as-usual fossil fuel use are perceived as damaging. Leading UK oil companies cite the unlikelihood of CCS for EOR in the UK, stating their lack of intention in developing this method [49]. Instead, developing shared infrastructure and injection, and incentivising collaboration and maximizing utilisation of storage through imports of CO_2 can help reduce storage costs in the UK while meeting emissions targets.

Promoting utilisation technologies can decrease dependence on large-scale storage infrastructure, reducing its overall cost in the value chain. The UK could further support research into CO_2 mineralisation, synthetic fuel production, or in construction materials. In construction, there are emerging CO_2 utilisation technologies, in which captured CO_2 can improve the materials properties while sequestering CO_2, reducing emissions associated with traditional curing processes and locking away CO_2 in a stable form [50].

The UK's offshore CO_2 storage capacity is estimated at 78 billion tonnes, nearly one-third of Europe's total geological storage potential [51]. Cross-border CO_2 transport and storage, if enabled, could significantly enhance utilisation rates. Currently, third-party storage is permitted between EU and EEA countries but not between the EU/EEA and the UK. If regulatory barriers are addressed, UK storage sites could accept CO_2 from EU sources, offering a cost-effective option for Europe while maximising the UK's storage assets. According to a CCSA report, by 2030, up to 16 million tonnes of CO_2 annually from EU sources could be stored in UK facilities. Increased utilisation would significantly decrease per-tonne storage costs.

Table 8: Carbon Storage Approach by Countries

Country	Carbon storage approach
China	Focuses heavily on scaling CCS through EOR and onshore saline aquifer storage. Also have an emphasis on integrating CCS into industrial clusters
Canada	Robust CCS ecosystem that includes onshore saline aquifer storage, offshore storage of CO_2 and a range of other waste gases (British Columbia), as well as EOR and shared infrastructure (CO_2 Trunk Line, Alberta).
Norway	Focus on offshore storage in both depleted oil and gas and saline aquifers, as well as EOR. Northern Lights Project is a major CO_2 injection facility near Bergen. CO_2 is captured and stored in saline aquifers near to major producing O&G wells.
UAE	The UAE's Al Reyadah project captures CO_2 from steel production and injects it into oil reservoirs for EOR
Germany	Strong emphasis on reducing reliance on subsurface storage by utilising captured CO_2 in value added products and focus on integrating CCS with CO_2 utilisation technologies such as mineralisation and conversion into synthetic fuels and chemical.

Key Drivers of Carbon Storage Costs in the UK

Site Selection: The cost of storage varies considerably based on site characteristics. Large-scale storage facilities are essential for reducing costs. Proximity to major emission sources also minimises transportation costs, further improving economic feasibility. Offshore storage is inherently more expensive than onshore storage due to infrastructure requirements and operational challenges. For example:

- Onshore Sites: Reusing existing infrastructure, such as depleted oil and gas fields, offers the lowest-cost option for CO_2 storage. Onshore storage is estimated to be 50% cheaper than offshore storage, but the lack of regulatory clarity and potential social engagement costs create uncertainties in actual project costs [52].
- Offshore Sites: Offshore saline formations or depleted fields with no existing infrastructure to repurpose are among the most expensive options. Leveraging existing offshore sites in the North Sea and Irish Sea is critical to cost reduction. Expanding to new storage locations, such as in the English Channel, could further optimise the UK's storage network.

Deployment and Injection Rates: Accelerating deployment and maintaining high injection rates are key to reducing operational costs. A high injection rate maximises the efficiency of storage operations, spreading fixed costs over greater volumes of CO_2 and lowering the cost per tonne.

Technological Advancements: Technological innovation is expected to deliver modest cost reductions in carbon storage. These improvements include:

- Equipment Refinement: Optimising existing technologies for higher reliability and efficiency.
- Digital Innovation: Automation and predictive maintenance can lower capital expenditure and operational expenditure. The International Energy Agency Greenhouse Gas programme supports this notion, with estimates that cost reductions of over $45m in CAPEX and $60m in OPEX could be achieved for a theoretical CCS facility storing CO_2 in offshore saline formations through digital advancements [53].

The UK's geological resources and policy environment make offshore storage the focus for early CCS deployment. By increasing storage utilisation, selecting optimal sites, maintaining high deployment rates, and leveraging technological advancements, the UK can substantially reduce the costs of offshore carbon storage. These efforts will enhance the economic viability of CCS as a key component of the UK's decarbonisation strategy.

Recommendations for cost improvement in storage:

Incentivising Marine CO_2 Import Facilities: Establishing financial incentives for storage operators to develop marine CO_2 import terminals will enable the UK to leverage its vast offshore storage capacity, attract international emitters, and generate economic benefits.

Promoting Carbon Utilisation Technologies: Reducing reliance on large-scale storage through CO_2 utilisation can lower overall costs. The UK should support research and commercialisation of CO_2 mineralisation, synthetic fuel production, and applications in construction (e.g., CO_2-cured materials). These technologies enhance productivity, sequester CO_2, and improve material performance while reducing emissions.

Expanding Cross-Border CO_2 Storage: Addressing regulatory barriers to cross-border CO_2 transport would allow UK storage sites to accept emissions from EU sources, optimising storage utilisation and reducing costs. By 2030, up to 16 million tonnes of CO_2 annually from EU emitters could be stored in the UK, enhancing the financial viability of large-scale CCS.

Optimising Offshore Storage Deployment: The UK's offshore geological storage potential, estimated at 78 billion tonnes, provides a strong foundation for CCS. By strategically selecting storage sites, maintaining high deployment rates, and integrating technological advancements, the UK can lower the costs of offshore storage and establish CCS as a central pillar of its decarbonisation strategy.

6.1.5 Conclusion

Costs are always project specific and there are significant variations in the cost of each of the components. Figure 14 which is from a study published by the Global CCS institute, further highlights this variation, illustrating how costs can range across each of the components in the CCS value chain. This underscores the importance of tailoring CCS strategies to regional conditions and the need for infrastructure investments that maximise economies of scale and operational efficiencies.

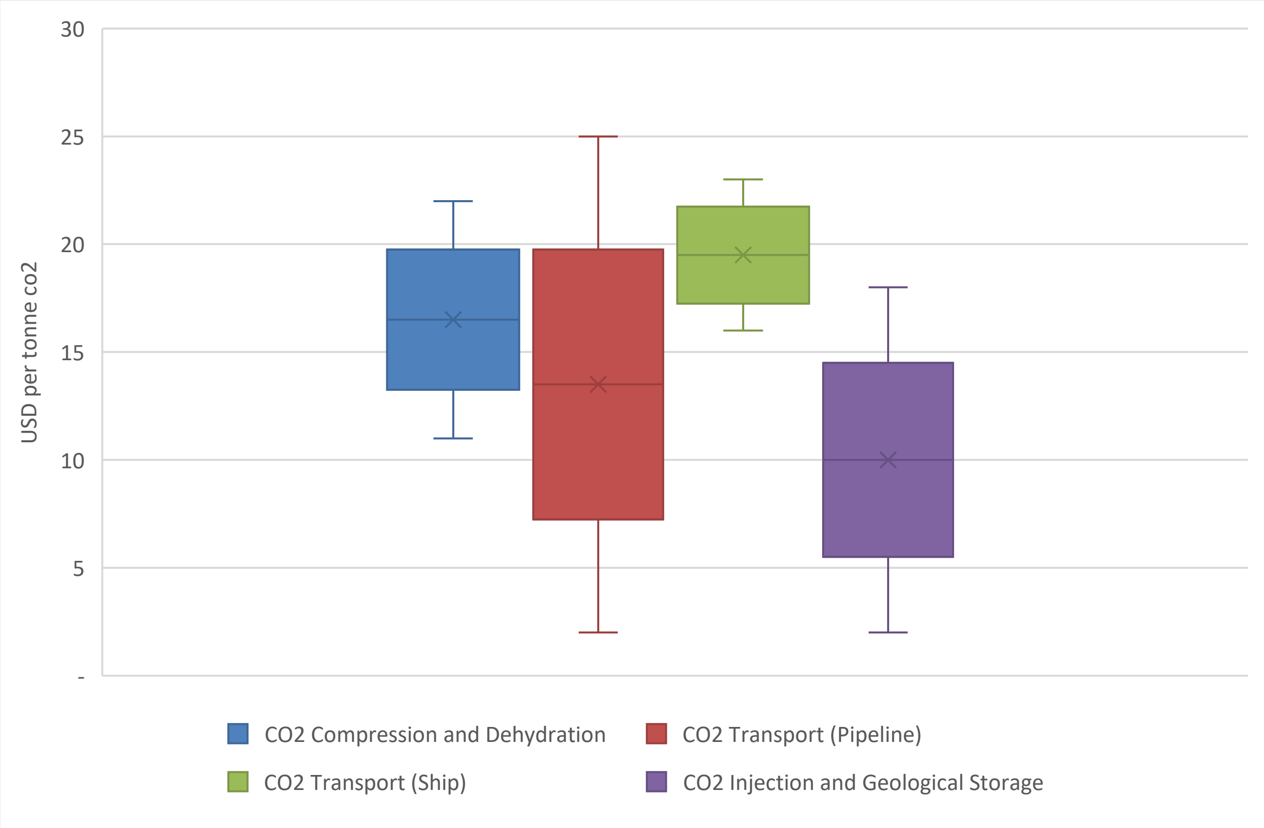


Figure 14: Indicative Cost Ranges for CCS Value Chain Components (Excluding Capture)

Source: Global CCS Institute, Technology Readiness and Cost of CCS, 2021 (2020 price base)

Strategic collaboration, advanced technologies and infrastructure optimisation are key drivers for making carbon capture more economically viable in the UK. The key cost efficiencies we have identified throughout this section are summarised below:

Economies of Scale: Projects can benefit from economies of scale across all stages of the value chain. Larger Projects, such as pipelines with greater capacities or high-volume compression systems, benefit from lower per-tonne costs due to economies of scale. Similarly, the use of shared infrastructure allows for increased scale of production which will reduce the per-tonne cost of captured CO_2. However, it should be noted, that there is a high initial investment for scaling CCS systems. In addition, there are break points for some of the equipment. For example, for projects capturing over 1 million tonnes of CO_2 per annum, there is a design break point where larger, rectangular equipment (e.g., absorber columns) become more cost-effective than cylindrical options.

Transport Infrastructure: The type of transport infrastructure plays a critical role in CCS economics. Pipelines generally offer the lowest transportation costs for high-volume and shorter-distance projects. However, shipping provides flexibility and accessibility for projects involving dispersed or international storage sites and is more cost-efficient for longer distances. Pipeline infrastructure, while effective, risks excluding smaller emitters that lack direct access. As such, alternative transport methods - such as rail or intermodal transportation - can minimise costs for smaller and dispersed emitters. These alternatives enable broader participation in CCS networks, improving economies of scale and increasing competition. Over the medium to long term, such integration can lead to reduced costs and more flexible storage site options.

Storage utilisation: Maximising storage utilisation directly reduces the per-tonne cost of CO_2 storage. Methods to increase utilisation include:

- **Flexible Transport Solutions**: Expanding transport options to accommodate smaller and dispersed emitters ensures fuller utilisation of storage sites.
- **Cross-Border Cooperation**: Enabling international CO_2 storage agreements can improve utilisation rates by broadening the pool of emitters contributing to UK storage facilities.

- **Dynamic Allocation**: Real-time monitoring and dynamic allocation of CO_2 to underutilised storage sites optimise capacity use.
- **Enhanced Injection Techniques**: High-capacity injection systems reduce downtime and operational inefficiencies, ensuring that storage sites operate closer to their maximum potential.

Whole system cost reduction opportunities:

Shared infrastructure: Establishing shared liquefaction, storage, and loading facilities at hubs may reduce operational expenses for emitters, by 'breaking the chain' and limiting emitter exposure to CO_2 transport & storage risks. This clustering approach may also allow smaller emitters to benefit from economies of scale. Micro-networks - where multiple smaller emitters pool resources - can distribute costs across participants, reducing individual capital expenditures and barriers to CCS adoption. By leveraging shared infrastructure, like pipelines and compressors, between emitters, costs can be distributed across multiple participants. Depending on the level of integration and proximity to storage, shared infrastructure can cut costs by £10-£15 [54]. However, implementing shared infrastructure relies on proximity and coordination among emitters. In regions with dispersed industries, substantial upfront investments are required to establish networks, potentially limiting participation from smaller facilities.

6.2 Reduction of Capture Technology Costs

Technological innovations are at the core of reducing the cost and improving the efficiency of carbon capture in the UK. The high cost of total CO_2 capture comprises a combination of both energy demand and capital cost. Energy efficiency has improved greatly over the last couple of decades reducing the cost of energy, and the use of renewable energy sources is set to bring further reductions in cost for CO_2 capture. On the other hand, capital costs remain a challenge for CO_2 capture, with a limited number of commercial systems in operation. Improvements in technologies have, although at a slow rate, reduced the capital cost of capture. The increased deployment of CCS will yield continued reductions in carbon capture technologies through learning induced improvements and creating a culture of sharing knowledge.

Carbon capture technology innovation

- Post combustion carbon capture
- Advancements in solvent technology
- Integration of heat recovery - Utilising exothermic reactions during CO_2 conversion or mineralisation to drive endothermic processes like solvent regeneration is another proposed strategy. Heat recovery reduces the net energy input, making the process more sustainable and cost-effective.

6.2.1 Post Combustion Carbon Capture (PCC)

Proprietary vs open art amines

Propriety amines are developed and owned by technology licensors who provide performance guaranteed for their use. These amines often have optimised chemical properties for specific application, including lower regeneration energy and higher CO_2 loading capacities. Open art solvents such as generic MEA or CESAR, are widely studied and technologically feasible. There are designs which are publicly available, but none have been deployed at scale to date. They offer lower upfront costs as no licencing fees are requires. As mentioned above researchers are advocating for exploring non-aqueous solvents, and amino acid-based solvents, which could bypass the inefficiencies of traditional methods. The technological performance of non-amine-based solvents has not been proven at scale yet. The maturity of the available CO_2 technologies is important as use of unproven or novel technology will require qualification. This adds risk to the project and requires additional time and resourcing during projects development.

Cost, performance and risk need to be balanced when choosing between proprietary and open art amines. Proprietary amines are favoured in high-risk projects or where performance guarantees are critical. Open-art systems are considered more suitable for pilot-scale or low-risk applications. The table below summarises the advantages and challenges of both.

Table 9: Proprietary Amines vs. Open-Art Amines

	Proprietary amines	Open-art amines
Advantages	Performance guarantees from licensors who back their proprietary solvents with guarantees for efficiency and longevity	Cost savings as these solvents eliminate the need for licencing agreements reducing CAPEX
	Reduced risk: proven performance data form other installations de risks adoption	Flexibility as users can customise and optimise the solvent system without restrictions
Challenges	Higher licencing costs as proprietary amines typically require payment of licencing fees, increasing upfront costs	Lack of guarantees: open art systems lack the performance guarantees provided by licensors, increasing operational risks.
	Limited flexibility as users must adhere to the licensor's operational guidelines, limiting innovation or adaption	Lower efficiency as generic solvents may require higher energy input for regeneration in comparison to proprietary alternatives

6.2.2 Capital cost reduction

The capital cost of the capture systems is influenced by (i) the size of the equipment (ii) the selection of materials and (iii) the complexity of the process. Innovations in solvent chemistry such as the development of next-generation amines, aim to reduce energy requirements for CO_2 capture and regeneration. Modular and compact systems are also being created with carbon capture units that are up to 10 times smaller than conventional systems, reducing both capital and operational expenditure [55]. Improvements in technology are either incremental (existing technologies) or breakthrough (new technologies). Incremental improvements are lower risk and more predictable. Examples of incremental improvements include the development of new CO_2 capture solvents, improved adsorbents, enhanced or more robust membranes, and through the use of engineering techniques like modularisation. Breakthrough improvements can be used to achieve step-change cost improvements over existing technologies. Examples include direct air capture (DAC) and inherent CO_2 capture technologies.

The table below summarises next generation capture technologies being explored by different vendors within industry. The majority of carbon capture technology cost reductions that have been explored throughout the literature and in practical applications are incremental improvements. However, historically incremental improvements in solvent based capture have not led to significant cost reductions due to inefficiencies inherent in water-heavy solvents, which dominate the process but do not actively contribute to CO_2 capture [56]. To overcome limitations, researchers advocate for exploring non-aqueous solvents, phase-change systems, and amino acid-based solvents, which could bypass the inefficiencies of traditional methods.

In the past decade, solvent-based processes have undergone numerous changes in formulation and process to increase efficiency while reducing costs for point-source emissions. Shifting from simple strippers to more efficient configurations such as, lean-vapour compression with absorber intercooling or two-stage flash regeneration as a means to recover heat. The continued development of advanced solvents aims to reduce energy requirements and operational costs.

The majority of innovations e.g., solvents, modular systems, process optimisation, focus on post combustion capture due to its adaptability and prevalence in retrofitting. Post combustion carbon capture captures CO_2 from the flue gases produced after fuel combustion and typically uses chemical solvents such as amines to absorb CO_2. Post-combustion carbon capture is readily available commercially and has a high CO_2 recovery potential of up to 95%. Its application includes retrofitting existing power plants and industrial facilities like cement and steel which are large emitters for the UK which are notoriously hard to decarbonise. Modular CCS systems are essential for small, remote emitters, which make up a large portion of UK industrial emissions. Without cost effective modular solutions, capturing emissions from these sites is not economically viable. Modular systems could lower the per-tonne capture cost by 20-30% depending on the deployment scale.

There are fewer innovations that target pre-combustion and oxy-fuel carbon capture systems. Oxy-fuel carbon capture combusts fuel in pure oxygen rather than air producing a flue gas primarily composed of CO_2 and water vapor. Although it produces a nearly pure CO_2 stream with a simplified capture process thereafter, it requires expensive oxygen production systems. Pre-combustion capture, captures CO_2 before fuel combustion and its applications are better suited to integrated gasification combined cycle power plants and hydrogen production plants. With this type of capture system, CO_2 is captured from a concentrated stream at higher pressures which, as stated above, contribute to making the process more energy efficient. However, this process also requires significant upfront investment and is limited in its application.

We have explored in brief detail the latest advancements in capture technologies, their key benefits and examples of applications in the UK where applicable.

Table 10: Summary of Latest Advancements in Capture Technologies

	Capture system type	Description	Benefits	Examples in the UK
Advanced solvent technologies	Post- combustion	Next-generation solvents are being developed to improve CO_2 absorption efficiency and reduce the energy required for regeneration. These include: • **Amine blends**: Enhanced formulations that balance absorption speed with thermal stability. • **Water-lean solvents**: Such as 2-EEMPA, which require less energy for CO_2 release due to lower water content. • **Solid sorbents and ionic liquids**: These materials hold potential for reducing solvent losses and minimising energy demands.	• Lower regeneration energy reduces operational costs. • Enhanced solvent lifespans minimise replacement expenses.	C-Capture, a UK-based company, has developed a solvent system that is free of amines and does not rely on toxic chemicals, offering safer and more cost-effective options.
Modular and compact carbon capture systems	Post- combustion	Pre-fabricated, skid-mounted systems that are compact and scalable for smaller industrial emitters. These systems are especially useful for distributed or smaller-scale facilities.	• Faster deployment and reduced engineering costs. • Scalability allows for incremental investment as demand grows. • *Modular capture systems for smaller and dispersed emission sources are identified as a way to integrate these emitters into the broader network without requiring extensive new infrastructure.*	Carbon Clean's modular systems are designed to reduce equipment footprint by up to **10 times**, making CCS viable for smaller emitters and hard-to-abate industries.
Process intensification	Post- combustion	This involves optimizing process configurations to reduce energy use and increase throughput. • **Absorber intercooling**: Reduces the temperature of the absorption process, enhancing solvent capacity. • **Lean vapour compression**: Compresses the CO_2-laden	• Improved energy efficiency leads to direct cost savings. • Compact configurations reduce capital expenditures.	Projects in the Humber and Teesside clusters incorporate process intensification to optimise CO_2 capture from flue gases.

		solvent, reducing the energy required during regeneration. • **Two-Stage Flash Regeneration**: Recovers waste heat for reboiler use, lowering thermal energy demands.		
Solid sorbent and membrane technologies	Post-Combustion (primarily) and Oxy-Fuel (potentially for CO_2 separation)	Alternative capture methods using solid materials or selective membranes for CO_2 separation. • **Solid Sorbents**: Capture CO_2 on a surface for later desorption with heat or pressure changes. • **Membranes**: Use selective barriers to separate CO_2 from other gases	• Lower operational costs for specific applications. • Reduced reliance on water-intensive systems.	The UK is exploring these technologies for deployment in sectors like cement and steel, where flue gas volumes and compositions pose challenges for traditional solvent systems.
Integration with utilisation technologies	Post-Combustion (primarily) and Pre-Combustion (for syngas utilisation)	Carbon capture is integrated with CO_2 utilisation technologies, converting captured CO_2 into valuable products like methanol, synthetic fuels, or building materials.	• Offsets capture costs by creating revenue streams. • Reduces energy requirements for long-distance transport.	Companies like Econic Technologies are developing ways to incorporate captured CO_2 into polymer production, offering a dual benefit of emissions reduction and material innovation.
Low-Pressure systems	Post- combustion	Innovative systems operate at lower pressures for solvent regeneration, reducing the energy demand for compression.	• Energy savings of up to **30%** in some configurations. • Reduced equipment wear and maintenance costs.	The Northern Lights project in Norway has demonstrated the feasibility of such systems, and UK projects are adopting similar designs to minimize costs.
Artificial Intelligence (AI) and Digital Twin Technologies	Applicable across all	AI-driven optimisation and digital twin models help improve real-time monitoring, predictive maintenance, and operational efficiency in CCS plants.	• Reduces downtime and operational inefficiencies. • Optimise energy use and process configurations.	The National Grid's CCS projects are utilising AI systems to simulate and optimise pipeline and capture processes.
Integration of Renewable Energy	Applicable across all	CCS plants are increasingly powered by renewable energy to reduce the carbon intensity of the capture process.	• Lowers the operational carbon footprint. • Reduces dependency on volatile fossil fuel prices.	CCS facilities in the East Coast Cluster are exploring renewable energy integration to power solvent regeneration systems.

6.2.3 Learning by doing

Solar PV modules have experienced learning rates of **18%** to **22%**, and module prices have fallen by around **80%** since 2010. Onshore wind has experienced a learning rate of **15%** for the cost of electricity delivered, as installed cost reductions. Wind turbine prices have fallen **38%** on average since 2009 [42]. The UK is the world leader in offshore wind installations, accounting for around 34% of installations. Technology costs for offshore wind have decreased rapidly over the last decade from 150 €/MWh in 2011 to 69 €/MWh in 2022 [43].

Recommendations from lessons learned:

Public and Private Collaboration

- UK Government should establish partnerships between public bodies and private firms to fund pilot projects and R&D for CCS technologies and expand innovation funding initiatives.

Leveraging Existing Resources and Skills

- UK Government should create reskilling programs to help workers from traditional energy sectors transition into CCS roles.

Setting Ambitious and Measurable Targets

- UK Government should set clear national targets for CCS capacity by 2030 and beyond, specifying sectoral contributions (e.g., industrial capture, power sector). Monitor and publish annual progress reports to ensure transparency and accountability.

Public Acceptance and Communication

- UK Government should launch nationwide campaigns to educate the public on CCS benefits, emphasising its role in achieving net-zero and creating jobs. Include community benefit schemes for regions hosting CCS infrastructure.
- Private companies should engage with local communities early in the project development process, addressing concerns about safety and environmental impacts. Highlight tangible benefits, such as economic development and employment opportunities.

Learning rates are important when it comes to development of certain technologies and can be a significant source of cost reduction. An observed trend is that as installed capacity increases the cost of technology decreases. The rate at which this happens is referred to as the learning rate, and we have seen excellent examples of this with other technologies such as solar PV modules and onshore wind technologies. For solar panels, with each doubling of installed capacity, the price of solar PV modules has dropped on average by 20%, and from 2010 to 2020, solar panel costs have reduced by over 80% due to learning by doing and economies of scale creating efficiencies in the manufacturing of these components. Similarly, wind turbine prices have fallen by 38% since 2009 [57].

Learning rates apply to carbon capture technology as well, and CCS has the potential to partially replicate these benefits as installed capacity increases, reflecting accumulated knowledge and economies of scale. For example, studies conducted for carbon capture learning rates found that a higher learning rate of 12% can bring; First of a Kind' (FOAK) capture plants closer to NOAK (N-th of a Kind) levels after approximately 30 installations, whereas a lower learning rate (3%) results in a 10%-20% reduction in FOAK costs, limiting the potential for significant cost improvements. With a rapid ramp up in installations predicted by the 2030s, coinciding with policy shifts i.e., UK ETS and the phase out of free allowances, and government funding for CCS, and a reduction FOAK costs to near NOAK levels making installations more attractive to investors. Early movers will play a critical role in driving down costs through learning [58].

It is also important to note that the maturity of the technology being used determines the significance of learning rates as a variable will have in reducing carbon capture costs as installed capacity increases. For example, Post combustion CO_2 capture technologies like amine-based absorption are already mature, which limits the cost reduction from technological improvements, but could see cost reductions in auxiliary equipment and solvent usage optimisation. Ultimately, as adoption scales, and the supply chain matures, the production of key capture components becomes more competitive lowering costs through bulk manufacturing and competition. In addition, over time, standardised designs of capture technologies, can reduce engineering costs and shorten project timelines.

6.2.4 Operational efficiencies

Carbon capture remains energy-intensive, and operational efficiencies play a critical role in reducing costs across the CCS value chain. Key strategies for improving operational efficiencies include:

- **Energy Optimisation**: Reducing the energy required for CO_2 capture and compression is vital. For example, advanced solvent formulations with lower regeneration energy demands can significantly cut energy costs. Heat integration within industrial sites—such as using waste heat—reduces the need for external energy inputs, further lowering costs.
- **Integration with Existing Systems**: Leveraging existing infrastructure can drive efficiencies. At the Humber Zero – VPI Immingham project, steam from combined heat and power (CHP) systems is utilised for solvent regeneration, reducing the need for additional boilers. Similarly, retrofitting existing industrial equipment for CO_2 capture avoids duplicative infrastructure investments.
- **Heat Recovery**: Advanced heat recovery technologies, such as waste heat energy exchangers, are effective in reducing energy consumption, particularly for high-temperature flue gas streams. By capturing and reusing waste heat, facilities can significantly reduce operational costs.
- **Automation and Digital Innovation**: Automating processes and employing predictive maintenance tools enhance reliability and operational efficiency. Real-time data monitoring and analytics can optimise energy use, reduce downtime, and lower maintenance costs.
- **Optimised Injection Techniques**: Improved CO_2 injection technologies that enable high-capacity and consistent flow rates reduce operational interruptions and maximise storage efficiency.
- **Renewable Energy Use**: Integrating renewable energy sources, such as solar or wind power, for CCS operations can reduce dependency on conventional electricity and lower operating costs, especially as renewable energy costs continue to decline.

These operational improvements are complemented by ongoing R&D efforts to develop more efficient capture technologies, refine solvent formulations, and optimise equipment designs, all contributing to a more cost-effective CCS ecosystem. Technological innovation is expected to deliver substantial cost reductions in storage and operational processes. These advancements include:

- Digital Innovation: Automation and predictive maintenance lower both capital and operational expenditures.
- Advanced Solvent Regeneration: New solvent formulations and regeneration techniques improve energy efficiency, reducing operational costs.
- Heat Recovery Systems: Utilising waste heat for CO_2 capture and compression minimises additional energy input, further driving cost efficiencies.

6.3 Modelling Methodology - Cost Reduction Scenarios

This report has considered 3 CCS cost improvement scenarios in the UK, the base case, low case and high case.

- **Base case:** The most likely scenario based on a trajectory of the current rate of cost improvements across the cost-reduction factors. For this case, we anticipate some improved development in the industry, specifically, technological improvements as well as good information sharing between traditional competitors contributing to accelerated learning rates. Moderate advancements in capture technologies are also assumed, as well as effective integration of CO_2 capture, transport and storage with existing infrastructure, ongoing energy efficiency improvements and the development of clusters/hubs.
- **High case:** The most optimistic or ambitious scenario based on the realisation of all cost-reduction factors: For this case we anticipate technology breakthroughs and faster economies of scale, leading to significant cost reductions across the CCS system. This would be triggered by a rapid implementation of CCS across one or more major global industrial sectors (such as cement/ aggregate/ concrete

production), and multiple global economic zones (such as Europe and North America, or Europe and South East Asia). Integrated pipeline and non-pipeline transportation is achieved in this scenario, enabling maximum liquidity in the CO_2 transport system, including competition between stores and optionality for CO_2 cargo delivery. Standardisation occurs within transportation (such as in tank sizes/ temperatures/ pressures for a) marine and b) rail transport, CO_2 purities for CO_2 pipelines, MMV and metering standards and technologies), enabling further CO_2 market integration, supported by aligned ETS systems in the EU, UK and in South East Asia. In capture, modularisation accelerates allowing cost-effective CO_2 capture in ever-smaller emitters, along with integrated waste heat reuse in industrial applications. Storage utilisation is maximised and hubs are developed to hold cargoes of captured CO_2 prior to injection.

- **Low case**: The most conservative scenario sees slow progress on the cost-reduction factors. For this case, implementation of CCS in the UK relies on a series of government-managed 'Track' programmes enabling only minor cost improvements, as each programme is developed separately and with more emphasis on racing to completion of large and complex clusters than more widespread scaling of CCS. Cost improvements are achieved largely via imported products and skills, since scale and integration of CCS is achieved first in the US, China and Indonesia. Self-sustaining economic viability of CCS in the UK is delayed, and the UK's CCS sector becomes a source of public controversy and pressure on public finances while still in its infancy.

The 4 core CCS deployment types have been examined. These are:

1. Natural Gas-Fired Power Generation + CO_2 Capture, Transport & Storage
2. Industrial carbon capture (Cement) + CO_2 Capture, Transport & Storage
3. Waste-to-Energy + CO_2 Capture, Transport & Storage
4. Hydrogen production from Methane (via SMR or ATR) + CO_2 Capture, Transport & Storage

6.4 Inputs

The cost of each of the components and subcomponents of CCS cost vary according to the size and location of the facility, and the characteristics of the source CO_2. There is a wide range in variability of costs depending on these factors, and with many elements not yet known or established due to the infancy of the industry. While precise future costs are uncertain, the most recent and high integrity data available has been used.

The starting costs for CCS by sector (if implemented today) are the following:

Power Generation	104	£/tCO_2	*Source: Arup Figures*
Industrial Carbon Capture (Cement)	91	£/tCO_2	*Source: Arup Figures*
Waste-to-Energy	170	£/tCO_2	*Source: Arup Figures*
Hydrogen production	91	£/tCO_2	*Source: Arup Figures*

These cost figures were attained from our internal cost database, where we have pulled together costs reported from numerous sources for each of the industries, and validated against technical and project experience. Sources include the Institute for Energy Economics, the IEA and the Global CCS institute. An exhaustive list of the sources included is provided in the Appendix A2.

These costs were then reduced by the following factors over the period to 2037:

Economies of scale	13	%
Integration with existing infrastructure	7.50	£/tCO_2
Advancement in capture technologies	25.00	£/tCO_2
Energy efficiency improvements	6.50	£/tCO_2
Standardisation and modularisation	7.50	£/tCO_2
Shared infrastructure savings	12.50	£/tCO_2
Waste heat recovery & reuse	6.50	£/tCO_2
Learning rate	11	%

For the cost reduction variables, we have opted to use a single, reputable source for each of the cost reduction variables in the model where possible, to ensure the data is consistent and directly aligned with the specific assumptions and methodologies of the selected source, providing a clear and focused basis for the model.

For the ***LOW*** scenario we have assumed the following saving factors:

Shared infrastructure savings	12.50	£/tCO_2	Full benefit achieved by 2035
Energy efficiency	6.50	£/tCO_2	Benefit plateau after 2035
Learning rate	11	%	Applied from 2030 onwards

Learning Rates: Studies show that learning rate increases with every doubling of installed capacity. UK CCS will also benefit from learnings gathered from global deployments of CCS, such as in the USA where onshore pipeline transport of CO_2 is well understood, mainland Europe where CO_2 transport by rail already occurs and is growing more widespread, and South and East Asia where shipping of CO_2 in merchant vessels is likely to get to scale first. As such, we have assumed that the learning rate will be applied in 2030, after which it will continue to grow until capacity doubles again in 2035, when the learning rate will again accelerate. Cost savings from learning rates are likely to continue to accelerate exponentially as the CCS system develops.

Shared infrastructure savings: Savings from shared infrastructure such as CO_2 transport pipelines and storage hubs has a limited capacity. Once the capacity is fully utilised additional projects will require either new infrastructure or expansion of existing system which will come at a higher cost. There are known technical risks with shared CO_2 transport infrastructure which we anticipate will limit the savings which can be achieved by combined trunk lines and even combined injection and storage for multiple emitters (impurity cross-contamination & corrosion risks). In our model, we have therefore assumed clusters to reach full capacity by 2035 after which savings from shared infrastructure will remain constant.

For the ***BASE*** scenario we have assumed the following saving factors:

Economies of scale	13	%	Accelerating benefit as global infrastructure system realised and CO_2 capture at industrial facilities burning natural gas, oil or solid fuels becomes a norm
Shared infrastructure savings	12.50	£/tCO_2	Limited benefit after 2035
Energy efficiency improvements	6.50	£/tCO_2	Ongoing improvements as CCS becomes widespread and waste heat re-use is optimised
Learning rate	11	%	Applied from 2030 onwards
Integration with existing infrastructure	7.50	£/tCO_2	Ongoing improvement

Economies of scale: costs reductions as production volumes increase will diminish over time. Earlier projects will benefit from increasing size and efficiency of operations, but as facilities reach optimal scale, building larger systems may no longer yield proportional cost reductions. To illustrate this in the model, Savings from economies of scale will peak in 2035, when clusters and hubs are fully developed, after which they will diminish start to diminish.

Integration with existing infrastructure: similar to economies of scale, there will be a decline in incremental savings from integration with existing infrastructure, as the most accessible and cost-effective opportunities are exhausted. With time, future projects will need to develop new infrastructure and expand into less optimal locations which are further from existing infrastructure. For the UK, we have assumed savings from integration with existing infrastructure will be fully realised by 2035. From 2036 onwards this saving will no longer apply.

For the ***HIGH*** scenario we have assumed the following saving factors:

Economies of scale	13	%	Exponential improvement as CCS grows to global scale
Shared infrastructure savings	6.25	£/tCO_2	Some ongoing improvement as technical challenges are solved and separate CCS systems develop where appropriate (e.g. Cement CO_2 Transport & Storage, Power CO_2 T&S.)
Energy efficiency & waste heat re-use at Capture	3.25	£/tCO_2	Ongoing improvement
Learning rate	11	%	Applied from start and accelerating with open information sharing in face of urgency underlined by increasing climate events
Integration with existing infrastructure	3.75	£/tCO_2	Ongoing improvement

Advancement in capture technologies	12.50	£/tCO_2	Accelerating improvements as capture technologies diversify and become deployable in ever-smaller emitter contexts
Standardisation and modularisation	3.75	£/tCO_2	Increasing from 2031 onwards

Integrated heat recovery: Facilities designed with optimal waste heat re-use early in deployment cycles will see substantial cost reductions, however these savings will begin to diminish after 2035 with later installations where heat recovery opportunities are less optimal and yield smaller incremental savings.

Standardisation and modularisation: Early projects benefit greatly from these efficiencies, but as production scales up, the cost savings plateau because the designs are fully optimised. We have applied this saving from 2030 onwards. Savings will eventually plateau when modular systems become mainstream in CCS deployment.

Advancements in capture technologies: There are likely to be rapid and significant cost reductions from advancements in capture technologies until 2035 as advancement improve capture efficiency, reduce energy consumption and extend equipment life. Over time, these technologies approach theoretical efficiency limits, where further improvements yield only marginal savings.

Cost savings applied with the note '*Diminishing benefit after 2030/ 2035'* indicates that the saving rate has been applied linearly from the start of the modelled period in 2026 to be at its full value in either 2030 or 2035, after which we have assumed savings will continue but at a slower rate, before eventually plateauing. This plateau marks the transition from rapid early-phase cost reductions to slower, stable improvements. Savings made will not reverse or savings increase except in cases where external factors i.e., resource depletion or inefficiencies, drive marginal costs upwards.

The focus period of 2026 to 2037 was chosen to capture the current development phase of the clusters through the subsided regime period to 2030 and then the transition period to 2035, assuming that savings after this point would be diminishing returns. There are good arguments that the modelled period could start anywhere in the period 2026 to 2030, and savings would mature over a much longer period (for example to 2050). The modelling has also assumed a common start date for all CCS applications on the basis that all applications have been included in Clustering Sequencing Track-1, Phase-2 projects. However, as the discussion on the outputs will show this does not affect the results significantly as the main driver for the intersection of costs against income is the implementation of a revenue stream.

Application of cost reduction variables for EfWbegin in 2029. This was done to reflect that the deployment of EfW is expected much later than industrial deployment and as such cost reductions will be actualised later. As the presence of EfW is expected to increase due to their inclusion in the ETS from 2028, cost reductions will impact the cost of capture the following year (2029).

6.5 Modelled Results

The graphs in this section show the reduction in costs over time of CCS on the 4 main applications. Data for the revenue plot (green) has been taken from the DESNZ Market Traded Carbon Values [59]. This source gives a range of price (and hence revenue) for carbon emissions. The Market Traded Carbon Values are aligned to meeting Net Zero goals and are the middle case of the price scenarios presented.

Key features for these graphs show a reduction in costs over time across all savings and applications. The base case has an average reduction of 49%, the High case of 86% and the Low case of 32%.

The impact of applying the lessons learnt in 2030 from the early track clusters can be seen in an increase in gradient of savings between 2030 and 2031. The gradient then quickly returns to one similar to before this point as there are diminishing returns from applying lessons learnt in a leaner and more efficient system.

The carbon price (green) has a noticeable feature whereby the cost of CO_2 decreases between 2029 and 2031. This is not directly referenced in the source material (traded carbon values used for modelling purposes, 2024) [59], but does suggest that this is indexed to high hydrocarbon costs and low growth during this period.

6.5.1 Power Generation

The high case in the power generation scenario reaches the breakeven point in Q4 2029, leading the base case breakeven point in Q3 2030 by approximately 9 months and the low case (Q1 2033) by approximately 27 months.

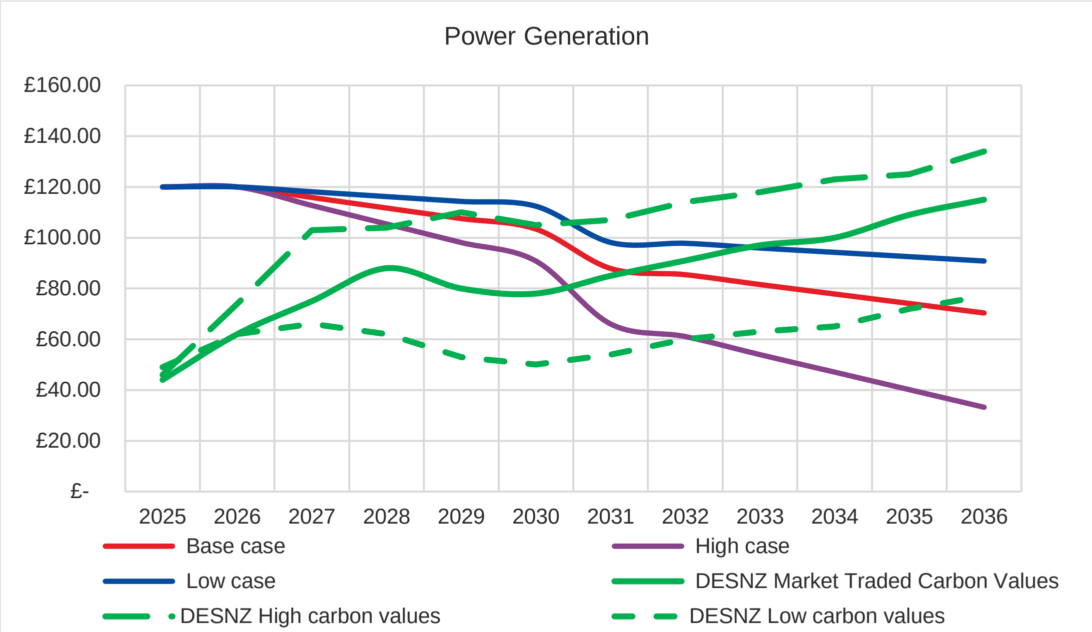


Figure 15: Power Generation Forecast

6.5.2 Industrial Carbon Capture

The high case in the ICC reaches the breakeven point in Q1 2031, leading the base case breakeven point in Q1 2032 by approximately 12 months and the low case (Q1 2034) by approximately 36 months.

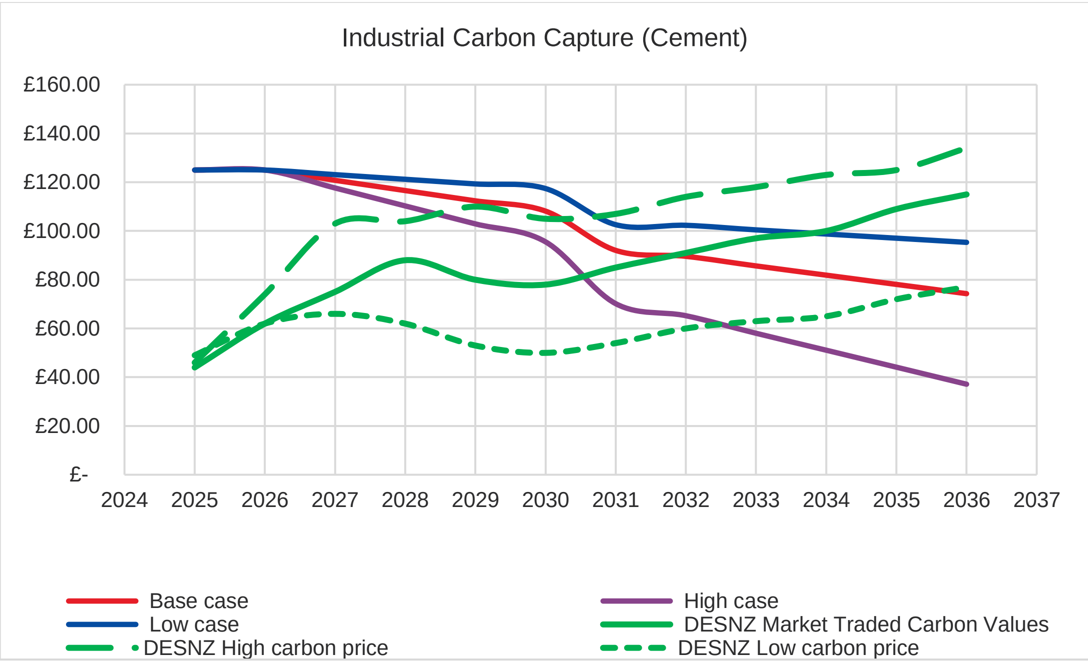


Figure 16: ICC (Cement) Forecast

6.5.3 Energy from Waste

In our analysis EfW has the highest total carbon capture cost across the industries. This is attributed to the premium on EfW as new infrastructure needs to be built to enable CCS as opposed to retrofitting existing plants as seen in the other industry sectors chosen for our analysis. This is evidenced by the Porthos Energy Recovery Facility a selected phase 2 project, which began construction in 2020. Construction was due to be completed in 2024 but is currently still underway [60]. Furthermore there is a relatively higher amount of impurities in the input gas, and thus greater amounts of pre-treatment will be required to purify the CO_2, which have been factored into the cost. The high case cost reduction in the power generation scenario reaches the breakeven point against market traded values in 2035, leading the base case breakeven point in 2037 by approximately 36 months and the low case (2039).

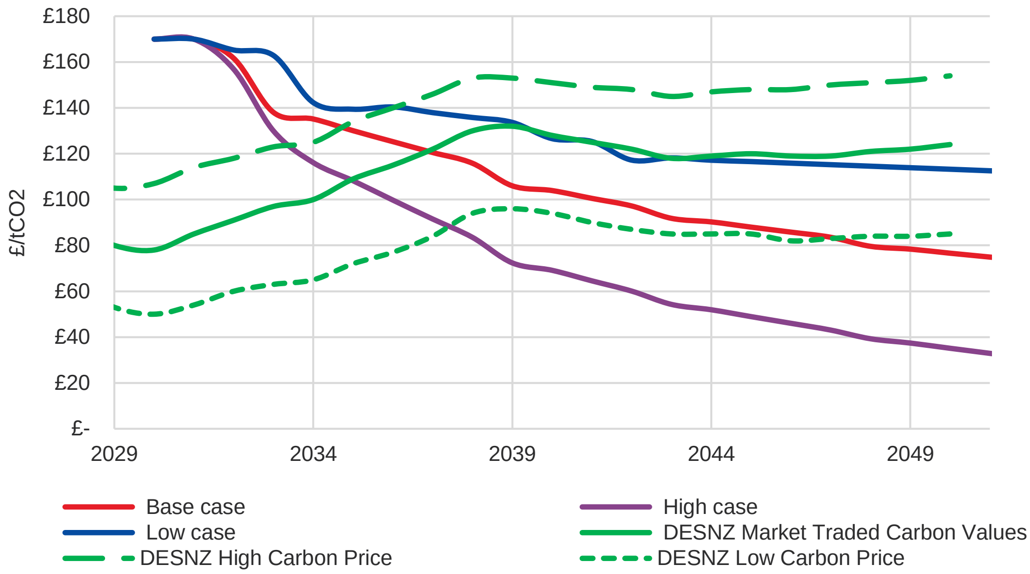


Figure 17: Waste to Energy Forecast

6.5.4 Hydrogen

The comparison of Blue Hydrogen against other applications (Power Generation, ICC, EfW) is not a strong one. CCS in power, industry, and EfW is framed as an emissions mitigation tool, and does not contribute directly to the creation of a marketable low-carbon product as blue hydrogen does. CCS is also essential for the viability of blue hydrogen whereas it is an add-on for the other applications in our analysis. In addition, blue hydrogen also benefits from distinct incentives tied to hydrogen markets making its financial dynamics fundamentally different. As such, in a discussion on costs for CCS applications it would be a noticeable exception to not include hydrogen.

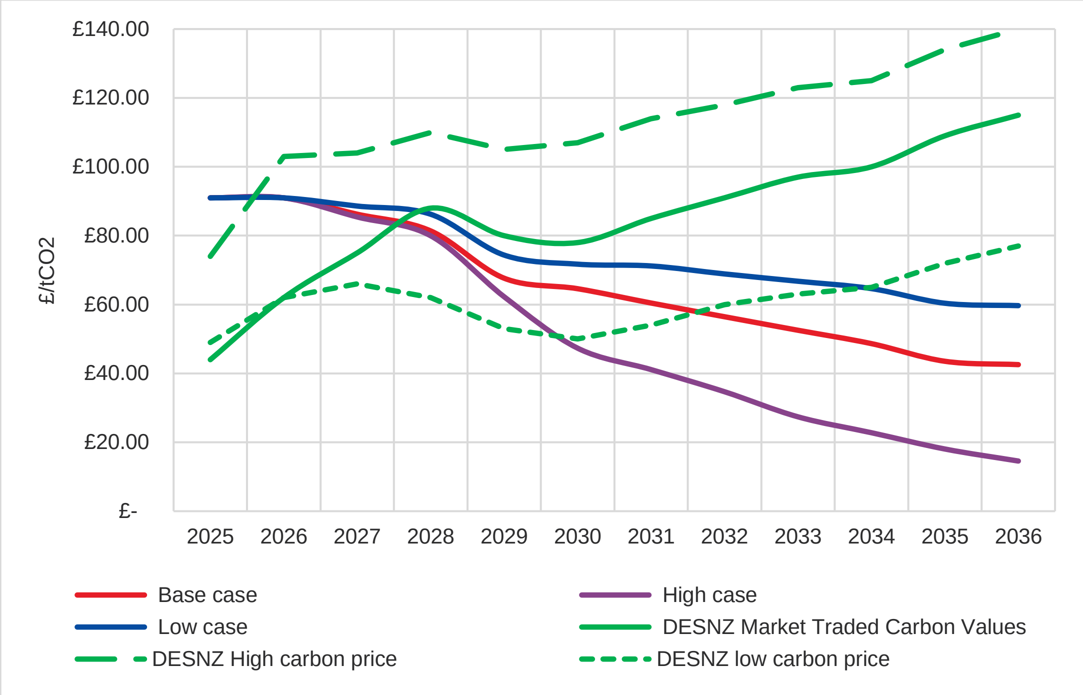


Figure 18: Hydrogen Forecast

6.6 Analysis

The data shows that Energy from Waste is the most sensitive to benefits with cost savings, with a difference of 4 years between the breakeven points of a high rate and a low rate of process improvement. This is indicative of the challenges in EfW as quite a challenging technology to implement due to the high variability in the exhaust plume to be cleaned, and hence a higher degree in variation of model outputs.

The second most sensitive is Industrial Carbon Capture, with an improvement in breakeven point of 36 months between the high and low-cost reduction scenarios. This is followed by Power Generation with a 27-month improvement.

Across all CCS deployment types examined here, the base case generally shows a balanced trend with carbon costs decreasing gradually, assuming a moderate pace of improvements in both policies and technologies. The high case illustrates major cost reduction opportunities with an average cost reduction of 86% across the sectors. This scenario typically exhibits the highest volatility suggesting more aggressive regulatory measure or market dynamics.

The dominating feature in the data of driving a breakeven point is the presence of a revenue stream linked to Market Traded Carbon Values aligned to the goals for Net Zero as defined in the DESNZ report 'Traded carbon values used for modelling purposes, 2024' [59]. Even if no cost reductions were realised at all, this projected revenue growth would enable an economically self-sustaining CCS market in Power Generation and Cement by 2036.

7. Full Recommendations List

Recommendations following the revised UK ETS to address the remaining concerns regarding its efficiency and effectiveness and its readiness for upcoming commitments.

Inefficient and Ineffective Processes:

- **Free Allocation**: The UK ETS Authority should review and refine the free allocation methodology, ensuring transparency and fairness, especially for high-emission sectors. Consideration should be given to aligning allocation methods with international best practices and ensuring consistent application across all regulatory bodies.
- **UK ETS Registry**: The Authority should streamline the UK ETS Registry's processes, particularly for registration and changes to authorised representatives and develop user-friendly online sources and improve communication channels to support international and domestic operators. In addition, it is also recommended to invest in resources to ensure efficient response times to user queries.

Market Liquidity and Volatility:

- **Increase Market Size**: The UK should aim to pursue a strong linkage or alignment with the EU ETS to increase the UK ETS market's size and liquidity. This could also improve price stability and efficiency.
- **Improve Market Design:** The UK ETS Authority should explore options to enhance market liquidity and actively consider measures to address traders' concerns about volatility. This could involve increased auction frequency, attracting more market makers, creating transparent and standardised trading mechanisms.

Lack of Policy Certainty:

- **Long-Term Policy Clarity**: The UK Government should clearly articulate a long-term vision for the UK ETS beyond 2026, fostering greater predictability for investors and businesses. This should incorporate mechanisms for a just transition.
- **International Alignment:** The strongest call from stakeholders was for closer alignment between the UK ETS and the EU ETS. Where operators were considering major investments, including future decarbonisation investments, they saw alignment between the UK ETS and EU ETS as providing more certainty and hence supporting their investment decisions. This was particularly an issue for organisations with international parent companies.

Recommendations for the evolution of CCS business models beyond their design for Track-1 that will help the development of a merchant model and alignment with carbon markets.

Industrial Carbon Capture (ICC BM)

Recommendations (ICC evolution beyond Track-1):

Align ICC BM with UK ETS

- Adoption of a **variable reference** price based on the emitter's carbon price exposure, creates a fairer market position. A variable reference price enables a longer-term market-based business case based on ETS with greater payment opportunity but underpayment risk.
- **The emitter should bear the risk of two-way payment** when the reference price drops below the strike price (ETS tracking) - i.e. the emitter paying the difference to the contracting counterparty (LCCC). Importantly, in a future scenario, an emitter can choose whether to enter into the ICC contract or invest in carbon capture outside the contract and avoid exposure to two-way payments. Currently DESNZ doesn't allow asymmetric payments and the emitter can't incur this risk.

- **Phase out of free allowance volume protection** at the end of the 10-year ICC period exposes the emitter to ETS fluctuation. Doing this earlier in the 10-year period alongside a variable reference price aligns with ETS earlier meaning the emitter must adapt to carbon markets exposure to be competitive.

Provision for 'Carbon-Capture-as-a-Service' Within the ICC

- This **broadens the reach of the ICC business model** beyond the major emitters able to afford CCS. By managing the costs of operating and owning carbon capture facilities, Carbon Capture as a Service (CaaS) can help smaller emitters decarbonise. A CaaS aggregator brings technical knowledge of CCS & local industries to enable the technical co-ordination of CaaS projects. However, current business model incentives and structures do not sufficiently accommodate small emitters.
- In the early stages, CaaS exhibits many traits of a high-risk investment. To secure the necessary funding, investors will need support in grasping the business case before committing.

DESNZ and Environment Agency Alignment on Minimum Capture Rate

- DESNZ stipulates a minimum capture rate of 85% in the ICC, however the Environment Agency require projects to use 'Best Available Techniques'. Capture rates can be as high as 95% however this isn't reflected in the ICC. **Incentivisation to achieve better capture efficiencies** will drive innovation and improve capture techniques.

ICC (Waste) BM

Recommendations (Waste ICC evolution beyond Track-1):

Align the Waste ICC with UK ETS

- Establish a clear distinction between captured fossil and biogenic CO_2. Certain biogenic CO_2 emissions have a zero rating under the UK ETS and no associated carbon price.

Ensure the Waste ICC is Delivering as per Original Design to Enable Future Evolution

- Establish a clear distinction between captured fossil and biogenic CO_2, ensures the waste ICC is delivering as per original design. This means projects aren't able to take advantage of biogenic emissions and the potential for negative ETS credits when instead they should be operating through the BECCS business model.

Generating Revenues from Negative Emissions is also a Way in Which Costs of CCS Could, in the Future, be Supported Beyond Contract Holders

- The sale of negative emissions during the Term (to the extent allowed by the counterparty in accordance with the terms of the Waste ICC Contract) could help to stimulate a market for negative emissions, which could help sustain CCS after Contracts end.

Align the Waste ICC with the Government's 'Biomass Strategy'

- As per the strategy, it's important the Waste ICC doesn't create incentives for unsustainably sourced biomass. The distinction between sustainable and unsustainable biomass is key as the latter is not zero-rated under ETS and the OPEX payment should reflect this. Unsustainable biomass should be exposed to the carbon price.

Dispatchable Power Agreement (DPA)

Recommendations (DPA):

Participation in a Capacity Market Once the DPA has Ended to Encourage Investment

- Allowing CCS facilities to participate in a capacity market can provide a revenue stream independent of energy market fluctuations. This stability is vital given the capital-intensive nature of CCS projects and the uncertainties surrounding carbon pricing and energy demand. CCS installations can also deliver flexible generation in an evolving energy mix, providing reliable resources especially during times of high demand or supply challenges. Therefore, expanding capacity market participation for CCS facilities is crucial for integrating these technologies into the broader energy landscape.

- However, there is current uncertainty surrounding future capacity market participation for CCS projects post DPA and further work examining the potential for future interaction between DPA and the capacity market scheme is still underway. It is strongly recommended that the Government establish a clear pathway for future CCS capacity market participation and develop a roadmap outlining the criteria and timeline for such participation. The roadmap should clarify the transition mechanisms, eligibility requirements, and potential modifications to existing capacity market regulations to accommodate CCS technologies. By doing this, investor confidence can be enhanced and thus reduce reliance on long-term government support.

Transformations in the Energy Mix Could Affect Dispatchability

- While flexible gas-fired power plants with CCS play a valuable role in the UK energy mixes, there are some potential challenges around how significant transformations in the energy mix could substantially affect the dispatchability of power CCS facilities. The increasing penetration of intermittent renewable energy sources could alter the electricity market's demand profile and merit order. This shift could reduce the need for flexible, dispatchable power generation from CCS plants and impact their profitability and the effectiveness of the current DPA business model which relies on a combination of availability payment and variability payment.

- Therefore, it is recommended that the current DPA model be enhanced to more accurately capture the full value of dispatchability and to include the value of CCS plants' flexibility in providing ancillary services. In addition, any future merit order interaction with new forms of dispatchable power, for example hydrogen power, should also be considered. The DPA should consider including a provision to cover risks associated with the potential for fuel supply of a power CCS facility to include a portion of hydrogen in the future. These approaches can create a robust and flexible business model well-suited to the dynamic energy landscape and enhance the market viability of CCS projects.

Alignment with the Review of Electricity Market Arrangements Consultation

- Aligning the DPA with the Review of Electricity Market Arrangements would be a critical step toward making the CCS business model more market driven. The underlying principle is to ensure the DPA does not inadvertently create market distortions or hinder the efficient operation of the electricity system. The alignment should aim to ensure the DPA operates efficiently within the broader electricity market framework, promoting fair competition and reducing long-term reliance on direct government subsidies. For example, the design and mechanisms of DPA should ensure that CCS plants are properly integrated into the existing electricity dispatch and ancillary services markets, and that payments reflect market dynamics and the value provided by CCS plants to the overall electricity system.

Incorporation of the Gain Share Mechanism

- Both project and sale gain share mechanism in the DPA are set to be retained. With respect to either a corresponding gain share mechanism, or a 'cap and floor' approach, either approach could be construed as a form of minimum revenue guarantee, which would be inconsistent with the fiscal rule under which the DPA has been developed. In addition, such an approach would disincentivise the efficient operation of plants in receipt of a DPA and increases the risk of gaming of a complex sharing system to push more risk and cost onto consumers. Instead, the gain sharing mechanism can align the incentives of investors with consumer protection goals, while promoting efficient market behaviours.

- The gain share mechanism ensures that while investors have the opportunity to achieve returns from successful projects, they also share some of those gains with consumers. This balance encourages investors to pursue efficiency and innovative strategies that align with market outcomes, rather than relying solely on subsidies. By incorporating gain sharing, projects are incentivised to achieve market competitiveness. Generators will be motivated to optimise costs and performance, and thus driving market efficiency. Gain sharing also acts as a safeguard against excessive profits derived from unforeseen market advantages, thereby ensuring a fairer price distribution. This mechanism reassures consumers that they will benefit from projects' success, keeping the market tempered and equitable. Therefore, incorporating the gain sharing mechanism serves as a helpful tool in transitioning to a market-driven model by balancing commercial incentives with consumer protection, encouraging competition, and stimulating innovative investments.

Transport and Storage Regulatory Investment Model (TRI)

Recommendations (TRI):

Introduction of an Investment Grade Issuer Credit Rating

- A mechanism for the future assessment of the T&SCo by the introduction of an investment grade issuer credit rating. It will be for the T&SCo to obtain and maintain that credit rating. With a future interconnected network, a credit rating gives emitters choice over T&SCo moving away from monopolistic nature of the RAB model. It also drives standards and encourages investment in infrastructure ensuring the T&SCo is operating best-in-class storage provision.
- The credit rating also drives standards when attracting investment and helps demonstrate which networks are performing best in a free market.

Include Provision for Both New Unsupported Projects and 'End-of-Contract' Unsupported Projects in the TRI

- Track-1 expansion HyNet included provision for 'unsupported projects' i.e. the connection of projects without a business model however at this stage these connections are unlikely. With the evolution of business models and opportunities to benefit out of contract taking advantage of the fluctuating carbon price, future emitters may decide not to enter into a contract.
- The TRI model is designed to cover the long-term operational lifespan of the infrastructure, this can vary but is expected around 25 years. The duration of CfD business models is 10-15 years. Mismatch in agreements means at the end of contract the project will become a de facto unsupported project.
- The TRI business model needs to accommodate more 'unsupported project' opportunities. These opportunities become more attractive as the sector matures.

Development of a Framework for Both the Onshore and Offshore Decommissioning Obligations on T&SCo

- This means infrastructure where required is new build and able to cope with the demands of dense phase CO_2 where repurposed infrastructure may not. Through sector maturation, the option for projects to proceed without needing business model support becomes more attractive.

Ofgem Will Play an Important Role Supporting the Evolution of Business Models to Create a More Flexible and Innovative Approach

- Currently there is a substantial regulatory oversight on transport and storage companies preventing the monopolistic effects of early market movement.
- Through its current regulatory oversight role, Ofgem will oversee the implementation of the TRI business model, ensuring it aligns with regulatory standards and promotes fair competition.
- Ofgem, along with the Low Carbon Contracts Company, will be responsible for collecting, monitoring, and verifying data related to power generation and carbon capture. This ensures accurate reporting and accountability.
- Ofgem will play an important role in supporting innovation and evolution of the TRI business model but must also ensure consumer protection. This allows the benefits of new business models are realised without compromising service quality (this also applies to the DPA where energy consumers will support power-CCS).
- Ofgem is also involved in the development of the Future System Operator, which will play a key role in planning and managing the UK's energy networks, including CCS infrastructure.

Greenhouse Gas Removals (GGR) BM and Power Bioenergy with Carbon Capture and Storage (Power BECCS) BM

Recommendations (GGR and Power BECCS):

Set of Reference Price Based on Achieved Sales Price

- For both GGR and Power BECCS, the Government proposes using the achieved sales price (i.e. the actual price achieved by the developer) of negative emission credits in approved markets as the reference price in the design of the GGR business model and the contract for difference for carbon (CfDc) element of the Power BECCS business model. This approach is a significant departure from fixed subsidies as it directly links payments to actual market value. A combined use with a Price Discovery Incentive, which incentivises developers to seek the highest possible sales price, further amplifies this market-drive approach. This is a key aspect of the business model to encourage market engagement, reduce the difference payment, and prevent poor value-for-money outcomes. Without these provisions, the Government could face low sales price and an overreliance on the difference payment to achieve the required strike price.
- Therefore, it is recommended that the developers and market participants actively engaged in market activities to achieve competitive sales prices and leverage the Price Discovery Incentive to optimise revenue and ensure alignment with market values. At the same time, policy makers need to continue to refine the reference pricing model by monitoring market trends and adjusting incentives to maintain a balance between market-driven payments and financial viability for GGR and Power BECCS projects.

Development of High-Integrity Voluntary Carbon Markets (VCMs)

- The UK Government is actively promoting the development of high-integrity VCMs to stimulate private investment in GGR projects. Despite the relatively small size of the global GGR sector, there is clear evidence of a rapid growth in voluntary demand for high-durability carbon removal credits, driven by large corporate commitments (e.g., Microsoft, JPMorgan Chase, Amazon) and initiatives like the Frontier initiative. This demonstrates a growing private sector valuation of engineered removals exceeding that of traditional carbon offsets and some compliance markets.
- To foster this market development, the Government is committed to take steps to maximise the potential of VCMs to channel private finance into GGR projects while ensuring that carbon credits issued under negative emissions business models meet high standards of integrity. Key approaches include:
- **Rigorous Credit Issuance and Tracking:** All Government supported GGR credits will be issued using approved standards and methodologies, subject to independent third-party verification. An approved registry will publicly track each credit from issuance to retirement.
- **Market Interaction and Interoperability:** The Government is exploring how VCMs can best interact with existing regulatory frameworks like the UK ETS, aiming for efficient credit fungibility and interoperability between markets. This is crucial to creating a more seamless and effective carbon credit system.
- **Conditional Support Instead of Price Guarantees**: Government support for GGR projects will be conditional on the successful sale of credits in the market. This approach moves away from direct subsidies towards market-driven incentives, fostering project viability and minimising government financial exposure. While acknowledging that initial government support may be necessary to boost market liquidity, they are explicit in their intent to not provide support if credits are not sold in the market. The intention is to transition towards a more market-driven system.
- **Additionality**: The Government addresses the crucial issue of additionality, emphasising that support would only go to projects where carbon removals from the project would not have occurred in the absence of the incentive created by carbon credit revenues. A variety of approaches including investment analysis, barrier analysis, market penetration assessments and standardised approaches (e.g. positive lists) will be used to demonstrate this, confirming that only genuinely additional carbon removal will be supported.

- Therefore, project developers should focus on meeting additionality criteria through comprehensive investment and market analyses to ensure that projects are genuine and have a positive environmental impact. The Government should keep implementing clear guidelines and verification processes for rigorous credit issuance and tracking, ensure that all VCM-related activities are transparent, enforce accurate registry practices, and encourage high-quality credit standards. It is also important that the private sector (e.g. corporations like Microsoft, JPMorgan Chase, and Amazon) increases commitments towards purchasing high-integrity carbon credits to further stimulate private investment in GGR projects.

Cross-Border Transport Recommendations

To fully unlock the potential of cross-border CO_2 transport and storage, the UK and EU must align regulatory and legislative frameworks to ensure mutual recognition of CO_2 storage, exempt emitters from surrendering allowances, and create an integrated CO_2 market. Below are the key recommendations to achieve this. By acting swiftly on these recommendations, the UK and the EU can eliminate key barriers to cross-border CO_2 storage and unlock economic and environmental benefits.

Amend the EU ETS Directive

- Effective alignment between the EU and the UK is essential for optimising cross-border transport of CO_2, particularly within the framework of ETS. The current provisions outlined in Article 12 of the ETS Directive are central to addressing this alignment.
- Article 12 governs the transfer, surrender, and cancellation of EU ETS allowances and importantly exempts facilities from allowances for CO_2 that has been captured, transported, and geologically stored. This provision indicates that CO_2 which is properly handled and stored should not count as an emission, thereby incentivising emitters to adopt carbon capture technologies. However, it is worth noting that this exemption currently applies only to CO_2 stored within the EU. Specifically, Article 12(3a) clarifies that an obligation to surrender EU allowances does not apply to emissions that are verified as captured and transported for permanent storage at a facility holding a valid permit under the CCS Directive. This is a crucial point for facilitating climate-friendly practices in the EU.
- However, the CCS Directive, as outlined in Article 2(1), restricts its application to the geological storage of CO_2 solely within the territories of EU Member States, their exclusive economic zones, and continental shelves as defined by the United Nations Convention on the Law of Sea (UNCLOS). Consequently, the scope of the CCS Directive does not extend to third counties, which creates a barrier for recognising CCS activities that occur in the UK. Moreover, the permitting process specified in the CCS Directive is designed so that only sites located within the EU can fulfil the requisite conditions, further complicating cross-border cooperation.
- In light of these limitations, it is recommended that Article 12(3a) of the ETS Directive be amended to incorporate provisions that recognise permits issued under the CCS permitting regime as part of an international agreement between the EU and the UK. This amendment would establish a framework for recognising CCS activities conducted in the UK, thereby fostering collaboration and alignment between the two systems. By facilitating this alignment, both the EU and UK can enhance their CCS efforts and contribute to global climate goals more effectively, allowing for a comprehensive approach to managing carbon emissions that crosses jurisdictional boundaries. This strategic adjustment will not only benefit the respective ETS but also support broader environmental objectives by ensuring that captured carbon is managed in a way that aligns with both jurisdictions' emissions reduction commitments.

Amend the EU ETS Monitoring and Reporting Regulation

- To enhance the effectiveness of the EU ETS in facilitating CCS, it is essential to amend the Monitoring and Reporting Regulation (MRR). Current provisions, particularly Article 49(1), dictate when captured CO_2 is considered transferred for storage and therefore not emitted. However, these regulations primarily pertain to storage within the EU, creating barriers for operations that involve cross-border CO_2 transport and storage, especially concerning third countries like the UK. Article

49(1) currently allows operators under the EU ETS to subtract certain amounts of captured CO_2 from their overall emissions, provided the CO_2 is transferred to approved facilities. These facilities must be permitted under the CCS Directive, which only applies to storage sites within the EU. This limitation hinders the ability to recognise and incentivise captured emissions intended for storage in third countries.

To address these limitations, the following amendments to the MRR are recommended:

- **Recognition of international agreements**: Amend Article 49(1) to include a provision that covers capture installations, transport networks, and storage sites permitted under the CCS permitting regime recognised in international agreements between the EU and the UK. This change would ensure that CO_2 captured for storage in the UK could be subtracted from the emissions liability of operators within the EU.

- **Clarification on transportation methods:** Modify Article 49(1) to clarify that the transportation of CO_2 by methods other than pipelines, such as shipping, does not affect the ability of emitters to subtract captured and permanently stored CO_2 from their EU ETS liabilities. This amendment would specifically recognise non-pipeline transportation methods, thus broadening the operational flexibility for CO_2 transport.

- **Update identification methods**: Revise Annex I(7)(d) to introduce a different method of identification for receiving installations located in the UK. This change would ensure that both EU and UK installations can seamlessly track and report CO_2 transfers, facilitating better regulatory alignment.

- **Approval and information sharing mechanism**: Adjust Article 48(3) to specify which entity should be responsible for approving adjustments in cases where discrepancies arise between the transferring and receiving installations, especially when the receiving installation is based in the UK. This amendment should also define the framework for sharing information between EU and UK authorities, ensuring efficient communication and regulatory compliance.

Amend the EU ETS Accreditation and Verification Regulation

- To enhance the consistency and effectiveness of the verification process within the EU ETS, it is crucial to amend the Accreditation and Verification Regulation (AVR). Currently, Article 17(4) stipulates that verifiers must ensure that the procedures outlined in Article 48(3) of the MRR are properly followed when assessing an installation's annual emissions report. As the regulatory landscape evolves, especially with anticipated changes to Article 48(3) of the MRR, it is essential to ensure that the AVR is aligned with these updates. This alignment will create a cohesive framework for verifying emissions reports across both regulations, thereby improving the reliability and integrity of data reported by installations.

- Therefore, it is recommended that Article 17(4) of the AVR be amended to incorporate the updated procedures and requirements established in the revised Article 48(3) of the MRR. This amendment will ensure that verifiers are operating under the most current guidelines, reflecting any new protocols or adjustments made to the MRR.

Amend UK Legislation to Accommodate Changes in the Above EU Legislation

To ensure that the UK's CCS framework remains fully compatible with evolving EU regulations, it is necessary to amend UK legislation in response to any changes made to the corresponding EU legislation. These amendments will largely depend on the minimum criteria established through international agreements on storage permit recognition between the UK and the EU. Given the existing high degree of alignment between the UK CCS permitting regime and the EU CCS Directive, any required changes are expected to be minimal and will primarily reflect significant alterations in EU law.

- Assuming a mutual recognition framework between the UK and the EU for their respective CCS permitting regimes, it is crucial to amend paragraph 23(a)(ii) of Schedule 4 of the Greenhouse Gas Emissions Trading Scheme Order 2020. This amendment would reinstate references to the EU CCS

Directive alongside those of the UK CCS permitting regime. Doing so would allow UK CO_2 emitters to subtract from their annual emissions reports any CO_2transferred to capture installations, transport networks, or storage sites that are permitted under either regulatory framework.

- Since the UK's departure from the EU, both the AVR and the MRR have undergone amendments. As such, it is essential to evaluate these changes and any future modifications to determine their material impact on UK legislation. Any adjustments to Article 48(3) of the MRR and Article 17(4) of the AVR, as discussed before, should also be mirrored in the relevant UK legislative provisions.

Establish a Bilateral Agreement Under the Trade and Cooperation Agreement (TCA)

- Currently, there is no recognition or equivalence system between the EU ETS and the UK ETS. Nonetheless, both the European Commission and the UK Government have acknowledged the importance of including CCS in their discussions under the TCA.
- Addressing CCS issues through the TCA could eliminate barriers between the EU/EEA and UK ETS. This could establish a degree of equivalence or recognition of CCS permitting regimes, without requiring full linkage of the two ETSs and could leverage the TCA's existing governance framework to enhance trade and cooperation for climate change mitigation, avoiding the need for entirely new treaties. The agreement should:
- Define minimum criteria that all CCS systems must meet
- Include a governance body to oversee implementation and address changes
- Establish a dispute resolution mechanism
- Ensure CCS contributes to overall CO_2 reductions and does not increase hydrocarbon recovery
- Provide mechanisms for sharing information on cross-border CO_2 transport and its inclusion in national greenhouse gas inventories.

Make Agreements under the London Protocol Provision

- While the 2009 amendment to Article 6 has not yet been ratified, provisional application of the Article 6 Amendment was permitted in 2019. This means that the London Protocol no longer acts as a barrier to EU/EEA-UK cross-border CO_2 transport and storage. It is now a procedural formality requiring adherence to the following requirements:
- **Formal Declaration**: The signatory must submit a formal declaration to International Maritime Organisation (IMO) of their intent to provisionally apply the Article 6 Amendment.
- **Agreements Between Parties**: Contracting parties must establish agreements or arrangements with importing countries to permit cross-border CO_2 storage.
- **Notification**: Such agreements or arrangements must be officially notified to the International Maritime Organisation (IMO).
- The provision has provided a legal foundation for countries to engage in cross-border CO2 transport and storage activities. The bilateral agreement between Belgium and the Netherlands has also demonstrated the feasibility of this approach. Therefore, it is recommended that UK and more countries in the EU make notifications and agreements or arrangements under the provision to enable cross-border CO_2 transport and storage. By implementing this, the London Protocol can be more effectively utilised to facilitate cross-border CO_2 transport, ultimately contributing to the global transition towards more sustainable carbon management practices.

Develop CO_2 Stream Specification and CO_2 Metering Standards

- To facilitate the effective transportation and storage of CO_2 across Europe, it is essential to establish uniform standards for CO_2 stream specifications and metering practices. The introduction of minimum

CO_2 stream specification standards is crucial for ensuring compatibility across various transportation methods, both pipeline and non-pipeline. These standards should define acceptable impurity limits for CO_2 streams without being overly restrictive, thereby enhancing flexibility in choosing storage sites. While certain transport and storage facilities may require CO2 specifications that exceed the minimum standards, establishing a baseline standard is essential for the industry to operate efficiently and effectively.

- In addition to stream specifications, it is vital to develop standardised methodologies for CO_2 metering across the entire value chain, from capture to storage. Implementing accepted metering standards will enhance compatibility for both domestic and imported CO_2 streams. High accuracy in CO_2 metering is also crucial for ensuring compliance with ETS requirements, as it allows for timely and precise assessment of data related to emissions.

Align Third-Party Access Principles in the TRI Business Model

- To create a conducive environment for CO_2 stream transport and storage businesses, it is essential to standardise and align third-party access principles across Europe. Such alignment would facilitate smoother operations and enhance competitiveness within the market.
- The UK is currently undertaking a review of the third-party access principle established in its 2010 CO_2 storage legislation. This review is part of the Transport and Storage Regulatory Investment (TRI) business model, aimed at developing a cohesive regulatory framework that balances access to pipeline infrastructure, shipping routes, and the handling of imported CO_2 streams. This review is anticipated to be finalised by 2025, setting the stage for a more integrated approach to CO_2 transport and storage.
- In parallel, the EU is also working on establishing a regulatory framework that addresses how third-party access is codified in network regulations across Europe. This initiative will help to harmonise standards and practices, enabling easier access to transport and storage facilities, which is vital for the movement of CO_2 across borders.

Solicit a UK-Wide Network Code Across Europe

- A crucial aspect of this initiative is the solicitation of a UK-wide network code that aligns with European standards. Developing a network code that encompasses both the UK and EU frameworks would enhance interoperability between the two regions, ensuring that CO_2 transport, and storage operations can seamlessly integrate across borders. This collaborative approach would provide clarity and consistency in regulatory requirements, further encouraging investment in CO_2 infrastructure and facilitating the efficient movement of CO_2 across the continent.

Start Developing Supporting Fit-for-Purpose Infrastructure and Facilities

- The long-term nature of planning and permitting for large-scale infrastructure projects, such as port terminal facilities for CO_2 transport, presents significant challenges. Additionally, the global supply chain disruptions experienced in recent years further complicate the timely development of such infrastructure. If development work does not commence immediately, there is a substantial risk that the necessary facilities will not be ready in time to take advantage of emerging market opportunities.
- To mitigate these risks, stakeholders in both the UK and EU must prioritise the investment and planning of essential infrastructure. This includes not only developing port terminals and transport networks but also ensuring that they are strategically coordinated across countries.
- Moreover, engaging with relevant stakeholders early in the planning process will facilitate smoother permitting and implementation, ensuring that infrastructure projects align with market needs and regulatory requirements. By fostering collaboration between countries and sectors, the transition to a Europe-wide CO_2 market can be accelerated.

Recommendations for Supporting Investment in Existing Subsidy-Enabled CSS Ecosystem and Mitigating the Uncertainty Surrounding Scale and Location of Demand for Hydrogen and CCS:

- **Focus on more core networks**: Prioritise development in areas with the least demand uncertainty to minimise the risk of underused or stranded assets. Enable interconnection between core networks and international emitters.
- **Development Expenditure**: Fund front-end engineering design studies to bring projects to the consent application stage. The National Wealth Fund can play a key role in providing development finance.
- **Finalising Business Models**: Implement business models such as regulated asset bases (RAB) for CCS and hydrogen pipelines and revenue floors for hydrogen storage to address revenue risks. Competitive processes should be used for awarding contracts to ensure value for money. Enable merchant model interconnection to RAB-funded T&S infrastructure.
- **Regulatory and Governance Framework**: Establish codes, standards, and governance systems to ensure compatibility and interoperability of networks, avoiding isolated development.
- Designate and Independent Systems Operator for each network to efficiently manage operations and plan for future network expansion.
- Set a target Timeline Deliver the core networks by 2035.

Recommendations for the Government to Ensure that Hydrogen and Carbon Capture Development Networks under Development are Viable, with Confirmed Users at both Ends.

- **Assurance at Each Stage**: Verify the presence of users at both ends of the network before awarding development expenditure or offering support via business models.
- **Adaptive Planning**: Plan for future stages of the network alongside the core development to address uncertainties and use an adaptive approach to enable quick decisions for network expansion as demand evolves.
- **Vision and Policies**: Set out a clear vision for core networks and supporting policies by the end of 2024 to guide development and expansion.
- **Future Expansion**: Expand networks to include
    - Imports and exports of hydrogen.
    - Connections to additional industrial areas like the Medway.
    - Carbon capture and storage for dispersed sites.
    - Increased demand from hydrogen-fired power generation.
    - Support for new hydrogen storage facilities.
- CCS infrastructure should be located near the core network
- Energy-from-waste plants, due to their dispersed locations, may not be economically feasible for pipeline transport. Alternatives such as road, rail, or ship transport will be viable, and the core network should accommodate these non-pipeline carbon transport methods.
- Based on the above, the core network should connect key industrial hubs, including Grangemouth, North East Scotland, Teesside, Humberside, Merseyside, the Peak District, and Southampton, maximising opportunities to link:
    - **Dispersed Cement and Lime Plants**: These industries require CCS for decarbonisation, with significant emissions outside core industrial hubs.
    - **Gas-Fired Electricity Generation**: Existing sites can be retrofitted with CCS or repurposed for new carbon-neutral generation projects.

Recommendations for Ports Infrastructure

- Ports should focus on developing strategic locations to serve as onshore CO_2 receiving terminals, leveraging their proximity to industrial CO_2 sources, offshore storage sites, and maritime transportation routes.
- Collaboration between ports and strategic landowners across the UK as well as internationally is crucial for knowledge sharing, best practice implementation, and the optimisation of CCS receiving infrastructure design - potentially employing modular construction to reduce costs and accelerate development. This collaborative approach will maximise the potential of CO_2 shipping and participation in the future carbon trading market.

Recommendations for Cost Improvement Opportunities

Carbon Capture: By targeting high partial pressure sources or exploring innovative solutions for aggregating low-pressure streams, industry can optimise both the economic and environmental benefits of carbon capture technologies.

Recommendation for the EA and HSE: Enhancing Carbon Capture Efficiency Through Targeted Focus on Solvent Development and Partial Pressure Optimisation

To ensure the affordability and scalability of carbon capture and storage (CCS) systems, it is critical to address the significant impact of capture costs on total system economics. Doubling or halving these costs dramatically affects the financial viability of CCS projects, underscoring the importance of prioritising advancements in capture technologies. This can be done by developing technical standards for solvent-based systems and partial pressure management to ensure consistency and safety across facilities for example. By streamlining the focus on solvent efficiency and partial pressure optimisation, the UK can drive meaningful reductions in capture costs, enabling widespread adoption of CCS while advancing national Net Zero objectives. This strategic alignment also strengthens the UK's position as a leader in carbon capture innovation.

We propose that the UK Environmental Agency and HSE adopt a dual-focus strategy aimed at:

- **Advancing Solvent-Based Capture Systems**:
  - Promote the development and deployment of next-generation solvents, including water-lean and high-capacity amines, which reduce energy consumption and operational costs.
  - Support research into solvents tailored to handle low-CO_2 partial pressure environments, typical of flue gases from industrial emitters. This includes funding pilot projects to test solvent performance under real-world conditions.
- **Incorporating Partial Pressure Optimisation in Capture Design**:
  - Establish guidelines and incentives for integrating systems that increase CO_2 partial pressure at the capture stage. Strategies could include pre-concentration technologies, multi-stream CO_2 aggregation, or improvements in compression and mixing systems.
  - Ensure that emission monitoring protocols encourage emitters to manage gas flows for optimal partial pressures, improving solvent utilisation and efficiency.

Key Recommendations for Cost Improvement Opportunities in Transport:

Pipeline Transportation

- UK Government should prioritise funding and policy support for the development of shared pipeline infrastructure in industrial clusters like Humber and Teesside to maximise economies of scale. Promote dense-phase CO_2 transport by setting volume thresholds and supporting emitters in achieving them to reduce operational energy requirements.

Shipping and Non-Pipeline Transport (NPT)

- UK Government should support the development of standardised port infrastructure for liquid CO_2 loading and unloading to reduce costs and encourage competition among storage operators. Facilitate intermodal transport chains (e.g., rail and road to ports) by subsidising key infrastructure projects in geographically isolated areas.
- Facilitate cross-border collaborations by supporting projects like the South Wales Industrial Cluster and Viking CCS, which integrate shipping into their transport strategies.
- Industry should invest in modular and scalable NPT solutions, and develop partnerships with rail, shipping, and port operators to streamline supply chains.
- Partner with international emitters to explore opportunities for CO_2 imports, using shipping as a flexible transport mode, and invest in marine infrastructure to capture emerging markets for cross-border CO_2 transport and storage, positioning the UK as a leader in global CCS solutions.

Standardisation and Innovation

- UK Government should establish technical and operational standards for CO_2 transport infrastructure, including pipelines, ships, and ports, to enable cost-effective scaling and reduce project risks.
- Industry can drive standardisation efforts by adopting uniform design and operational practices for CO_2 transport infrastructure.

Recommendations for Cost Improvement in Carbon Storage:

- **Incentivising Marine CO_2 Import Facilities:** Establishing financial incentives for storage operators to develop marine CO_2 import terminals will enable the UK to leverage its vast offshore storage capacity, attract international emitters, and generate economic benefits.
- **Promoting Carbon Utilisation Technologies:** Reducing reliance on large-scale storage through CO_2 utilisation can lower overall costs. The UK should support research and commercialisation of CO_2 mineralisation, synthetic fuel production, and applications in agriculture (e.g., greenhouse CO_2 enrichment) and construction (e.g., CO_2-cured materials). These technologies enhance productivity, sequester CO_2, and improve material performance while reducing emissions.
- **Expanding Cross-Border CO_2 Storage:** Addressing regulatory barriers to cross-border CO_2 transport would allow UK storage sites to accept emissions from EU sources, optimising storage utilisation and reducing costs. By 2030, up to 16 million tonnes of CO_2 annually from EU emitters could be stored in the UK, enhancing the financial viability of large-scale CCS.
- **Optimising Offshore Storage Deployment:** The UK's offshore geological storage potential, estimated at 78 billion tonnes, provides a strong foundation for CCS. By strategically selecting storage sites, maintaining high deployment rates, and integrating technological advancements, the UK can lower the costs of offshore storage and establish CCS as a central pillar of its decarbonisation strategy.

Recommendations from Lessons Learned:

Public and Private Collaboration

- UK Government should establish partnerships between public bodies (e.g., UKRI) and private firms to fund pilot projects and R&D for CCS technologies and expand funding for initiatives like the Industrial Decarbonisation Challenge to accelerate collaboration on shared CCS infrastructure.

Leveraging Existing Resources and Skills

- UK Government and industry should create reskilling programs to help workers from traditional energy sectors transition into CCS roles.

Setting Ambitious and Measurable Targets

- UK Government should set clear national targets for CCS capacity by 2030 and beyond, specifying sectoral contributions (e.g., industrial capture, power sector). Monitor and publish annual progress reports to ensure transparency and accountability.

Public Acceptance and Communication

- UK Government should launch nationwide campaigns to educate the public on CCS benefits, emphasizing its role in achieving Net Zero and creating jobs. Include community benefit schemes for regions hosting CCS infrastructure.

Private Companies should engage with local communities early in the project development process, addressing concerns about safety and environmental impacts. Highlight tangible benefits, such as economic development and employment opportunities.

8. Conclusions

As demonstrated in this report, a self-sustaining UK CCS industry is within our reach. In the UK we are already seeing the costs and risks reduce as a result of considerable investments made. We are on the cusp of world leadership in this new sector, which is the only way to permanently and safely remove the most widespread greenhouse gas from our atmosphere.

With a trend in the energy industry now emphasising security and access over decarbonisation, we are now facing a world in which investment in carbon capture, hydrogen and other energy transition technologies can no longer be relied upon. We now must look to the power of our own industry, our own investments, and our own powers to attract capital to make it happen. Crucially, we must pro-actively open our doors to European CO_2, and in the management and safe storage of this dangerous waste gas, we must become Europe's preferred partner.

The merchant model envisages in time a self-sustaining market not only for CO_2, traded in cargoes around the world, but also for Hydrogen as a valuable clean fuel and flexible energy store. In time, we are sure that hydrogen will become an essential energy vector, primarily for transport and storage of renewable energy, vertically integrated with CO_2 and traded in parallel. For now however, it falls to CCS in the UK to get to scale first.

It is our conclusion that, with a few key regulatory decisions in place, CCS developers in the UK will develop UK stores for participation in a national and international market for CO_2, without necessity for further UK government subsidies.

Two agreements in particular must urgently be achieved: 1) an ETS carbon price aligned to the EU such that EU emitters can easily store their CO_2 in the UK, and 2) agreements under the London Protocol enabling movement of CO_2 across boundaries, particularly bilaterally with Belgium, France and Germany to the UK.

For those in the UK's current Track programme, we see a different set of challenges. Emitters and T&S providers in these hubs have in most cases tied their business models tightly to UK government funding, particularly to predictable and secure revenues and cost recovery under the RAB model. In Track-1, developers are facing the need to continue down the existing route with limited flexibility and at considerable cost, but there is a light at the end of the tunnel, as evidenced by recent FIDs and other financial commitments.

For those in 'Track-2' or 'Track-1a or b' the situation is bleak: lacking clarity, information or commitment from government, they have CCS assets, CO_2 emissions and CO_2 capture investments tied up in a programme of potential future cost and risk sharing over which they have neither control nor visibility.

It is urgently necessary that these programmes are supported to the maximum possible extent by government, and that remaining support is transparently delivered and agreements concluded. These developers and emitters can then make clear plans for their next steps based on a commercial reality. It is our responsibility to end the limbo these investors find themselves in, during which their investment is wasted and emissions to the atmosphere continue.

For developers outside of the Track programme, investors need to see a line of sight to a return on their investment in store development and associated infrastructure, and that line of sight is becoming increasingly evident. Upstream developers have a growing understanding of the infrastructure required and its costs, and are seeing mounting pressure on emitter sectors with no other option to capture and store their CO_2, notably cement and waste to energy. Many in the North Sea have exceptionally well placed and high-quality CO_2 stores, some of which may depend on CCS to have a future.

The basics of this new clean growth sector are in place: we simply need to lift some critical barriers, enable clear safety protocols, and ensure that commercially self-sustaining CO_2 storage in the UK meets no further obstacles in the road.

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