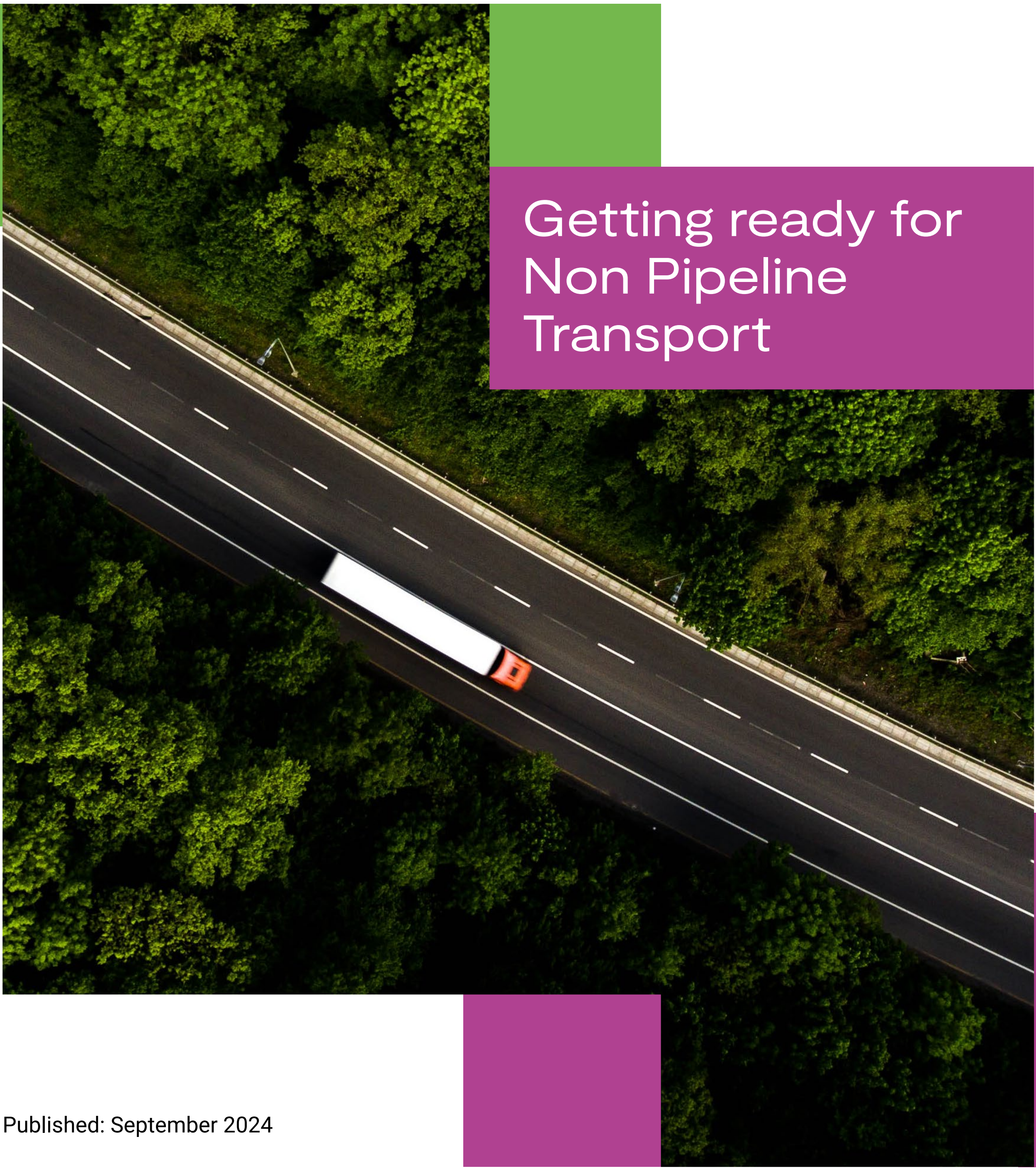
This report was commissioned by the Industrial Decarbonisation Challenge

Delivered by
Innovate UK

Industrial Decarbonisation



Getting ready for Non Pipeline Transport

Published: September 2024

Disclaimer

This document (including any annexes, appendices and associated computer files) was authored by DNV. UKRI and DNV accepts no liability for loss or damage suffered by any party resulting from use of this document, other than as provided for by the contract under which this document has been produced.

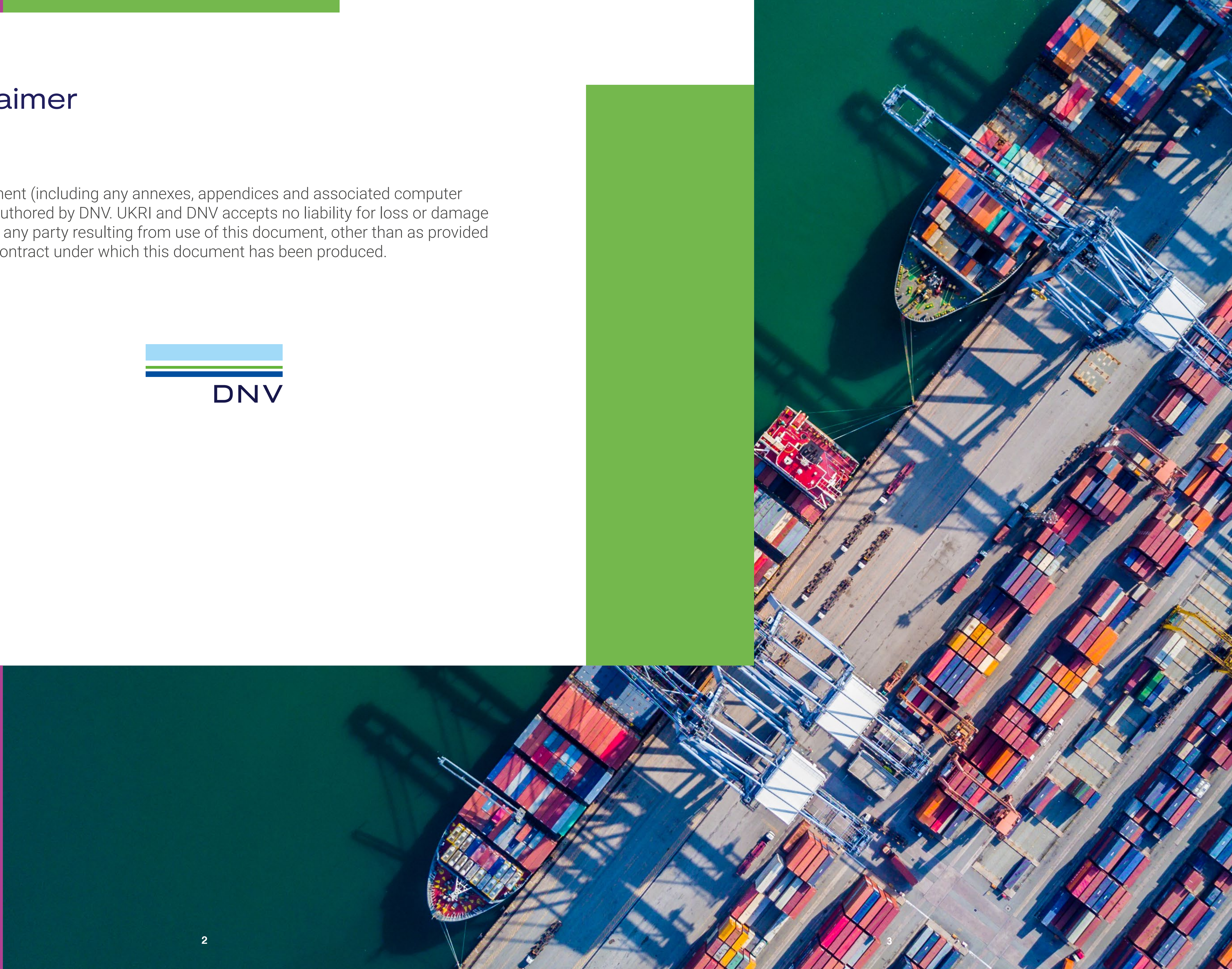


Table of contents

Two minute guide

Why capture CO_2?	UK decarbonisation target of net zero CO_2 emissions by 2050. For some emitters CO_2 capture may be the only option to allow continued long-term operation.	**Page 8**
Where do I send CO_2?	Sequestration sites off the East Coast and in the Irish Sea are being developed and more will follow.	**Page 24**
How does it get there?	CO_2 pipelines may eventually connect the main clusters but users away from these centres will need to use Non- Pipeline Transport i.e. Road, Rail and Ship.	**Page 7**
Who pays for it?	The UK Government is currently developing a business model to support and drive the transition to a self-sustaining Carbon Capture and Storage industry. Potential NPT users should monitor and participate in the process to ensure their needs are met by the final business model.	**Page 8**
Who do we work with?	Industrial CO_2 emitters will need to work with transport operators, shippers, CO_2 stores and other emitters to identify how they can best work together to identify the best transportation and storage options.	**Page 17**
How will the contracts work?	Once subsidies, incentives and other support mechanisms are known, each company that contributes to the value chain will require contractual certainty on risks and revenues. To manage full value chain risk, these different contracts will need to be cohesive and collectively comprehensive, which means that there needs to be a degree of oversight or coordination between companies.	**Page 26**
What will we need?	Sites will need access to space to safely accommodate and operate CO_2, capture, liquefaction, storage and loading facilities. In some cases, shared liquefaction, storage and loading could be implemented by a group of emitters	**Page 10**
How long will it take?	Many industrial CO_2 emitters are already working with CO_2 transporters and store operators. Once Goverment funding models are confirmed they expect to be ready to start NPT of CO_2 by the early 2030s.	**Page 26**
What are the showstoppers?	Capture, storage and shipping technologies are all ready to deploy but business models and support mechanisms are still to be published by Government. Costs, space and permitting may be a challenge but working with other emitters may be a solution.	**Page 29**

1 Introduction

This brochure provides an overview of the opportunities, considerations and actions to be undertaken by emitters that are planning to deliver CO_2 for long term storage using shipping and/or other non-pipeline transport (NPT) within the UK. It has been prepared from recent industry studies and engagement with an extensive range of stakeholders from across the full Carbon Capture and Storage (CCS) chain, with a view to provide insights into how to prepare for NPT.

NPT transport modes include shipping, road and rail transport. Selection of the appropriate NPT mode(s) will depend on factors such as the scale of CO_2 emissions, access to infrastructure and the cost of the transport mode for a given distance.

KEY POINT
CO_2 emitters need to engage with CO_2 transporters and storage operators and begin conducting feasibility studies to understand the CO_2 volumes and the most viable transportation options to move their CO_2 to suitable storage sites.

KEY POINT
NPT may allow additional operational flexibility compared to pipeline transport. For example, captured CO_2 from a single site could be exported to a number of different CO_2 stores, providing resilience to the emitter and transport and storage network operators, if for example the geological store has an unplanned outage.

Once potential modes are identified, the emitter will need to estimate average CO_2 capture rates, peak demand, turndown and identify intermittent operational requirements such as duration of outages or seasonal periods when CO_2 capture will be reduced. This will enable the transporter and the store operator to determine the effects on the whole system to ensure availability requirements are met and costs are minimised.

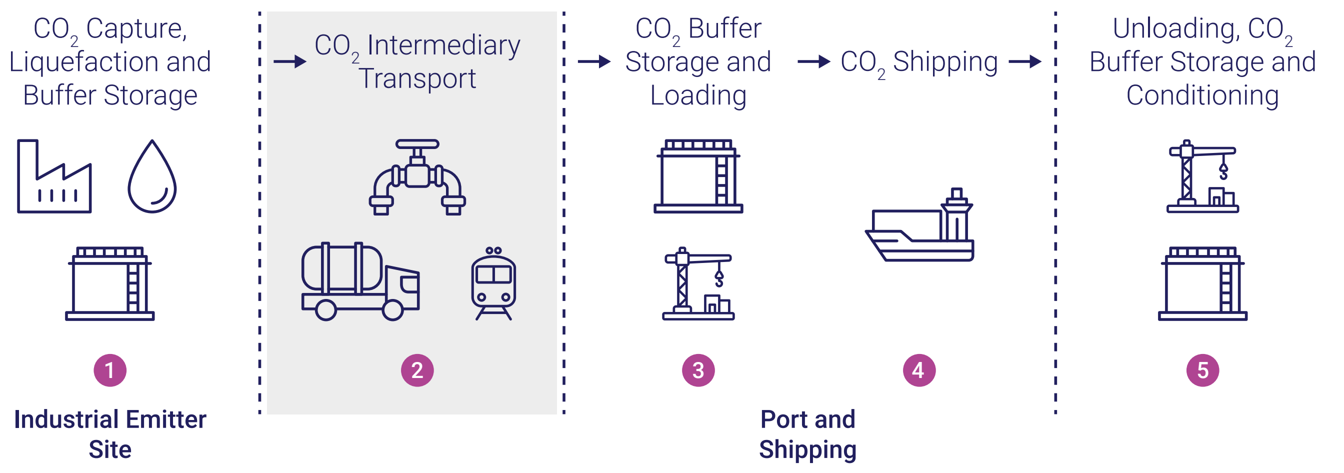
CO_2 Capture and Non-pipeline Transport Chain

A typical NPT CO_2 project might include multiple transport modes. This will often be the case for shipping where, unless the emitter site is located at the port, CO_2 transport via small scale pipeline, rail or road will be needed to get the CO_2 from the emitter site to the storage facilities at the port or CCS cluster.

A set of coherent contracts, across the CO_2 value chain, will be needed with one party, which could be the store, the emitter or an intermediary, taking the role of a co-ordinator or aggregator.

Figure 1 provides additional context for each step of the CO_2 NPT value chain.

Figure 1 Individual CO_2 NPT Value chain steps.



① **CO_2 Capture:** The emission source and capture process will influence the size and type of gas processing and purification needed to meet the CO_2 specification.

① **Liquefaction:** Gaseous CO_2 occupies a large volume. To efficiently transport CO_2 via train, truck or ship it should be liquified.

① ③ ⑤ **Buffer Storage:** Storage is needed to act as a buffer between the CO_2 from the emitter and the batch transport mode of road, rail or ship. Buffer storage is also required at the receiving terminal prior to geological storage. Purification and liquefaction may be needed if CO_2 arrives at the hub via a local pipeline.

② **Intermediary Transport (Gathering Pipeline):** CO_2 pipelines typically require high pressure operation at 45-70 bar and 10 to 30°C. A gathering pipeline may be used to transport CO_2 from the industrial emitter site to the port for liquefaction, storage and onward shipping.

Intermediary Transport (Rail): Liquid CO_2 can be transported by train in ISO Containers or in specially built CO_2 rail tankers.

Intermediary Transport (Road): CO_2 tankers, typically operating at 20 bar pressure and -20°C, are already in use to transport CO_2 for use in the food and beverage industry.

④ **Port:** The port needs to have adequate berth capacity, bunkering and buffer storage facilities, as well as equipment for CO_2 loading and unloading.

CO_2 Ship: Medium pressure ship designs currently range from 7,500 to 20,000 tonnes capacity of liquid CO_2. Ship size must be optimised as it determines the size of the port facilities required.

⑤ **Loading and Unloading:** CO_2 is loaded and unloaded using a flexible cryogenic hose (for tankers) or articulated loading arms (similar to those used for other liquefied gases) for ships and rail.

Conditioning: CO_2 needs to be conditioned into a suitable state (usually high-pressure gas or dense phase) for injection into the final storage site.

Final Storage Site: The CO_2 will ultimately be permanently stored long-term in robustly monitored geological stores.

Case for NPT of CO_2

The UK environmental policy is underpinned by an overarching commitment to achieve net zero by 2050. This is a challenging target and will necessitate significant changes to the whole energy system. With Industrial emissions making up around one sixth of total UK emissions, carbon capture is likely to be a key decarbonisation option for certain industrial CO_2 emitters to enable continued long-term operation[1]. Such emitters might include those with significant process[2] emissions of CO_2 where fuel switching isn't an option.

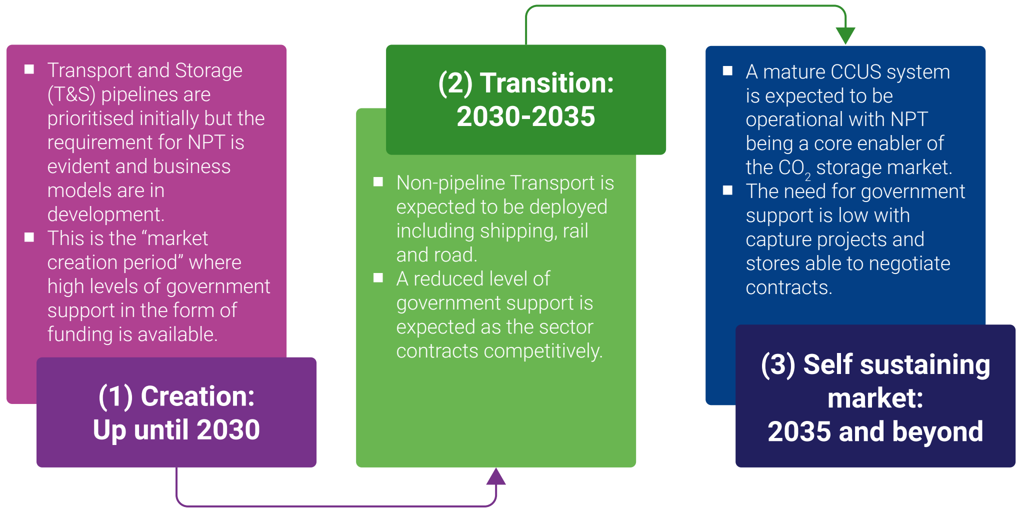
KEY POINT
NPT is vital for emitters that cannot decarbonise through other means (such as fuel switching) or have limited prospects of getting access to a CO_2 pipeline infrastructure.

For cost reasons, the transport of CO_2 by pipeline to a local storage site offshore is the preferred option for many large industrial emitters. For UK regions where no direct pipeline access to planned CO_2 storage sites is currently feasible (e.g. due to lack of local storage, distance, relative scale of emissions, or geographical constraints), NPT of CO_2 will play a vital part in the CO_2 storage chain.

Current Status of NPT

The UK government has ambitions to capture and store 20–30 megatonnes per annum (Mtpa) of CO_2 by 2030 and at least 50 Mtpa by 2035. The approach to achieving these ambitions is set out in the government's "CCUS Vision" document (see Figure 2 below), over three distinct phases: Market Creation, Market Transition and Self-sustaining Market. To date, industrial decarbonisation incentives have focussed on pipeline-based projects in the UK's major industrial clusters, but it is estimated that shipping and other NPT infrastructure enabled capture projects could account for as much as 30% of targeted capture emissions (15 Mtpa CO_2) by 2035[3]. In the long term, the UK ETS carbon price is likely to be the main lever to drive a self-sustaining business model.

Figure 2 Government's 2023 CCUS Vision Timeline[4].



(1) Creation: Up until 2030

- Transport and Storage (T&S) pipelines are prioritised initially but the requirement for NPT is evident and business models are in development.
- This is the "market creation period" where high levels of government support in the form of funding is available.

(2) Transition: 2030-2035

- Non-pipeline Transport is expected to be deployed including shipping, rail and road.
- A reduced level of government support is expected as the sector contracts competitively.

(3) Self sustaining market: 2035 and beyond

- A mature CCUS system is expected to be operational with NPT being a core enabler of the CO_2 storage market.
- The need for government support is low with capture projects and stores able to negotiate contracts.

---

[1] Industrial Decarbonisation Strategy (publishing.service.gov.uk)

[2] Such as cement works, where CO_2 is emitted from the materials being processed rather than as a by-product of meeting process heat or power requirements.

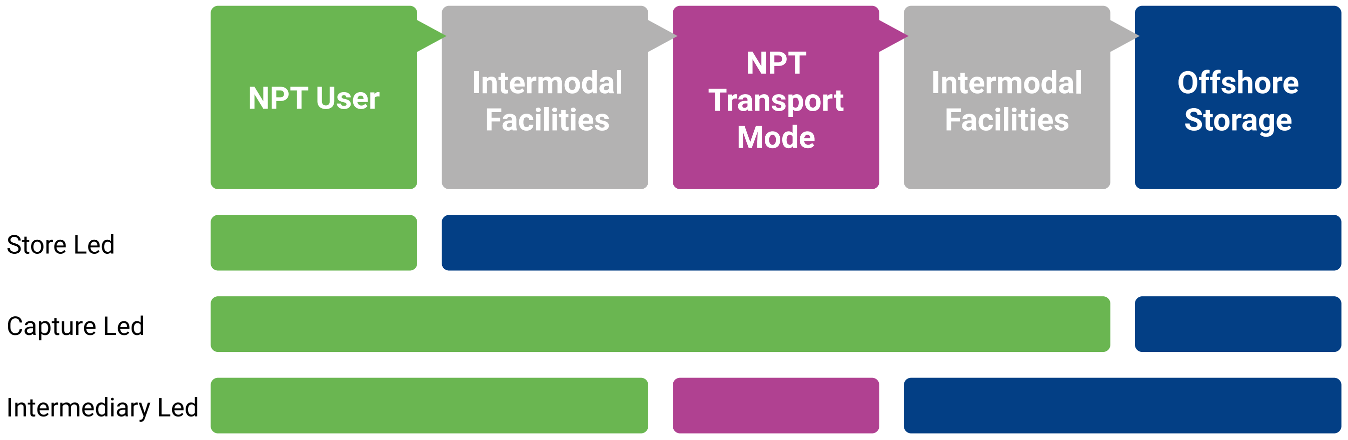
[3] CCUS Delivery Plan 2035. CCSA. 2022

[4] Carbon Capture, Usage and Storage (publishing.service.gov.uk)

To progress the development of CO_2 NPT, the UK Government published a Call for Evidence (CfE) in May 2024, outlining a potential long-term vision. The CfE seeks to understand the role of Government during the market transition phase[5], and will be followed by policy development, industry consultation (likely to be in 2025), and business model development. Potential NPT users should monitor and participate in the process to ensure their needs are met by the final support package.

The CfE describes three archetypes for NPT projects (Store Led, Capture Led and Intermediary Led as per Figure 3 below), each with differing responsible parties for the collection of CO_2 and ownership and operation of the NPT chain facilities:

Figure 3 NPT Delivery Archetypes (from Call for Evidence)



The most appropriate archetype for one CO_2 value chain may be different to another. For example, on the basis of cost efficiency (no third-party expenses), reliability (no third-party reliance) and scalability, a single large emitter may opt to construct transportation facilities and manage the transportation of its own CO_2 (i.e., opting for an "Capture Led" model). A small emitter may find owning dedicated CO_2 liquefaction and transportation assets uneconomic; in such a case, CO_2 transport might be facilitated by the operators of a CO_2 storage site or by an intermediary acting to transfer the CO_2 from the emitter to the store. In some cases, regardless of scale, it could be more cost effective to utilise a 3rd party for the T&S, where the available expertise could lead to a more reliable system.

---

[5] Carbon capture, usage and storage (CCUS): non-pipeline transport and cross-border CO2 networks - call for evidence (publishing.service.gov.uk)

2 Industrial Emitter Site Considerations

To determine whether CCS and NPT is a suitable decarbonisation strategy for a facility, site operators should consider the following factors:

Can I capture and transport CO_2 from my site?

- CO_2 Purity Requirements — **Page 10**
- Liquefaction — **Page 11**
- Buffer Storage — **Page 12**
- Land availability — **Page 13**
- Safety and Environment — **Page 13**

CO_2 Purity Requirements

For safety and operability, the exported CO_2 must be pure enough for respective steps in the value chain which may include various transport modes as well as the CO_2 store specification. Components of particular concern to purity include[6]:

- SO_x, NO_x, O_2, H_2S (can produce corrosive components);
- H_2O (can react with CO_2 to form corrosive carbonic acid); and,
- H_2 (can cause embrittlement of steels).

Impurities in the CO_2 stream can have a substantial impact on the temperatures and pressures at which it transitions between its gas, liquid and solid phases. This makes it more challenging to maintain CO_2 in a specific phase, such as the liquid phase: this has a particular impact on requirements for CO_2 shipping, as the CO_2 is likely to be carried in its liquid phase.

---

[6] Insight-146-CO2-Shipping-for-CCS.pdf (oxfordenergy.org)

There is currently no standard CO_2 composition specification for NPT in the UK and projects are working to specifications agreed between the participants. The Norwegian Northen Lights project, which is capturing, liquifying and transporting industrial CO_2 emissions by ship, has published a detailed specification and revisions to this are ongoing to widen the range of emitters engaging with their programme[7]. A number other CO_2 specifications have been published: Aramis[8], Porthos[9], Fluxys[10], TES[11], ISO/DIS 27913 (Pipeline)[12].

It is desirable for the CO_2 specification to be broad but it must be compatible with the materials and process conditions across the entire transport chain. For example, pipelines may have a less onerous CO_2 specification than for shipping, but if shipping is part of the export route a stricter specification will be required. There could be a competitive advantage for transport and storage operators requiring a less onerous CO_2 specification, but this will impose technical and operational limitations and limit flexibility. If an emitter were to produce CO_2 to a lower purity specification it may restrict their export route and storage site options, unless additional purification facilities or blending with a higher purity CO_2 stream is an option further down the value chain.

KEY POINT
CO_2 specifications are important for safety and operability reasons.

The most stringent requirements are dictated by CO_2 shipping. Production of a lower purity CO_2 stream may limit an emitters future flexibility.

In a value chain where economics will be challenging, purity standards which are more demanding than they need to be may lead to purification costs which preclude the participation of some emitters.

Liquefaction

Unless a pipeline is used, the export of captured CO_2 as a gas is challenging due to the large volume of the gaseous phase. For nearly all NPT options, it is therefore likely that the CO_2 will be liquefied, reducing the volume to be transported by around 500 times versus gas.

Figure 5 shows the phase envelope for pure CO_2. Liquid CO_2 only exists at pressures above 5.2 bar and temperatures down to -56°C. At lower pressures and temperature solid CO_2 will form. CO_2 is typically stored and transported at temperatures between -50 and -20°C and pressure from 5 to 20 bar.

---

[7] Northern Lights and DNV collaborate to update the CO2 Quality specifications for carbon transport and storage

[8] ARM-Template_Memo (aramis-ccs.com)

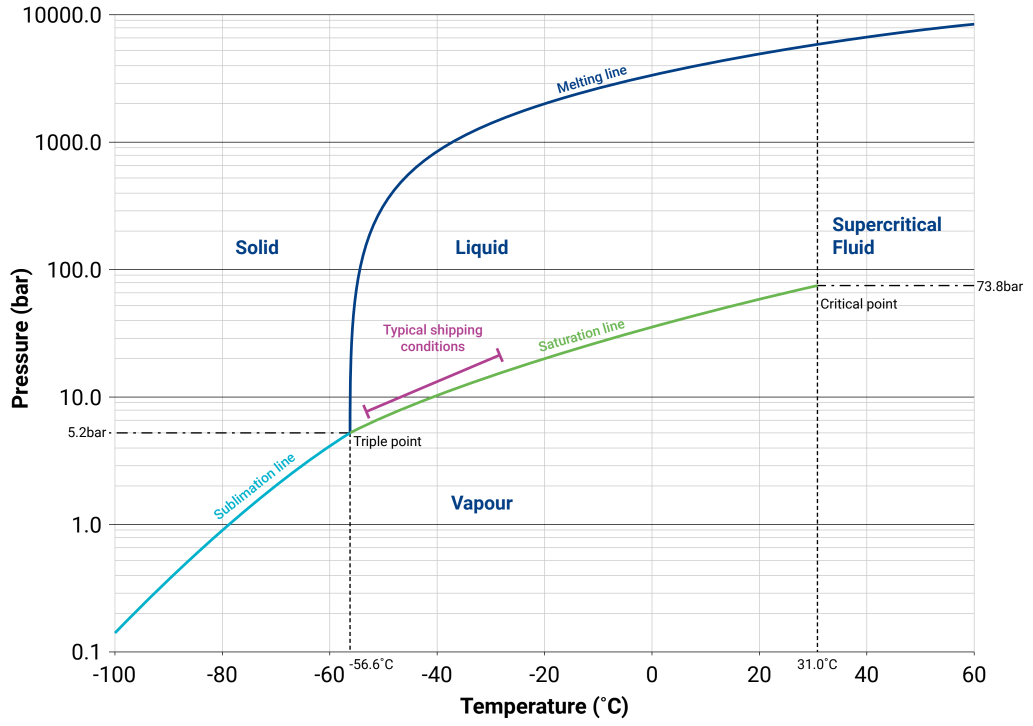
[9] CO2-specifications.pdf (porthosco2.nl)

[10] CO2: Preparing to build the network (fluxys.com)

[11] CO2-Spezifikation (oge.net)

[12] ISO/FDIS 27913 - Carbon dioxide capture, transportation and geological storage — Pipeline transportation systems

Figure 5 CO_2 Phase Diagram[13]



Compression, turbo-expansion and cooling with refrigerants can all be employed to liquify CO_2: however it is an energy intensive process due to the pressurisation and cooling necessary. As such, the cost of liquefying CO_2 is largely made up by utilities costs[14]. For liquid CO_2 delivery at 20 bara pressure, a specific power consumption for CO_2 liquefaction of around 65 kWh/tonne is achievable, delivery for transport at lower pressures necessitates lower temperatures and raises the power demand. In most cases, the liquefaction plant capacity will need to be sized to meet the maximum expected CO_2 capture rate from the site or sites as CO_2 would otherwise need to be vented during peak operating periods.

Buffer Storage

Storage will be required to act as a buffer between the delivery of CO_2 from the emitter to the selected batch transport mode (which in turn will provide a reservoir from which a ship, train or truck can be rapidly loaded). The storage must be capable of handling the daily and seasonal variations in captured CO_2 and should also take account of possible disruptions such as weather delays to ships, road closures or rail line disruption. Understanding these parameters, by dynamic modelling of the whole export chain, is needed to identify the optimum combination of storage and transport capacities.

---

[13] DNV RP-F104

[14] Shipping CO2 - UK cost estimation study (publishing.service.gov.uk)

The type of storage solution will be influenced by factors such as the site layout, available plot space, constructability, and operational requirements. Options may include a single large vessel or multiple smaller vessels in designs such as spheres, tanks or bullets. When storing CO_2 at higher pressures, an increased steel wall thickness is required, leading to a higher CAPEX. At lower pressures, although a lower wall thickness is required, insulation material is needed to maintain the low temperature and the vessel is typically larger.

Land Availability

The availability of land at the emitter site for the carbon capture plant, liquefaction plant and buffer storage is an important consideration. Table 1 provides an indicative footprint for the assets, although an additional allowance for safety zones will be needed.

Table 1 Indicative Footprint Requirements[15]

	Estimated Footprint	
Capture Scale (ktpa)	**Carbon Capture Plant**	**Liquefaction and Buffer Storage**
40	13 x 23 meters	Data Unavailable
100	19 x 24 meters	+ 50% of CC Plant
400	30 x 55 meters	+ <50% of CC Plant
>400	Bespoke	

Safety and Environment

CO_2 is not currently defined as a dangerous substance under the UK Control of Major Accident Hazards Regulations 1999 ('COMAH') or as a dangerous fluid under the Pipelines Safety Regulations 1996 ('PSR'). This means that for sites with large quantities of stored CO_2, the Health and Safety Executive (HSE) do not provide Land Use Planning ('LUP') advice, and the site operators are currently not subjected to the legal duties associated with COMAH site classification. However, as an emerging sector, this may change in the future.

Aside from CO_2 storage handling, the site will have to consider other hazards associated with capture and storage. This might include risks associated with the refrigerant used in a liquefaction plant or vent emissions associated with the CO_2 capture solvent. The introduction of these processes may impact the site's COMAH tier.

KEY POINT

Capture and NPT of CO_2 must be accomplished safely. CO_2 is not currently regulated under COMAH but this may change.

---

[15] Based on Aker Carbon Capture values. Just Catch™ – Aker Carbon Capture

3 Selection of NPT mode

Selection of the NPT mode(s) should consider the following factors:

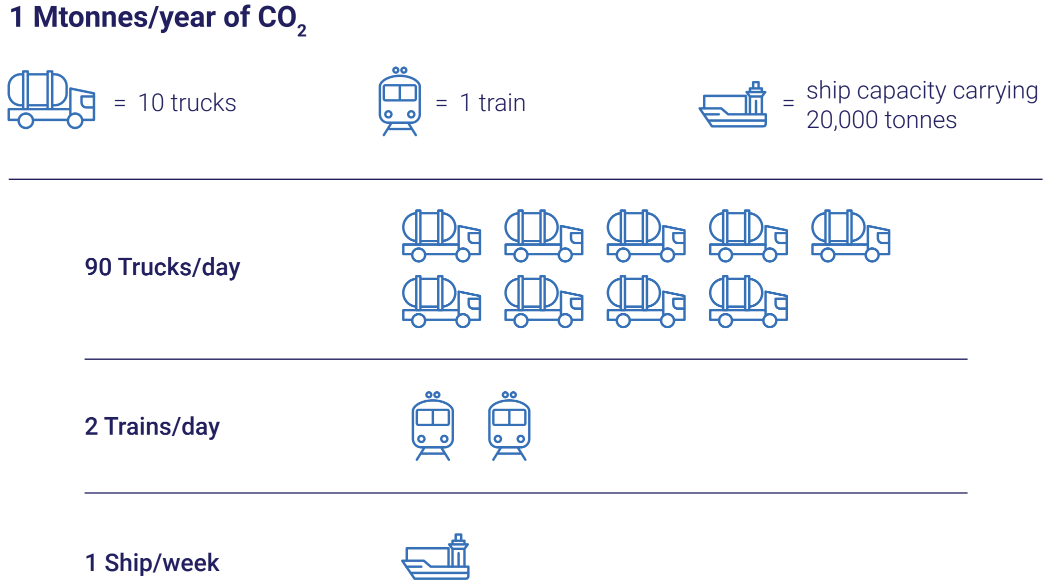
How do I select my CO_2 NPT option?

- Capacity **Page 14**
- Cost **Page 16**
- Distance **Page 16**
- Emissions **Page 17**
- Contracting approach **Page 17**

Carbon Capture Capacity – Influence on Transport Mode
Along with the availability of infrastructure, connections and other constraints, the production capacity of the carbon capture operation will directly influence the viability of different NPT modes. Thresholds for consideration that can dictate the suitability of the different NPT modes include the following:

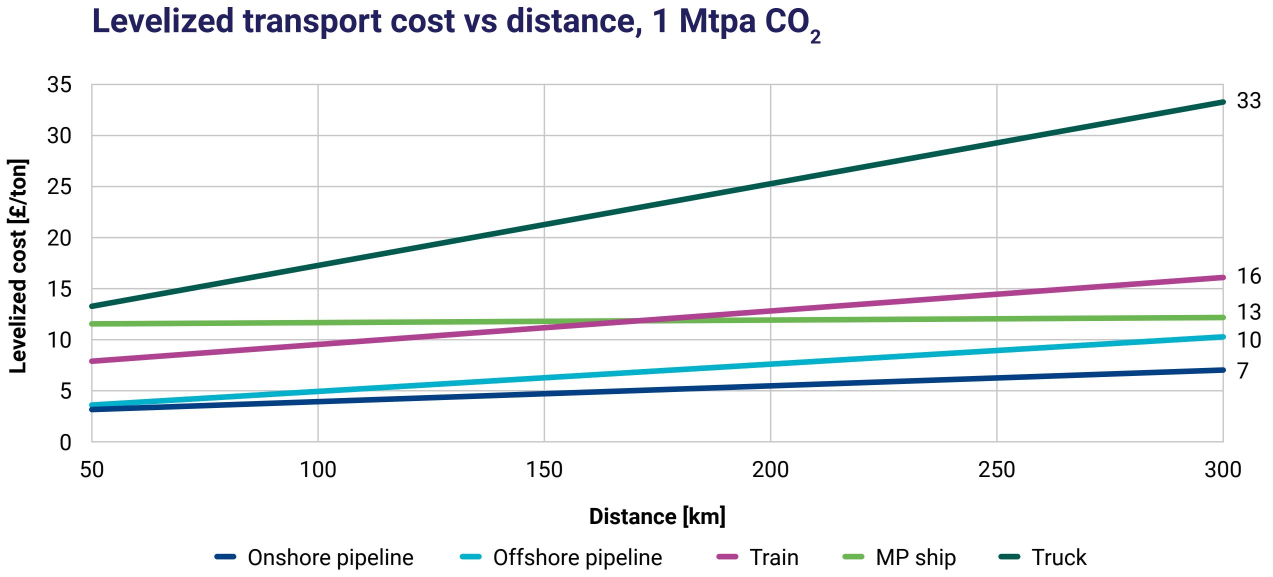
- Trucks are more suited to smaller scale operations. Their nominal capacity of 30 tonnes CO_2 per truck means that the storage and loading facilities are relatively small but above about 10,000 tpa, multiple trucks per day would be required.
- A cryogenic rail tanker has a typical capacity of 80 tonnes CO_2/wagon, but the number of wagons is restricted to the length of the rail siding. To export 1 Mtpa of CO_2 would require two trains of twenty wagons per day.
- Ships are best suited to long distances and large volumes as extensive storage and port infrastructure is needed. Assuming a ship can transport 20,000 tonnes of CO_2 to the store location in a single weeklong round trip, a facility producing 1 Mtpa would require 1 ship operating, without downtime, throughout the year.

Figure 6 Illustrative number of vehicles per day for a facility producing 1 Mtpa of CO_2



The effect of distance is shown in Figure 7 which has indicative CO_2 transportation costs for NPT of 1 Mtpa of CO_2. The cost of transport via a dedicated pipeline is included for comparison but will not be feasible for some locations and small emitters. Figure 7 shows that based on the assumptions made, of the NPT modes, road transport is the costliest for any given distance. There is a crossover at around 170 km whereby rail becomes more expensive than shipping (as the lower OPEX of shipping outweighs its higher CAPEX) but it should be noted that for a particular site different transport types may necessitate a longer export route.

Figure 7 Indicative transport costs by mode and distance[16]



---

[16] The model assumes necessary infrastructure is pre-existent. See main assumptions in Appendix

Cost Components of NPT

In terms of Capital Expenditure (CAPEX) and Operational Expenditure (OPEX), the primary cost component in the NPT chain[17] is the vehicle itself (i.e., whether it is a ship, train or truck). Figure 8 below illustrates the indicative costs for NPT using a control case of 1Mtpa of CO_2 travelling 200km in distance:

Figure 8 Indicative transport CAPEX and OPEX for NPT for 1Mtpa of CO_2 and 200km

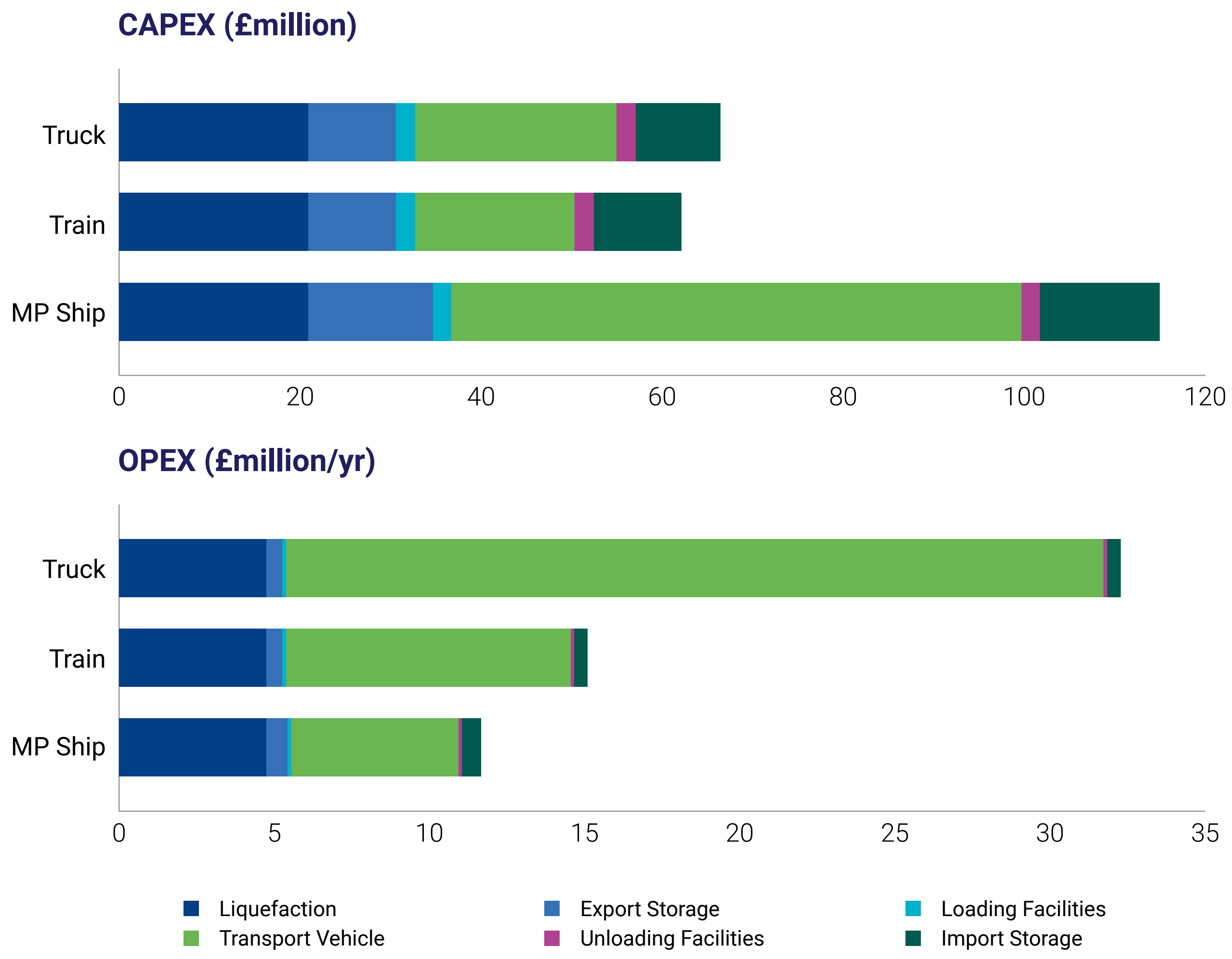


Figure 8 shows that the CAPEX associated with use of a train is lower than both road trucks and medium pressure (MP) ships[18]. MP ship is the most expensive with respect to CAPEX and it should be noted that the hierarchy shown with respect to CAPEX doesn't appear to change with respect to greater CO_2 volumes.

---

[17] The system chain in the model is defined as: Liquefaction, buffer storage (export), loading, transport vehicle, unloading and buffer storage (import).

[18] MP Ships are the most mature, existent shipping technology for CO_2 transport

At greater distances (i.e., over 300km), modelling shows that the OPEX of the train and truck modes increases by around 30% over the 200 km case, however for the MP ship OPEX remains similar (i.e., there are greater operational efficiency gains with shipping over longer distances against the higher fuel consumption of the truck and train routes). CAPEX also increases for all modes with respect to distance however it is the truck mode that observes the greatest increase in CAPEX as more vehicles are required to transport the CO_2 for the same rate of production.

KEY POINT
To optimise the cost of transporting CO_2, emitters must consider the transport distance, CO_2 production capacity and proximity to CO_2 infrastructure.

Emissions associated with different Transport Modes

A further consideration when selecting NPT modes is the CO_2 generated during the transport of the CO_2 which will negate some of the benefits of the CCS. Current UK Government Conversion Factors[19] suggest rail freight transport emissions are less than 50% those of road transport per tonne km. This is largely due to the electrification of the rail network. Road tankers could also use greener fuels, but additional societal benefits for rail such as reduced road congestion may have an impact on the ease of permitting.

For long-distance shipping, Liquid Natural Gas (LNG) is the most prominent alternative fuel technology choice and other low-carbon fuels such as ammonia and e-methanol are also expected to replace the high carbon fuels currently used.

KEY POINT
Many emitters would benefit from the cost savings associated with larger scale shared facilities.

Working with other emitters

If emitters have the opportunity to share infrastructure, due to the proximity to one another, they can take advantage of the associated economies of scale. Such a cluster might be centered around a large 'anchor' site (e.g. a refinery, ceramics, glass or other site with large CO_2 emissions). The cluster could be a local pipeline based gathering system feeding the CO_2 to a port for purification, liquefaction and onward shipping to a storage site or a road based system catering for small emitters. The facilities might be owned and operated by one of the emitters (probably the anchor industry), jointly by the users or by a 3rd party company.

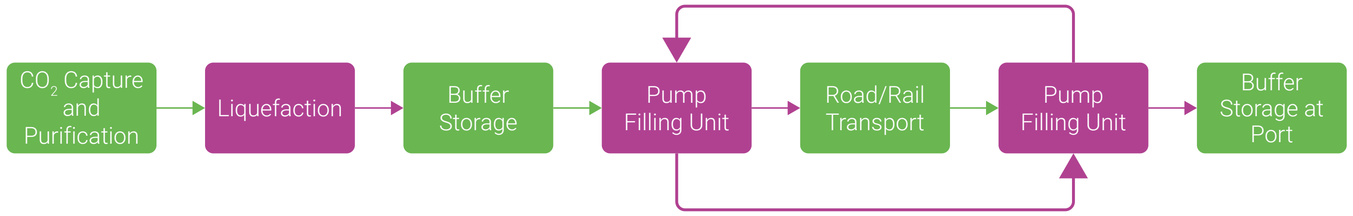
---

[19] DESNZ and DEFRA, UK Government GHG Conversion Factors for Company Reporting, 2023

4 Transporting CO_2 by Rail or Road

A typical CO_2 transportation chain via road or rail involves the key steps shown in Figure 9. The rail wagons or road tankers cycle between the loading and unloading facilities from the emitter site to the port.

Figure 9 CO_2 Road/Rail chain



CO_2 by Rail
Rail transport of CO_2 is under cryogenic conditions. Sizeable facilities will be needed as rail tankers are loaded using dedicated loading arms to pump liquid CO_2 from storage and rail sidings are needed to accommodate sufficiently large trains of CO_2 tankers during this process. Individual rail wagons can hold up to 80 tonnes of CO_2 and are 15m long; a train could comprise 20 or more wagons. If frequent small loads are exported, there may be potential for rail wagons to act as short-term storage for the site whilst in the rail siding which can then be taken away and replaced by other wagons when full.

NPT via rail can provide a CCS decarbonisation route to inland areas, especially where sites are located close to the rail network. In some cases, industrial sites will already benefit from historic rail connectivity as a result of historic delivery of coal. Unless a site has an existing connection to rail infrastructure, the option of rail transport may be expensive as new transport infrastructure or a pipeline to storage and loading facilities located at the nearest appropriate rail connection will be required. Rail network capacity may also be a potential limitation as some sections of the national network are highly utlised and may have limited capacity for freight trains. Rail network restrictions may also affect the size and type of trains that can be accomodated.

Case Study – 7CO2


7CO2

7CO2 is investigating the development of a carbon capture and shipping hub, based around Avonmouth, with shared liquefaction, storage and ship loading facilities located at Bristol Port. 7CO2's hub would enable CCS for local and regional emitters by pipeline and rail for onward shipping to geological storage, with the potential to capture over 8MtCO2pa from regional emitters. Engineers Petrofac have completed initial design of the hub and rail studies have been completed with GB Rail, Network Rail and VTG.

CO_2 by Road
Like rail, bulk CO_2 road transport is as a cryogenic liquid. A loading bay with a bottom loading arm pump filling unit is used to load the truck tank. Road tankers have a significantly smaller capacity than rail and there are limitations around allowable gross vehicle weight[21].

Road transport is an option suited for transporting smaller quantities of captured CO_2, especially where there is no existing access to rail infrastructure. Industries such as Energy from Waste (EFW) can already have high road transport use for carrying waste feedstock as an input to the process. This may reduce the viability of adding further trucks to the area's road systems. In general, areas with high congestion may oppose an increase in road transport, and this would be considered as part of the planning application.

---

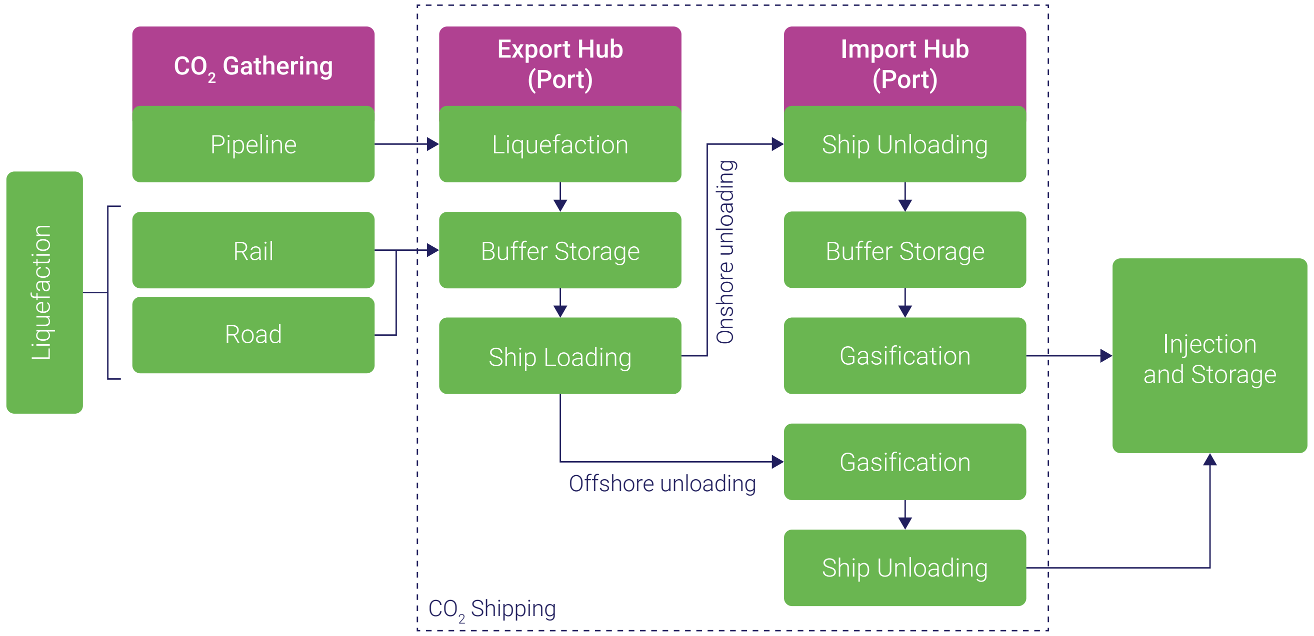
[20] A low-speed track section distinct from a running line or through route typically used for storage, loading and unloading.

[21] Evaluation of onshore transportation methods for captured CO2 between facility and harbour in Stockholm. 2021. FULLTEXT01.pdf (diva-portal.org)

5 Transporting CO_2 by Ship

Before it can be shipped, CO_2 must be delivered to a suitable port, possibly by another NPT mode. A typical CO_2 transportation chain via ship might involve all the key steps shown in Figure 10, especially if the port CO_2 facilities are shared by a number of emitters.

Figure 10 CO_2 Shipping chain



Port Suitability
The port will require the space and facilities to handle ships carrying liquid gas. In general, for a port to be suitable it requires the following characteristics:

- Landside suitability
  - Ship bunkering facilities
  - Land footprint for CO_2 storage and handling facilities
  - Electricity and other utilities for the facilities
- Suitable maximum vessel size - smaller vessels may require ports to have more berths.
- Berthing capacity - ports with a high level of ferry movements or refinery jetties with high congestion may not be suitable.

Case Study - RWE


RWE

RWE plans to capture CO_2 from their operations at Pembroke power station and transfer it via an undersea pipeline across the estuary to Dragon LNG. Dragon LNG is exploring the integration of CO_2 liquefaction into their site and expanding their jetty to accommodate CO_2 ships, enabling CO_2 from RWE to be transported to a storage facility. Together this will form the Milford Haven CO_2 Project, which aims to connect industry from the south and north sides of Milford Haven, supporting decarbonisation through innovative pipeline and shipping transportation routes. This project is a crucial component of the South Wales Industrial Cluster (SWIC) Deployment Project, with RWE serving as the lead partner. The partners will collaborate and align their individual projects and scopes to ensure a successful overarching Milford Haven CO_2 project delivery; to support the UK's net zero targets through to 2050, safeguard jobs and boost the economy.

The Pembroke Power Station would enable the generation of up to 2.2 GW of flexible, decarbonised low carbon power - capturing up to 5 Mtpa of CO_2.

Case Study - Cory Decarbonisation


Weedon Architects

Cory Decarbonisation is an Energy from Waste (EfW) with Carbon Capture and Storage project, based in London. Cory is one of the UK's leading waste management businesses. It has been operating on the Thames since at least 1785; today, its fleet of tugs and barges transport waste from London and the Southeast to the Riverside 1 EfW facility in Belvedere. With a second EfW facility currently in construction on the same site, Cory will be processing around 1.5 Mtpa of waste by 2026. Cory's carbon capture potential is therefore estimated to be around 1.37 Mtpa CO_2e of which c. 50% will be fossil carbon, and 50% biogenic. Cory is currently maturing the design with their technology partners and applying for a Development Consent Order (DCO) for the CCS project, and plans to capture, compress, condition and liquefy CO_2 on site by 2030. The captured CO_2 would then be transferred via a new export jetty onto purpose-built gas carrying ships, that will transport the liquid CO_2 to the Port of Immingham (owned and operated by Associated British Ports) and ultimately for permanent storage in the Viking CCS store in the North Sea.

Liquefaction

Captured CO_2 may arrive as a gas via a pipeline gathering system or may arrive in a liquefied state if transport is via road or rail[22]. CO_2 delivered as a gas will require liquefying at the port for storage and onward travel as at present all CO_2 ship designs carry liquid CO_2. Liquefaction will also be needed to recover CO_2 boil off gas from the storage tanks and that generated during ship loading.

Buffer Storage

Port CO_2 storage requirements will be determined by a range of factors. A report by the Zero Emissions Platform and Carbon Capture and Storage Association suggests that Port storage capacity should be at least 140% of ship capacity[23] but in practice storage will be determined by berthing capacity, expected variation in CO_2 deliveries, ship capacity and travel times, land availability and other site restrictions. Some project developers are looking at floating storage barges which can be towed away and replaced when full.

Ship Type and Capacity

Shipping technology using small liquid gas tankers for food-grade CO_2 are in place, with four CO_2 carriers of 1,000-2,000m^3 capacity operating for a while. At the larger scale, currently, only Medium Pressure (MP) (15-20 barg, -30 to -20°C) CO_2 ships have seen commercial operation. Four MP ships are being built for the initial phases of the Northern Lights project and most shippers are currently basing their studies on similar ships. MP operation is expected to be the norm for most UK and Northern Europe based projects, with ships up to 25,000m^3 capacity, but for longer distances, larger ships operating at lower pressures (5-10 barg, -55 to -40°C) may be preferred.

Loading/Unloading

Portside loading and unloading is typical for projects being planned at present with the CO_2 being transferred into storage tanks at the reception port before being conditioned and exported for injection through an offshore pipeline. Offshore unloading of CO_2 directly to the injection facilities may become an option in the longer term.

During loading, liquid CO_2 will be pumped from the onshore storage tanks to one or more articulated loading arms (similar to those currently used for Liquefied Petroleum Gas (LPG) and Liquefied natural gas (LNG)) which connect to the ship cargo tanks. The cryogenic liquids displace gaseous CO_2 from the tanks during loading and some boil-off will also occur. This is sent via a return line back to the onshore liquefaction plant.

The loading time will vary depending on the flow rate and ship size. Large ships may have multiple loading arms which would be used in parallel[24]. Unloading of liquid CO_2 at the destination is done by cargo pumps located on the ship pumping it to the storage tanks via a similar set of loading arms.

Figure 11 Liquefied gas loading/unloading arms at Milford Haven

---

[22] See "Industrial Emitter Site Considerations: Liquefaction" for further technical considerations.

[23] ZEP_report_HD-1.pdf (zeroemissionsplatform.eu)

[24] Shipping CO2 - UK cost estimation study (publishing.service.gov.uk)

6 CO_2 Sequestration

Long-term geological storage is expected to be the main destination for most captured CO_2. There are currently several proposed CO_2 storage sites across the UK, and these are typically located offshore of the identified industrial clusters. Some industrial clusters do not have a local geological store and will therefore need to transport CO_2 to regions with available storage capacity. In a "self-sustaining market", there is also the potential for all clusters to eventually have non-pipeline transport connectivity to unlock flexibility between emitters, transport systems and stores.

NPT plans at the clusters are outlined in Table 2 below. At present, the HyNet and East Coast Clusters are the most advanced with both expected to take Financial Investment Decision in Q3 of 2024 and to commence operations from 2027. The Scottish Cluster and Viking are the next most advanced clusters while the others listed are much less developed.

Table 2 Clusters and NPT plans

Cluster	Operator	Nearest Port	NPT Plans
HyNet	ENI	Eastham, Stanlow	Initially pipeline only project however there is potential for imports from non-pipeline transport in a future phase.
East Coast Cluster	BP, Equinor and Total- Energies	Teesside (proposal to connect to Humberside)	Initially pipeline only project however there is potential for imports from non-pipeline transport in a future phase.
Scottish Cluster / Acorn	Storegga	Peterhead	Plans for pipeline and port infrastructure and CO_2 imports from shipping.
Viking CCS	Harbour Energy	Grimsby and Immingham	Plans for pipeline and port infrastructure and CO_2 imports from shipping.
South Wales Industrial Cluster	-	Milford Haven	Plans for import infrastructure accommodating pipeline, ship and rail.
Port Talbot	-	Milford Haven Port Talbot Barry Cardiff	Plans for port infrastructure and CO_2 export via shipping.
Barry	-	-	Exploring NPT options for CO_2 export.
Cardiff	Plans for port infrastructure and CO_2 export via shipping.	Bristol	Plans for port infrastructure and CO_2 export via shipping.
Morecambe Net Zero Cluster	Spirit Energy	Barrow	Potential for port infrastructure and CO_2 imports from shipping.
	Plans for import infrastructure accommodating pipeline, ship and rail.	Southampton	Pipeline project with potential for CO_2 imports via shipping.
Black Country Industrial Cluster	-	-	Exploring NPT options for CO_2 export.
7CO2	-	Bristol	Potential for port infrastructure and CO_2 export via shipping.
Bacton Thames Net Zero	ENI	Great Yarmouth	Potential for port infrastructure and CO_2 imports from shipping.
Solent Cluster	Exxon-Mobil	Southampton	Pipeline project with potential for CO_2 imports and export via shipping[25].

CO_2 Utilisation

An alternative to CCS is Carbon Capture and Utilisation (CCU). CCU projects are typically on smaller scale (generally ktpa) than CCS (typically Mtpa) and may have different CO_2 quality requirements (e.g. food grade). NPT of CO_2 for utilisation will have similar challenges to NPT for CCS but the CO_2 delivered may command a higher price making small scale road tanker transport viable. Current UK CO_2 production is approximately 600 ktpa, equivalent to approximately 400 road tanker loads of CO_2 per week.

---

[25] 3730-The-Solent-Cluster-Socioeconomic-Report-Digital_Dec-23.pdf (asp.events)

7 Other Considerations

Planning and Development Timeline
For companies to invest in costly Pre-FEED (Front End Engineering Design) and FEED studies there needs to be sufficient certaintly around the short-term, medium-term and long-term business case of any final NPT-enabled value chain. Key steps in the development timeline for NPT are expected to be permitting and shipbuilding.

Permitting can take as little as 18 months but up to 3 years. Engineering design must be initiated early and must run in parallel ton securing investment and permitting as outputs will be needed for input to these processes.

CO_2 ships take 30 months to build but this is subject to a suitable yard being available. At present (Q2, 2024) many shipbuilding yards have full order books and build periods of 3-4 years are being offered.

Figure 12 Estimated planning and development timelines

CARBON CAPTURE	~3 years
SHIPPING	~3 - 4 years
STORAGE SITES	4+ years

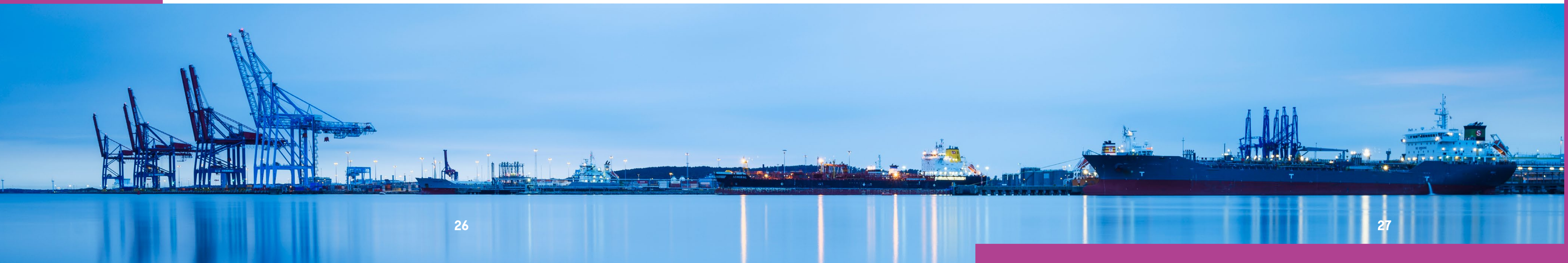
Contractual agreements
Once subsidies, incentives and other support mechanisms (which might relate to risk management) are known, each company that contributes to the value chain from emitter to store will require contractual certainty on risks and revenues. In order to manage full value chain risk, these different contracts will need to be cohesive and collectively comprehensive, which means that – at least in the start-up phases - there needs to be a degree of coordination or oversight.

It could be the emitter that provides a degree of coordination for the full value chain, or the store, or it could be an intermediate entity like the shipper or a third party that manages the various contracts from emitter to store. It is not necessary that ownership of the CO_2 changes at each interface: the emitter could own the CO_2 and take responsibility (capture-led) through the full NPT value chain until it is handed over to the Transport and Storage Company (T&S Co) who takes ownership and responsibility for storage, or the T&S Co (store-led) could take ownership and responsibility directly from the emitter.

KEY POINT
There is a need for rapid development of a business framework and funding model for NPT to meet the 2030 target, given potentially length planning and development timelines

In these cases, other companies who do the purification, conditioning, liquefaction and transportation could be paid on a throughput or tolling basis. In the case of contractual coordination provided by another entity, like a shipper or another third party (intermediary-led), it might be the intermediate company that takes title and therefore responsibility for the CO_2 from the emitter through until receipt by the store T&S Co.

Understanding Demand
Engagement with all parties within the whole CO_2 export chain is critical, especially in the earlier market development stages. When potential routes have been identifed, modelling of the whole value chain will be needed to assess routine CO_2 export rates and impacts of turndown, peak system demand or intermittent operation. An industry with intermittent operation and therefore intermittent carbon capture, would need the system (including liquefaction and buffer storage) to be designed to the plant's full capacity and be capable of high turn down ratios. Ship, road or rail capacity, including loading, unloading and any further intermediate storage facilities, will then need to be sized to take account of the expected CO_2 delivery patterns.



8 Opportunities and Challenges

Emitter Opportunities within Carbon Capture and NPT

- NPT will enable CCS at sites where there is **no direct pipeline access** to planned CO_2 storage sites (e.g. due to lack of local storage, distance, relative scale of emissions, or geographical constraints).
- Non-pipeline transport allows **multiple stores** to be utilised, providing resilience to the transport and storage network. This reduces the risk of limited sequestration capacity and provides flexibility to the emitter.
- A hub approach, with local emitters collaborating on NPT provides the potential for **funding of shared infrastructure** so that duplication of assets for multiple NPT projects (e.g. purification, liquefaction and storage at ports) is avoided.
- In the longer-term the **CO_2 price** is expected to increase, and the costs of capture transport and storage are expected to decrease. This will make operating with CCS a lower cost option for emitters.
- CCS and NPT can support emitters who need to meet customer **demands for a low carbon option**.
- Regeneration of carbon capture solvents produces significant quantities of low grade heat. **Heat recovery** to district heating or other use may offer an additional income stream for some emitters.

General Opportunities within Carbon Capture and NPT

- There are opportunities to use the **early learnings** from more advanced projects such as Northern Lights and Longship.
- **Pragmatic standard CO_2 specifications** will support the flexibility and resilience of the T&S network, while optimising storage utilisation and therefore decarbonisation potential, by ensuring CO_2 can be accepted by multiple operators. However, care must be taken that an overly restrictive specification does not add unduly to the overall end to end costs of compliance.
- **Knowledge sharing** between local councils that are more advanced in CCS and those who are new to the sector to ease planning and permitting.

Emitter Challenges within Carbon Capture and NPT

- **Business Model(s)**, which will include custody transfer agreements and the handling of carbon leakage (which effectively reduces the CO_2 delivered to store and increases overall value chain costs), have not yet been finalised.
- NPT projects are typically more **complex and costly** than projects (which are lucky enough to have) access to pre-existing, or the option to construct pipeline systems to the store; therefore, funding allocations need to reflect this.
- A realistic view of the **development timeframe** shows that operation of NPT projects by 2030 is challenging.
- Capture projects working across different national or regional jurisdictions may experience **cross-border permitting challenges**.
- **Infrastructure constraints** such as suitable Ports and access to rail the network may limit the NPT options available. Industrial Clusters also need reception facilities for NPT.
- **Planning and permitting** needs to be carried out in parallel to engineering design, delays in this can have impact on the overall timeline.

General Challenges within Carbon Capture and NPT

- **Supply chain constraints** - At present (Q2, 2024) many shipbuilding yards have full order books and build periods of 3-4 years are being offered.
- Individually each element of the value chain has a relatively high maturity, however the bringing together of the whole chain is at a lower **Technology Readiness Level (TRL)**, mainly in terms of commercial considerations including interdependent contractual arrangements across the full CO_2 value chain.
- Large scale CO_2 shipping is feasible but **full chain demonstration projects** from first movers are needed to progress investment.
- **Planning and permitting** agencies need to recognise the national imperative to decarbonise quickly, by allocating resources effectively and as an integral part of their planning and permitting decision frameworks and processes.

9 Who should be approached for further information?

- Government
  - Department for Energy Security and Net Zero (DESNZ)
  - The Crown Estate
  - The Crown Estate Scotland
  - North Sea Transition Authority
  - Offshore Petroleum Regulator for Environment & Decommissioning
- Permitting
  - Health and Safety Executive (HSE)
  - Environment Agency
  - Scottish Environmental Protection Agency (SEPA)
  - Natural Resources Wales
  - Local Planning Authorities including National Park Authorities
  - Marine Management Organisation (MMO)
- Trade Organisations
  - Carbon Capture and Storage Association (CCSA)
  - Society of International Gas Tanker and Terminal Operators (SIGITTO)
  - Network Rail
- First movers and early adopters
  - Northern Lights joint venture with Norway government working with JV partners Equinor, Shell and TotalEnergies are investing in Norway's first licence for CO_2 storage on the Norwegian Continental Shelf
  - In the UK Track 2 CO_2 storage projects with plans to receive CO_2 by NPT are the Acorn Project in Scotland and Viking in the East of England
  - UK Track 1 hubs (Hynet and East Coast Cluster) may seek NPT volumes to either smooth existing volumes or to scale up to higher storage rates at some point in the future

10 Acknowledgements

The following stakeholders generously offered input and comment during the preparation of this guide:

Equinor
BP
Shell
CCSA
Cory Group
Breedon Cement
Progressive Energy
RWE

Storegga
DESNZ
Enfinium
Eni
Milford Haven Port Authority
7CO2
Aker Clean Carbon
Navigator

11 References

Useful reports	
Global CCS Institute	*Technology readiness and costs of CCS, 2021. Technology-Readiness-and-Costs-for-CCS-2021-1.pdf (globalccsinstitute.com)*
International Energy Agency	*CCUS in Clean Energy Transitions, 2020. CCUS technology innovation – CCUS in Clean Energy Transitions – Analysis - IEA*
CCSA/ZEP	*Achieving a European market for CO_2 transport by ship, 2023. Achieving a European market for CO_2 transport by ship - Zero Emissions Platform*
	Network Technology: Guidance for CO_2 transport by ship, 2022. ZEP-CCSA-Report-on-CO2-transport-by-ship-March-2022.pdf (zeroemissionsplatform.eu)
	Integrating CO_2 transport by ship into the Track-2 and Track-1 expansion capture bidding process – CCSA Position Paper, 2023. https://www.ccsassociation.org/resources/download?id=4242
Clarksons/CCSA	*CLARKSONS/CCSA report on updated costs for CO_2 ship transport, 2024.*
	Clarksons/CCSA Report: Updated Costs for CO_2 Ship Transport - CCSA (ccsassociation.org)
Element Energy	*CCS deployment at dispersed industrial sites, 2020. CCUS at dispersed sites (publishing.service.gov.uk)*
The Oxford Institute for Energy Studies publication	*What do we need to know to make CO_2 shipping for CCS a reality?, 2024. What do we need to know to make CO_2 shipping for CCS a reality? - Oxford Institute for Energy Studies (oxfordenergy.org)*
	Carbon capture from energy-from-waste (EfW): A low-hanging fruit for CCS deployment in the UK?, 2024. CM09-Carbon-capture-from-energy-from-waste-EfW-Final.pdf (oxfordenergy.org)

Call for Evidence	
DESNZ	*Call for evidence on non-pipeline transport and cross-border CO2 networks, 2024. CCUS: non-pipeline transport and cross-border CO2 networks - call for evidence - GOV.UK (www.gov.uk)*

HSE	
	Assessment of the major hazard potential of carbon dioxide (hse.gov.uk)
	Pipeline design codes and standards for use in UK CO2 Storage and Sequestration projects (hse.gov.uk)

Industrial Decarbonisation Challenge (IDC) Supported Clusters	
UKRI – IDC	*Enabling Net Zero: A Plan for UK Industrial Cluster Decarbonisation. IUK-131023-UKRI_EnablingNetZero.pdf*
Humber Industrial Cluster Plan	*HICP - The Largest CO2 Emitting Cluster in the UK (humberindustrialclusterplan.org)*
Net Zero North West	*North West Cluster | Net Zero North West (netzeronw.co.uk)*
Tees Valley Combined Authority	*Net Zero - Business (teesvalley-ca.gov.uk)*
Scottish Net Zero Roadmap	*Scottish net zero roadmap (snzr.co.uk)*
Black Country Industrial Cluster	*BCIC - Home (bcinc.org.uk)*
South Wales Industrial Cluster	*SWIC | South Wales Industrial Cluster*

Other Emerging UK Projects	
HyNet	*HyNet North West*
East Coast Cluster	*East Coast Cluster*
Scottish Cluster	*Acorn | Growing Our Decarbonised Future - The Acorn Project*
Viking CCS	*Viking CCS | Humber CCS | Carbon Capture and Storage - Viking CCS*
7CO2	*7CO2: The Severnside Carbon Capture and Shipping Hub: Overview | LinkedIn*
Morecambe Net Zero Cluster	*Homepage - MNZ Cluster*
Bacton Thames Net Zero	*Bacton Thames NetZero. | An initiative for the future. (eni.com)*
Solent Cluster	*The Solent Cluster | Working towards a lower carbon future*

Other Project References	
Northern Lights	*What we do - Northern Lights (norlights.com)*
Longship	*Developing Longship - Key lessons learned - Fullskala (ccsnorway.com)*

12 Appendix – Main Assumptions

General assumptions

- Project rate ranges from 5 kton/y to 1 Mton/y
- Lifetime is 25 years
- Discount rate is 5.5%
- Fluid is assumed to be pure CO_2 and to be in compliance with transport mode requirements
- All cost values are provided in GBP, 2023. Currency conversions are performed by applying CEPCI indexes and then converting the currency at 2023 rates
- Costs do not include contingencies

Value chain items

- Buffer storage:
  - The size of buffer storage is assumed to be able to accommodate up to 4 days of project rate. This value should provide a good compromise between operational flexibility and cost efficiency.
  - The cost of buffer storage varies linearly with capacity
- Loading/unloading
  - Unloading will take place onshore for ships
  - Loading and unloading are assumed to be the same since the same equipment is expected to be used
  - Loading/unloading OPEX are assumed to be 3% of CAPEX

Shipping-specific assumptions

- Port-to-port transport
- Medium Pressure (MP) configuration vessels, since it's considered the most mature existent technology (15-20 barg, -30 to -20°C)
- Ship capacities in the range 6-20 kton
- Ship fuel assumed to be LNG

Truck-specific assumptions

- T between -30 and -19.5 °C and p between 14 and 20 bar
- Average truck velocity is assumed to be 50 km/h, average tanker capacity is 30 tonnes
- It is assumed that necessary infrastructures are pre-existent (adequate roads, bridges, etc.)

Train-specific assumptions

- T between -30 and -19.5 °C and p between 14 and 20 bar
- Average train velocity is assumed to be 60 km/h, average tanker capacity is 80 tonnes
- It is assumed that necessary infrastructures are pre-existent (railways, sidetracks, etc.)

Pipeline-specific assumptions

- Onshore pipeline cost is evaluated assuming the line to be located in populated areas, such as central Europe. This implies that costs might be over-estimated with respect to pipelines located in sparsely populated or deserted or desert areas.
- Offshore pipeline has been modelled the same as onshore, except the cost of installation is much higher for offshore and the "right of way acquisition" is zero for offshore.
- The default steel cost evaluation assumes grade API 5L X65
- OPEX are assumed to be 1% of CAPEX
- No booster stations
- The fluid phase is dense (highly compressed fluid that demonstrated properties of both liquid and gas)
- The cost estimation includes compression cost, with the following assumptions:
  - Max train size 2 Mton/y
  - Cost includes intercooling, water removal and installation costs
  - Inlet pressure is atmospheric, outlet pressure is assumed to be 150 bar. This means that if the pipeline inlet pressure calculated by the tool is lower, the cost of compressor is overestimated. This effect is however small since the cost associated with dense phase CO_2 compression is relatively low.

This report was commissioned by the Industrial Decarbonisation Challenge

Delivered by
Innovate UK

UK Reasearch and Innovation (UKRI)
Polaris House
North Star Avenue
Swindon SN2 1ET

T: 01793 444000
E: communications@ukri.org

www.ukri.org