Australia's National Science Agency

Northern Territory Low Emissions Carbon Capture Storage and Utilisation Hub

International Hub Examples – Task 4 Report

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CSIRO Energy

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Foreword

Transitioning the global energy system while rapidly reducing emissions to net zero by 2050 is a vast and complex global challenge.

Modelling of a range of emissions pathways and decarbonisation scenarios from the Intergovernmental Panel on Climate Change (IPCC, 2023), International Energy Agency (IEA, 2024) and Net Zero Australia NZA (2024) shows that to meet net zero greenhouse gas emissions targets by 2050, a wide range of emissions reduction technologies will be required to decarbonise existing and future industries globally.

These organisations identify that emissions elimination from hard-to-abate and high-emissions industries will require using carbon capture and storage (CCS) alongside other abatement strategies, such as electrification, underpinned by power generation from renewable energy sources such as photovoltaics and wind.

Globally, there is considerable effort to identify industrial hubs and clusters where common user infrastructure can enable rapid decarbonisation of existing industries and enable future low-emissions industrial development.

Australia has an opportunity to create new low-carbon growth industries and jobs in these areas, but may lack the infrastructure, skills base and business models to realise this in a timely manner. The transition to net zero will have greater impact on regional communities, particularly those reliant on industries in transition, but it may also create economic opportunities through a wide range of new industries and jobs suited to regional areas.

The Commonwealth Scientific and Industrial Research Organisation (CSIRO) is working to identify decarbonisation and transition pathways for existing and potential future industries that may be established in the Northern Territory by developing a Low Emissions Hub concept in the Darwin region.

CSIRO has established a portfolio of projects to explore and evaluate a range of emissions reduction and emerging transition technologies and approaches. This includes research into the Northern Territory's renewable energy potential, hydrogen demand generation and storage, carbon capture utilisation and storage (CCUS) and compressed air energy storage (CAES). CSIRO is working collaboratively with industry and government to understand their needs, drivers and strategic directions so that our research is informed and relevant. This includes establishing appropriate pathways and partnerships to understand and incorporate the perspectives of First Nations peoples.

A key activity is the research into a business case project (CSIRO, 2024; Ross et al., 2022) that aims to enhance understanding of the viability of a CCUS hub centred on the Middle Arm of the Darwin Harbour.

The work has three elements comprising 15 tasks:

1. analysing macroeconomic drivers, Northern Territory and regional emissions, low-emissions product markets (Ross et al., 2023a), identifying key learnings from other low-

emissions hubs being developed globally, and cross-sector coupling opportunities (Tasks 0–5)

2. completing CCUS hub technical definition and technical risk reduction studies, including detailed studies on the infrastructure requirements for a CCUS hub, renewable power requirements for existing and potential future industries, and road-mapping for CO_2 utilisation industries that could be established to produce low or net zero products (e.g. zero-emission chemical feedstocks) (CSIRO, 2023) (Tasks 6–9)
3. creating a business case to appreciate the scale of investment required to develop a Low Emissions Hub and the economic returns from doing so. This will lead to suggested business models and routes of execution (Tasks 10–14).

The CCUS business case project will involve research that is based on possible industrial development scenarios, models of future potential emissions, market demand, enabling technologies and costs. The project is intended to provide an understanding of possible future outcomes. Industry development will be determined by individual industry proponent investment decisions, government policies and regulation, and the development trajectories of technologies essential to the energy and emissions transition.

On completion of this research, outcomes of the CCUS business case project will be made publicly available.

The work summarised in this report comprises Task 4 of the Northern Territory CCUS business case project. It provides an overview of international CCUS projects and a review and summary of selected low-emissions hub developments, with a particular emphasis on European examples. In addition to the synthesis of publicly available data, the report also includes the results of CSIRO interviews with hub proponents, participants and policymakers in other jurisdictions. This has allowed a deeper appreciation of the learnings that have been obtained from these low-emissions hub developments.

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Acknowledgements

CSIRO acknowledges the Traditional Owners of the land, sea and waters, of the area that we live and work on across Australia. We acknowledge their continuing connection to their culture, and we pay our respects to their Elders past and present.

The authors of this report acknowledge the support and funding provided by CSIRO to undertake this work. We thank the internal CSIRO independent peer reviewers for their review of the report and valuable comments and suggestions.

While this report is an output from a CSIRO-funded initiative, we would like to thank our industry and government collaborators for their insights, contributions and suggestions, which have improved the report outcomes.

Although CSIRO has sought feedback from government and industry on the technical content of the report, CSIRO has sole discretion on the inclusion of this feedback.

Northern Territory Low Emissions Carbon Capture Utilisation and Storage Hub business case project

The Northern Territory Low Emissions Carbon Capture Utilisation and Storage Hub business case project is a result of a collaborative approach between CSIRO, government and industry to develop a business case to assess the viability of a large-scale low-emissions carbon capture utilisation and storage hub outside Darwin.

The project includes inputs from the wider Northern Territory Low Emissions Hub (NT LEH) collaboration group, whose current members include the Northern Territory Government, Xodus, INPEX, Santos, Woodside Energy, Eni, TotalEnergies, Tamboran Resources and SK E&S.

Abbreviations

A$	Australian dollar
BECCS	Bioenergy CCS
CapEx	Capital Expenditure
CCS	Carbon capture and storage
CCUS	Carbon capture utilisation and storage
CDR	Carbon dioxide removal
cm	Centimetre
CO_2	Carbon dioxide
CO_2-e	Carbon dioxide equivalent
CO_2-EOR	Carbon dioxide-enhanced oil recovery
CSIRO	Commonwealth Scientific and Industrial Research Organisation
DAC	Direct air capture
DACCS	Direct air carbon capture and storage
DESNZ	Department for Energy Security & Net Zero
DPA	Dispatchable power agreement
EC	European Commission
EOI	Expression of interest
ERA-NET	European Research Area - Network
ESG	Environmental, social, governance
ETS	Emissions Trading Scheme
€	Euro
EU	European Union
FEED	Front-end engineering design
FID	Final investment decision
GGR	Greenhouse gas removal
£	Great British Pound
GW	Gigawatt (109 watts)
H_2	Hydrogen
HAZID	Hazard identification

HAZOP	Hazard and operability study
HSE	Health, safety and environment
ICC	Industrial carbon capture
IEA	International Energy Agency
km	Kilometre
$ktCO_{2-e}$	Kilotonnes of carbon dioxide equivalent
LNG	Liquefied natural gas
m	Million
MASDP	Middle Arm Sustainable Development Precinct
Mt	Million tons
Mtpa	Million tonnes per annum
Mt	Million tonnes
MW	Megawatts (106 watts)
NECP	National energy and climate plans
NOCS	Norwegian offshore continental shelf
NOK	Norwegian krone
NOPTA	National offshore petroleum titles administrator
NO_x	Nitrogen oxides
NSW	New South Wales
NT	Northern Territory
NT LEH	Northern Territory Low Emissions Hub
NTG	Northern Territory Government
NW	North-west
NZT	Net Zero Teesside
OpEx	Operating Expenditure
OPGGS Act	Offshore Petroleum and Greenhouse Gas Storage Act (2006)
PCI	Projects of Common Interest
Porthos	Port of Rotterdam CO_2 Transport Hub and Offshore Storage
QLD	Queensland
R&D	Research and development
RCSPs	Regional Carbon Sequestration Partnerships
ROAD	Rotterdam Opslag en Afvang Demonstratie
SA	South Australia

SACS	Saline aquifer CO_2 storage
SCCS	Scottish carbon capture and storage
T&S	Transport and storage
t	Tonnes
tpa	Tonnes per annum
TSRI	Transport and Storage Regulatory Investment
US	United States
UK	United Kingdom
Vic	Victoria
WA	Western Australia

Summary

The aim of this report is to appreciate what can be learned from the experience of international CCUS hubs. As such, the report provides an overview of selected international low-emissions hub developments with a particular emphasis on European examples.

As the emphasis of CCS has moved from mitigation of emissions from electricity generation to mitigation of emissions from the hard-to-abate sectors, there has been an increasing focus on the development of business models that can avoid some of the project risks associated with the single-source-to-sink model.

A large amount of thought and consideration has been given globally to the development of low-emissions hubs or clusters (Figure 1). In these hub models, shared infrastructure is used to connect multiple emitters to a CO_2 sequestration site. These models acknowledge that often there are multiple emissions from different industries within a region that can be accessed. Also, the volume of CO_2 captured allows consideration of greater transport distances and multiple CO_2 sink locations. These hubs cannot be viewed in isolation as CCUS hubs only. It will be critical that these hubs also need to incorporate renewable energy and fuel substitution as part of the wider emissions reduction strategy.

The benefits of activating hubs, clusters or zones as low-emissions precincts seem a logical response to sharing risk and reducing emissions. However, previous attempts at developing hub projects around the world have frequently had setbacks due to inadequacies of the business model used and as a result of policy failures. While policy, legislation and regulation are referred to throughout the report, a more detailed analysis of these political and regulatory factors is undertaken in the *Task 10 report.*

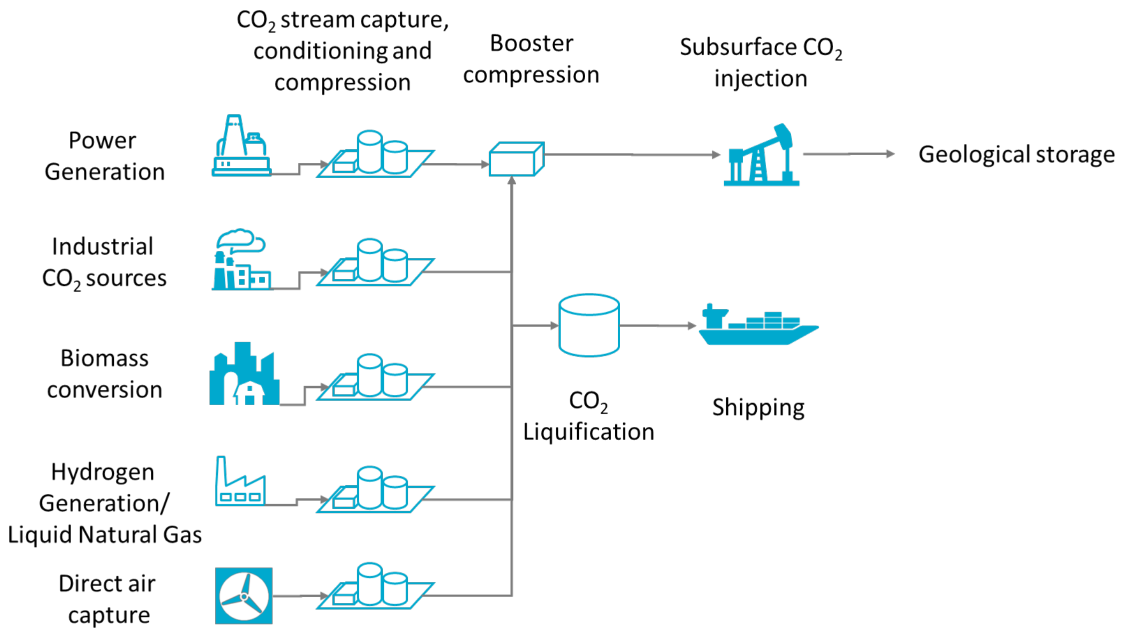

Figure 1: Simplified low-emissions hub or cluster model

Over the last few years there has been a rapid increase in the number of CCS projects in either construction or development worldwide (Global CCS Institute (2024c)). The strong growth in capture facilities globally necessitates the growth of transport pipeline infrastructure and subsurface CO_2 storage capacities. In regions where there is a strong geographical clustering of capture facilities, CCUS hubs are being developed. Based on data from the Global CCS Institute, these industrial clusters have an average capacity of 10.84 Mtpa, although there is a considerable range in the data.

Globally there are different CCUS hub models being pursued, and these can provide insights into the development of CCUS hubs in Australia and the Northern Territory.

Europe

The EU CCS Directive and related mechanisms for developing a CCUS industry have facilitated the development of more than 100 commercial-scale facilities. Several countries – including France, Germany, the Netherlands and UK – have used carbon contracts for difference to facilitate support for some projects. The EU Emissions Trading Scheme (ETS) reached €100/tonne at the start of 2023, which has had a positive effect on business case development for CCS projects in specific sectors (Levina et al., 2023). Levina et al. (2023) do note the need for acceleration of projects, including the construction phase, to provide more concrete examples of CCS, CCUS and hub projects to reduce uncertainty and unfamiliarity with this emerging industry.

Many of the countries at the vanguard of the development of CCUS hubs are building on the experience from prior rounds of CCS development. These prior experiences have informed the need for more coherent and sustainable business models. In Europe this is being achieved through long-term strategies, policy development and funding mechanisms to reduce financial uncertainty. Notable examples of hubs include the Porthos project in the Netherlands, which was identified as an EU Project of Common Interest (PCI) and in 2021, the Dutch Government set aside €2.1 billion ($3.4 billion) through the SDE++ (Stimulation of Sustainable Energy Production and Climate) subsidy reservation to support the project development. Combined with the Aramis and CO2next projects, also in the Netherlands, these projects will capture and transport tens of millions of tonnes of CO_2 from the Netherlands, Belgium and Germany and store it in depleted gas fields in the North Sea.

The activities in the Netherlands and those associated with the Northern Territory CCUS hub as part of an NT Low Emissions Hub (NT LEH) have some similarities. For the Porthos project, reservation of infrastructure corridors has been critical to the success and progression of the project and this same approach is being implemented for the Middle Arm Sustainable Development Precinct (MASDP). In addition, the projects in the Netherlands are building on prior work from the ROAD project and this is also occurring in case of the NT CCUS hub with prior Bonaparte Basin CO_2 storage assessment research being used to accelerate CO_2 storage appraisal activities by INPEX and other companies.

While the projects in Denmark are less mature than those in the Netherlands, the urgency in the development of the projects is notable, with the projects moving forward rapidly, driven by clear European and Danish Government policy and a need to continue to decarbonise the region. These projects, if realised, will materially reduce Denmark's CO_2 emissions. The breadth of collaboration on the Danish CCS hub projects is also insightful, as it includes industries that typically do not work together.

In Norway, a jurisdiction with significant experience with CCS, strong financial support from the Norwegian Government for Norwegian-based activities has significantly reduced the burden of risk and uncertainty while the partners learn by doing the business of developing and operating a CCS hub. The investment by the Norwegian Government into the nascent CCS industry is seen as a national competitive advantage that can be leveraged to generate revenue for Norwegian industries and the taxpayer over the medium to long term.

The UK has an objectives-based strategy for CCUS, which differs from those in Europe, with a sectoral approach being taken for each of the CCUS business models that has been developed by the government. For each business model there are support mechanisms for the development of the respective CCUS hubs, which include cost for difference models and contractual mechanisms to defray cross-chain risk (i.e. participants of hubs not maintaining alignment on project delivery and timing).

North America

While not the primary focus of this report, North America provides further insights for CCUS hub development. The driving forces for hubs in the US have some distinctive features. One is the very long (five decades) and effective support for the development of CCS via the US Department of Energy and its Office of Fossil Energy. There has been a sustained and well-considered set of programs that have built up Federal support from small test injections through to the current set of basin-scale programs. A comprehensive atlas of suitable geology in the US was created along the way.

An underlying structural strength is the long history of CO_2-EOR systems, which are in effect hubs and mean that there is deep expertise and significant finance to build CCUS clusters. The 45Q tax credit, especially because it is fungible and perceived to be adequately secure over the long term, is a powerful financial driver and probably much more attractive than the historically volatile European carbon price (Statista, 2024). Any cost efficiencies that can be obtained through scale and shared infrastructure represent enhanced returns. These incentives do not exist in Australia and as such there are not the same drivers to seek both scale and efficiency.

Proponents of CCUS hub development in North America, particularly on the Gulf Coast, are looking at very large-scale hub developments, partly due to the very large aggregate size of emissions available (some of which are already captured) for capture and storage, but also as an enabler for new, greenfield industrial development around port and CCUS hub infrastructure (e.g. Corpus Christi Carbon Storage Hub; Businesswire (2023)). For the NT CCUS hub the vision includes a similar scale of operations, combining already existing sources of CO_2 that are being captured from liquefied natural gas (LNG) processing together with greenfield development of new low-emissions industries.

CCUS hub stakeholder interviews

As part of this study, a series of interviews were conducted addressing a range of topics associated with CCUS hubs. The focus of these interviews was on the UK and Europe, and questions were designed to obtain perspectives on the key challenges of stakeholders ranging from hub developers, transport and storage proponents, and emitters to government representatives.

Key themes that emerged from these interviews showed that collaboration is essential across the complex activities of design, development and deployment of low-emissions hubs and clusters irrespective of their geographical location. If the mechanisms by which they are supported/derisked by government intervention preclude the ability to share knowledge and key learnings, then there is a huge risk to the successful and timely deployment of new hubs to meet domestic and international obligations.

There is a requirement to improve levels of strategic coordination by increasing overall coordination, knowledge sharing, detailed planning and development, using existing infrastructure, identifying common user shared infrastructure, and developing longer term strategic benefits that future-proof investments in hub infrastructure.

CCUS hub business models are complex and understanding the interplay of financial, regulatory, strategic, public and private roles and responsibilities is highly challenging. Simplification should be sought where possible. There is the need for understanding each organisation's roles in managing risks, incentives and obligations when engaging with stakeholder, shareholder and community perspectives.

A clear understanding of roles and responsibilities is instrumental in advancing the progress of low-emissions hub development and deployment. Institutional knowledge (and detailed documentation of prior projects) can help navigate the history of CCUS hub development and reduce the risk of reinventing the wheel.

All stakeholder interviews reinforced the need for government mechanisms to support hubs. Many feasibility studies look to initial government support (this does not have to be exclusively financial) to reduce a range of risks that in turn enables private sector investment.

Key learnings

The conclusions and synthesis of the case study examples and stakeholder interviews identified the following key learnings that could be applied to CCUS hubs in Australia and the Northern Territory.

The emergence of CCUS hubs

The evolution of the CCUS hub model has been a response to the risks associated with single-source-to-sink models, which carry significant risk of failure if one part of the value chain fails. Hubs still require anchor emitters; however, they diversify risks through the inclusion of multiple emitters and in some cases multiple sinks. The collation of additional emissions sources also, in principle, leads to greater volumes of CO_2 being stored over the phased development.

A long-term vision

Many countries as well as the EU have developed strong long-term policy visions and have a holistic view of emissions reduction, including a requirement for CCUS as part of their emissions reduction strategies. The EU provides a clear market signal on future CCUS capacity requirements and statements of the desire to achieve targets, including the role of CCUS hubs in attaining negative emissions over the long term.

Building on prior work

While it can be hard to piece together the evolution of hubs in many jurisdictions, they often represent the continued development of prior studies, building on that past work. Ultimately, neither the fundamentals of many of the CCUS hub projects nor the industrial regions from which emissions are generated and their proximity to potential sinks have changed. What has changed is the scale and diversity of CCUS hubs, and the development of a range of new business models to enable their implementation and operation.

Reducing business model uncertainty

In all CCUS hub developments, governments are involved, either through direct funding, cost for difference mechanisms or tax incentives. Each government has a clear understanding of the benefit and return on investment (e.g., continued manufacturing capability in hard-to-abate industries and the economic and employment opportunities those sectors provide). In the case of Norway, the government has recognised CCUS as a national opportunity that can generate revenue and further Norwegian company technology and skills exports.

Government involvement is also important in setting boundary conditions. Aside from providing incentives, there is also the implementation of other measures such as a carbon tax or requirements on hub operators to allow fair and equitable access to infrastructure. Irrespective of financial incentives, governments have also provided certainty and enabled risk reduction to allow private sector investment. To unlock private investment, understanding and having certainty on return on investment is critical. In this regard, the UK is working on an objectives-based framework, which includes an independent economic regulator, the need to understand costs and performance, improved certainty of return over the long term (including adequate return on investment) and protection against demand-side risk to revenue (cross-chain risk).

The role of a coordinating body

In the development of CCUS hubs a single representative organisation is typically identified. This can be a joint venture or government company (e.g. Gassnova in Norway). In the case of Gassnova, this entity is at arm's length to government, enabling it to execute its role without being part of the day-to-day machinery of government. A feature of many CCUS hubs globally is that they incorporate academia and R&D organisations with strong expertise in CCS. This helps minimise risk and allay public concerns, as well as develop future workforce capacities.

Collaboration is critical

Collaboration is essential across the complex activities of the design, development and deployment of low-emissions hubs and clusters no matter their geographical location. The single CCUS hub coordinator role allows common definitions around metrics and project goal success/failure (as undertaken in *Task 0* of this study; Ross et al. (2023b)), without which there could be a lack of alignment between the proponents. The central CCUS hub coordinating organisation can act as a contract clearing house and undertake many of the administrative activities and, as such, reduce the costs of entry for hub participants. In addition, this organisation can be responsible for knowledge capture and sharing.

Recording progress

Enduring corporate and institutional memory and a clear understanding of roles and responsibilities are instrumental in advancing the development and deployment of low-emissions hubs. It was observed in the deep dive of the different project case studies for North-west Europe (e.g. ROAD and related projects in the Netherlands), that several of the currently active projects are revaluations of older projects that had failed, mainly due to lack of a strong business case. Institutional knowledge (and detailed documentation of prior projects) can help navigate the history of some of these project failings and reduce the risk of repeating earlier mistakes.

Building emissions reduction capacities

While the development of many of the CCUS hubs is being driven by oil and gas companies and their need to reduce their own emissions, opportunities exist to provide much greater capacities that will bring about wider industrial decarbonisation. However, without market demand signals, these hubs may not be developed with sufficient capacities to maximise economy-wide emissions reduction opportunities and secure economic activity in hard-to-abate sectors. The breadth of organisations (23) involved in Project Greensand demonstrates the interest and drivers for industry and the wide range of skills and expertise that is required to execute not only CCUS hubs but also progress towards broader low-emissions hub developments.

1 Introduction

To understand the requirements of any industrial development, it is prudent to learn from existing examples of similar developments. This is no different when considering the development of low-emissions and CCUS hubs. Through the study of other hub developments, insights can be gained into approaches that have worked and those that have not. Through learning from these other examples, mistakes can be avoided and best-practice approaches can be implemented.

This report aims to provide an overview of international CCUS projects (section 0) and a review and summary of selected low-emissions hub developments (section 3). The report has a particular emphasis on European hub examples as they typically involve collaboration between government and industry in their development, and detailed information is available. In addition to the synthesis of publicly available information, the report also includes the summarised results of CSIRO interviews with hub proponents, participants and policymakers in these jurisdictions (section 3.2). These interviews have provided insights that otherwise would not have been disclosed and have allowed a deeper appreciation of the learnings that can be obtained from a number of significant low-emissions hub industrial developments.

It is worth considering the genesis of the concept of CCUS hubs as it provides salutatory lessons for their development. Early solutions for CCS typically involved simple source-to-sink solutions for the capture and permanent removal of CO_2 (Figure 2). These configurations were predicated on a source/emitter capturing its CO_2, transporting it and storing it at a geological site that was anticipated to be within a reasonably short distance from the emissions source. In Australia this source-to-sink matching approach was exemplified by the work presented in the *National Carbon Mapping and Infrastructure Plan – Australia* (Carbon Storage Taskforce, 2009).

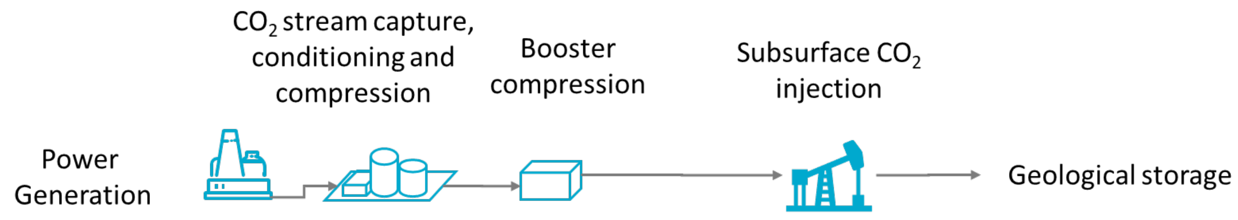

Figure 2: Example of a simple source-sink model for CCS

Single-source-to-sink CCS models, while simple and typically only involving one or two commercial parties, have inherent risks. In particular, the single source and sink of CO_2 represents a critical failure point. For example, if the business model of the industry that provides the CO_2 for storage becomes unviable, the whole project fails. In these cases, there may not be any technical impediment to the CO_2 capture and storage. Another failure mode is lack of a suitable storage site or unforeseen risks for storage, again preventing the CCS project from proceeding. In both circumstances, the significant financial risk taken by individual proponents is not defrayed.

As the emphasis of CCS has moved from the mitigation of emissions from electricity generation to the mitigation of emissions from the hard-to-abate sectors, there has been increasing focus on the development of the business models that can avoid some of the project risks associated with the single-source-to-sink models. A large amount of consideration has been given globally to the development of low-emissions hubs or clusters. In these hub models, shared infrastructure is used to connect multiple emitters to a CO_2 sequestration site (or in many cases, multiple sequestration sites; see later discussion) (Figure 3). These models acknowledge that often there are multiple emissions from different industries within a region that can be accessed. The hubs usually include several anchor emitters; however, incorporation of emissions from other emitters can further defray risks. Also, the volume of CO_2 captured allows consideration of greater transport distances and multiple CO_2 sink locations.

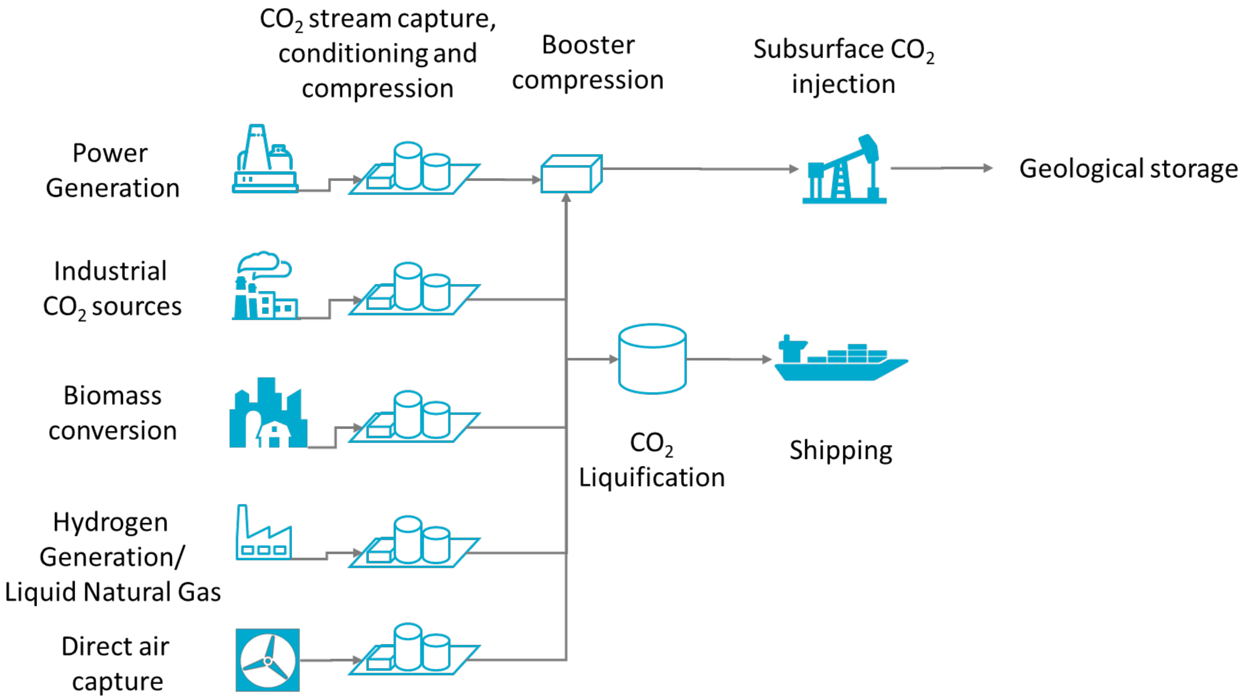

Figure 3: Simplified low-emissions hub or cluster model

Based on emissions sources, 10 locations in Australia were identified by the Carbon Storage Taskforce (2009) as potential hub locations (Table 1). Table 1 shows that hubs or clusters have the potential to consolidate large volumes of CO_2 if capture technologies are installed and there is sufficient volume of CO_2 to facilitate upscaling and cost reductions associated with transport and storage. Also of note is that the total CO_2 emissions projections reported for 2020 by the Carbon Storage Taskforce (2009) were not always a good predictor of actual CO_2 emissions for 2020 provided by the National Greenhouse Energy Reporting Scheme (APPEA, 2023). However, these hubs or zones are still major contributors to CO_2 emissions.

More recent evaluations (e.g. APPEA (2023), now known as AEP) both update and validate the earlier work with a similar approach, resulting in the identification of nine potential hub and cluster locations, though these do not align geographically one-to-one with the earlier study (Table 1).

Table 1: Examples of locations of high-emissions intensity as seen as potential hub or cluster zones. Data from Carbon Storage Taskforce (2009) and AEP (2024). Values in $ktCO_2^e$. Note that total scope 1 emissions reported for 2020 were 315,000 kt
Source: Clean Energy Regulator (2021)

	Carbon Storage Taskforce (2009)			AEP (2024)	
Location (2009 study)	Projected emissions (2010)	Projected emissions (2015)	Projected emissions (2020)	Location (AEP (2024))	2020 Emissions (AEP (2024))
Gladstone, Rockhampton & Biloela, Qld	31,687	32,532	29,792	Central Qld	53,330
South-east Surat Basin, Qld	23,287	24,649	27,540	Brisbane & Surat Basin	23,350
Hunter Valley & Newcastle, NSW	44,763	40,616	38,721	Sydney-Newcastle	65,490
South NSW West/Lithgow, NSW	28,432	28,837	29,086		
Latrobe Valley, Vic	60,631	44,391	30,603	Melbourne-Gippsland	43,930
Port Augusta, SA	8,963	7,772	3,842	Adelaide-Port Augusta	5,700
Perth & Kwinana, WA	27,878	25,420	25,139	Perth	21,200
Pilbara, WA	7,661	13,982	26,527	Pilbara, WA	36,920
Kimberley, WA	0	0	8,520		
Darwin, NT	1,739	8,839	14,286	Middle Arm Sustainable Development Precinct	9,000
	-	-	-	Cooper Basin	2,590
Total key sites	**235,041**	**227,039**	**234,056**		**261,510**

At the present time, the 9 nine zones identified in the APPEA (2023) study counted for approximately half of Australia's total annual emissions for 2020, with a total of 483.9 million tonnes of CO_2 (Department of Industry Science Energy and Resources, 2021) relative to the total zone's volume of 261 million tonnes of CO_2. These hubs cannot be viewed in isolation as CCUS

hubs only. It will be critical that these hubs also need to incorporate renewable energy and fuel substitution as part of the wider emissions reduction strategy.

Activating hubs, clusters or zones as low-emissions precincts seems a logical response to defraying risk and reducing emissions. However, previous attempts at developing hub projects around the world have frequently had setbacks due to inadequacies of the business model used and as a result of policy failures. Sometimes hubs have been in the right place and with the right concept but at the wrong time with respect to policy, financial support, regulation or legislation or else they have been derailed by unanticipated external factors. These perceived failures are seldom related to scientific or engineering challenges

This report seeks to ascertain the key drivers of both successes and failures of low-emissions or CCUS hub developments so that learnings and best-practice approaches can be identified. Policy, legislation and regulation will be referred to throughout the report, but a more detailed analysis of policy, legislation and regulation is undertaken in the *Task 10 report.*

2 Global overview of CCS projects

Globally over the last few years there has been a rapid increase in the number of CCS projects either in construction or in development (Global CCS Institute (2024c); Figure 4). This is due to accelerated international action on emissions reduction, which has led to enhanced policy and financial support for CCS. The global status of CCS is reviewed on an annual basis by the Global CCS Institute (2024c) and elements of its latest report are summarised below along with other sources of data.

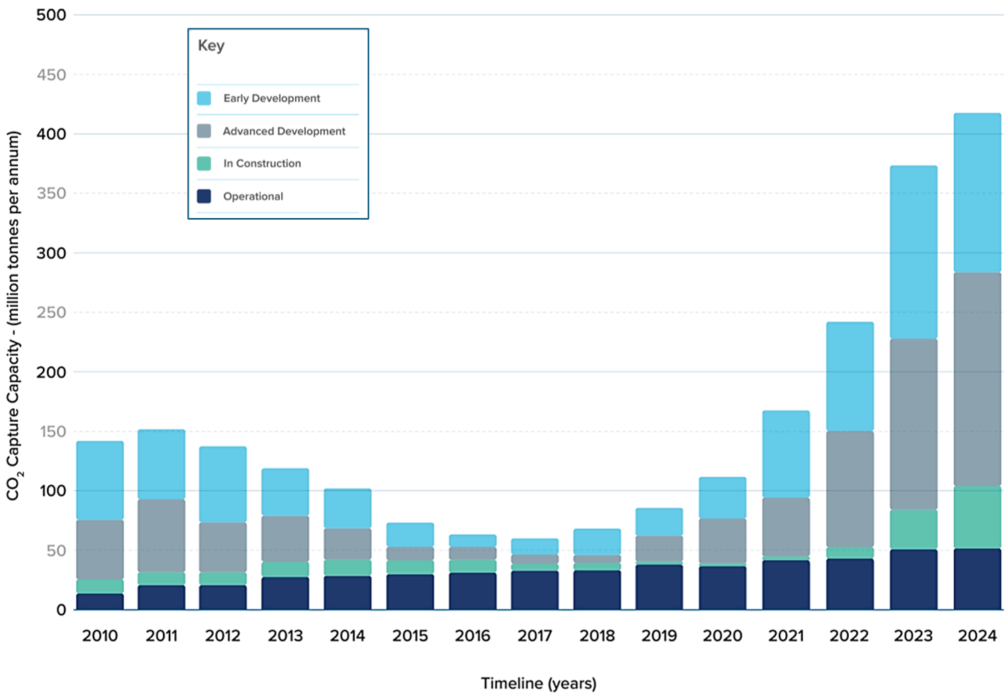

Figure 4: 2010–2024 CO_2 capture capacity of commercial CCS projects by project phase. Note that CO_2 capture capacities are shown and do not include storage capacities
Source: Global CCS Institute (2024b)

Globally CCS capture projects are associated with a wide range of industries, and while there are still many projects associated with capture from power generation, there are significant numbers of projects associated with hydrogen and ammonia generation and bioethanol production (Figure 5); typically where the CO_2 is generated as a by-product of the chemical process (i.e. capture is an embedded cost and not an additional cost on top of current industry practice).

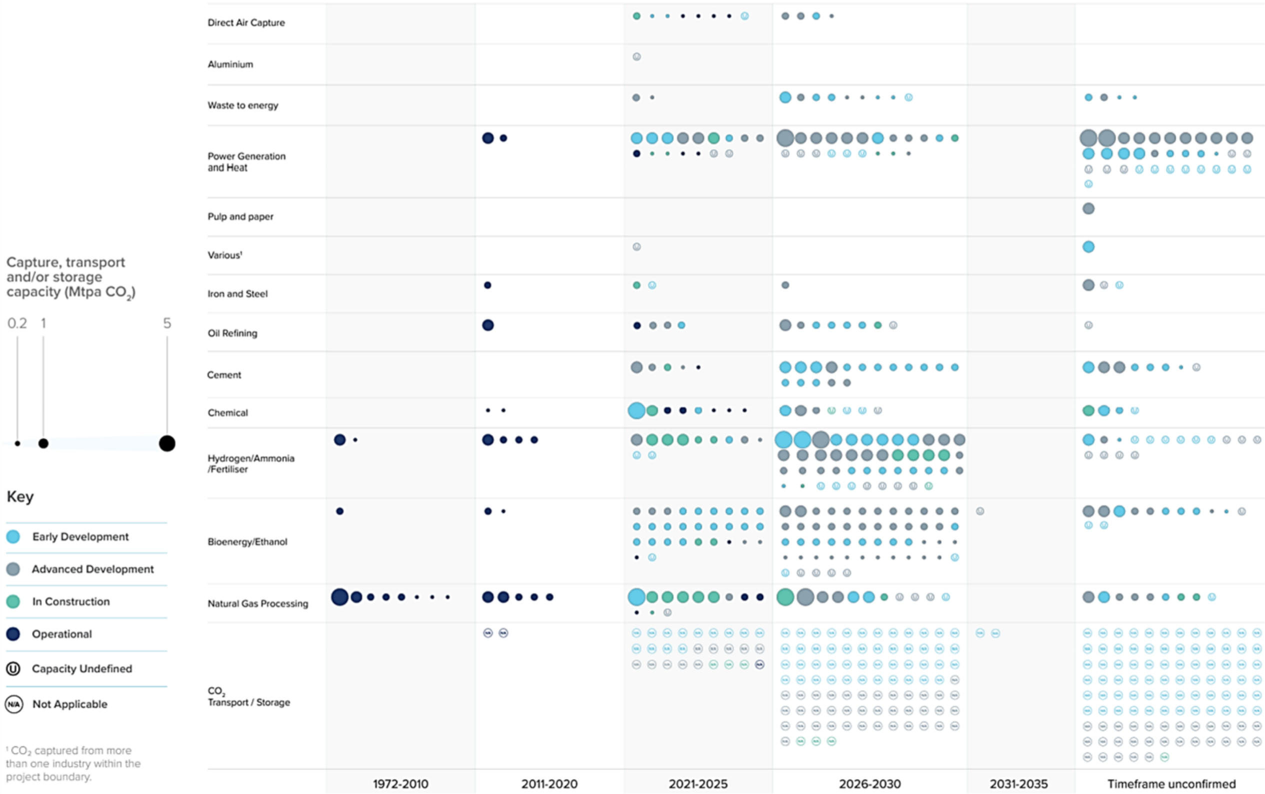

Figure 5: Global CCS project pipeline by industry and by anticipated year period of operation
Source: Global CCS Institute (2024c)

In addition to the increase in the number of CCS projects in operation and under development, there is uptake of CCS across the globe (Figure 6), with the most number of projects found in the US (267 projects) and Canada (58 projects), partly a reflection of the long history of enhanced oil recovery using CO_2 that has produced network infrastructure for transporting CO_2 by pipeline, and favourable policies enacted in the US and Canada that are encouraging the uptake of CCS (Global CCS Institute, 2024c).

In Europe, there are many CCS projects in various stages of development, with the two most active jurisdictions, the UK and Norway, having 65 and 16 projects, respectively (Figure 6).

In the Middle East, much of the focus of CCS projects has been on the Gulf Coast states associated with their oil and gas infrastructure.

In the Asia-Pacific region, there are fewer CCS projects, with the largest number being in China (25) (Figure 6). The difference in this region is due to many of the countries being developing nations and not subject to the same emissions restrictions as the developed nations. As such, until recently many of these countries did not have the policy and legislative frameworks to support the development of CCS, although this is rapidly changing (see below and *Task 3 report*; Joodi et al. (2024a)).

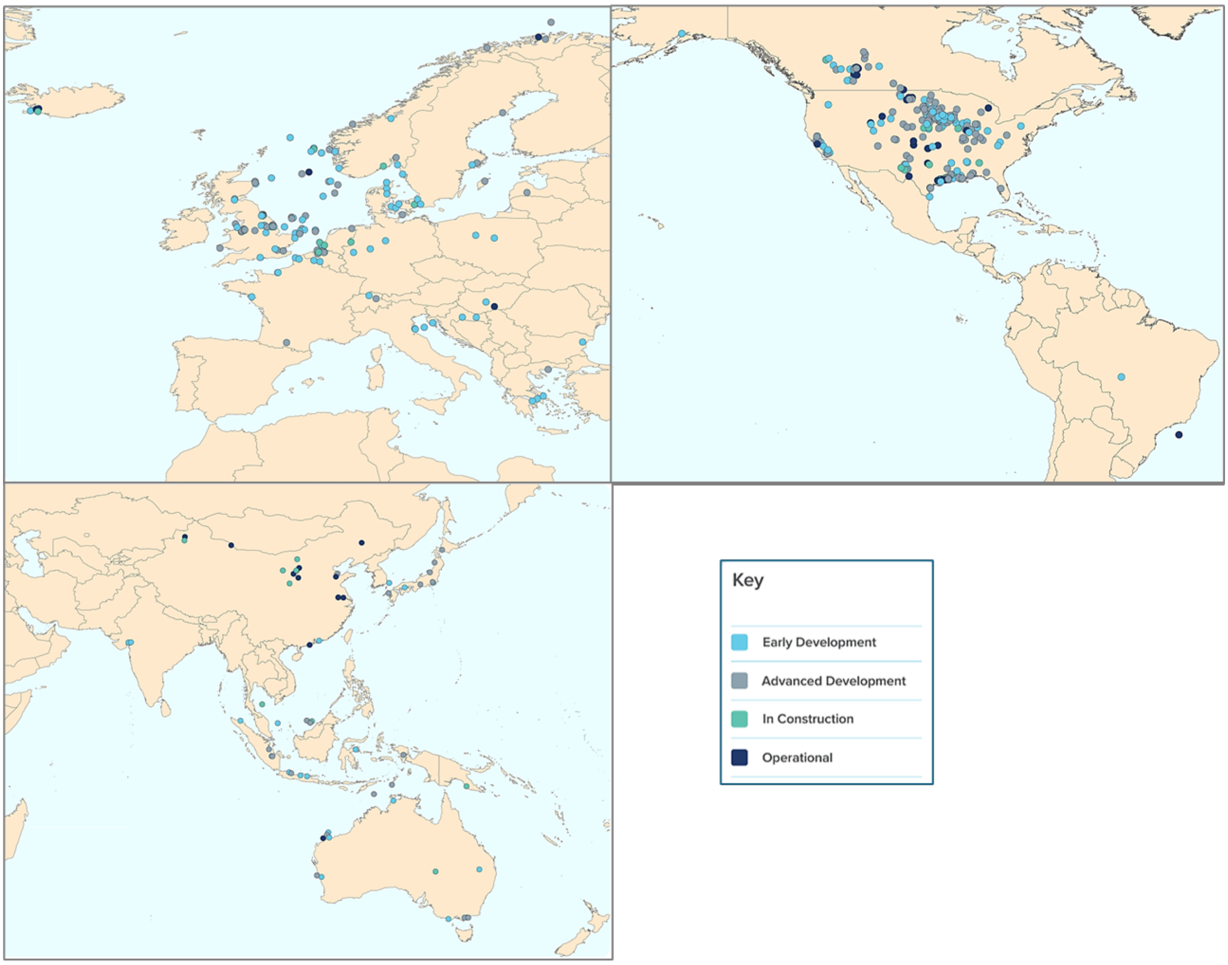

Figure 6: Regional CCS projects for Europe, the Americas and the Asia-Pacific region. Note that both capture and storage facility locations are shown.
Source: Global CCS Institute (2024b)

The strong growth in capture facilities globally necessitates the growth of transport pipeline infrastructure and storage capacities. In regions where there is a strong geographic clustering of capture facilities (Figure 6), CCUS hubs are being developed.

The Global CCS Institute CO2RE database CCS networks dataset (accessed 20 July 2023) was used to establish the distribution of CO_2 capture and storage capacities of nominated industrial hubs globally. To do this, the dataset was filtered by facility type to only include storage and transport facilities. A mean and standard deviation of CO_2 facility capture capacity (max) were derived from the data, after which a normalised distribution was plotted (Figure 7).

While the overall count in industrial clusters is low (n = 27) and the spread of the data is wide (min 0.5 Mtpa, max 50 Mtpa) – contributing to the large standard deviation (11.84 Mtpa) – the average industrial cluster size is 10.84 Mtpa. This size is above the typical capture plant size shown in Figure 5, which would be associated with single-source-to-sink projects. The unimodal normalised distribution in Figure 7 shows that a number of projects globally have much greater capacity ambition than that of the mean project size.

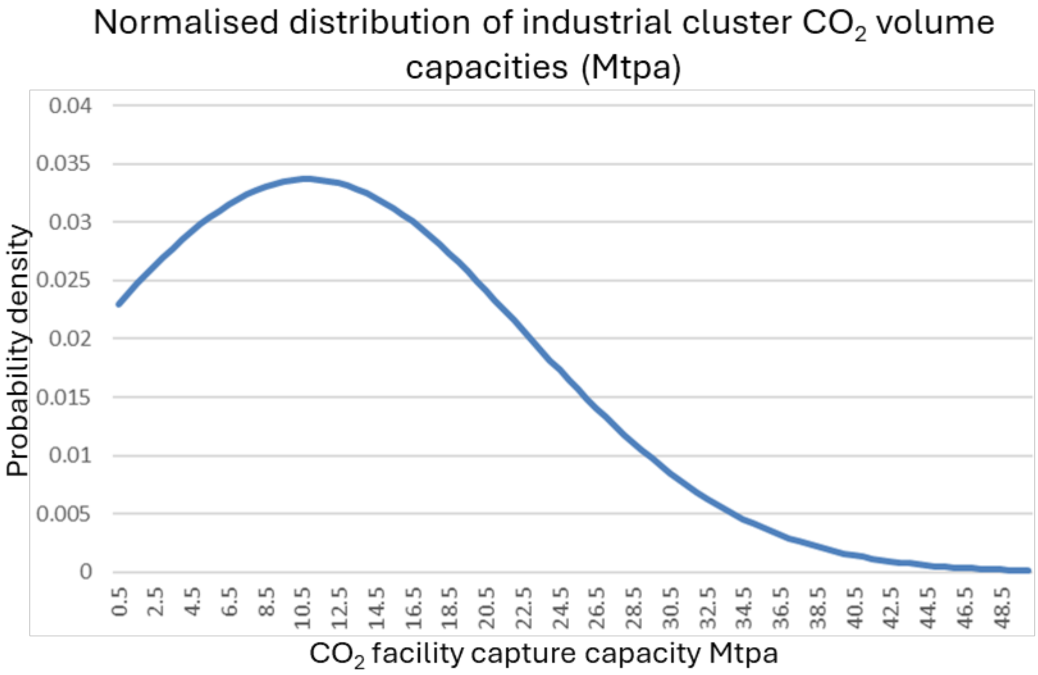

Figure 7: Normalised distribution plotted capture and transport facilities from Global CCS Institute CO2RE database CCS networks dataset
Source: Global CCS Institute (2024b)

3 Selected hub examples

Within this section several CCUS hubs are described, with particular emphasis on European examples. The purpose is not to review all CCUS and low-emissions hubs, but rather to use these examples to illuminate the key elements of CCUS hub development.

3.1 Europe

The EU CCS Directive and related mechanisms for developing a CCUS industry have facilitated the development of more than 100 commercial-scale facilities, which are in various stages of development (Levina et al., 2023). Most of the activities to date are focused in or on the margins of the North Sea, a proven petroleum province with well-characterised subsurface geology and significant CO_2 storage capacity. There are new opportunities emerging in the Mediterranean, while only a few onshore European locations are under consideration. The European Union Net-Zero Industry Act was introduced to drive investment in infrastructure and requires that oil and gas producers within its jurisdiction invest in a 50 Mtpa CO_2 injection capacity by 2030.

The governments of Denmark, Norway, the Netherlands and the UK have been at the forefront of CCS activities, due in part to their proximity to the North Sea, and as a consequence, the governments of these countries have already outlined and/or implemented a range of policies and project support to facilitate or activate the CCUS industry (see the *Task 10 report* for more detail). Some countries are in consultation phases to expedite CCUS policy development, while others are already in the process of developing bilateral agreements, declarations or other mechanisms for the transboundary movement of CO_2 to countries that have suitable geological storage. To this end, European governments have now developed 23 bilateral agreements related to CCS (Global CCS Institute, 2024c). A few projects have had delays due to costs, public acceptance or legal challenges (Levina et al., 2023).

Funding of CCUS in the EU has come from the Innovation Fund and the Connecting Europe Facility for Energy (see the *Task 10 report*), as well as discrete national programs. Several countries, including France, Germany, the Netherlands and the UK, have used carbon contracts for difference to facilitate support for some projects. The EU ETS had reached €100/tonne at the start of 2023, which has had a positive effect on business case development for CCS projects in specific sectors (Levina et al., 2023). Levina et al. (2023) do note the need for acceleration of projects, including the construction phase, to provide more concrete examples of CCS, CCUS and hub projects to reduce uncertainty and unfamiliarity with this emerging industry.

It is worth considering the key learnings obtained in Europe and how these activities compare and contrast with those occurring in Australia and particularly the Northern Territory. Table 2 below briefly lists the key learnings from Europe and maps their equivalent in Australia. Elements of these key learnings will be revisited in the more detailed hub example sections below.

Table 2: Key learnings from the EU-level synthesis by the Global CCS Institute and how these learnings are reflected for Australia
Source: modified from Levina et al. (2023)

Key learning point	NT LEH reflection
Projects	
Overall, CCS and CCUS deployment to decarbonise is increasing. Projects in the EU have risen 61% from 2022 to 2023, to 119 in various stages of development in 2023. Information from Global CCS Institute CO2RE database indicates over 200 project activities in the region (Global CCS Institute, 2024d).	Australia has seen rapid growth in the number of projects in development in the same timeframe, with two offshore acreage release rounds with 15 locations open for bidding. There are several conversions of hydrocarbon production permits to CCS permits underway. New onshore legislation in various states is facilitating new project developments.
Legislation	
European Commission support for accelerated CCS in the form of policy, legislative and regulatory actions under Fit for 55, Green Deal Industrial Plan, Sustainable Carbon Cycles, Projects of Common Interest and others emerging. A new EU Industrial Carbon Management Strategy has been released and covers CCS, carbon capture utilisation and CO_2 removal (see the *Task 10 report*).	OPGGS Act and a range of Federal legislative and regulatory tools are in review (Australia Government, 2023). The Safeguard Mechanism amendments enacted in 2023 will drive a reduction in emissions from industrial facilities. The London Protocol amendment for CO_2 shipping was ratified in November 2024. SA has onshore CCS legislation, new WA onshore legislation was passed in 2024 and onshore legislation for the NT is being considered.
Government funding	
For first-phase deployment, financial support is required to be economically viable. The Innovation Fund, Connecting Europe Facility for Energy and Horizon Europe are the main funding mechanisms for CCS developers in the EU. National support from Climate Energy and Environmental State Aid is being directed to CCS projects in some countries (see the *Task 10 report*).	Federal funding for CO_2 capture technologies through the Carbon Capture Technologies Program. Eligibility for industries under the Powering the Regions Fund's Safeguard Transformation Stream for grants to support carbon capture and storage. Various state-based grants for carbon capture utilisation and CCUS technology development. No specific funding for CCUS in the NT (see the *Task 10 report*).
Storage locations	
Offshore, particularly the North Sea, dominates, where there is a long history of oil and gas extraction and the geology is very well understood. After false starts with onshore storage, new opportunities are emerging in a range of locations.	Majority of focus in offshore locations is associated with prior oil and gas activity (e.g. NW shelf, Gippsland). Activities offshore are increasing with two recent acreage release rounds (including awards of acreage in the Bonaparte Basin adjacent to the NT). Offshore CO_2 storage in Timor-Leste waters is yet to be resolved. Onshore storage is possible in Vic and SA. WA is preparing regulations, and legislation is under consideration in the NT. Qld has recently made changes severely restricting the deployment of CCS onshore.

Negative emissions	
Bioenergy and direct air capture with CCS (BECCS and DACCS) are being incorporated into new regulations and investments via the European Commission Carbon Removal Certification Framework and Innovation Fund. It is recognised that further policy intervention is required.	Direct air capture is a growing area of research in Australia, but it is recognised that there are currently scale and cost limitations. BECCS has not been a priority focus area following some preliminary studies that have not considered changing perspectives or fuel sources that might be available. Limited opportunities for BECCS in the NT.
Coordination	
Value-chain coordination across public institutions, private companies and communities, and managing across jurisdictions is essential to manage cost and risk e.g. London Protocol Article 6 ratification, bilateral agreements will reduce uncertainty to facilitate investment.	The purpose of the NT LEH activities has been to provide a space to consider value-chain coordination between the NTG, industry partners (INPEX, Santos, TotalEnergies etc.) and the NT community. NT LEH activities have shed light on the ability to consider shared infrastructure, location, skills and risks for the ongoing definition of the hub project.
Community support	
Support for CCS in Europe is variable. Further work is required to obtain government and community recognition of CCS as a means of decarbonising at scale. Current projects need to demonstrate commercial activity as exemplars of the industry to familiarise all with their impacts and risks.	Australia has had pilot and demonstration-scale CCS activities onshore for ~20 years (CO2CRC Otway Project). It also hosts the largest current CCS project in the world (Gorgon). Messaging around these examples needs to be reiterated and made more accessible. More projects are needed to demonstrate the technology and increase familiarity with CCS and CCUS. Transparency in methods for defining best sites, monitoring, mitigation strategies and anticipated impacts will reduce public, government and industry concerns.

3.1.1 The Netherlands

The path to developing CCS projects in the Netherlands has faced a number of challenges. An initial CCS project in an onshore depleted gas fields by Shell in 2007 resulted in strong debate and public opposition (Feenstra et al., 2010). This ultimately caused the project to be delayed, and then much later, terminated.

In subsequent projects, emitters across relatively small geographical footprints have worked together to facilitate capture and gather systems for offshore geological storage in the Dutch North Sea sector.

The ROAD project

An early hub project was the ROAD project, which aimed to develop a CCS hub at the port and industrial surrounds of Rotterdam (Figure 8). The project recognised the need to build infrastructure in the region to manage emissions in NW Europe. Early emissions mapping (Read et al., 2014) indicated that the port and immediate industrial area was responsible for 17% (or 28 Mtpa) of CO_2 emissions in the Netherlands in 2013 and was a gateway to further opportunities for an emissions reduction hub. The area is comparable with the Teesside and Humber areas in the UK and the Ruhr industrial area of Germany. The vision set had mapped out the regional opportunities for capturing from EON's Maasvlakte power plant (Arts et al., 2012), Shell's Pernis natural gas to hydrogen facility, Abengoa's first-generation bioethanol plant and contemplated CO_2 utilisation through greenhouses (Read et al., 2014). P18-4, a depleted gas field approximately 25 km offshore, was the proposed storage site.

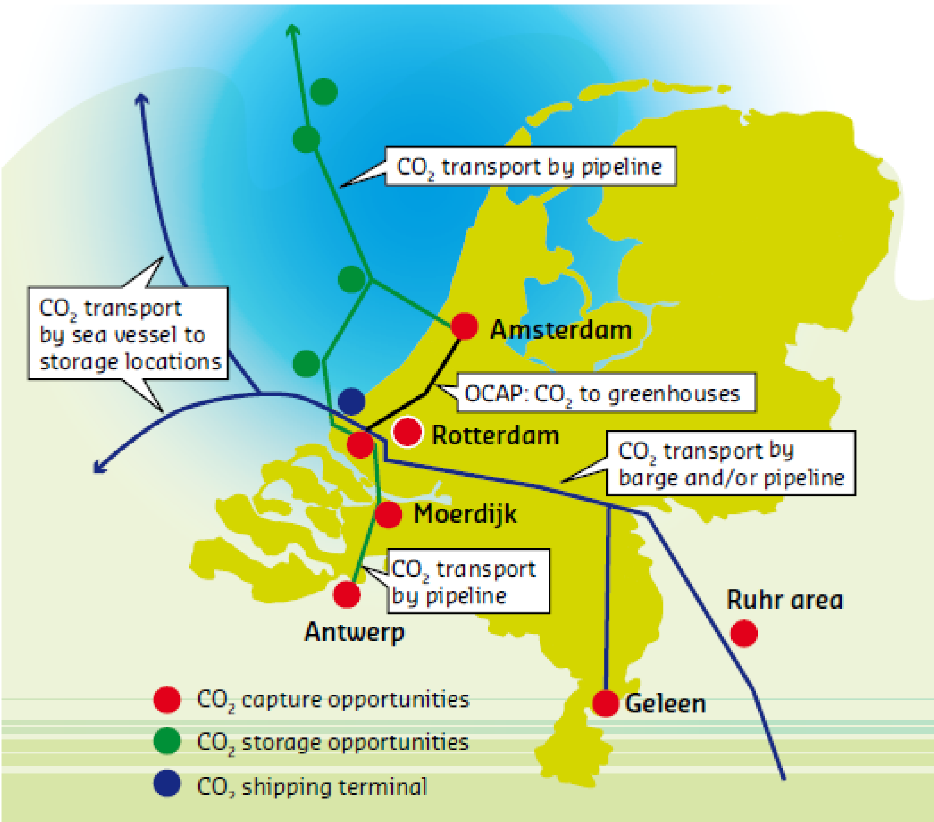

Figure 8: Rotterdam vision for the ROAD project, a CO_2 hub for North-west Europe
Source: Read et al. (2014)

In 2018, the ROAD CCS provided a series of close-out reports as a final deliverable for the grant funding that had been obtained. The overview report (Read and Kombrink, 2018) and a subsequent peer-reviewed publication (Read et al., 2019) discussed a series of lessons learned from technical, financial, risk management, permitting and regulation.

By the time the project closed, the model had essentially become a single-source-to-sink project, involving the Maasvlakte power plant, a 25 km pipeline and storage at the P18-4 gas field offshore. This did not reflect the earlier screening of potential emitters such as Shell's refinery or other larger-scale opportunities for capture. Initial grant funding was €180 m (A$300 m) from the European Commission (under the European Energy Program for Recovery) and €150 m (A$250 m) from the Netherlands Government. The Global CCS Institute provided €4.3 m (A$7 m) as a knowledge-sharing partner, and the Port of Rotterdam supplied the CO_2 pipeline infrastructure.

Phase 1 was undertaken between 2009 and 2012 to FID, but the collapse of the carbon price prevented FID from being taken. As a result, the project pivoted to focus on finding alternative funding mechanisms. A new storage site that required only a 6 km pipeline was considered but no path to a sustainable business case could be found and the project was terminated in 2017. This was after identifying a capture plant design for the 250 MW coal-fired power plant, a successful design for the value chain, including a transport solution with warm CO_2 and methods to inject CO_2 into a very low-pressure depleted gas field. This project was the first to obtain an EU CCS Directive storage permit that was deemed to have met both EU and Dutch regulations.

Shortcomings of the project were as follows:

- Lack of sufficient business case – no funding mechanism was identified, and market mechanisms were immature or inadequate. Ultimately ROAD had no customer.
- Public and political acceptance of coal-fired power generation in the region – the design and build of new coal-fired power (or possibly any form of hydrocarbon-derived electricity generation) was not supported. Renewable energy alternatives were preferred.
- Liabilities and responsibilities – the EU CCS Directive regulations at the time were challenging for commercial parties and represented unacceptable or too high risk for new entrants and first-of-a-kind projects in CCS. The project developers felt the liabilities were not in their control and identified that risks would be better held by government.

Table 3 briefly lists the key learnings from the ROAD project and how they may be reflected for the NT LEH.

Table 3: Highlights of the ROAD project close-out reports and how these learnings may be reflected for the NT LEH Source: Read and Kombrink (2018)

Key learning point	NT LEH reflection
Success of CCS is determined by the funding and business cases, not by technical issues. All technical and permitting issues proved to be solvable, or at least manageable.	The development of a robust business case to reduce risk and uncertainty has been a key focus of the study because it has been recognised in several 'failed' projects that technical issues are rarely the fundamental reason behind a project's termination.
In terms of capture and compression, significant work was conducted to develop necessary information to take FID. Challenges and technical risks were overcome, such that there was confidence that the technology was available to conduct full-scale post-combustion capture.	Industry proponents feel confident that they can design, procure and build appropriate facilities for capture, transport and storage such that FID can be reached. Technical and other challenges are surmountable. There is an infrastructure requirement that a module offloading facility is available in the MASDP to allow large plant components to be brought to site.
Transportation of CO_2 to a safe and appropriate design was possible. Practices would be dependent on the combination of storage location and proximity to captured CO_2.	Design parameters and plans for reuse of infrastructure and design of pipelines and/or ship-based transport are required in the NT. These are mostly covered by existing standards and codes. Territory and Federal governments are evaluating their regulations for implementing onshore, offshore and transboundary CO_2 transportation.
Depleted gas fields are taken to be suitable analogues for geological carbon storage. History matching of production data is particularly effective for characterisation and permits for storage.	CO_2 storage in depleted gas fields can provide a large volume of data and derisking of future performance of storage intervals. But it comes with different risks with respect to repurposed infrastructure and legacy wells. Jurisdictions have differing perspectives on associated risks, especially with wells. In the NT CCUS hub, depleted

	field reuse and a new saline aquifer storage site are both being investigated, mitigating risk.
Commercial arrangements and liabilities for storage were identified – with help from government required. ROAD's proposed solution for storage liabilities was believed to require help from government, and ROAD may not have felt successful in this endeavour.	ROAD may have closed out but the outcomes of this work were significant input material to the Porthos and Aramis projects (sources of CO_2, offshore storage locations and transport options). Commercial arrangements, public/private considerations and maturing EU regulations and perspectives may provide greater certainty for the project to be revisited in a different form. Australian and NTG legislation changes need to consider the balance of liabilities between commercial entities and the government to ensure that emissions reduction strategies can be practically implemented.
A conventional risk management approach was successfully applied to the ROAD project. However, this did not mitigate all risks and the project was still closed in its ROAD form.	The projects that have emerged from ROAD (e.g. Porthos, Aramis) have demonstrated there were outstanding risks that at that time could not be mitigated, but new business models and policy/regulatory changes have mitigated some of these risks. Comparing those risks with current risk strategies at the NT LEH will improve the business case and its proponents to execute the NT CCUS hub either in its current form or for discrete elements of the hub.
The ROAD project was successfully permitted (the first in the Netherlands) and was first under the EU CCS Directive. Some changes to legislation were required. Good communication and cooperation between project proponents and regulators was essential but took significant time. But not all aspects were ultimately tested (e.g. storage liability).	The importance of communication and cooperation cannot be understated. A collaborative approach between industry and government will be essential to managing permits, regulations, monitoring and community acceptance for the NT CCUS hub. The ability to review and amend regulations and legislation has been repeated here and elsewhere. OPGGS Act may have been enacted almost 20 years ago, but it has not been tested. Updated and new legislation/regulation needs to be sufficiently flexible that it can be adapted as experience grows.
Governance – company structure, project structure, governance and compliance were generally conventional.	The NT LEH business case may require detailed discussion on best ways to tackle any governance and compliance. Particularly as the governance and company structures may not mirror existing industry approaches. This will be dependent on the type of vehicle being developed for the NT LEH CCUS hub. Clarity on governance structures will have a strong impact on this matter to who holds various responsibilities and liabilities.
Project costs, funding and financial risk were presented by ROAD for both phases of the work, together with projected incomes and future costs. This economic assessment reviewed set-up, capital costs, operating costs and abandonment to provide transparency where government funding was used.	The objectives of this study are to develop a business case that will consider these financial aspects. The development of the business case is intended to identify risks and opportunities for the existing and new proponents so that they can consider the benefits and drawbacks of a CCUS hub in the NT and how it might be integrated with future transboundary movement of CO_2. Understanding who benefits other than the industry

	participants will aid broader community understanding of the benefits of CCUS hub development.
Financial and control systems, records, reporting and grant/subsidies were reported to provide transparency for other entities that intend to bid on large EU grants. Costs incurred and monies claimed were presented from 2010 to 2017. Obligations for reporting were described.	With any funding from government entities, the financial reporting can be detailed and onerous; levels of disclosure may come at a significant cost to industry proponents. This is a risk with respect to managing commercial-in-confidence activities as well as a risk in its own right. However, the detailed disclosure of public funding can be used to demonstrate co-investment for a common purpose.
The ROAD Knowledge Sharing & Dissemination Plan recognised the need to provide sufficient information to facilitate future strategies, and aid partners in developing action plans for future hub projects. The Close Out Report series has been a valuable tool for disseminating the information for future use.	This CCUS business case project will be made publicly available. The output, in the form of a series of reports, will attempt to distil the key considerations required for CCUS hub development in the NT. The results will have broader applicability to the Australian and South-east Asian context.
Public engagement was conducted for the ROAD project, some of which came via the Knowledge Sharing & Dissemination activities. Lessons learned from projects such as Barendrecht have enabled better-considered discussions and transparency around what a project might look like, who benefits, risks and responsibilities. It has been an integrated part of the project, together with an outreach plan.	Public engagement and outreach remain vitally important for the deployment of major infrastructure projects of any type. However, with FIDs often taking place far later than the project activities, lack of early engagement is a critical risk. The approach to outreach and engagement needs to be decoupled from the FID and brought about far earlier. The risks of not doing so are well-documented and expensive.

Three projects have followed on from the ROAD project in the Netherlands: Porthos, Aramis and Athos. The Netherlands has committed to a 55% emissions reduction target by 2030, and these projects are at various stages of development to meet this target.

Porthos CCS

The Porthos project is centred around the Port of Rotterdam (Figure 9) and is developing a gather system to obtain emissions from a range of industrial emitters (Porthos, 2023b). A 20 km pipeline will take the emissions to a depleted gas field in the Dutch North Sea sector at the P18 block (i.e. where the ROAD project had previously conducted studies). In total, it is expected to store 37 Mt over a 15-year period (i.e. 2.5 Mtpa). This project took FID in October 2023 and aims to be operational in 2026.

There are currently four emitter customers for the hub: Air Liquide, Air Products, ExxonMobil and Shell. Each has signed a Joint Development Agreement with Porthos and discussions are continuing with other potential emitters. Further agreements are in place to advance the definition of the transport and storage term sheets.

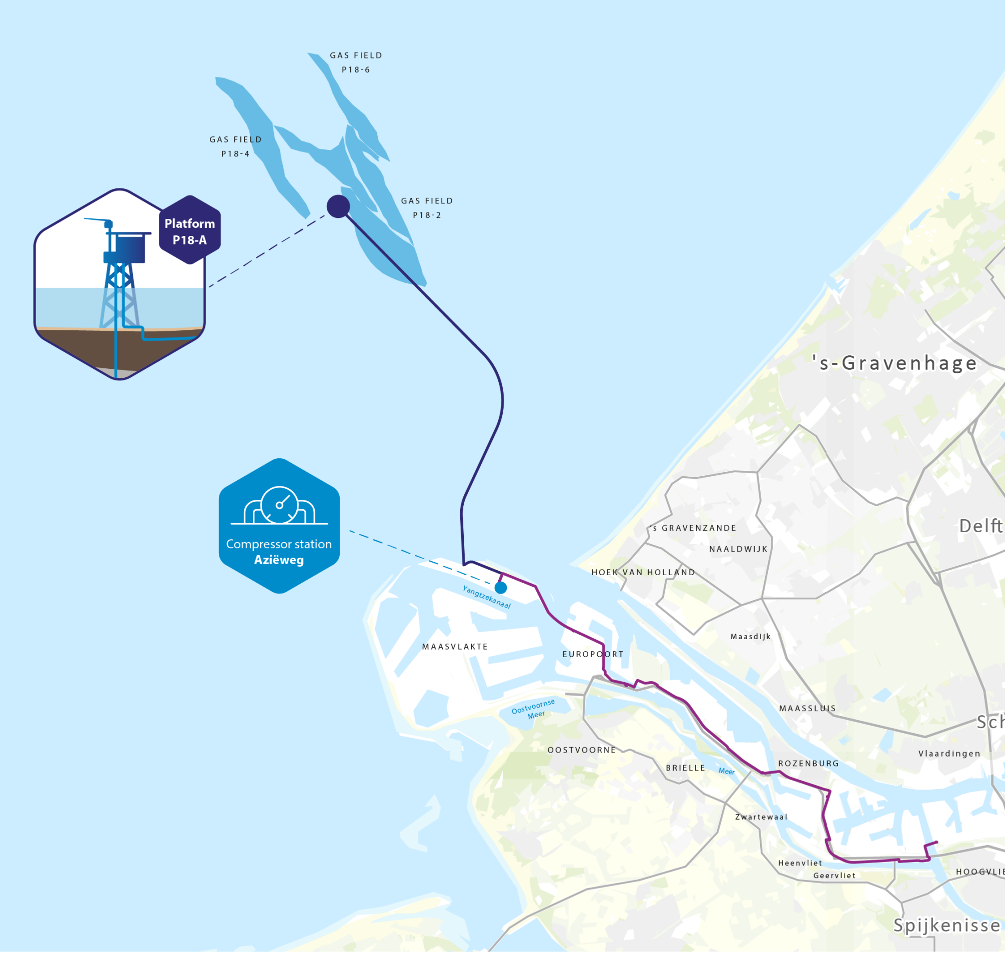

Figure 9: Porthos CCS project location. The onshore pipeline/gather system is ~30 km long and CO_2 will flow as a gas at 35 bar through the 108 cm (42") diameter pipe. The compressor station will bring the CO_2 to a maximum of 130 bar prior to being sent offshore. A 22 km pipeline of 40 cm (16") diameter will take the compressed gas to the P18-A Platform. Storage will be in the depleted gas field.
Source: Porthos (2023b)

The EU PCI scheme has recognised this project. In 2021, the Dutch Government set aside €2.1 billion (A$3.4 billion) through the SDE++ (Stimulation of Sustainable Energy Production and Climate) subsidy reservation. This scheme provides support to projects to aid emissions reduction collectively for the Netherlands. The purpose of this funding is to manage the economic gap between the ETS values and the cost of CCS so that companies can reduce emissions but not risk their financial position (cost-for-difference mechanism). This funding is part of a budget reservation where monies up to this value may be paid to grant recipients. Modelling suggests that because the EU ETS rate is likely to climb as emissions targets are ratcheted down, the expectation is that not all SDE++ subsidies will be required (see the Task 10 report).

By June 2024 the pipeline to Porthos was being laid with drilling under canals in the onshore region completed. Design specifications for the compressor station have been reviewed and upgraded as the project better understands flow rates, and trade-offs between CapEx and OpEx, but ultimately, as the project is in first-of-its-kind territory, there will be lessons learned during operations that will inform future projects greatly (Porthos, 2023a).

Aramis CCS

Shell, with partners TotalEnergies, EBN and Gasunie, is developing several storage fields in the offshore Dutch North Sea sector. The Aramis CCS project will connect these storage fields to the CO_2 emitters. This is a public-private partnership to develop open-access transport infrastructure for reducing industry emissions.

The first storage field is in K14FA, and work conducted to date enabled progress to FEED in late 2023 (Shell Netherlands, 2023). It is anticipated by the proponents that the depleted gas field will be one of the first Dutch storage fields to receive CO_2, with design anticipated to be ready in 2025 and operational by the end of 2028 (ARAMIS, 2023a).

One of the main emitters is the Maasvlakte power plant (Uniper, 2022), previously a major emitter partner for the ROAD project. From there, a ~200 km trunkline will be run offshore into a series of depleted gas fields. This project is designed to transport up to 22 Mtpa to a series of depleted gas fields, and this capacity is the next order of magnitude greater than that of Porthos (2.5 Mtpa) and will provide significant insights into the overall upscaling of larger-scale CO_2 handling and geological storage volumes.

The Aramis partnership business model provides a transport and compression service to 'shippers' Figure 10. The role of the shippers is to offer services to emitters, which is a combined transport and storage service. Shipper partners include Eni Energy Netherlands, Shell Offshore Carbon Storage NL, TotalEnergies Equity Marketing and Wintershall Dea Carbon Management Solutions. They have published CO_2 specifications to manage operational challenges across the potential range of conditions the CO_2 might experience during transport and storage (ARAMIS, 2023b).

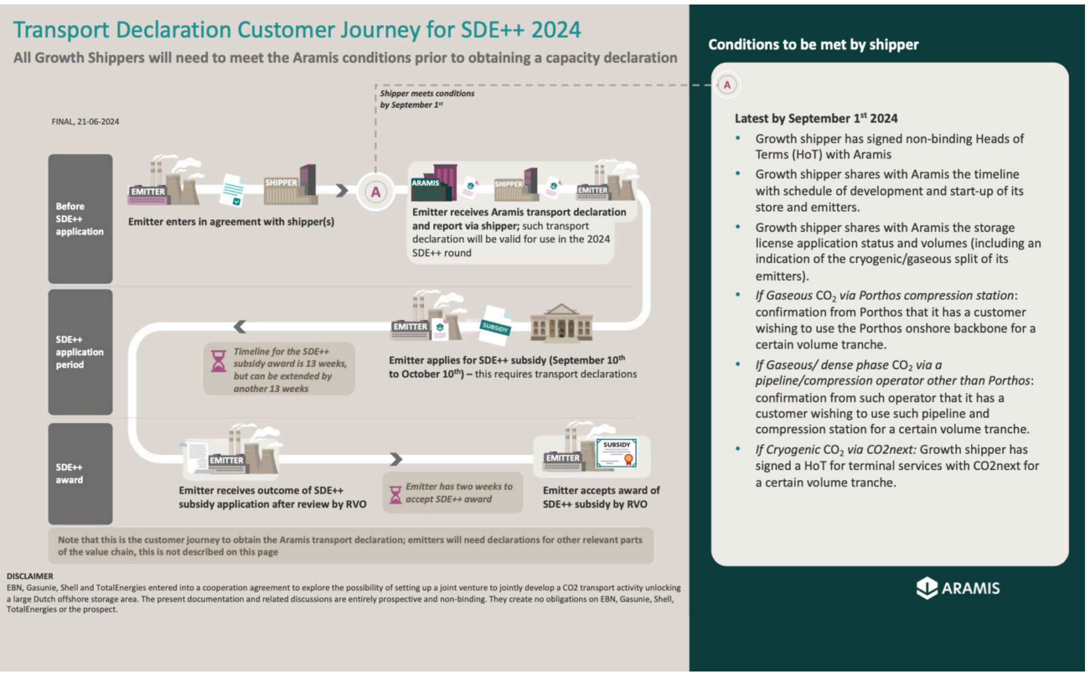

Figure 10: Information provided to potential shippers to participate in the Aramis project, and how they can access SDE++ funding in 2024
Source: ARAMIS (2024)

CO2next project

A new project that aims to be connected into the Aramis facilities is the CO2next project (Figure 3.4; (CO2next, 2024a). It is a partnership between Gasunie, Vopak, Shell and TotalEnergies, and centres around a liquid CO_2 import/export terminal that will act as a clearing house for captured gas prior to storage offshore by Aramis and other potential projects. This facility will focus on shipping of liquid CO_2 for customers that are not able to use pipeline transport options. As Figure 11 shows, there is a vision to consider a broader variety of transport options to access emissions from facilities that are in part landlocked through the use of river barges along the Rhine and Ruhr corridors from Germany and northern Belgium. The potential to use trains, trucks or canals may be complemented by shipping from other coastal countries where port terminals could also offtake to the Port of Rotterdam and then out to the Dutch North Sea storage sites identified by the Aramis project.

This could see the development of a terminal that could initially manage 5.4 Mtpa, with growth options up to 15 Mtpa depending on future capacity development for offshore storage. This model could then be used for the design and development of other import/export port facilities globally for LCO_2, such as those envisaged in the MASDP (see the *Task 6 report*; Joodi et al. (2024b)).

Permitting submissions have commenced for CO2next in collaboration with Aramis CCS, and the permitting and progress can be accessed publicly (Netherlands Enterprise Agency, 2021). A significant number of permits is required, and one of note is a 'preparatory decision' that was published in June. The Aramis Preparatory Decision (Official Gazette of the Kingdom of the Netherlands, 2024) handed down by the Minister for Climate and Energy and Minister of the Interior and Kingdom Relations is applied to 'prevent spatial developments from occurring in the area of the project decision that would make the area less suitable for achieving the objective of those rules'. The decision takes into account the Environmental Act and makes clear that there have been consultation activities with the municipality of Rotterdam and other relevant partners, so project decisions can be made. PCI status and Clean Energy Fund subsidy have been granted by the EU. The expected operation date for the first phase of the project is 2027.

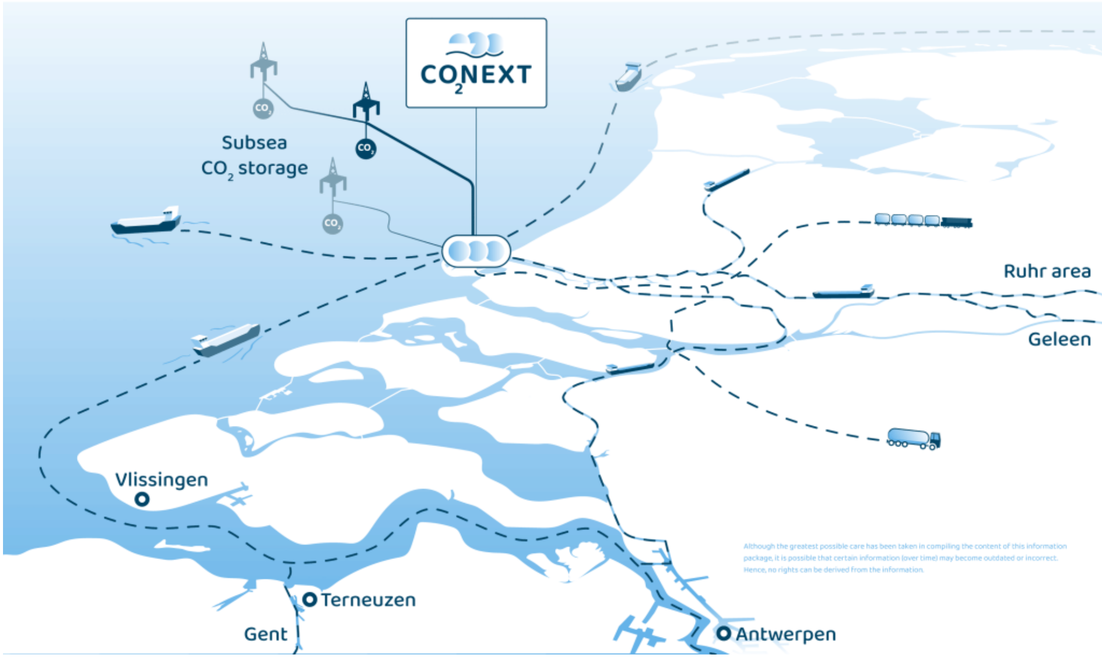

Figure 11: Schematic of the CO_2next facility
Source: CO2next (2024b)

Athos CCS

The Athos project (**A**msterdam-IJmuiden CO_2 **T**ransport **H**ub & **O**ffshore **S**torage) was terminated when its key emitter client (Tata Steel) decided to invest in an iron reduction process using hydrogen rather than a more conventional energy source and managing carbon emissions (S&P Global, 2021). Once again, the overreliance on a single key emitter made the project unviable. However, the background work on the P18 licence area has continued to be added to from initial work on the ROAD project and now with the Aramis and CO2next projects.

Lessons learned for the NT LEH

Comparing activities in the Netherlands with the NT LEH studies provides some comfort for proponents addressing the risk of potential project failure. While the ROAD project did not reach a positive FID, it did lay significant groundwork for identification of potential emitters and future partners for a low-emissions hub (or several hubs) near major ports and offshore storage infrastructure. Since the ROAD project the same depleted gas fields near the port infrastructure have remained under evaluation. This is because they are close to likely locations for onshore hub infrastructure, and no ‘showstoppers’ in terms of storage capacity, containment security and injectivity have been identified as yet. The production history, exploration data and infrastructure that can be repurposed for transport and storage are important assets for any CCS project in the region.

The re-establishment of CCS concepts in this region builds on the knowledge generated and lessons learned from previous feasibility studies. This demonstrates that value is created even though some of these projects may be described in the media as ‘failed’. A comparison in context of the NT LEH would be geoscience studies in the Petrel Sub-basin. The region’s geology, and other Australian locations (Figure 12), was first studied for CCS as part of the GEODISC work for the APCRC from 1999 to 2003 (Bradshaw et al., 2002; Geoscience Australia, 2023).

Much of these GEODISC materials were combined with other information acquired through conventional oil and gas exploration and production activities to generate the 2009 Carbon Storage Taskforce reports (Carbon Storage Taskforce (2009); Figure 13).

Under the OPGGS Act, two exploration blocks (2006 PTRL-01 and PTRL-02) were released in 2009 but were closed by 2014. Geoscience Australia then conducted an in-depth study of the area, published by Consoli et al. (2014) and funded by the National CO_2 Infrastructure Plan, which ran from 2012 to 2016 (Figure 14).

A new funding round from the Department of Industry, CCS Research Development & Demonstration, facilitated a further study that was this time industry-led. Shell, then Eni in collaboration with CSIRO, brought together both open-file and commercial-in-confidence data to consider the potential for the Petrel Sub-basin to host significant quantities of CO_2. Within this series of studies, work was conducted to identify storage capacity at a sequence of locations (Figure 15). The results of this work did two things: firstly, it increased the resolution of the study areas to the point where locations to drill were beginning to be identified, in a step away from broad-brush basin-scale evaluations; and secondly, discrete, bounded storage capacity estimates were presented that could inform future acreage bidding decisions.

Recent acreage nomination and release rounds managed by NOPTA have included the award of G-7-AP to INPEX in 2022, where the West Peron-1 and 2 CCS appraisal wells were drilled from July 2024 to December 2024 to obtain new data and samples for the potential development of a future storage site.

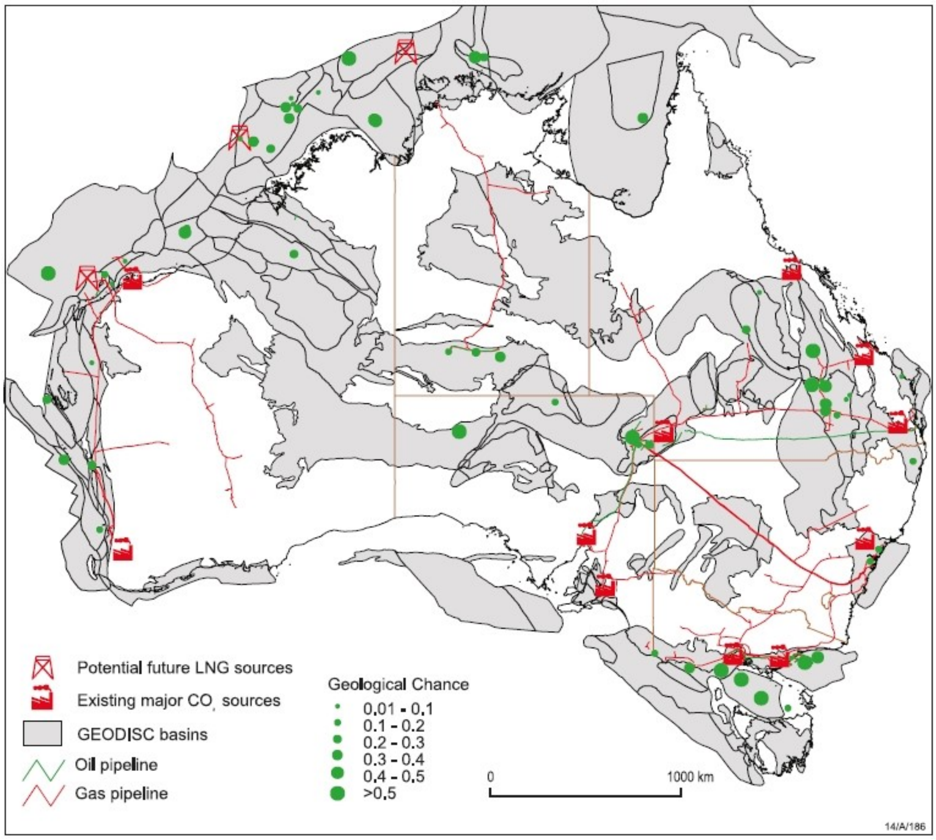

Figure 12: GEODISC study data consolidated
Source: Bradshaw et al. (2002)

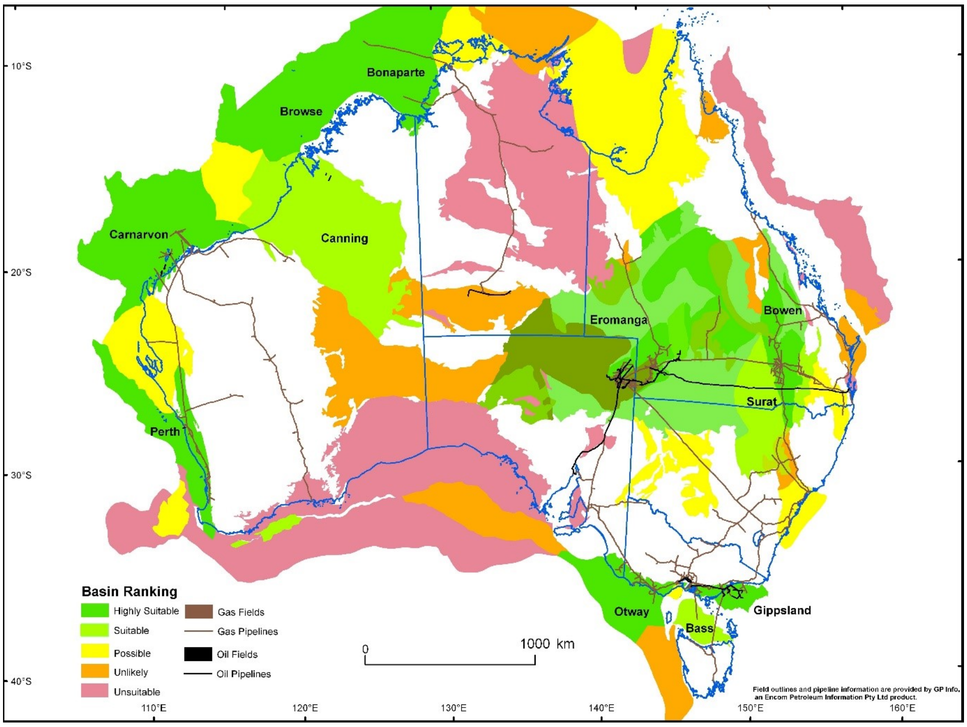

Figure 13: The Carbon Storage Taskforce (2009) study further consolidated geoscientific information, but also began to consider more deeply the potential for source-to-sink matching as a precursor to hubs and clusters
Source: Carbon Storage Taskforce (2009)

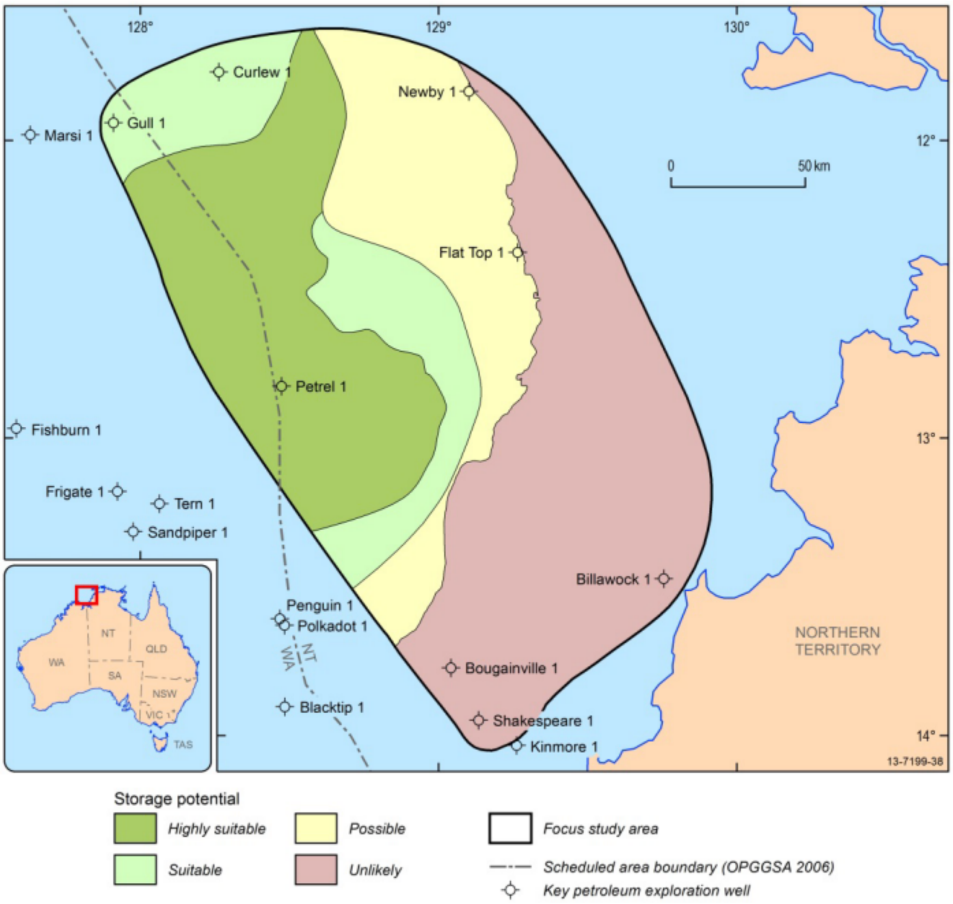

Figure 14: Detailed study of the Bonapart Basin. A more detailed study identifies the potential for geological storage. Full details in the report are complemented by data hosted by Geoscience Australia.
Source: Consoli et al. (2014)

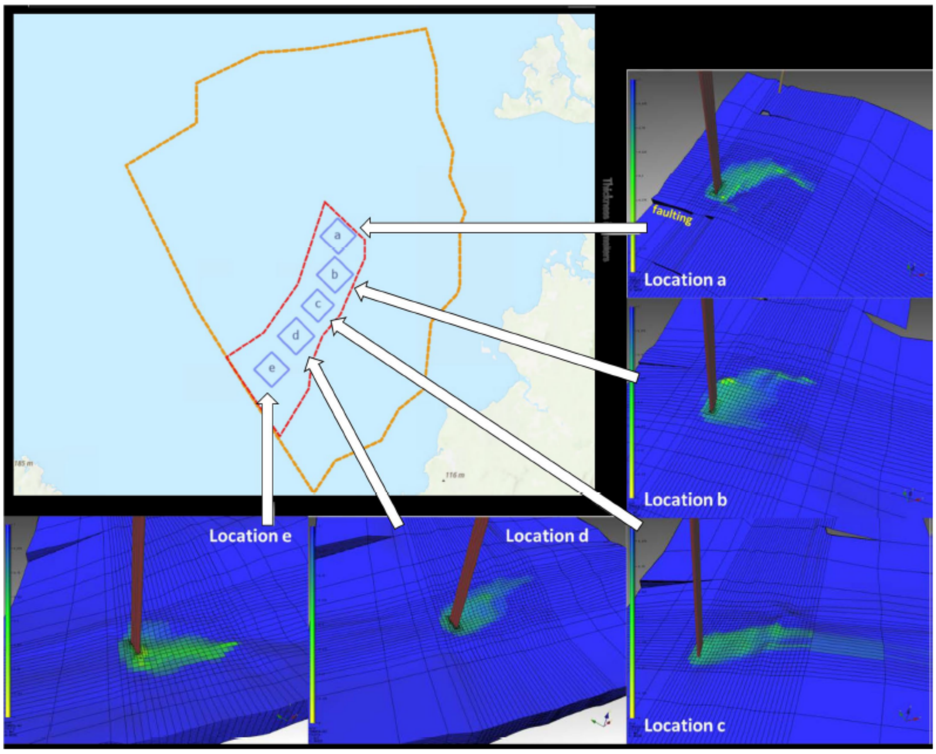

Figure 15: Further geological evaluations in the Petrel Sub-basin reaching towards a potential drilling location
Source: Johnstone and Stalker (2022)

3.1.2 Denmark and Belgium

Project Greensand

In 2023, Project Greensand became the first project to undertake a test injection of CO_2 into a depleted oil field in the Danish North Sea sector (Skopljak, 2023). It was also a first because the CO_2 had been transported across borders from Belgium at the INEOS Oxide petrochemical site to be stored at an INEOS operated field, Nini. The injection was part of a trial at the Nini West platform, Figure 16, where FID for a full-scale project is imminent (Green Sand, 2024). Over time, the plan is to access the main Nini field so that the project can ramp up to 1.5 Mtpa of CO_2 injection in 2025/2026. Further expansion to 8 Mtpa by 2030 will be accommodated by the Siri Fairway Expansion Project, where Siri and other fields in the area will also become part of the storage capacity. This is aimed to mitigate 13% of Denmark's annual CO_2 emissions.

Figure 16: Nini Platform, offshore Denmark, receiving CO_2 a vessel delivering offtake from Belgium
Source: INEOS Energy

A significant consortium of 23 organisations is involved in Project Greensand, including research institutions, emitters, engineering companies, well and drilling companies and renewable energy providers, covering the entire value chain. With varying degrees of experience and expertise, knowledge sharing between the partners aims to accelerate the deployment of CCS. Existing field data and production history information have been an important asset in the accelerated development of this storage site. Project Greensand received funding for all initial (Phase 1) technical validation studies, as well as €27 million (A$44.7 million) for Phase 2 (pilot proof of concept study) from the Energy Technology Development and Demonstration Program via the Danish Energy Agency (The University of Edinburgh, 2024c).

Project Bifrost

The oil and gas industry is leveraging its expertise to identify further transport and storage opportunities offshore Denmark in the Harald Field. The project is taking a technology-led approach to advance CCS through the establishment of the Danish Underground Consortium, a partnership between TotalEnergies, Nordsøfonden and Noreco, with Ørsted and the Technical University of Denmark. While still in the early stages of feasibility, the consortium has received €10.3 million (A$17.1 million; December 2021) for initial studies from the Energy Technology Development and Demonstration Program via the Danish Energy Agency (The University of Edinburgh, 2024b).

The primary aim of Bifrost (Figure 17) is to develop CO_2 transport and storage focused on using the consortium's existing offshore assets. The use of the term 'all offshore' (Prevost et al., 2022) for the first phase of storage signals the use of floating storage and injection facilities, rather than port-based with pipeline infrastructure. This concept has been identified as a potential business model in Australia by deepC Store (deepC Store, 2024).

A series of work packages has been defined by the consortium (Bifrost, 2024), including a range of engineering, geoscience and socioeconomic aspects of the project (Figure 17). In particular, the Harald Field is a chalk reservoir, and so may have some different behaviours or performance during injection. The research partners are investigating this further (e.g. Bonto et al. (2021) so that additional data can be collected on chalk formations other than sandstones, even though chalk reservoirs have historically undergone CO_2-EOR in the past.

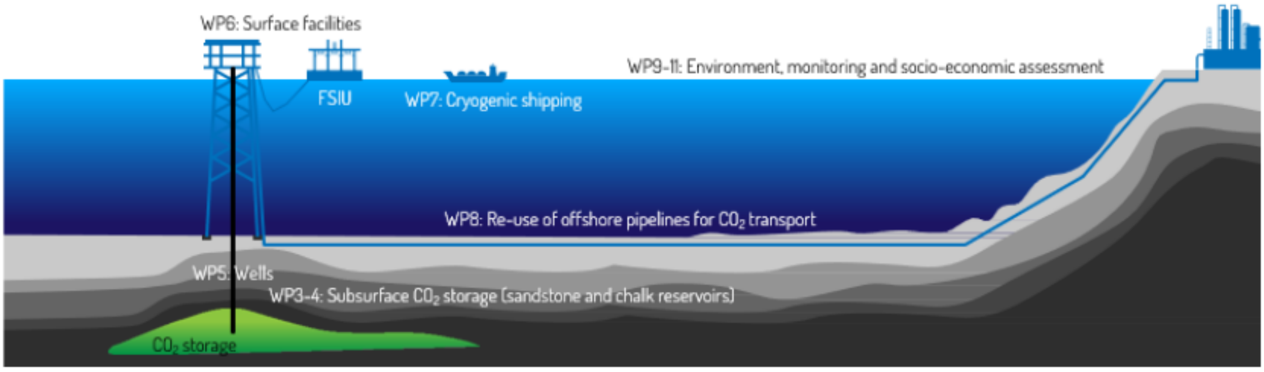

Figure 17: Project Bifrost concept, which will address a range of work packages to derisk further storage sites in Denmark
Source: Prevost et al. (2022)

In addition to the floating storage and injection facilities, feasibility studies are underway to evaluate the potential to repurpose the gas pipeline infrastructure, along with additional investigations on the design and build of new onshore CO_2 offloading and buffer storage facilities (Figure 18).

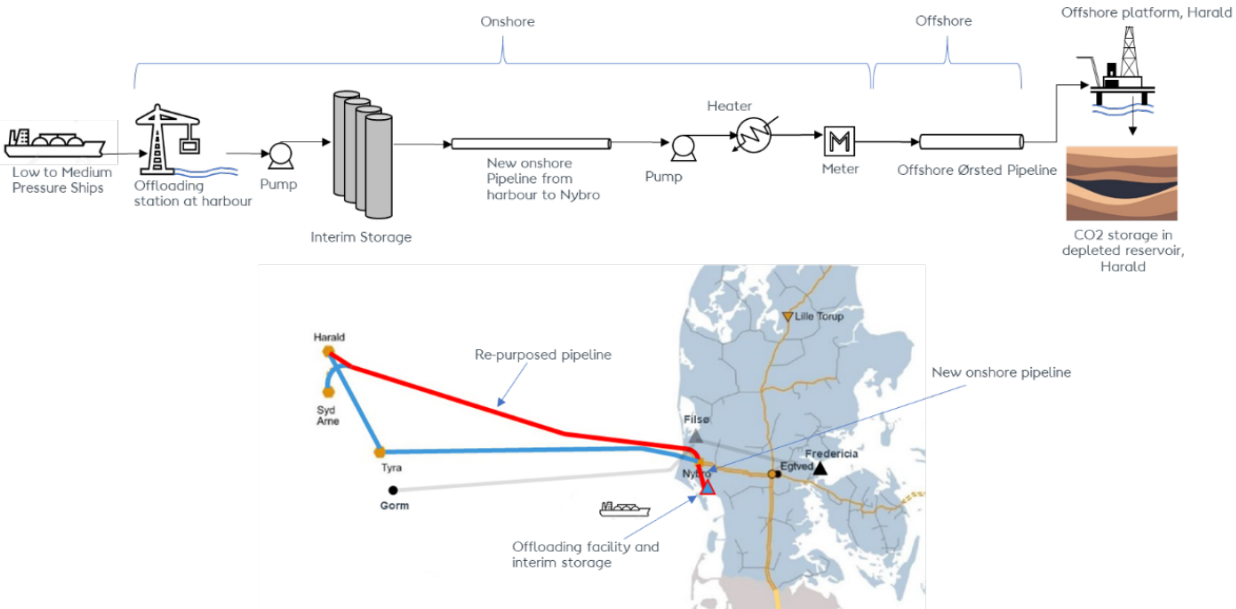

Figure 18: Future pipeline developments to connect onshore emitters to offshore storage in Denmark
Source: Prevost et al. (2022)

Lessons learned for the NT LEH

While the projects in Denmark are less mature than those in the Netherlands, the urgency in the development of the projects is notable, with the projects moving forward rapidly. These projects, if realised, will materially reduce Denmark's CO_2 emissions. The projects are exploring new business models (transborder shipping and floating storage and injection systems). The projects also have a wide range of project partners, notably including renewable energy companies. The strong support from government and the broad industry and academic consortia is an important facet of the projects, as it will both increase the literacy and skills of a large number of organisations, but also allow a wide range of skills to be applied to address and manage risk.

For development of the NT CCUS hub, having a wide cohort of organisations is important to bring different facets of the hub to fruition and build on the shared vision. The inclusion of academia is important as these organisations will be responsible for the education and training of the scientists and engineers that will make up the future hub workforce.

3.1.3 Norway

Norway has a long history of CCS R&D and commercial application of CCS since commencing the Sleipner CCS project in 1996. This has facilitated knowledge growth in the area and socialised the potential for CCS as a future industry in Norway early on, and it continues to be a clear part of the Norwegian Government's future growth strategy. A CCS strategy was tabled in Parliament in 2014–15 which outlined the government's intent to be involved and support the technology. This was, in part, due to the lack of deployment of the technology where the barriers were mainly commercial in nature. Thus, innovations in business models, policy and regulation were recognised as requiring funding from government to support further investment by industry while Norway developed policy and industry became familiar with these new markets and developed new value chains and new approaches to decarbonisation.

In 1991 the Norwegian Government began to signal a transition to a lower emissions economy with the introduction of the CO_2 Tax Act on Petroleum Activities (Norwegian Petroleum, 2024). Other regulations to support the tax include the Petroleum Act, the Sales Tax Act, the Greenhouse Gas Emissions Trading Act and the Pollution Control Act. Emissions are reported by Offshore Norge's Footprint database (Collabor8, 2024).

The CO_2 tax is levied on the following:

- all combustion of gas, oil and diesel in petroleum operations on the Norwegian continental shelf
- release of CO_2 and natural gas.

The rates for the last 2 years (2023–2024) are presented in Table 4.

Table 4: Carbon tax rates in Norway and the EU ETS
Source: Norwegian Petroleum (2024)

	Carbon tax, 2023		Carbon tax, 2024	
	NOK	A$	NOK	A$
Standard cubic metre gas	1.78	0.25	1.85	0.26
Litre of oil/condensate	2.03	0.29	2.10	0.30
Natural gas combustion (tonne of CO_2)	761	107.09	790	111.18
Natural gas emissions to air (cubic metre)	13.67	1.92	16.89	2.38
EU ETS price per tonne CO_2*	974	137.07		
Carbon tax and EU ETS combined*	1750	246.27		

*Actual paid emissions could be lower because there are some free-of-charge carbon credit allocations.

The corresponding ETS for Norway, administered under the Greenhouse Gas Emissions Trading Act, commenced in 2005, and Norway subsequently joined the EU ETS in 2008. The EU ETS is a cap-and-trade system, with the cap being reduced year on year to ensure that emissions targets can be reached during the specified period. The price has been variable in the past but has increased in recent years (Table 4). Other emissions (e.g. NOx) also incur a range of penalties but are not discussed further here.

Historical greenhouse gas emissions from the petroleum sector have been recorded from 2000 to 2023 and are projected out to 2030 by the Norwegian Offshore Directorate (Figure 19). While emissions reductions from the petroleum sector in Norway (including CCS) have made a material contribution to a reduction in emissions over the past 20 years, during a period of significant oil and gas development, emissions reduction progress is slowing towards 2030.

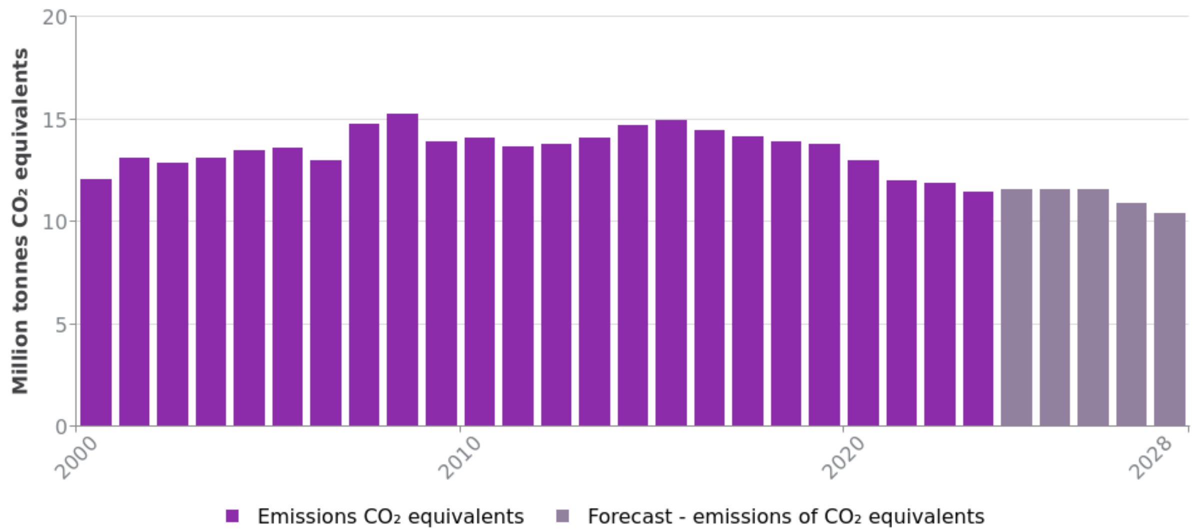

Figure 19: Greenhouse gas emissions from the Norwegian petroleum sector
Source: Norwegian Petroleum (2024)

Early Norwegian investments in CCS activities have resulted in several outcomes. The initiation of the Sleipner CCS project (Ringrose, 2020 and references therein), the subsequent Snøhvit project (Ringrose, 2020 and references therein) and large-scale test facilities for capture at Technology Centre Mongstad have made significant contributions to knowledge development, new innovations and fundamental research into all aspects of the CCUS value chain (TCM, 2024).

This investment has enabled Norway to accelerate deployment of CCS technologies and make early transitions from single-source-to-sink sites like Sleipner and Snøhvit to the emergence of large-scale hub and cluster models such as the Northern Lights project and Langskip (Longship) project (Northern Lights Project, 2024b).

Sleipner

Norway was an early adopter of CCS with the first commercial-scale CCS project commencing in 1996 in the Norwegian Offshore Continental Shelf side of the North Sea in response to the implementation of a carbon tax by the Norwegian Government (Zhang et al., 2022; Furre et al., 2017). Sleipner is a single-source-to-sink CCS project that was established to manage naturally occurring CO_2 present in the produced hydrocarbon assets of the Sleipner Field of the Norwegian North Sea. The amount of CO_2 varies in each of the hydrocarbon field areas that make up the greater Sleipner area, ranging from 4% to 9.5% (Baklid et al., 1996). This exceeded the offtake agreement for transportation by pipeline (maximum CO_2 content of 2.5%) and so gas had to be removed at the platform. Flaring of acid gas was not considered an option due to the implementation of the carbon tax, so subsurface storage was employed.

An amine CO_2 separation plant was installed on an offshore platform and the separated CO_2 is injected in the Utsira Formation, a saline aquifer, at a depth of 1 km (Figure 20). This formation can receive from a single well injection rate of 0.9 Mt per annum. The project has sequestered more than 18 Mt of CO_2 and has been regularly monitored with high-quality marine seismic surveys (C&C Reservoirs, 2023).

The Sleipner CCS project was initially permitted under Norwegian oil and gas regulation. Since Norway has had to conform to EU rules in many matters, Sleipner was re-permitted in 2016 to comply with the EU Directive on geological carbon storage. A short account of that process is given in a Carbon Sequestration Leadership Forum (2017) report.

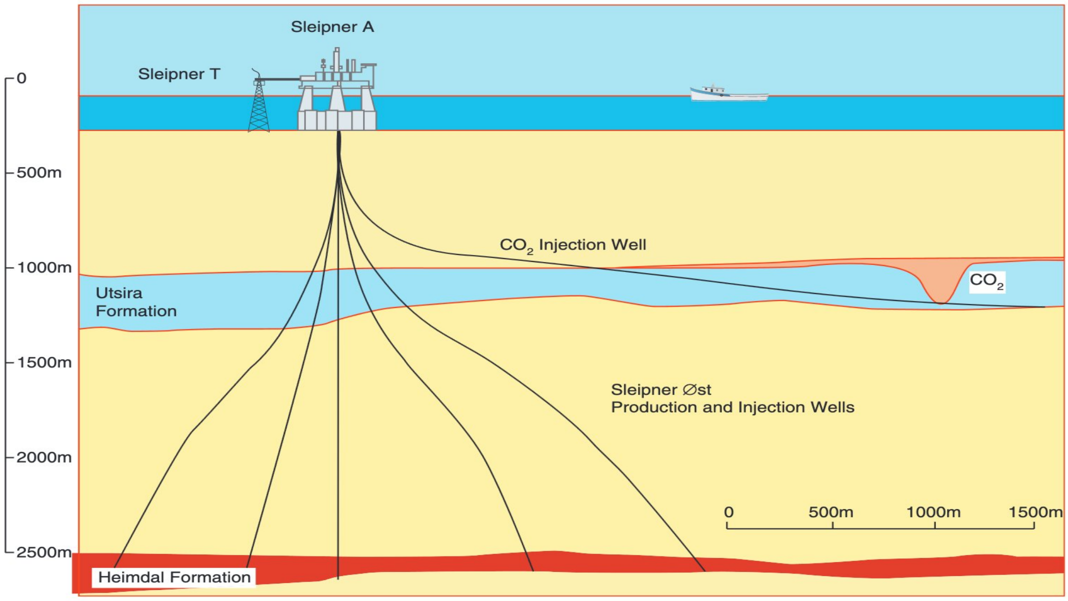

Figure 20: Schematic of the Sleipner Field and CO_2 sequestration site
Source: modified from SACS Project SINTEF (2008)

While the Sleipner CCS project has been a success, the learnings from the project for hubs are somewhat limited.

Longship and Northern Lights

Noting that there had already been several pilot and demonstration-scale activities in CCS, in the 2014–15 CCS strategy the Norwegian Government stated that 'an industrial full-scale and full-chain demonstration is needed' (Gassnova, 2020).

The Longship project represents a different CCS business model to prior CCS projects in Norway on several fronts. The project represents a move to a cluster model and is the first project to implement liquid CO_2 shipping transport at scale (beyond small volumes transported for fertiliser and food and beverage industries).

For Longship, the project proponents felt it important to split the chain into three: capture, transport and storage. This enabled individual organisations to manage their sub-projects independently, but also address differences in expertise, competency and experience. It was overseen by Gassnova (see call outbox below), which coordinated and integrated the activities. While this comes with some risk, the outcome reported by Gassnova (2020) suggests that it was a key factor in the overall success of this integrated CCS chain. The benefit of allowing emissions source industrial proponents to focus solely on the capture element would be to identify the best solution for probably the costliest part of the value chain.

For the foundation emissions, Longship includes capturing CO_2 from industrial sources in the Oslo fjord region (Norcem Heidelberg Cement in Brevik and Fortum Oslo Varme waste-to-energy plant) and shipping liquid CO_2 from these industrial capture sites to an onshore terminal on the Norwegian west coast.

The Northern Lights project (scheduled to begin operation before the end of 2024) is responsible for developing and operating CO_2 transport and storage facilities, open to third parties, as part of the Longship project. The Northern Lights project is a collaboration between Equinor, Shell and TotalEnergies. The project aim is to bring to bear:

- scalable transport and storage infrastructure for a range of emitters
- a novel application of both EU and Norwegian CCS regulations that tests levels of harmonisation
- a full value chain across a hub or cluster of different industry emitters.

The risk of compartmentalising the various sub-projects has been mitigated through a technical committee of emitters, transport and storage participants and Gassnova, commencing at concept select stage, so that items of common interest could be identified early. These common areas included, but were not limited to:

- CO_2 specification
- export rates from capture facilities
- use of loading arms between the capture export terminals and the transport medium (in this case ships)
- scheduling of ship movements
- management of off-specification captured gases.

The risks associated with these and other features meant that a formal project integrator was required whose role was to manage definitions and engage in monitoring progress of the development of the design basis through audits and verifications. Evaluation of delivery from the partners, including technical evaluations and ranking of the potential capture projects and their candidacy, HSE, HAZID and HAZOP sharing to manage the interface between each step, and additionally incurred emissions, were taken into account as well. Technical activities and agreement negotiations were also part of the integrator's remit. Reporting to the project steering committee included risk management and monitoring of potential subsidy stacking and benefit realisation. The Gassnova report (2020) did identify that one risk was a lack of common definition around metrics and project goal success/failure. This may have led to lack of alignment between the proponents, which can be of significant risk in complex stakeholder and shareholder situations.

In the early identification of emissions, activities commenced with the mapping of potential capture opportunities, which identified 30–35 potential large emitters, each generating more than 100,000 tpa of CO_2. These industries included oil refineries, gas processing plants, petrochemical plants, cement factories, metal processing plants and others. This approach has been replicated within this CCUS business case project (see the *Task 2 report*; Rogers et al. (2024)).

Gassnova

In accordance with the Articles of Association, Gassnova's purpose is to act as a strategic and technical advisor to the Ministry of Energy on CO_2 management and represent the Norwegian state's interests in the capture, transport and geological storage of CO_2. The company has an important responsibility to contribute to the knowledge base for the further development of CO_2 management and is tasked with actively facilitating the exchange of knowledge and experience in Norway and abroad. The company is responsible for the implementation of the government's overall CO_2 management policy, to which it also contributes.

Gassnova actively brings together specialist areas within research, industry and public sector organisations and, through its various tasks, its own initiatives and in cooperation with others, acts to facilitate achievement of the government's goals for CO_2 management.

It is tasked with:

- mapping opportunities and measures for CO_2 management at combustion and process plants in Norway, based on existing instruments – this work is to be seen in the context of the management of the CLIMIT Demo.
- identifying opportunities for reducing CO_2 emissions in industry, with particular emphasis on industrial clusters.

Gassnova manages the Longship project, the Mongstad Technology Centre and the CLIMIT program (Norway's national program for research, development and demonstration of CO_2 CCS) on behalf of the government.

Once a thorough review of technical, commercial and financial arrangements had been conducted, and companies consulted directly, the remaining candidates to participate in Longship were reduced to Yara Ammonia Plant (Herøya) and Norcem cement factory (Brevik). Fortum Oslo Varme followed the other entrants as a credible partner with which they and the Norwegian Government could develop valuable learnings and expertise for a future CCS industry.

Uncertainty in future opportunities for an ammonia industry initially caused Yara to withdraw from Longship (Gassnova, 2020). Challenges in predicting the potential for fuel switching for ammonia and hydrogen will continue to impact investment decisions by industry and could lead to delays for some hubs and clusters like Longship in the future. However, in November 2023, Yara signed the first fully termed commercial transport and storage agreement for the project (Northern Lights Project, 2023). This was followed by an agreement with Ørsted (Danish Energy Agency) to transport and store biogenic CO_2 from its biomass power plants. This also paves the way for transboundary movement of CO_2 between Denmark and Norway.

Prior to 2019, Northern Lights sought to mitigate CO_2 supply risk through the signing of multiple memoranda of understanding with a range of large emitters, including Air Liquide, Arcelor Mittal, ERvia, Fortum, Preem, Heidelberg Cement and Stockholm Exergi. These initial indications from a range of emitters helped to mitigate uncertainty that there was a lack of demand for transport and storage in the near future.

Subsequently, this demand has been reinforced through establishing customer discussions between emitters and Northern Lights. This has included the opening of an EOI to enable the more technically and economically mature companies to help predict the need for future expansion of the storage facilities and overall need for increased capacity. This has led to more than 200 customer dialogues, the completion of four agreements for transport and storage, and identification of the potential for more than 100 Mtpa supply from 15 countries. These discussions identified more than 10 market segments including biofuel/gas, cement, chemicals, direct air capture, fertiliser, hydrogen production, metals, refinery, steel and waste-to-energy producers (Northern Lights Project, 2024b).

The result has been the development of a public–private partnership that has evolved as the project has matured. Since Gassnova's review in 2020, further activities have commenced to expand the Longship project, increase the number of potential emitters involved and expand the storage potential for growth in emissions reduction as countries aim to meet their 2030 and 2050 targets.

Longship's success has come in part from state backing and business arrangements with the industrial partners. Funding for the project is administered by Gassnova, a state enterprise that is owned by the Norwegian Ministry of Petroleum and Energy.

The benefits to the Norwegian state of its involvement through Gassnova include the ability to study each of the stages of capture, transport and storage, as well as being closely involved in managing the project schedule, acting as a negotiator on terms (e.g. state aid, construction and operations) and assessing cross-chain risks and performance. At the same time, each partner remains responsible for its own project and its components in the development of the overarching hub concept.

This is not unlike the approach being used by the NT LEH from the perspective of each proponent being responsible and unencumbered to deliver its own project activities. However, for the NT LEH there is yet to be a centralised administrative and funding body. It is important to note Gassnova's unique role and how this differs from other government approaches (e.g., the UK).

Lessons learned for the NT LEH

A thorough review and exploration of challenges and lessons learned for project Longship has been conducted by (Gassnova, 2020). It highlights some of the key lessons learned from the project from the pre-feasibility study in 2014 up to the completion of the FEED studies and FID in 2020. While some aspects are unique to Norway, many of the learnings are directly relevant to future hub and cluster infrastructure developments in other jurisdictions (Table 5-6).

The overall steps from 2017 to 2024 are presented in the *Northern Lights Annual Report* (2023), which highlights various construction phases (offshore, at the offtake facility, major contract milestones, award of operational partnerships and ship building; Table 7), culminating in the expectation that Northern Lights will receive its first CO_2 by the end of 2024.

Table 5: High-level learnings determined by Gassnova (2020) on the Longship CCS project and how these learnings are reflected for the NT LEH
Source: Gassnova (2020)

Key learning point	NT LEH reflection
A CCS venture that includes capture, ship transport and geological storage is technically feasible and safe, but the business model may be demanding.	The business model for the development of a CCS hub in the NT that includes capture, pipeline transport, CO_2 import and offshore geological storage is likely to be complex, but learnings from project Longship can be implemented to reduce uncertainty. Ship-based transport, once established, is feasible and the results from project Longship will derisk this transport option.
The London Protocol: the 2019 temporary amendment to allow export of CO_2 for offshore storage has removed the last regulatory showstopper (at that time).	While Australia has ratified the amendment to the London Protocol, bilateral instruments are still required. The Australian legislation and regulation activities are still in progress. A full review and alignment process across Federal departments is underway to reduce duplication. As the OPGGS Act has not been tested yet, some uncertainty remains.
CCS value chain technologies are not new. This has reduced risk profiles. Amine technologies for capture are not backed up by new innovation – no fall-back solutions have been identified.	There is rapid innovation and increasingly varied options for carbon capture (e.g. cryogenics, calcination, membranes, direct air capture) that may complement traditional amine offerings. Amine types, stability and behaviour are improving.
In 2020 there were few comparable CCS hub or cluster projects globally. Levels of experience, competency and knowledge from adjacent geoscience and gas process engineering etc. mean that technical know-how and workforce participation are achievable.	Historically the NT has struggled to attract skilled workers. However, the CCUS hub would build on skills and expertise that are already present in the NT from the adjacent LNG industry.
First-of-a-kind projects are more expensive. The resultant cost per tonne for capture, transport and storage is projected to be high initially (1,280 NOK or A$180 per tonne for 800,000 tpa). With increased utilisation, build-out etc., costs are projected to decrease.	NT LEH activities are still likely to be regarded as early examples and as such may attract a risk premium as well as a premium for the NT's remote location. The scale of the potential CCUS hub will lead to economies of scale that will help mitigate early upfront costs.
From feasibility to delivery from an engineering perspective takes time (on top of any regulatory or financial decision making). Retrofit of capture alone could take 42 months.	The time taken to go from feasibility to concept selection, design steps and engineering remains challenging when considering the 2030 emissions reduction commitment targets and other obligations such as the Safeguard Mechanism. Opportunities should be sought to find ways to accelerate and disseminate the knowledge from first-of-a-kind projects where regulation and legislation have not been tested previously, or where stakeholders feel unfamiliar or uncertain about perceived new technologies. This will have flow-on effects of providing certainty to other hub developments.

Parliamentary approval will see agreements for an emitter (Norcem) and the transport and storage company (Northern Lights) to obtain state aid for construction and the first 10 years of operations of the CCS components of the facilities. The Norway has determined (based on risks and opportunities) to bear 84% of Norcem and 73% of Northern Lights project costs. Fortum Oslo Varme may be eligible for 40% cost coverage if it can secure additional third-party funds.	Financial support for industry participants from governmental sources remains uncertain. The NTG has provided land access at Middle Arm and aims to obtain precinct-level environmental approvals for the MASDP. Currently, all other financial risks lie with individual industry parties.

Table 6: Learning points with respect to project development stage gates
Source: Gassnova (2020)

Key learning point	NT LEH reflection
Separation of capture, transport and storage activities allowed emission source owners to develop standalone business cases in areas where they have more expertise. This avoided the need to establish their own transport and storage concept, which may have been far outside their area of expertise.	The current LNG industry in the NT has expertise in the whole value chain. New participants will be able to take advantage of this expertise, particularly for transport and storage. Some of the same proponents involved in the NT CCUS hub are also involved in Northern Lights.
The Norwegian government accepted costs and risks associated with the uncertainties that occur across the capture to transport and storage activities.	Inherent risk remains for early adopters. This will diminish over time as both technical understandings and markets mature. In the NT, cost and risk are predominantly carried by industry.
The Norwegian government developed and retained a project integrator role via Gassnova (noting Gassnova wrote the report that states this positively).	A project integrator and oversight role is critical for responsible monitoring of taxpayers' money.
Development of a range of committees made up of the integrator and the industrial partners has allowed knowledge exchange in areas of common interest. This has aided alignment across the value chain and resulted in more effective and foreseeable decisions.	A platform such as the NT LEH working group can provide a series of committees and working groups that enable knowledge exchange and concerns across partner interfaces. It allows for troubleshooting and airing of new ideas, such as the potential for common user infrastructure and derisking activities.
Conventional approaches to technology scans, design and costing considerations are typically closely connected. In this first-of-a-kind project, lack of commercial and regulatory information and experience in CCS made this approach challenging. A staged development was essential to work through each step – which facilitated trust between government and industry while technical and commercial aspects were fleshed out in parallel.	The NT LEH industry and government have had some advantages on being able to follow early leads from other hub and cluster networks in development globally. But they also bring unique insights from working in a remote region, and focus on cost has facilitated discussions on identification of common user infrastructure. A phased approach based on the shared strategy where government and industry work together collaboratively will develop trust while the hub develops. Working with Territory and Federal governments on legislation and regulatory gaps should continue in parallel, but in the absence of government-led financial support, the lack of legislative and regulatory certainty

	may be a barrier to timely investment by industry on emissions reduction projects heavily reliant on CCS.

Table 7: High-level learning points from Northern Lights
Source: modified from Northern Lights (2023)

Key learning point	NT LEH reflection
The absence of a regulatory framework for cross-border CCS required significant time to consider political risks related to the development of a new value chain/industry. Even with the confidence of government support and facilitation, the proponents saw investment in infrastructure and entering long-term contracts without bilateral agreements as high risk.	This point is directly relevant to the NT LEH. While domestic emissions are anticipated initially to be transported and stored, the economic models and growth potential assume transboundary movement of CO_2 from Japan, South Korea, Singapore etc. Background work by governments is underway to investigate bilateral agreements to mitigate this risk.
Agreement language has been challenging. Transport and storage company services are closely aligned with the oil and gas sector, while power companies and industrial manufacturers operate in different environments with different terminology. A common language was defined to avoid confusion.	The challenge of the value chain working across very different industry sectors has been identified early in Australia (e.g., coal-fired power generators and oil and gas sectors in the early years). Early adoption of draft term sheets has been used to manage some of these challenges. However, at this stage, proponents of the NT LEH are predominantly in the gas sector, but they will have to consider how they engage more broadly with emitters as part of their growth strategy.
Pioneering industries signed on to new commercial agreements. These were critical to sparking the commercial market and flagged a significant step for the sector. It highlights the need for cornerstone or anchor project proponents to signal project relevance and importance for future commerciality.	The NT CCUS hub will be initiated through transport and storage of CO_2 that is already being captured from the NT LNG plants. These projects will act as the anchor projects for the hub. Retaining sufficient capacity for growth is critical to the success of the hub and future industries over the long term. Evaluation of the industrial mix that would optimise the MASDP initiation and growth is important (this study). Is there sufficient diversity across the interested parties to share risks and costs as the project develops?
Differences in industry cultures have become evident during negotiations. There is a lack of shared common practice, absence of precedents and only nascent industry standardisation – both domestic and international in nature. HSE and construction requirements are noted as having been particular challenges.	Industry culture clashes may not yet be a major concern due to the gas industry being a significant driver of the NT LEH at its outset. Understanding drivers and required outcomes will help proponents gain a common understanding (e.g. Task 0 vision setting). Other hubs are already having to surmount standardisation, HSE and construction issues, and learnings from these can be applied to the NT CCUS hub.
CO_2 specifications have been re-evaluated over the project's development as new knowledge has emerged. These CO_2 purity specifications have been defined with respect to integrity of infrastructure and safe operations. Northern Lights established a taskforce (led by DNV) to provide updated perspectives on risks to cross reactions,	Legislation and regulation for offshore storage of CO_2 are in development in Australia. Changes to the Sea Dumping Act to facilitate transboundary movement of CO_2 was passed in 2023. An Interim National Action List for defining likely incidental associated substances and levels for the purpose of human and environmental

development of corrosive fluids, their impact on ship design, and the potential for new allowable impurities across the value chain. The recent specifications are documented by the Northern Lights project (Northern Lights Project, 2024a).	impacts was released for comment in early 2024. A review of the OPGGS Act and OPGGS (Environment) Regulations 2023 is underway to facilitate streamlining and reduce duplication. Other legislation and regulation are likely required to be reviewed or developed as earlier works may have only considered single-source-to-sink (not multiple offtakes) or onshore to offshore storage.
Environmental risks, consistent regulatory frameworks and low margins are nascent CCS financial risks. Regulators have requested financial security from the injection licence operators for 'very low probability' risks (well failure, emissions of CO_2 to seabed). Long-term 20 years post-closure licence guarantees and decommissioning, monitoring, operations and contingencies are perceived as incongruent to this very low probability. The insurance industry does not have a common approach as yet, nor does it have a fund to manage any risk.	Consideration of the risks of negative impacts of CCS operations is required but it is important that risks are assessed based on best-available science and engineering data. This can be challenging to quantify with little direct data from CCS projects (particularly over the long term), but enhanced oil recovery and subsurface industry experience provide some relevant metrics and approaches. The insurance industry may only be relevant to companies not able to self-insure or where government is not willing to take on long-term liabilities, noting this will substantially increase costs for proponents.

To conclude this deep dive using Longship and Northern Lights project activity in Norway and adjacent EU emitter countries, the work conducted to date provides a detailed perspective of the risks and uncertainties around a first-of-a-kind CCS hub, and the challenges surrounding its establishment. The strong financial support from the Norwegian Government for Norwegian-based activities has significantly reduced the burden of risk and uncertainty, while the partners learn by doing the business of developing and operating a CCS hub. The investment by the Norwegian Government into the nascent CCS industry is seen as a national competitive advantage that can be leveraged to generate revenue for Norwegian industries and the taxpayer over the medium to long term.

3.1.4 The UK

The UK has, like many other countries, seen several false dawns during the evolution of the implementation of CCS projects to mitigate climate change. These projects have benefitted from both EU and UK funding over the years, but as yet no CO_2 emissions have been stored in the subsurface (Rütters et al., 2021).

Several single-source-to-sink projects have been initiated, commencing with evaluations of the Peterhead combined cycle gas turbine power plant sending emissions to the depleted Miller gas field, 240 km offshore. That project conducted concept studies but was unable to secure funding to progress further. This was an indicator of the financial risks associated with CCS, which the UK Government has attempted to address through a range of mechanisms over the intervening years.

The use of competition-based mechanisms commenced in 2007 with the launch of the UK CCS competition, which identified two projects: Kingsnorth CCS and Peterhead/Longannet CCS. Neither project proceeded at the time, partly due to failed negotiations between the parties.

A second round in 2012 shortlisted four projects, and subsequently two were selected:

- The White Rose CCS included the Drax power plant, with geological storage within the Endurance Structure offshore in the UK North Sea. A CCS trunkline was to be developed by National Grid Carbon, and other technical providers were identified. A two-year FEED study was funded by the Department of Energy and Climate Change and the EU provided €300 million (A$500 million) from NER300 (a low-carbon technology program). Other FEED activities (e.g. pipelines) were initiated, but ultimately HM Treasury withdrew capital funding from the Commercialisation Competition, and a statement by the Secretary of State announced that there were insufficient funds for the project, which effectively ended the project at that time (The University of Edinburgh, n.d.).
- The Peterhead Project also focused on the power plant in that location with storage in the Goldeneye field offshore in the UK North Sea. Proposing to retrofit one of the gas turbines and to repurpose an offshore pipeline, in 2012 the project received the first UK licence for permanent sub-sea storage in the UK. It too received FEED study funding under the Commercialisation Competition and contracts were awarded to engineering firms. Knowledge-sharing reports were published by the UK Government (some of which have been used to provide background knowledge for estimations and evaluations in the Petrel Sub-basin under the CCS Research Development and Deployment program conducted in 2016–2018 in Australia by Shell then ENI). Planning permission was granted for the onshore aspects of the project, but again HM Treasury withdrew funding from the Commercialisation Competition, which effectively stopped further work beyond the committed FEED studies in 2016 (The University of Edinburgh, 2024a).

As the UK has attempted to navigate the challenges of implementing CCS projects, it has conducted CCS licensing rounds through the (North Sea Transition Authority, 2024). Recent acreage awards (Figure 21) are mostly focused on the North Sea, particularly close to several potential East Coast hub and cluster projects, and one in the Irish Sea, which is being considered by the HyNet North West Project (HyNet North West, 2024b) Further CCS acreage awards have been offered for the offshore Channel area, south of Portsmouth, where potential sites will have to carefully consider extensive marine and conservation areas in the region as part of any submissions.

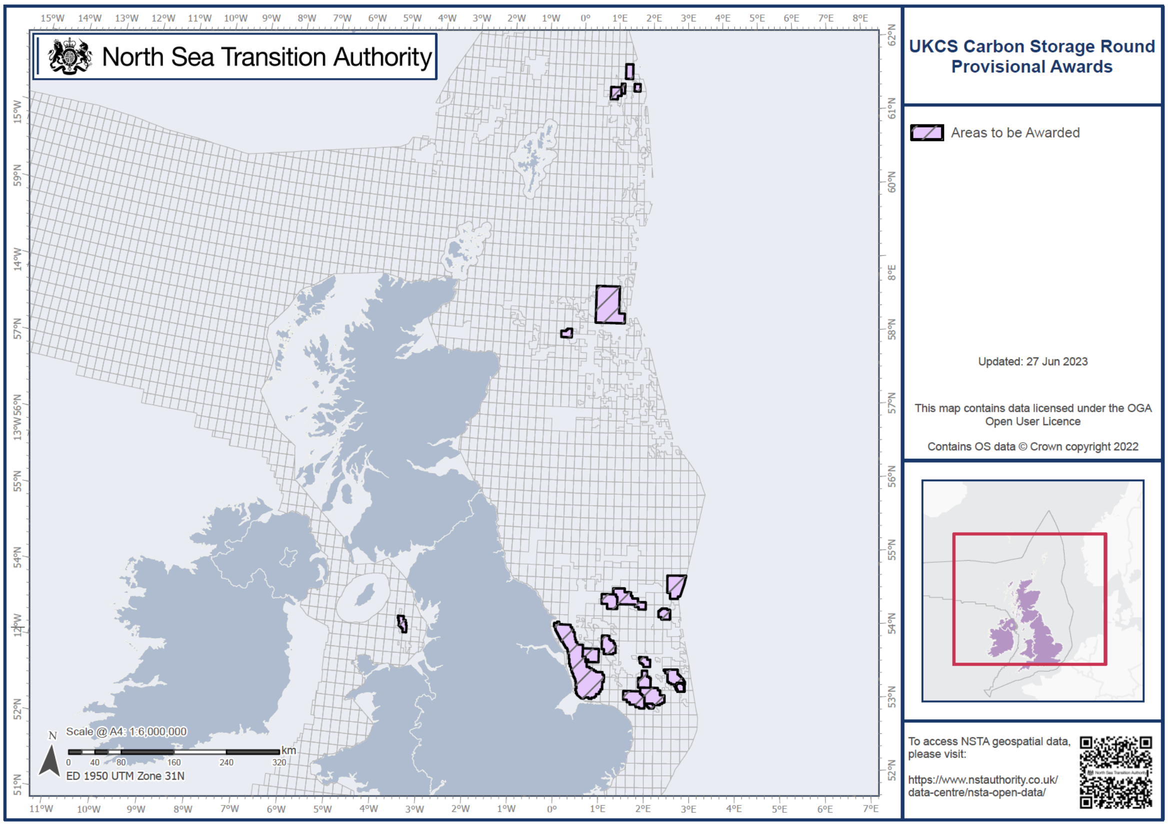

Figure 21: Licensing rounds in the UK
Source: North Sea Transition Authority (2024)

CO_2GeoNet noted four active CCS appraisal and storage licences at the time (Rütters et al., 2021). Table 8 overviews some of the key information from each project and its associated CO_2 capture facilities, but this process is somewhat hampered by a combination of factors:

- legacy web information is not always updated and/or is removed, resulting in differences in the cohort of partners and activities at each site
- some of the projects, especially Northern Endurance, are an amalgamation of several other (quite sizable) projects, so it is difficult to draw the evolution of the project(s) easily together and identify who the partners are and how they have been supported by public funds
- participants within each project are encumbered by strict contractual obligations, limiting disclosure (noted informally by CSIRO stakeholder interviews in the UK and the Netherlands in April 2024 and elaborated on below).

Table 8: General overview of four major projects under consideration in 2021 as part of the UK's CCS portfolio. Many changes to focus, partnerships and funding arrangements have occurred, so the details may be incomplete

Project	Partners	Details
Northern Endurance Partnership	Endurance storage site and East Coast cluster (BP, Equinor and TotalEnergies – storage; NZT Power,	Development consent awarded in February 2024. Southern North Sea site aiming to inject up to 27 Mtpa by 2030, but ambition to be far higher. Completed FEED in 2022. Focus on Teesside region (and associated Teesside low-emissions projects) and potential Zero

	H2Teesside and Teesside Hydrogen – CO_2 capture) (bp United Kingdom, 2021; Cluster, 2024; Net Zero Teesside, n.d.)	Carbon Humber activities. Two pipelines from shore to storage site, a new build. UKRI's Industrial Strategy Challenge Funding for Phase 2 and previously obtained Phase 1 funding. East Coast Carbon Capture Cluster (Figure 22). Anticipating operations in 2025. Storage licence granted for Endurance structure in 2012. Storage licence ID CS001.
Goldeneye	(Shell UK, 2016)	No longer proceeding (see below on infrastructure reuse). Located in north-east Scotland with storage offshore in the North Sea. Single-source-to-sink project. Storage licence ID CS002.
Acorn	Acorn CCS and several different partners over the years SCCS, Bellona, Liverpool and Radboud Universities in study consortium Secondary project, Acorn CO_2 Sapling PCI Project (Acorn, 2024)	Demonstration project including CCS and Acorn Hydrogen, and DAC. Focus on reuse of existing assets to underpin a more extensive network in the future. Located in North-east Scotland with storage offshore in the North Sea. Connected to the Scottish Cluster. Capture at St Fergus Gas Terminal (Aberdeen) of CO_2 from offshore produced gas and plans to send via Goldeneye pipeline to a new injection well. Focus on reuse of infrastructure where possible. Project aimed for 2023 operation but was delayed. Other CO_2 capture from 1 Mtpa DAC plant to demonstrate plug-in ability with amine capture. Steam methane reforming generation of H_2 in 2025. Storage licence ID CS003. A 'reserve project' in 2021, in CCUS Cluster Sequencing Track 1, and Track 2 status awarded in 2023. Public funding awarded including EU ERA-NET Act, UK and Scottish governments, and EU funding. The second project, Sapling, is considering potential to store 12 Mtpa by developing relevant transport and infrastructure to service onshore emitters in central Scotland and establish pipeline and shipping through Peterhead. This cluster will be comparable to other major clusters such as Net Zero Teesside and Northern Lights. Anticipated to commence late 2020s following initial Acorn Project delivery. It is a PCI and received €300,000 (A$500,000) and €2.8 million (A$4.6 million) in 2018. In 2019 EU Connecting Europe Facility provided funds of €7.9 million (A$13 million) and funds were also obtained from the UK and Scottish governments.
HyNet North West	Large number of private partners, supporting organisations and public sector through local authorities and constituencies HyNet North West (2024a); Figure 23)	A hydrogen production project (with CCS) servicing England's west coast and Wales (Figure 23). More than 40 offtake partners for hydrogen signed with the project for manufacturing and electricity generation. Underground hydrogen storage also earmarked. Use of existing and new infrastructure anticipated for the hydrogen manufacture and transport of both hydrogen and associated CO_2 emissions. Storage will be offshore in depleted gas fields (Hamilton, Hamilton North and Lennox) in Liverpool Bay by Eni (Eni, 2024).

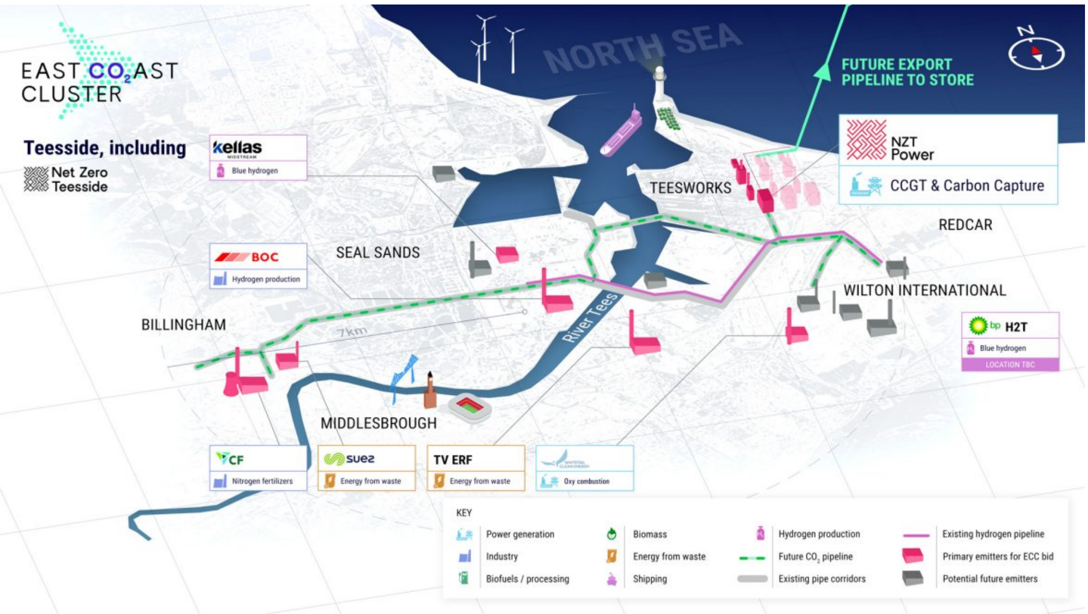

Figure 22: East Coast cluster schematic identifying the Northern Endurance storage area
Source: bp United Kingdom (2021)

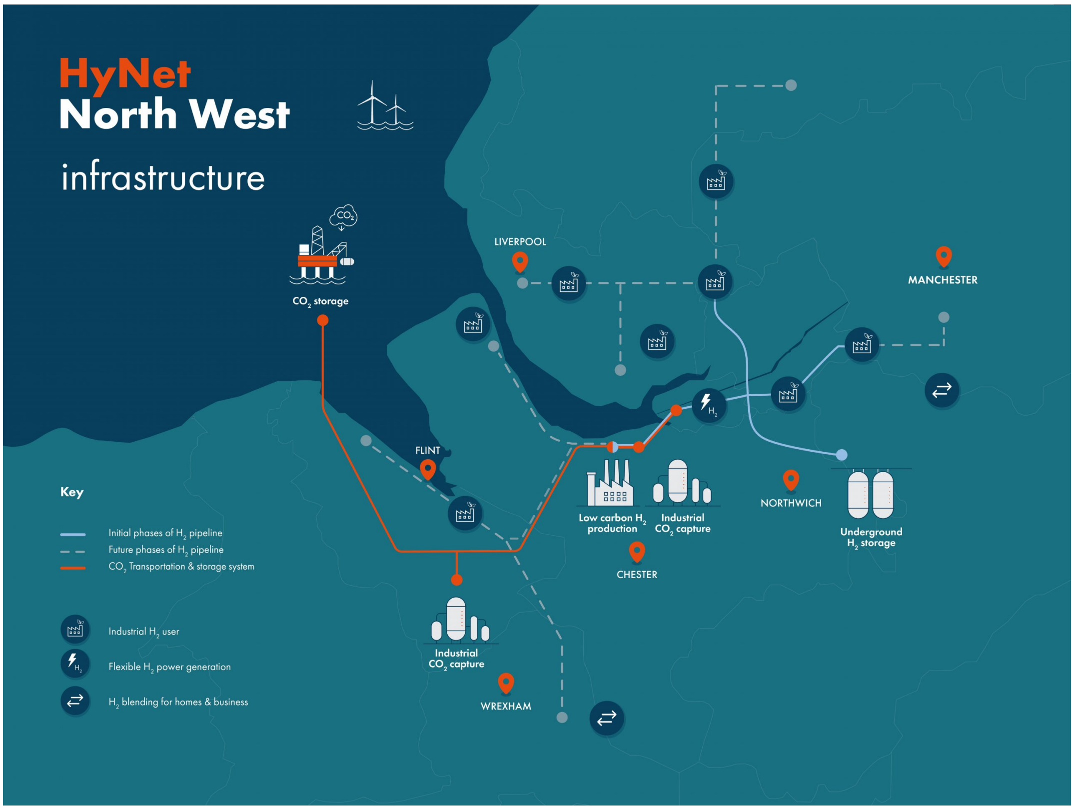

Figure 23: Schematic of the HyNet project showing the key elements of the network and infrastructure plan
Source: HyNet North West (2024c)

In 2021 the UK Government undertook a strategy review (HM Govenment, 2021; HM Government, 2021), which was summarised in a presentation to the Global CCS Institute by the Department for Energy Security & Net Zero in Figure 24. In the review, the government acknowledged that aligning the different decarbonisation approaches was challenging and there was a need: for the right context (i.e., net zero targets); to address market failures, including investments and cross-chain risks; to develop the right skills across engineering, geosciences, policy, regulatory and research to have the capability and capacity to deliver; and for perseverance in the face of headwinds of varying types (Figure 24).

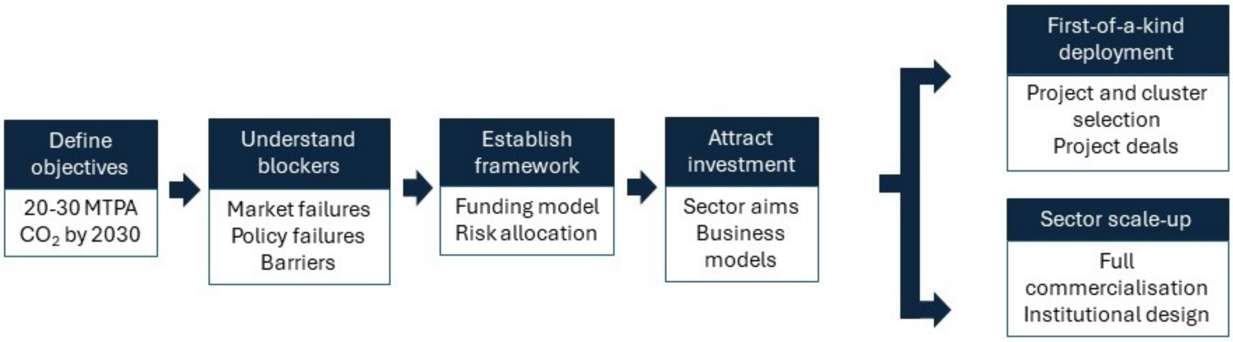

Figure 24: Summary of the process conducted by the UK Government to deploy a decarbonisation strategy and support an emerging industry
Source: Global CCS Institute (2023a)

Following this strategic review, the UK revisited the industrial CCUS clusters. The current approach is to focus on industrial clusters with the introduction of two Track 1 and subsequent Track 2 clusters (Figure 25). The East Coast cluster and the HyNet North West were awarded Track 1 status in 2021. It should be noted that these clusters were modified from prior cluster designs (e.g. Net Zero Teesside and NetZero Humber). The new clusters under Track 2, announced mid-2023, are Acorn CCS (for the Scottish Cluster) and Viking CCS. Together with the Track 1 East Coast cluster and HyNet cluster, they will be able to access the previously committed £1 billion (A$1.95 billion) to support deployment by 2030 (Global CCS Institute, 2023b). In October 2024 the UK Government announced £20.7 billion (A$42.4 billion) of funding for the Track 1 East Coast cluster and the HyNet cluster, with the intention that these clusters store 8.5 Mtpa of CO_2, secure 50,000 jobs in key UK industries and create 4,000 new jobs (HM Government, 2023b).

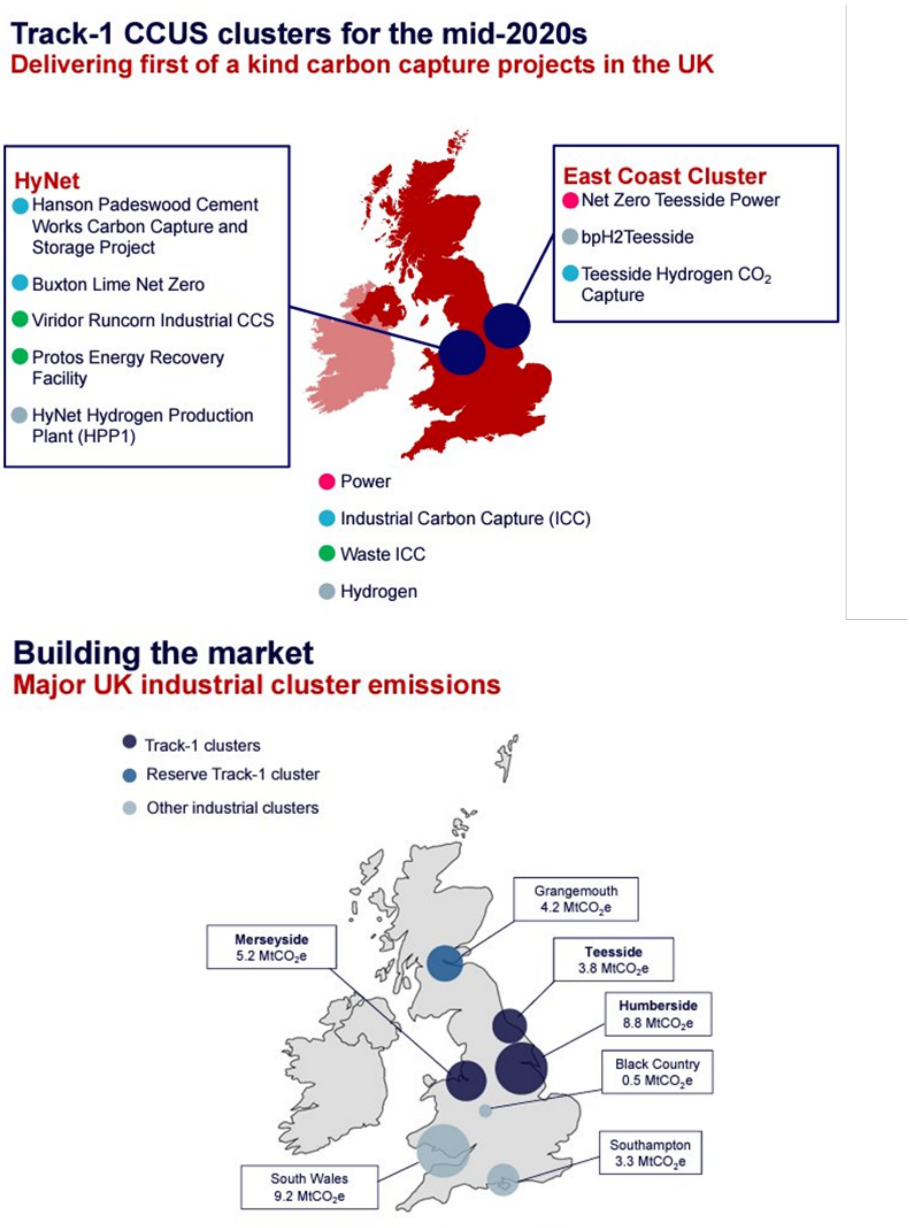

Figure 25: Track 1 CCUS clusters and future CCUS clusters in the UK
Source: HM Government (2023a)

While the UK Government has undertaken a competitive selection process to prioritise or track each cluster, it has been acknowledged that all clusters will have to go through a competitive selection process (see the antitrust box below), with each needing to map out the sequence of the activities to be implemented.

It is anticipated that this cluster sequencing model (Figure 26) will enable the storage of 20–30 Mtpa by 2030, with the expectation that the next sequence of clusters will be identified at this time. It is expected that these CCUS hubs and clusters will include: (1) at least one CO_2 capture-enabled gas-fired power plant; (2) at least 1 GW of CCUS-enabled hydrogen within the 2020s and 10 GW by 2030; (3) capture of up to 3 Mtpa of CO_2 from industrial sources as soon as possible, 6 Mtpa by 2030 and 9 Mtpa by 2035; and (4) 5 Mtpa of CO_2 through greenhouse gas removal (using BECCS or DACCS) by 2030 (Global CCS Institute, 2023a).

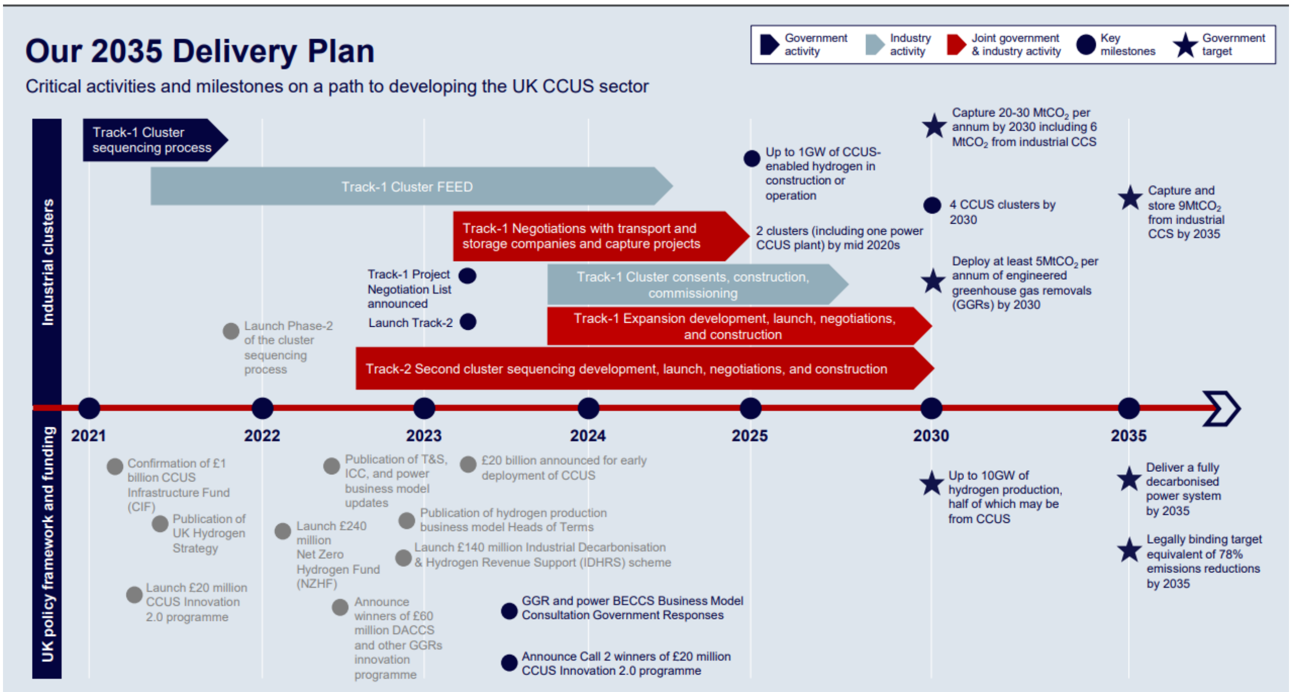

Figure 26: How the UK Government is sequencing activities to meet 2035 ambitions
Source: HM Government (2023a)

The government's ambition is to derisk the whole value chain through demonstration of CCUS, hydrogen and negative-emissions technologies. To do this, the approach has been to divide the value chain into different sectors:

- industrial CCS, power CCS
- DACCS and BECCS
- blue hydrogen production (with CCS)
- transport and storage
- green hydrogen development and stimulation of hydrogen users in industry, homes and transport.

For each of these sectors the UK Government has designed a different business model to support a discrete part of the value chain. These models are briefly summarised in Table 9. More detailed information on each model is available from the UK Department for Energy Security and Net Zero (HM Government, 2024).

Table 9: Summary of the UK Government's CCUS business models

Sector model	Description
Industrial carbon capture (ICC)	Business models (including the waste ICC business model) are designed to incentivise the deployment of carbon capture technology for industrial users that often have no viable alternatives available to achieve deep decarbonisation (i.e. the hard-to-abate sectors such as steel and cement).

Dispatchable power agreement (DPA)	Incentivises mobilisation of private finance to enable power and CCUS to play a valuable mid-merit role in the generation mix.
Power BECCS	BECCS business model to incentivise projects to provide negative emissions and firm low-carbon electricity.
Greenhouse gas removal (GGR)	A business model developed to attract private investment in a portfolio of engineered GGR technologies including DACCS, where the original 'source' of the CO_2 is decoupled from the emitter.
Transport and storage (T&S) and regulatory investment (TRI)	A model based on the regulated asset base model (i.e. typically referencing nuclear private investment). Key objectives as applied to low-emissions hubs are: (1) attract investment in T&S network to establish a new CCUS sector; (2) enable low-cost decarbonisation in multiple sectors; and (3) develop a market for carbon capture in the long term.
Hydrogen production business model	Avenue to develop revenue support that fills the operating cost gap between low-carbon hydrogen and high-carbon counterfactual fuels (Department for Energy Security & Net Zero, 2023b).

The Department for Energy Security & Net Zero (DESNZ) published its ICC Business Model in 2022 (Department for Energy Security & Net Zero, 2024). It set out fundamental design principles in its ICC business models following a consultation process. This updated approach was developed to incentivise carbon capture technology for hard-to-abate sectors. There was potential to obtain capital grants and/or revenue support as well as other contracts to facilitate risk reduction during the long-term investment, build and operation of facilities participating in industrial decarbonisation and hydrogen production. There are provisions to aid industrial proponents where capture levels are hard to predict, as volumes of capture (and storage) are critical elements to cost and price (per tonne of CO_{2e}). The report by the DESNZ provides significant detail if further information is required and equivalent guidance on CCUS has been updated and published (Department for Energy Security & Net Zero, 2023a).

The UK Government will use a transport and storage regulatory investment model that attracts investment to build out infrastructure, enable low-cost decarbonisation and support a developing CO_2 capture market through a common user regulatory model. This approach facilitates certainty in the rate of return for the transport and storage developer that is efficient and ensures availability of storage at the right time.

It protects the transport and storage company from independent events such as variation in supply from capture plants/emitters or completions of developers out of sequence ('event of first user delay' – that is, the first offtake client is unable to meet its delivery obligation), which could leave transport and storage companies awaiting offtake and therefore incurring significant costs to mitigate critical elements of cross-chain risk or unforeseen elements, through the government's ability to underwrite elements of risk.

The model also includes force majeure contingencies, which may result in some relief, as well as relief for other events (e.g., ability to commence storage, ability to accept the specified rates of CO_2, need for remedial actions and other events).

The model is now designed to:

- consider an independent economic regulator
- consider a need to understand costs and performance
- improve certainty of returns over the long term
- design efficient returns on investment that are adequate
- protect against demand-side risks to revenue.

The current considerations and model will evolve as deployment of the technology occurs and the activities take on a mature market role, such that continuous review and amendments to regulation will be necessary to transition from supportive to standalone operations for developers.

Many of these contracts are being negotiated to run over 15-year terms, and use approaches that have previously been deployed by the UK Government to incentivise the renewable energy sector (Global CCS Institute, 2023a).

Lessons learned for the NT LEH

The UK's experience with the development of hubs has been characterised by a series of false starts, with significant effort and expenditure occurring at each stage. While considerable learnings have been carried forward, much institutional knowledge has also been lost between these iterations (see the interview responses below). In considering these learnings for the NT LEH, where possible prior work should be used in the development of the NT LEH. For example, the prior offshore CO_2 storage assessment research is already being used to expedite the appraisal of offshore CO_2 storage locations in the Bonaparte Basin.

Documenting and sharing insights on the development of the NT CCUS hub is important for future learnings, and arguably enhanced public and regulatory acceptance. While this can be difficult due to perceived commercial drivers, the UK experience has shown that without this documentation there can be reinvention of the wheel in the future that incurs additional costs.

The UK CCUS models differ from those in Europe with a sectoral approach being taken for each business model. This adds to the complexity of the development of hubs with the possibility of misalignment between the drivers and goals of each business model.

While the UK has an objectives-based framework for CO_2 storage, the competitive selection process to prioritise or track each cluster has led to notable omissions from cluster development, which could impact on the overall delivery of the objectives. This could also impact on the viability of industries exposed to carbon pricing.

The NT CCUS hub as a whole should be considered to identify least-cost options for hub development that attempt to balance cost with greatest flexibility and widest industry participation. This will help diversify risk, potentially enhance volumes of CO_2 for storage and in principle lower unit costs.

Antitrust and collaboration challenges

An article published in May 2024 by Nordlander and Bowring (2024) highlights one of the recurring themes of the interviews undertaken as part of this study that occurred in North-west Europe. Its title 'Decarbonization can only be achieved by businesses working together: so is antitrust law a barrier?' highlights a complexity caused by the competition-based processes used by the UK Government to identify potential low-emissions or net zero projects that could transition industry and industrial hubs. Competition rules (in their strictest sense) have meant that collaborations and partnerships that are essential to low-carbon futures may be highly encumbered, and the proponents have struggled to navigate the fine lines between collaborative openness and appetite for risk of breaching regulations.

As a result of this risk and uncertainty, in the Netherlands, the UK, the EU, Singapore and Japan agencies and commissions have both published detailed guidance and offered direct but informal advice to provide clarity. However, as has been recognised in Australia too, net zero collaboration spans multiple jurisdictions, departments and regulators. Some countries evaluate society-wide benefits of specific low-carbon collaborations against the potential to harm competition, implying that there are occasions where upholding the competition rules would occur even if it were harmful to some customers. The EC will consider competition law exemptions but only where the net impact on the consumer is positive. Not all of the country-based policies match the EC policy and conflict has arisen. Some jurisdictions have no formal guidance on this matter, and some remain sceptical of measuring environmental sustainability considerations against competition assessments with US Federal Trade Commission, noting 'there's no such thing as an ESG exemption'.

While global alignment is unlikely, a pragmatic mechanism to enable meaningful discussions between proponents within a hub or cluster development would seem to be of vital importance to be able to deliver a cost-effective, safe and sustainable project that benefits all. Collaboration between national and international agencies facing this challenge and learning about the positive and negative impacts of restricting participation from deployment experience should be considered to mitigate roadblocks and break down obstacles for more rapid deployment of low-emissions hubs everywhere.

3.2 North America

Hubs, defined as commercial arrangements connecting multiple CO_2 sources and sinks, have a very long history in North America (National Petroleum Council, 2019). The reticulation of CO_2 from sources, mainly geological, to service multiple CO_2-EOR projects is part of business and operates successfully because the product – oil – is valuable. There are more than 8,000 km of CO_2 pipelines (Global CCS Institute, 2024a) in the US (Figure 27). While the Permian Basin in Texas is the most prominent area of CO_2-EOR activity, there are other areas of North America where CO_2-EOR has been a functioning business for decades. The most recent example is the Alberta Carbon Trunk Line, a 400 km pipeline system that connects sources and sinks for enhanced oil recovery (Canadian Energy Centre, 2023). Unlike in the US, this project had some state subsidy for start-up but now operates as a business. CO_2-EOR 'hubs' have evolved within a large industry (oil production) with stable regulation (Railroad Commission of Texas, 2024; The State of Wyoming

Legislature, 2024) and financing and are a straightforward capitalist response to an opportunity for profit built on technical opportunity and innovation.

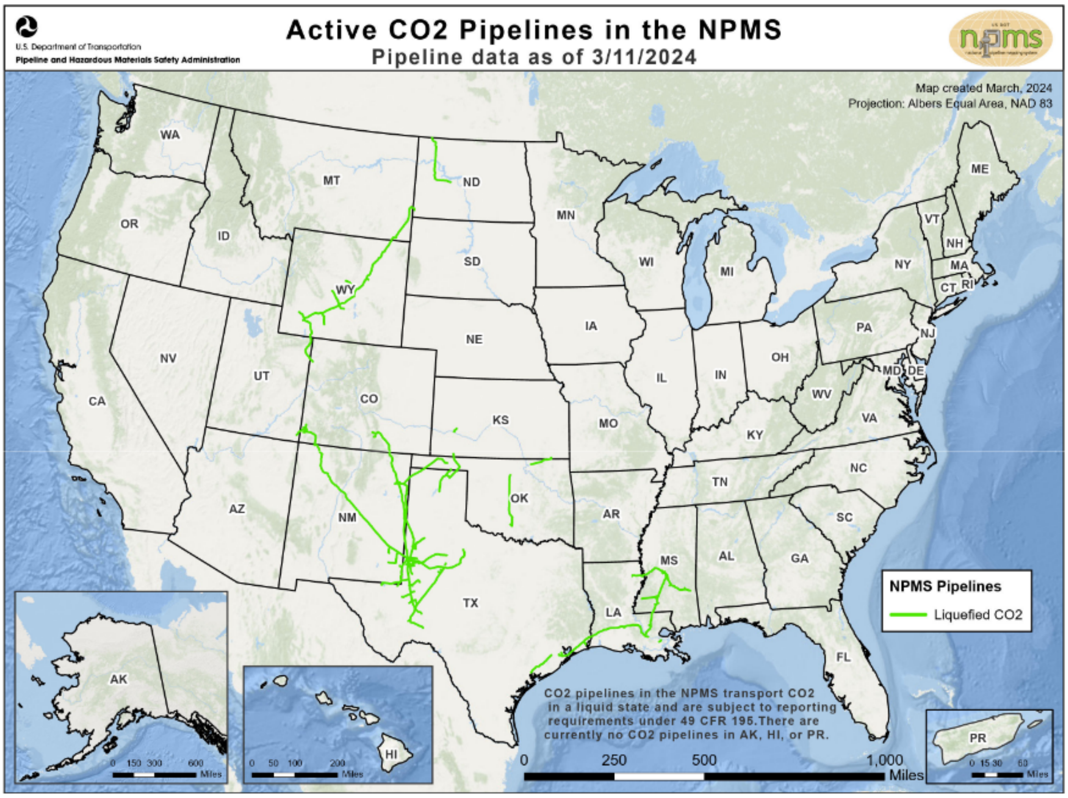

Figure 27: Map from the National Pipeline Mapping Service
Source: U.S. Department of Transport (2024)

Significant early examples of single-source-to-sink CCUS projects in North America – Petra Nova (Power Engineering, 2023) and Boundary Dam (International CCS Knowledge Centre, 2024) – relied on the sale of CO_2 as part of their project economics, as does the Port Arthur Air Products hydrogen plant. The 45Q tax credit (Congress Research Service, 2023) rise to US$85/tonne means that there is a business opportunity in disposing of CO_2 in saline aquifers. Paradoxically, this could encourage emitters to produce *more* CO_2, although recent rulings by the US Environmental Protection Agency may limit emissions from generation.

Economies of scale and risk diversification have led businesses to develop hubs for CO_2 storage. Many storage projects in emissions-intensive areas, such as the Gulf Coast, denote themselves as 'hubs' because, even without settled arrangements to offtake CO_2 from emitters, they are confident that they can execute sufficient offtake agreements to make money out of a storage site, and are already doing so.

Two examples are the Bayou Bend project on the Gulf Coast (CCS, 2024) and the Summit Carbon Solutions project in the Dakotas, Iowa, Minnesota and Nebraska (Summit Carbon Solutions, 2024). The former is a partnership between Chevron, Equinor and TotalEnergies and plans to store CO_2 from unspecified industrial sources in the Houston Ship Channel and Port Arthur areas. This project is a private enterprise hub that will develop infrastructure, such as pipelines and storage sites, and set up the necessary commercial arrangements. The Summit project plans to link 57 ethanol plants by pipelines to sequester (without enhanced oil recovery) around 16 Mtpa of CO_2. This is an extremely attractive business proposition because capture from fermentation is easy (the gas stream is nearly 100% CO_2) and, as mentioned, there is a tax credit of US$85 per tonne stored. Indeed, this is a carbon-negative project. The weakness of the project (as with many hubs) is the concerted public opposition to pipelines.

In summary, the driving forces for hubs in the US have some distinctive features:

- There is the very long (five decades) and effective support for the development of CCS via the US Department of Energy and its Office of Fossil Energy.
- A sustained and well-thought-through set of programs has built up Federal support from small test injections through to the current set of basin-scale programs. A comprehensive atlas of suitable geology in the US was created along the way.
- An underlying structural strength is the long history of CO_2-EOR systems, which are in effect hubs and mean that there is pipeline infrastructure in place across several oil producing states and deep expertise and significant finance is available to build CO_2 hubs.
- The 45Q tax credit, especially because it is fungible and perceived to be adequately secure over the long term, is a powerful financial driver and probably much more attractive than the volatile European carbon price (Statista, 2024).
- The current areas where hubs are under development, mainly the Gulf Coast and the mid-West, have some of the highest concentrations of CO_2 emissions sources anywhere in the world, some of which are already being captured.
- CCS hubs are seen as an opportunity for profit by private enterprise, not as a set of problems to be solved with direct government interactions.
- Risks such as signing up emitters and negotiating pipeline routes are seen as simply part of the cost of doing business. To some extent, this reflects cultural attitudes, but it also reflects the fact that there is low-hanging fruit in the areas mentioned above that first movers can seize.

As noted, nuances may develop in this market. The nature of the tax incentives for industry will mean that there will be winners and losers, with early projects having considerable advantage over latecomers as the costs of capture and storage are likely to increase.

Pipelines are a key weakness of any hub and may yet be an area where governments have to intervene for social benefit reasons. Utilisation of pore space is an issue where governments have already started adjusting their management of subsurface assets (Offshore, 2024). The potential problem is the very large pressure footprints of hub-scale storage, footprints that could overlap the surrounding area and, in effect, sterilise it for storage (Bump and Hovorka, 2024).

Apart from regulation, the role of the Federal government in incubating CCS has been considerable. The long-term and consistent support of the US Department of Energy has been mentioned. The architecture of this decades-long program is described by the Department of Energy as follows:

> 'The United States (US) Department of Energy (DOE) created a nationwide network of seven Regional Carbon Sequestration Partnerships (RCSPs) early in the Carbon Storage Program, to help determine and implement the technology, infrastructure, and regulations most appropriate to promote carbon storage in different regions of the US and portions of Canada. After successfully concluding multiple small- and large-scale injection test projects,

storing more than 11 million tons of carbon dioxide in geologic formations with no indications of negative impacts to either human health or the environment, they positioned the US as world leaders in the development of CO_2 storage technologies' (National Energy Technology Laboratory, 2022).

The partnerships operated in three phases over 2003 to 2013 – characterisation, validation and finally development – where six projects collectively stored more than 11 Mt of CO_2.

The most prominent successor to the RCSP is the CarbonSAFE program:

> 'The Carbon Storage Assurance Facility Enterprise (CarbonSAFE) Initiative began in 2016 with the goal of addressing the key gaps on the critical path towards Carbon Capture and Storage (CCS) deployment. Building upon the knowledge and experience of the Regional Carbon Sequestration Partnerships' (RCSPs') efforts, this initiative is performing identification and detailed characterization of geologic storage sites. The vision of CarbonSAFE is to understand the development of a CCS storage complex from the feasibility study until the point of injection through the following phases of project progress: Integrated Carbon Capture and Storage Pre-Feasibility, Storage Complex Feasibility, Site Characterization and Permitting, and Construction. The CarbonSAFE Initiative will reduce technical risk, uncertainty, and the cost of commercial-scale saline storage projects. Results will improve the understanding of project screening, site selection, characterization, baseline monitoring, verification, and accounting (MVA) procedures, and information necessary to submit appropriate permit applications for such projects.'

In many respects the RCSPs and the CarbonSAFE program have similarities to prior basin and sub-basin scale and national flagship programs undertaken to explore the feasibility of locations for CCS in Australia.

Lessons learned for the NT LEH

As with the other jurisdictions studied, the value of prior work should not be underestimated and is often the foundation for hub locations. The location of the NT CCUS hub takes advantage of prior work undertaken in Australia for subsurface characterisation. The US has extensive experience with CO_2 transport and utilisation and as such companies and regulators are comfortable with CCS business and risks. Further discussions with companies, regulators and governments in North America would enhance understanding of key business and technical risks for CCUS and allow participants in the NT CCUS hub to determine key requirements, notwithstanding that not all elements will be common between Australia and North American jurisdictions.

Proponents of CCUS hub development in North America, particularly on the Gulf Coast, are looking at very large-scale hub developments, partly due to the scale of emissions available for capture and storage but also as an enabler for new, greenfield industrial development around new port and CCUS hub infrastructure (e.g. Corpus Christi Carbon Storage Hub; Businesswire (2023)). For the NT CCUS hub, the vision includes similar scales and greenfield development of new low-emissions industries. As such, the approach being used has strong similarities. Businesses in the US have strong financial drivers for CCUS with generous tax incentives, which are realised irrespective of the cost of capture transport and storage. As a result, any cost efficiencies that can be obtained through scale and shared infrastructure represent enhanced returns. These incentives do not exist in Australia and as such there are not the same drivers to seek both scale and efficiency.

3.3 South-east Asian region

While there is significant activity in the South-east Asian region with the development of several hubs, much of the key activity has been focused on legislative and regulatory changes, which are discussed in the *Task 10 report*.

Across Asia, storage hubs and cross-border CCS projects, which involve CO_2 capture in one country and transport and storage in another, are a major focus (see the *Task 8 report*; Tocock et al. (2024)). Nations with limited geological storage resources, such as Singapore, Japan and South Korea, are actively exploring opportunities with nations that have large potential CO_2 storage resources, such as Indonesia, Malaysia, Timor-Leste and Australia.

Consortia like the Shepard CCS project (https://shepherdccs.com/), a public-private partnership between the South Korean and Malaysian governments and a number of private companies, are helping to connect the demand side to storage hubs. With all this activity in the Asia-Pacific region, CCS project development in the region is starting to accelerate. There is now one facility in operation, four are under construction and 52 are at various stages of investigation (Global CCS Institute, 2024).

The Chinese Central Government announced six CCS projects in April 2024 that will be supported through grants and other forms of low-cost finance. There are several single-source-to-sink projects under construction or completed:

- the Huaneng project is on track to complete the world's largest integrated coal-fired power project with CCS with a capacity of 1.5 Mtpa
- the Xinjiang oil field has begun construction of a 2 Mtpa coal-fired power plant with CCUS
- China Building Materials is operating the world's largest oxy-fuel project in the cement sector with a capacity to capture 200,000 tonnes of CO_2 per year (Global CCS Institute, 2024).

China is also continuing with international collaboration and in late 2023, under the Sunnylands Agreement, the US and China committed to each having at least five large-scale cooperative CCUS projects by 2030 focusing on carbon capture from industrial and energy sources (Global CCS Institute, 2024).

4 Interviews with industry and government on hubs implementation – challenges and risks

As part of the NT LEH study, a series of interviews were conducted with stakeholders associated with CCUS hubs addressing perspectives on a range of topics. The focus of these interviews was on the UK and Europe and questions were designed to obtain perspectives on a range of key challenges including the following:

- Regulatory environment and policy support. Are relevant regulations in place and do these sufficiently govern specific cases of mixed sources and sinks with a view to hub and cluster development?
- While national/state regulations may be in place, how do local planning procedures cross-cut potential locations? Can those perceived as having a lesser role (i.e. local government authorities, town councils etc.) derail a hub?
- Are there financial mechanisms (e.g. tax breaks and/or other subsidies) available? If so, are they guaranteed or do they provide some time-bound security?
- Are there barriers or enablers for transnational movement of CO_2?
- To what degree has sovereign risk impacted decisions around the energy transition? Does that influence the number of projects to be developed, or the size of sustained support needed to mitigate issues that can occur across electoral cycles?
- What is the technology readiness level of hubs and their design and implementation? Is there anything different about a hub relative to existing storage projects?
- What is the range of capture technologies in use, and do they increase hub complexity?
- How are project proponents and partners approaching contractual arrangements between emitters and transport and storage companies? Is there clarity on who pays for what? How are issues of liability and risk addressed? Who does what first?
- How are hub proponents managing social licence, community engagement and outreach for large-scale, high-impact projects? Who is designing those approaches and delivering/receiving the messages? Who is responsible for orchestrating these tasks?

The stakeholders ranged from hub developers to transport and storage proponents, emitters and government representatives. Responses were collated and the key themes are collated in Table 10.

Table 10: A synthesis of findings from UK and European interviews and how the NT LEH may consider their influence

Key learning point	NT LEH reflection
Government participation UK projects that thought they had obtained a component of secure support were abandoned as policy changes and implementation approaches were repurposed or removed. The DESNZ has had to consider many factors in its approach to both developing net zero policies and supporting each policy objective within nascent markets. For example, addressing subsidy development following the identification of a range of 'market failures' that have limited the production and offtake of low-carbon hydrogen at scale. The roll-out of different models for support and subsidies has included several failed competition-based mechanisms. CCS infrastructure such as gather systems, booster stations, pipelines and low-emissions precincts has been compared to national utilities or special-purpose vehicles like water, rail or major infrastructure construction projects. The UK has a history of public utility development, before privatisation steps occur. There is a strong degree of government involvement beyond regulation that is crucial for reducing emitter costs (both CapEx and OpEx and related risks). Despite the use of government oversight, there is a recognised need for private company involvement due to their critical expertise in the technical and project delivery aspects.	**Territorial and Federal participation** Clarity and consistency in policy that incorporates long-term planning are essential to provide guarantees to project proponents and enable investments to be made. The learnings from Europe need to be incorporated into the development of frameworks for CCUS hubs in Australia to reduce development times and costs. Considerations of the appropriate subsidy mechanisms for 'failed markets' that appropriately incentivise the market, taking on learnings from other jurisdictions, are important. The NT LEH has begun to evaluate potential risk and cost savings that relate to common user infrastructure; however, a single operator model is yet to emerge. The model is a critical consideration and is time sensitive as industrial proponents will make individual decisions in the absence of clarity on common user infrastructure. There are clear learnings from other global models on government involvement that could be implemented in Australia to reduce financial risks. Currently, the NT LEH is being undertaken as a partnership between industry and government. However, to progress further the roles of government and industry need to be defined.
Financial risks and challenges There is significant financial pressure on proponents to manage emissions and bring return on investment to shareholders – these constraints, combined with regulatory pressures, are causing proponents to withdraw support and participation, or to completely reframe projects (repeatedly in some cases). Risk can be mitigated through emerging insurance offerings, but these are an expensive additional burden on companies, and ultimately flow through to the customer. Proponents have found that some of the financial risks can be managed when government has taken on specific risks (especially infrastructure and other high-value liabilities e.g. security of supply of offtake) but other risks are not being sufficiently vested with government. All up, this adds further complexity to project financing, reporting etc.	**Lowering barriers – business case development** With respect to financing projects, proponents have initially looked to government for aid in reducing the initial set-up costs. However, the mechanisms to use that funding, what may be eligible expenditure, reporting obligations etc. are perceived to be challenging. Commerciality concerns (e.g. loss of intellectual property and confidentiality) are risks. Maintaining the value chain to guarantee revenue will become more of an issue as projects reach FID. Early understanding of the business model for this is critical.

Additional challenges arise when governments make frequent changes in policy direction or delays through uncertainty of messaging that combine to cause project delays.

Global perception of such changes may be compared with other international investment clarity (e.g. the Inflation Reduction Act and 45Q activities in the US) resulting in significant capital flight to other jurisdictions where resources are more favourably matched.

There is a requirement for policy and regulatory certainty to enable assessment of commercial viability and long-term returns. Lack of clarity leads to greater risks and increases in the cost of capital, which can delay or prevent CCUS projects proceeding, which in turn can delay emissions reductions or lead to other jurisdictions being favoured.

Market dynamics and government intervention

There are many examples of changing signals from government in the UK over the last 20 years. The selection process of first projects through a competition approach with a value-for-money lens has limited broader opportunities and has potentially overlooked long-term value and strategic benefits by limiting incorporation of new ideas through learning and restricted collaboration due to the implications of competition law (see the antitrust box). This stifles long-term vision execution and impacts the viability of emissions-intensive industries. Clear understanding of the long-term vision is required, as are the impacts of not including emitters in CCUS hub development.

The role of long-term contracts (e.g. contracts for difference over 15 years) may provide stability but there can be risk if new governments decide to exit. When laid alongside a value-for-money test, there can be a highly conservative valuation of long-term benefit and that could reduce appetite for investment all round.

Government intervention in Australia

The current focus by industry is mainly related to regulatory and legislative certainty (e.g. transboundary movement).

Previous grant funding is considered to have risks due to the imposts of granting schemes (e.g. reporting). Granting also does not necessarily consider the wider regional or hub strategy, leading to a patchwork of granting that may not benefit hub development.

There is a need for long-term vision to align all the key aspects to facilitate navigation of complex hub and cluster developments.

Long-term certainty on returns is required to enable 30+ year investment decisions to be made. Arm's length arraignments could be considered to reduce policy uncertainty.

Collaboration and competition law

Repeated comments from UK and Dutch representatives intimated challenges around competition law as a barrier to collaboration. Rules (see Net Zero Act) limit knowledge sharing, hindering the ability to identify and exploit opportunities for improvements and better technical outcomes. Even the UK government's knowledge-sharing websites omit key information, and proponents are restricted in sharing lessons learned. This differs from the approach taken in Norway, where detailed information from projects is widely disseminated.

Elicitation and consolidation

The NT LEH evolution has been facilitated through a third-party consolidation of information. By conducting expert elicitation interviews, and consolidating each to gather common themes, the approach taken in the NT LEH has been able to more rapidly and effectively share knowledge and information between participants to accelerate deployment. This is critical for early projects to facilitate accelerated deployment. Further work is required to disseminate information more widely (e.g. the CSIRO NT LEH CCUS business case) and provide the ability to consolidate and de-identify owners of issues to still allow for knowledge exchange and provide opportunities for review by peers.

Sectoral approaches

In the UK, the decoupling of hubs and clusters into industry-led sectors (emitters versus transport, hydrogen versus heavy industry etc.) with different business models and sector-specific approaches adds significant

Sectoral mapping in Australia

The recently released Sector Pathways Review (CCA, 2024) looked at six areas and noted that pathways can combine to collectively generate net zero targets in the future. Some of these pathways are more mature and

complexity to overall hub and cluster development. This can result in market distortions and subsidy stacking and/or waiting to pick technology winners. Having a wide range of models could also lead to critical dependencies to a single business model on which all others rely. The ongoing operation of hard-to-abate sectors such as heavy industry and the growth of new industries (e.g. hydrogen) have a strong influence on strategic CCS deployment. Hubs and clusters play a strong role in underpinning the continued economic returns and employment from these industries and the broader economic growth of NW Europe. Transport and storage (T&S) companies that rely on scaled-up emissions tonnage may feel exposed through sector decoupling. Revenue support agreements could manage short-term shortfalls as markets are established.	could be accelerated while continuing with rapid development of others. However, each sector cannot be looked at in isolation within hub and cluster designs and there is a need to take a detailed regional analysis of hub locations to establish both current and future emissions reduction approaches and allow understanding of future industrial developments that may take advantage of emissions reduction infrastructure (e.g. renewable electricity, hydrogen, CCUS).
Strategic and operational concerns After several false starts in the UK and the Netherlands with early projects and/or approaches to initiating them, interviewees thought that the UK is trying to find a 'perfect solution' through the repeated cancellation of prior rounds for CCS or emissions reduction projects and complex business models. The challenge of 'perfect' getting in the way of 'good enough' may have resulted in lack of visible successful projects, and an absence of opportunity to learn by doing. Demonstrator projects help identify challenges with integration across value chains and new markets.	**False starts in Australia** The cancellation, delays or underperformance of projects anywhere, for any reason, is often reported as a 'failure' of a particular technology. But each CCS project to date has provided important advances through learning by doing. 100% success for nascent industries is highly atypical of any new activity, especially where business models are under development. Limited messaging around the initial start-up of Gorgon has allowed for misinformation and fact-picking exercises, which additional energy has been required to mitigate and reverse. Demonstration projects can help share knowledge and learning and improve overall familiarity with new technology. Stepwise changes to projects (from feasibility to demonstration to commercial scale) can allay the concerns of those who feel new technologies may be poorly tested and understood. Complex business and contract models that aim to foreshadow and address all future scenarios increase risks and costs.
Conservatism in hub design Concerns were expressed about the nature of the hub designs and their over-specification. This, in part, was to address contractual and regulatory risk, but also considered that some elements were unnecessary and contributing to high costs for hub development. The co-design of projects with industry and government would lead to a detailed understanding of risk and the implication of risk mitigation on costs. This would enable	**CCUS hubs in Australia** A collaborative approach based on trust with appropriate independent peer review is important to identify key risks. This would allow an appropriate response to those risks so that CCUS hub development costs are appropriate.

identification of critical risks and the impact of the regulatory and contractual requirements on cost.	
CO_2 standardisation It is becoming increasingly of concern for the T&S companies that the CO_2 should have a standard**,** well-defined composition. This aids management of operations, reduces the risk of damage to extensive infrastructure and meets HSE regulations. While this was originally a concern for pipelines, it is increasingly becoming more stringent for ship-based transportation. Where the responsibility lies for conditioning gas to meet a standard could result in adverse behaviours (e.g. divergent views on who pays or using different offset mechanisms to permanent storage).	**Sector recoupling to deliver a large-scale low-emissions hub** The NT LEH will start off large-scale but the initial phases may be regarded as low complexity with respect to offtake production. Offtake is largely from LNG production, and only as the hub evolves will additional sources of CO_2 become available. Some may come from international shipping, which may be of high purity based on design requirements. However, understanding the range of compounds and the offshore regulations (specifically the sea dumping permit) will rapidly focus attention on the range of composition that is allowable.
Institutional and corporate memory Job rotation is very typical in many industry and government settings, but this can lead to a lack of continuity, lack of awareness, need for skill building, loss of appropriate network contacts and many other negative aspects. The loss of corporate or institutional memory can be highly significant and impede progress. The result is wasted resources through reinvention where a new incumbent conducts yet another review when this has been completed previously. This was considered a significant impediment to projects being realised in the UK in particular.	**Staff rotation and human investment** The NT LEH has had a period of significant buy-in and support from partners. But, over time, turnover in industry and government representatives has occurred. Where possible, stability in project teams is required. Those who are part of the initial team have far more at stake than those who inherit a project or task. Newcomers need to be sufficiently empowered and motivated to invest their time and expertise in an activity and this is increasingly challenging. The same risks of reinvention and delays while climbing up the knowledge curve etc. are equally challenging over the longer term. Where possible, implementation should occur rapidly to reduce the impact of corporate knowledge loss, and details of projects should be recorded and disseminated so that new entrants can learn from past experience.
Appetite for risk and investment – repurposed infrastructure Some sectors have expressed concern that there is a missed opportunity in facilitating the reuse of existing infrastructure for new hub and cluster projects. Prior infrastructure is the result of huge investments to build and deploy, but for an incremental cost it could be maintained or mothballed appropriately for future use. However, there is a reluctance to invest in infrastructure maintenance by industry, especially when regulations require its removal. Decommissioning cost management at the lowest possible cost is preferred by industry. Government support to maintain or appropriately mothball infrastructure for future investment is seen as an obvious mechanism for mitigating costs while maintaining what could be deemed a national asset. This is not suggested as a way to avoid decommissioning	**The cost of regret – infrastructure opportunity** Historical infrastructure developments in Australia have shown that working in isolation, companies have made large investments that are not networked or well-integrated and have therefore taken up huge investments that could have been used in more efficient ways (e.g., the LNG sector in Australia). Identification and assessment of potential infrastructure reuse are important to reduce future infrastructure development costs, and this has direct implications for the costs of CCS. In addition, by identifying early opportunities to co-design facilities to support a low-emissions hub, funds can be more effectively used, total infrastructure footprint and costs reduced, and future decommissioning penalties diminished.

liabilities but as a way to avoid unnecessary costs through the development of new infrastructure.	The potential benefits of common user infrastructure in the NT LEH could drive better outcomes and smaller facility footprints and improve community concerns (Poore, 2024).
Gaps and discrepancies UK and EU carbon pricing, and lack of experience in carbon credits by many companies, are complicating how these countries interact. Lack of cohesive strategy in the UK may have led to inefficient models (design and business case developments) that have resulted in delays, inefficiencies, replication, poor choices and less strategically valuable projects – again, a lack of long-term vision was noted.	**How to realise benefits** Lack of experience in navigating the range of credit options and predicting their values and long-term benefits in the early phases of an industry is challenging. Consolidating risks and reducing costs go a long way towards minimising exposure to market challenges as a new hub develops.
Policy and regulatory risks Policy and regulation are both required to be flexible and evolutionary as this emerging area and future industry evolves. At the early stages, there is a risk of over-regulation to compensate for lack of experience and expertise, resulting in highly risk-averse conditions. With time, and this has been seen in Norway (P. Ringrose, personal communication, 2024), growing confidence and understanding of offshore CCS, the combined knowledge exchange and learning by doing have facilitated the streamlining of regulations to be much more fit for purpose and transparent.	**Australia – top of the regulation table, 2023** A report by the Global CCS Institute (Havercroft and Raji, 2023) puts Australia at the top of the league table with a score of 70 out of 100, beating 55 other countries engaged in CCS activities. While some countries have renewed and updated focus areas on CCS-specific laws, resulting in a general uplift in regulatory regimes across the board, Australia continues to strengthen existing regulation. The increased focus on transboundary movement has resulted in renewed focus on the London Protocol, with ratification and consideration of future bilateral agreements for transboundary movement with partners in Japan, South Korea, Singapore etc. Care is required in implementing policy and regulation that risks are appropriately managed using the best-available scientific and engineering experience. At a higher level, there needs to be an understanding of the implications of different policy and regulatory requirements and how they interact, so that unnecessary regulatory burdens are not placed on projects. The NTG may not have prepared all of its legislation and regulation for CCS specifically, but it has parallel materials to draw on from the oil and gas sector, though amending this will take time. The Federal Government is working through much legislation and regulation across the board, and now conducting a review of the offshore carbon capture and storage regulations process.
Land and development issues Securing land for CCS and related projects is complex. Regulatory and planning requirements are dealt with by a range of different departments at different levels of government. This can result in decisions needing to be taken at the local town planning to Federal level, often at differing timescales and with different perspectives on	**Place** Designation of locations for activation or regeneration for large-scale hub and cluster activities can attract significant positive and negative interest. The ability to set aside zones for large-scale industrial-based activities is valuable if there is suitable buy-in from a range of stakeholders and community members.

strategic planning and support. The role of brownfield sites to address some of the challenges, and their relationship with renewal and regeneration of industrial zones (e.g. Net Zero Teesside), can have strong meaning for local communities looking to replenish job opportunities in net zero activities.

The need to find suitable locations (even at the scale of hubs and clusters) still goes back to source-to-sink matching. These are very large-scale emissions zones, often in quite tight geographical clusters, and can address many more emitters, and gather systems can be developed alongside shared infrastructure. Upscaling is important to factor in, as projects go from a few Mtpa to potentially >10 Mtpa over the next decade.

The potential location of the NT LEH will be alongside existing facilities in the MASDP where consolidation of existing activities and space for new and emerging industries can provide a suitable industrial ecosystem with relevant supporting infrastructure, such as port facilities. This allows proponents and government agencies the opportunity to masterplan for the hub.

The NT LEH intends to be multi-user and while initial partners will come from the LNG industry, the proponents do not see it as exclusively defined by that industry. Hydrogen, sustainable aviation fuel and other industries are anticipated. This contrasts with some global regions.

Recommendations and solutions can be drawn from the interview materials outlined in Table 10:

- **Collaboration** is essential across the complex activities of design, development and deployment of low-emissions hubs and clusters, no matter their geographical location. If the mechanisms by which they are supported/derisked by government intervention preclude the ability to share knowledge and key learnings, then there is a huge risk to the successful and timely deployment of the new hubs to meet domestic and international obligations.
- **Improving levels of strategic coordination**. By increasing overall coordination, knowledge sharing, detailed planning and development there are greater opportunities to recognise and use infrastructure, identify common user-shared infrastructure, and develop longer term strategic benefits that future-proof investments in hub infrastructure.
- **Reducing complexity**. Understanding the interplay between financial, regulatory, strategic, public and private roles and responsibilities is highly challenging. Simplification should be sought where possible. Understanding each organisation’s role in managing risks, incentives and obligations versus stakeholder and shareholder perspectives, community engagement is critical.
- **Enduring corporate and institutional memory**, as well as a clear understanding of roles and responsibilities, is instrumental in advancing the progress of enabling low-emissions hub development and deployment. Seen in the deep dive of the different project case studies for North-west Europe (e.g. ROAD and related projects in the Netherlands), several of the current projects are revaluations of older projects that have failed, mainly due to lack of business case. Institutional knowledge (and detailed documentation of prior projects) can help navigate the history of some of these project failings and reduce the risk of reinventing the wheel.
- **Government support mechanisms** are very beneficial. Many feasibility studies look to initial government support (this does not have to be exclusively financial) to reduce a range of risks to enable private sector investment.

5 Conclusions

To understand the requirements of any industrial development, it is prudent to learn from existing examples of similar developments. This report has provided an overview of selected international low-emissions hub developments with a particular emphasis on European examples. In addition to the synthesis of publicly available information, the report also includes the summarised results of CSIRO interviews with hub proponents, participants and policymakers in these jurisdictions.

The aim of the report has been to develop an appreciation of the learnings that can be gained from these hubs.

The emergence of CCUS hubs

The CCUS hub model has evolved in response to the risks associated with single-source-to-sink models, which carry significant risk of failure if one part of the value chain fails. Hubs diversify risks through the establishment of an anchor facility with low capture cost emissions, common transport and compression infrastructure, and the successive inclusion of multiple emitters and in some cases multiple sinks. The collation of additional emissions sources also, in principle, leads to greater volumes of CO_2 being stored over the phased development.

A long-term vision

Many countries, as well as the EU, have developed a strong long-term policy vision and have a holistic view of emissions reductions, including a requirement for CCUS as part of their emissions reduction strategies. The EU provides a clear market signal on future CCUS capacity requirements and statements of the desire to achieve targets, including the role of CCUS hubs in attaining negative emissions over the long term.

Building on prior work

While it is hard to clearly understand the evolution of hubs in many jurisdictions, they often continue the development of prior studies, building on that past work. Ultimately the fundamentals of many of the CCUS hub projects have not changed, and the industrial regions from which emissions are generated and their proximity to potential sinks have not changed. What has changed is the scale of diversity of the CCUS hubs, and the development of a range of new business models to enable their implementation and operation.

Reducing business model uncertainty

All CCUS hub developments have some form of government involvement through direct funding, cost for difference mechanisms or tax incentives, as governments have a clear understanding of the benefits and return on investment (e.g. continued manufacturing capability in hard-to-abate industries and the economic and employment opportunities those sectors provide). In the case of Norway, the government has recognised CCUS as a national opportunity to generate revenue and further Norwegian company technology and skills exports.

Government involvement is also important in setting boundary conditions. Aside from providing incentives, there is the implementation of other measures such as a carbon tax or requirements on hub operators to allow fair and equitable access to infrastructure. Irrespective of financial incentives, governments have also provided certainty and enabled risk reduction to allow private sector investment. To unlock private investment, understanding and having certainty on return on investment is critical. In this regard, the UK is working on an objective base framework, which includes an independent economic regulator, the need to understand costs and performance, improved certainty of returns over the long term (including adequate returns on investment) and protection against demand-side risk to revenue (cross-chain risk).

The role of the coordinating body

In the development of CCUS hubs, a single representative organisation is typically identified. This can be a joint venture or a government company (e.g. Gassnova). In the case of Gassnova, this entity is at arm's length to government, enabling it to execute its role without being part of the day-to-day machinery of government. A feature of many CCUS hubs globally is that they incorporate academia and R&D organisations with strong expertise in CCS. This helps minimise risk and allay public concerns, as well as developing future workforce capacities.

Collaboration is critical

Collaboration is essential across the complex activities of design, development and deployment of low-emissions hubs and clusters no matter their geographical location. As such, the single CCUS hub representative allows common definitions around metrics and project goal success/failure (as undertaken in Task 0 of this study), without which there can be a lack of alignment between the proponents. The central CCUS hub coordinating organisation can act as a contract clearing house and undertake many of the administrative activities and therefore reduce the costs of entry for hub participants. In addition, this organisation can be responsible for knowledge capture and sharing.

Recording progress

Enduring corporate and institutional memory and a clear understanding of roles and responsibilities are instrumental in advancing the progress of low-emissions hub development and deployment. Observed in the deep dive of the different project case studies for North-west Europe (e.g. ROAD and related projects in the Netherlands), several of the current projects are revaluations of older projects that have failed, mainly due to lack of a business case. Institutional knowledge (and detailed documentation of prior projects) can help navigate the history of some of these project failings and reduce the risk of reinventing the wheel.

Building emissions reduction capacities

While the development of many CCUS hubs is being driven by oil and gas companies and their need to reduce their own emissions, there are opportunities to provide much greater capacities for wider industrial decarbonisation. However, without market demand signals these hubs may not be developed with sufficient capacities to maximise economy-wide emissions reduction opportunities and secure economic activity in hard-to-abate sectors. The breadth of organisations (23) involved in Project Greensand demonstrates the interest and drivers for industry and the wide range of skills and expertise required to execute not only CCUS hubs but also broader low-emissions hub development.

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