Net Zero Technology Centre

CCUS Enabling Infrastructure Study

Study Report

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The data and analysis presented in this report has been prepared by Xodus, a Subsea7 company. Xodus is a global energy consultancy who unite unique and diverse people to share knowledge, innovate, and inspire change within the energy industry. Xodus provides support across the energy spectrum, from advisory services to supply chain advice across the full lifecycle of energy projects.

Subsea7 is a global leader in the delivery of offshore projects and services for the energy industry, including the offshore energy transition solutions the world needs.

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EXECUTIVE SUMMARY

Carbon Capture, Utilisation and Storage (CCUS) is a core element of decarbonisation and climate change plans in Europe and beyond. Previous studies carried out by Xodus in conjunction with the Carbon Capture and Storage Association (CCSA) have highlighted that transport and storage of captured carbon dioxide (CO_2) across borders within the European Union/European Economic Area and the United Kingdom (UK) is crucial to effective and timely emissions reduction.

Previous work highlighted that non-pipeline transport would be a key element in enabling cost effective transport of CO_2 from emitters to safe and secure storage sites. This project concentrates on the infrastructure required to transport CO_2 to offshore storage sites, as they currently make up most of the currently identified potential CO_2 stores within Europe. Consideration of direct injection was deemed to be outside the scope of this study.

Figure E-1 illustrates the high-level options available to gather and transport CO_2 from emitters to offshore storage sites

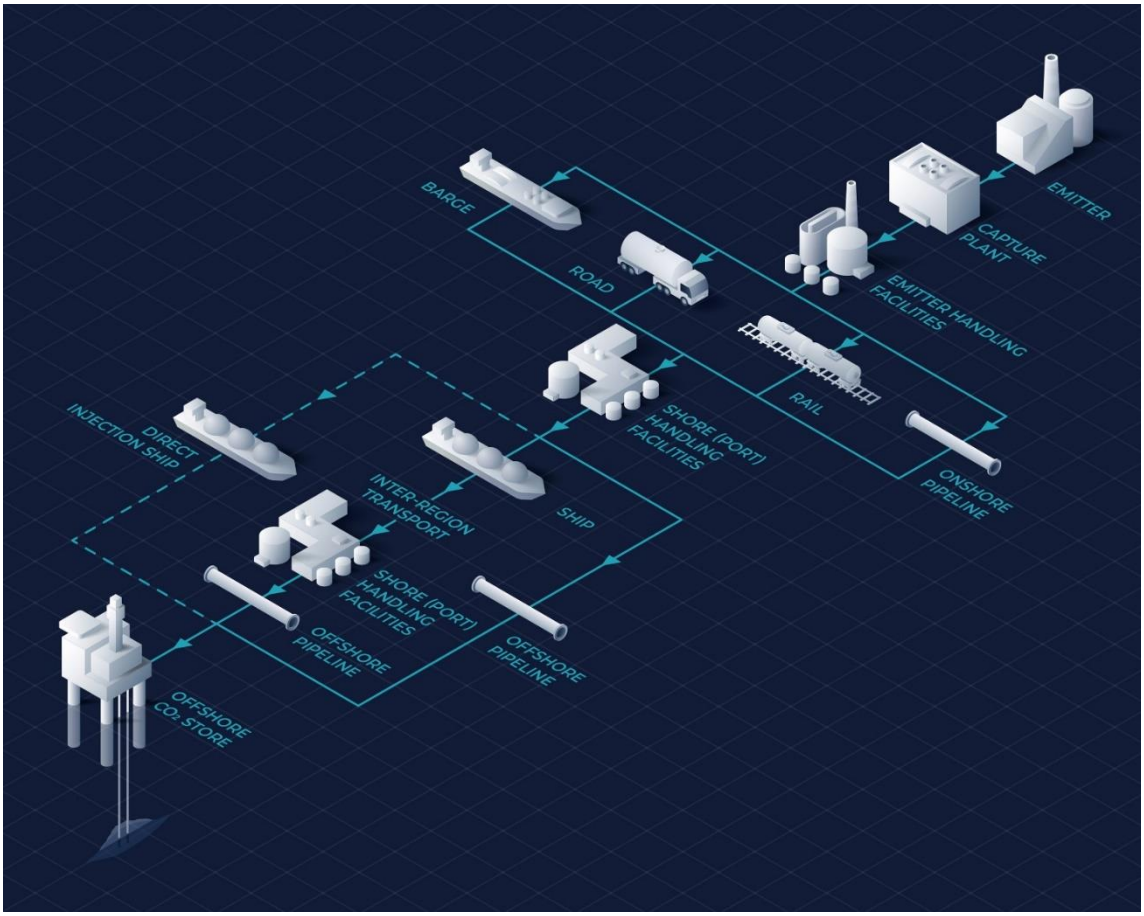


Figure E-1 – CO_2 Transport Options

Figure E-2 illustrates the geographic spread of identified potential CO_2 stores and potential captured emissions across Europe. The captured emissions point sources in the figure are translated from work carried out by the European Joint Research Council (JRC), using their scenario C1 [Reference 3].

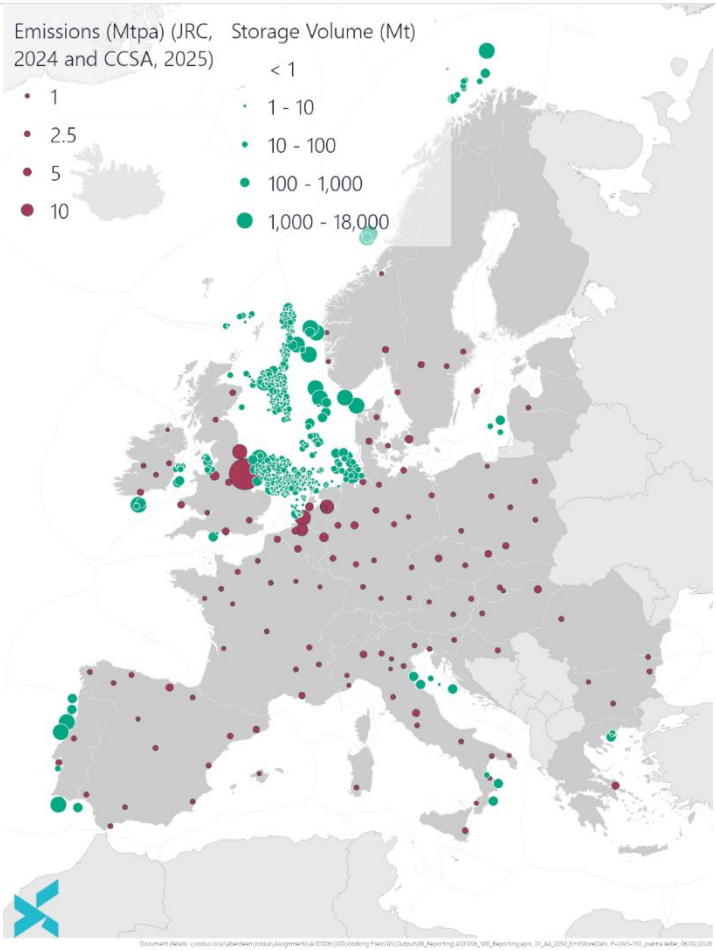


Figure E-2 – Predicted Emissions Sources in 2050 and Identified Offshore CO_2 Stores.
Data sourced from CCSA and JRC [Reference 1, 3], Xodus analysis for UK and Norway.

As is evident from Figure E-2, there are a range of potential emitters across Europe who are located significant distances away from potential stores. As a result, ports, shipping and onshore transport are all likely to be critical parts of the overall infrastructure required to gather CO_2 from emitters and transport it to the offshore stores.

This report reviews the following three main areas to gain insight into the potential for non-pipeline CO_2 transport within Europe:

- Technology Assessment: Assessment of the amount and type of CO_2 storage and treatment infrastructure likely to be required for onshore non-pipeline transport, including a high-level understanding of capital investment requirements for port infrastructure.
- Port Assessment: Assessment of the scale and suitability of existing port infrastructure across Europe (including the UK) needed to support gathering of CO_2 emissions from local industry and transport of the CO_2 directly to nearby offshore storage CO_2 stores or to other ports located near to cost-efficient offshore CO_2 stores.
- CO_2 Volume Assessment: Assessment of the potential volumes of CO_2 emissions that may be transported between countries within Europe via ship and pipeline at 10-year time intervals from 2030 to 2050, including analysis of likely transport routes, ship movements and port requirements.

The key findings from the study are as follows:

Technology Assessment

- Most of the technologies required to enable a Europe-wide CCUS transport network are already established and proven, either in analogue industries (particularly the LPG transport industry) or directly in CO_2 service. There is a need to evolve those technologies in terms of scale and adapt them to CO_2 service at scale, but there are already examples of the technologies being used in industry, especially through the advent of the Northern Lights CCUS project.
- Non-pipeline transport (NPT) presents a realistic alternative to pipeline transport for aggregating captured CO_2 prior to accessing offshore storage services:
  - Road tankers are particularly suited to small emitters who are located at a distance from established CO_2 infrastructure. The transport of CO_2 by road is already established and CCUS can scale the use of CO_2 tankers quite readily. However, the use of road tankers is most suited logistically to relatively low volumes of CO_2 transport.
  - Rail cars are also a potential route for non-pipeline transport using established technologies. They offer the potential to transport a higher volume of CO_2 than road tankers over longer distances but the implementation of this transport route at scale could be constrained by competition with other rail users due the high utilisation of existing railway networks across Europe.
  - Barge transport could be considered for transport of CO_2 where emitters are located alongside major rivers. The size and scale of barges required to deliver effective CO_2 transport is likely to limit their use to major rivers, but there is the opportunity to service multiple emitters with common barges. Technologies from the LPG industry (where barges are already used) will need to be adapted for use on CO_2 service but the theory of this has already been proven through the delivery of ship-based CO_2 handling systems.
  - Ship transport is already being implemented within the CCUS industry with projects such as Northern Lights relying on a fleet of ships to transport the captured CO_2 to their gathering port. The technology required for these ships is analogous to that widely used for decades within the LPG industry for the transport of "semi-refrigerated" liquefied gases.
- Pipeline transport is typically the most cost-effective method for onshore transportation of CO_2 at high volume and over long distances (See Table E-1) but has a comparatively long lead time to implement due to planning and consenting requirements involving multiple stakeholders (typically many different landowners and regulators across long pipeline routes).
  - Long term operating costs of pipelines are also comparatively lower than non-pipeline transportation options.
- Non-pipeline transport does introduce technology challenges outside those that apply to pipeline transport of CO_2:
  - The handling of non-condensable gas impurities in captured CO_2 needs careful consideration across the full transport chain. The facilities required to maintain the comparatively low temperatures and pressures required for efficient non-pipeline transport of CO_2 may lead to conditions where a small amount of non-condensable gas (e.g. nitrogen, hydrogen, etc., plus trace amounts of CO2) will need to be periodically vented to atmosphere.
  - Composition requirements across the transport chain need to be considered to ensure that the most efficient balance is struck between the scope and scale of facilities required throughout the chain rather than enforcing potentially overly strict composition requirements on all emitters feeding into the chain.
  - NPT requires transfer of CO_2 between transport and storage at multiple points in the chain which can increase CO_2 losses due to small amounts being vented to atmosphere during each transfer process.

- Metering and analysis of CO_2 is known to be a challenging area and is the subject of significant research and testing. NPT has the potential to make this more critical due to the multiple custody transfers between steps in the transport chain (e.g. emitter to land transport method to gathering port to ship transport to receiving port to pipeline to store).

Table E-1 illustrates the estimated most cost-effective method of onshore transport for captured CO_2 for a range of transport volumes and distances:

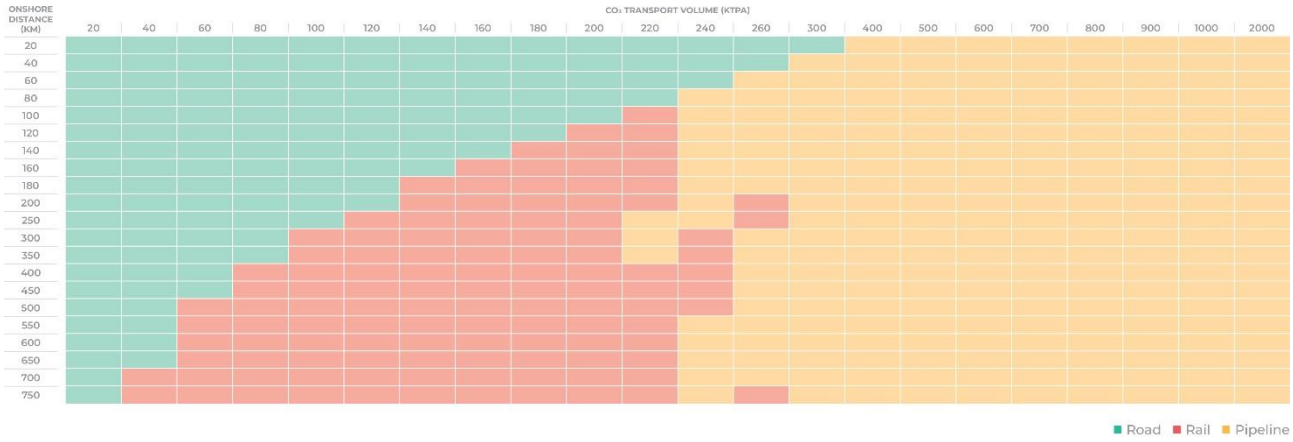


Table E-1 – Most Cost-Effective Mode of Onshore Transport Matrix

Port Assessment

- All operating ports across Europe were assessed to investigate their potential suitability for handling CO_2 transport. Approximately 850 ports were screened down to circa 200 ports by comparing the size and types of ships currently handled with those expected to be required for CO_2 shipping.
- The analysis is based on modelled outcomes generated through algorithmic assessment and data inputs. Results are indicative and are intended to support comparative analysis rather than provide definitive forecasts. The model excludes existing commercial agreements, memoranda of understanding and development plans for emitters, ports or transport and storage operators. Any representation of emitters, ports or CO_2 flows reflects a least-cost allocation within the study's dataset and does not imply commercial intent or preferred configurations.

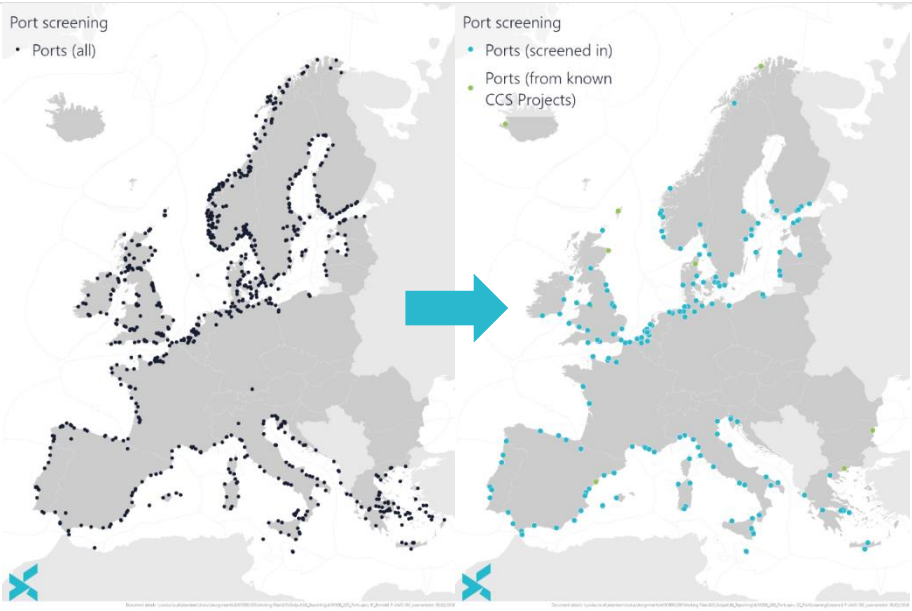


Figure E-3 and 3-3 – All Ports in Europe, and the Screened ports

- An analysis was carried out to compare the proximity of shortlisted ports to projected CO_2 emissions over time and to identified offshore CO_2 storage sites. This analysis highlighted which ports are best positioned to function as either:
  - Emitter ports – aggregating CO_2 from onshore emitters for export.
  - Store ports – receiving aggregated CO_2 for onward transport to offshore storage sites.
- The modelling indicated that, by 2050, approximately 53 Emitter ports and 19 Store ports could be suitable for use. 12 of the Store ports were also identified as Emitter ports, resulting in a total number of 60 ports assessed to be suitable for use as part of a Europe-wide CO_2 transport chain by 2050.

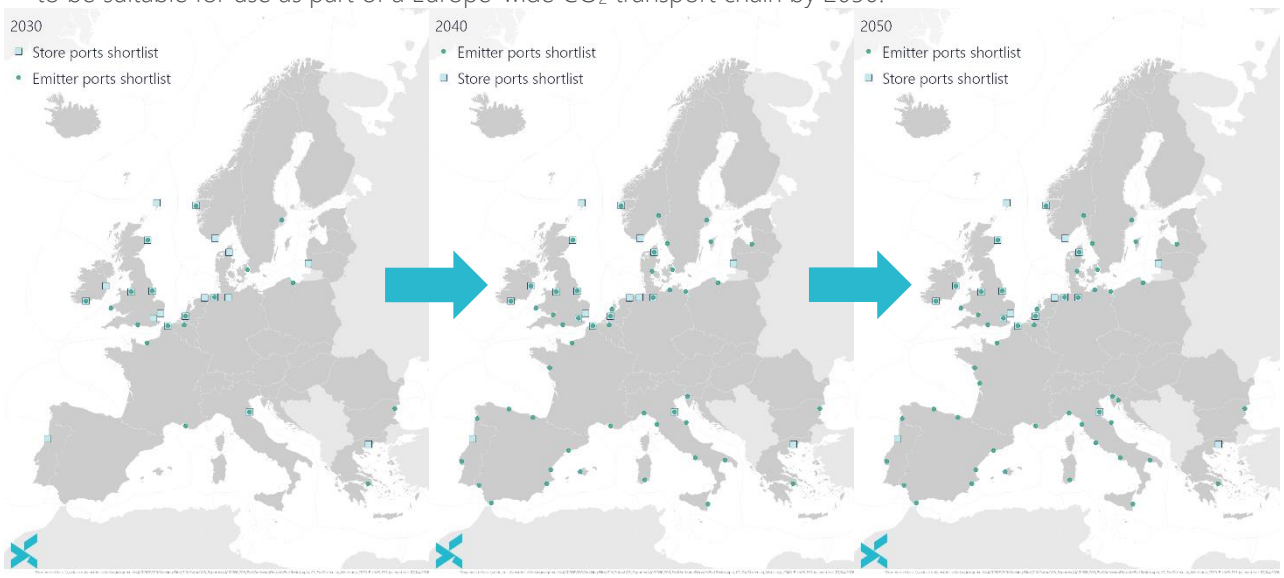


Figure E-4, 3-5, and 3-6 – Shortlisted "Emitter" and "Store" Ports in 2030, 2040, and 2050

- Many of the identified "dual-purpose" Emitter/Store ports are located in highly industrialised areas such as the Port of Rotterdam, Humberside and Liverpool Bay.
- The number and distribution of suitable ports aligned well with the findings of the CO_2 Volume Assessment, which used a top-down approach based on project shipping demand and typical port sizes required for economies of scale.
- No additional weighting or modifying factors were needed to "promote" ports with known CCUS interest, as the methodology naturally scored them high due to their location in heavily industrialised regions with strong transport networks and significant potential for future CO_2 capture.

CO_2 Volume Assessment

- Non-pipeline transport for Emitter-to-Port movement is likely to handle a significant proportion of the total amount of captured CO_2 that will be transported across Europe. The non-pipeline transport market is predicted to grow rapidly during the early phases of the CCUS industry, while remaining a sustained and investable element of emitter logistics over time.
- Ship transport will provide the additional resilience and flexibility in the overall CO_2 transport system, which is key to ensuring a robust and cost-efficient European CCUS infrastructure network.
- The study predicts that the overall transport market for captured CO_2 across Europe will evolve from 2030 to 2050 as a hybrid system between a range of onshore and offshore transport methods with shipping and ports playing a major role in the overall system throughout this period. Figure E-5 and Figure E-6 show this evolution in the coming decades and illustrates how emitters would access a storage facility through shipping (maritime region in blue) or pipeline (pipeline region in orange), with the expectation that both approaches could co-exist in coastal areas (co-existence region in green).

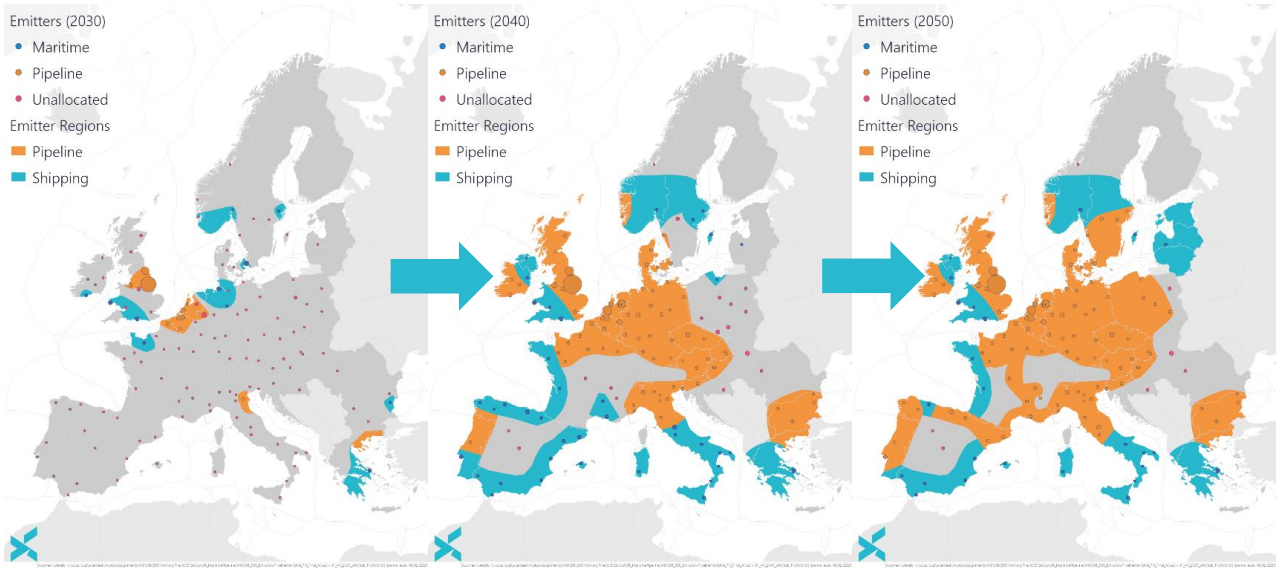


Figure E-5 – Modelled Evolution of Pipeline and Shipping CO_2 Catchment Regions Over Time

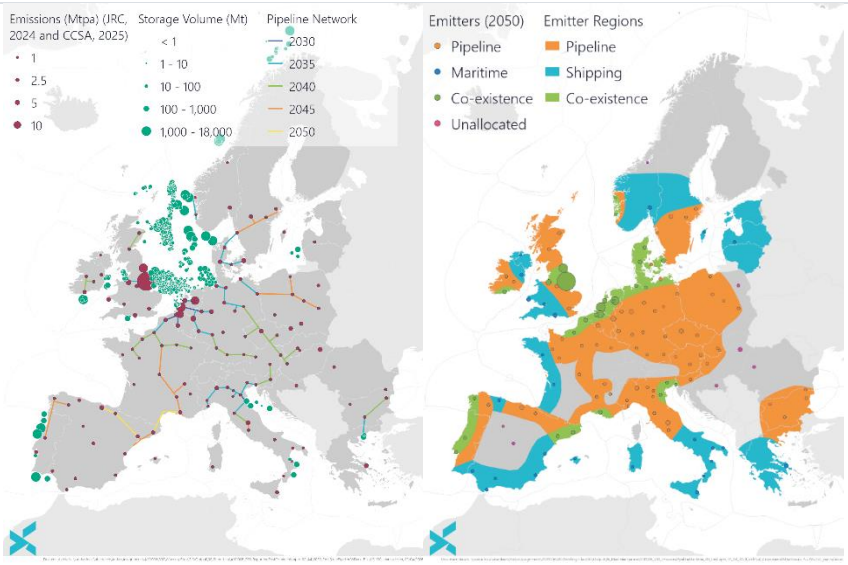


Figure E-6 – Xodus Pipeline Design from 2030 to 2050, and Shipping / Transport Co-Existence Map.

- The model outputs suggest that despite market share for shipping decreasing (from approximately half in 2030 to approximately a quarter in 2050), the absolute volume of CO_2 transported by ship is estimated to increase over time with up to 79MTPA predicted by 2050, given the significant overall growth of the CCUS market during that period. This is shown in Figure E-7.

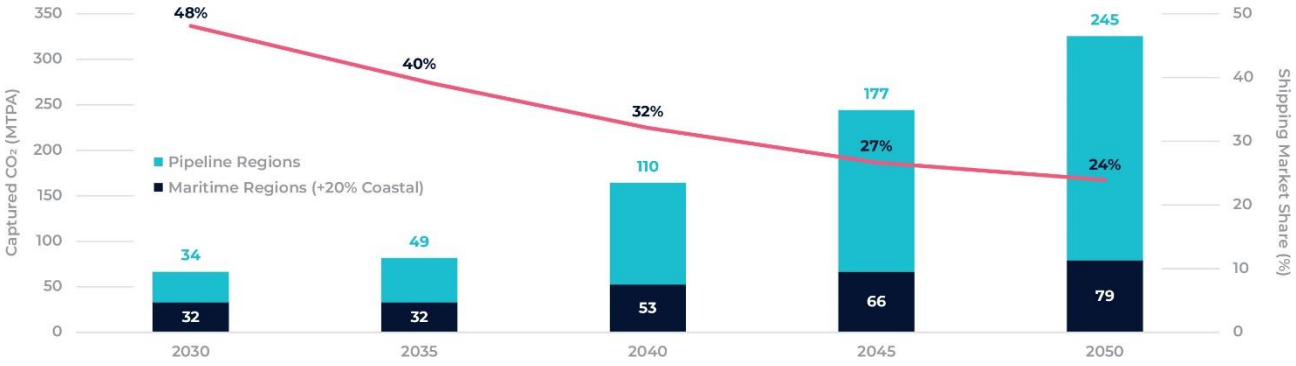


Figure E-7 – Option 2: Shipping Market Share with 20% Coastal Region Emitters Included

- The model suggests that cross-border shipping is expected to play a major role in the overall CO_2 transport market with the North Sea being the dominant CO_2 sink across Europe, despite other maritime regions playing a significant part in the overall market.

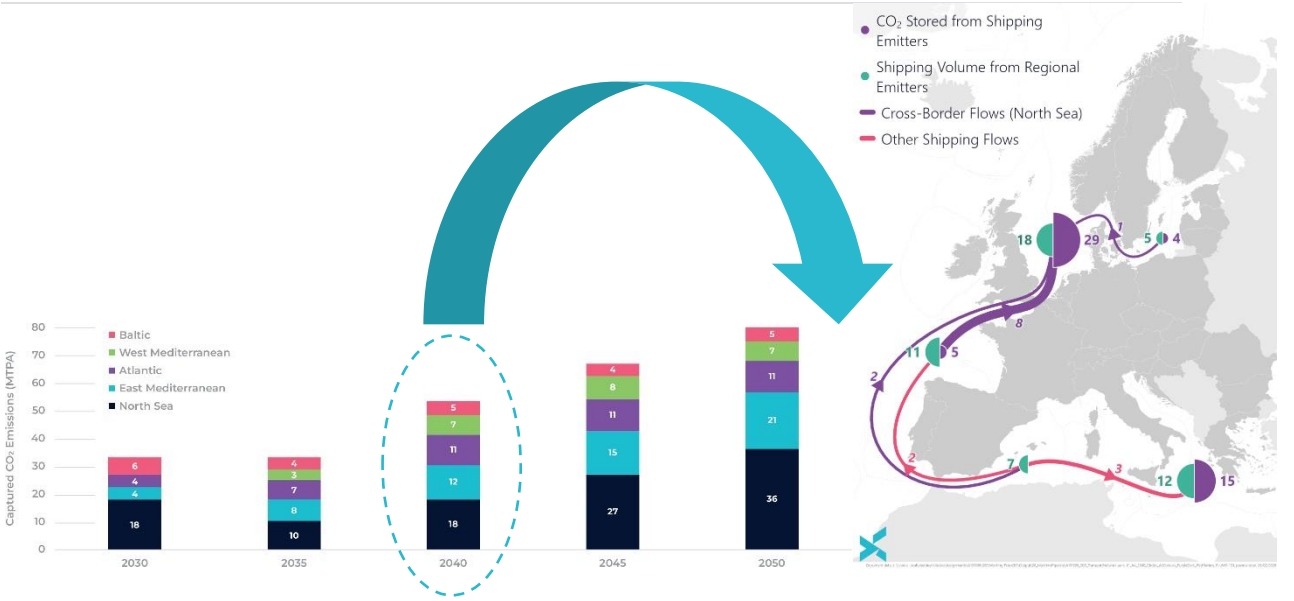


Figure E-8 and 4-11 – CO_2 modelled to be transported by ship by maritime region, and Maritime CO_2 Shipping Flows: Import and Export Volumes Across European Shipping Regions in 2040

- The number of ports and ships required to support this transport market will also evolve over time resulting in the potential need for circa 23 emissions gathering / export ("Emitter") ports and 10 receiving and onward transport to storage ("Store") ports (out of the 60 ports identified as suitable by 2050) with the fleet of associated ships growing from 22 to 65 based on an average assumed cargo carrying capacity of 15,000tonnes per ship (which is roughly the mid-range of the ship sizes anticipated to be deployed within Europe).
- The model findings suggest that Europe will operate a limited network of high-throughput ports, supported by a smaller set of regional export sites, with port requirements evolving over time as pipelines expand and new offshore storage becomes available.

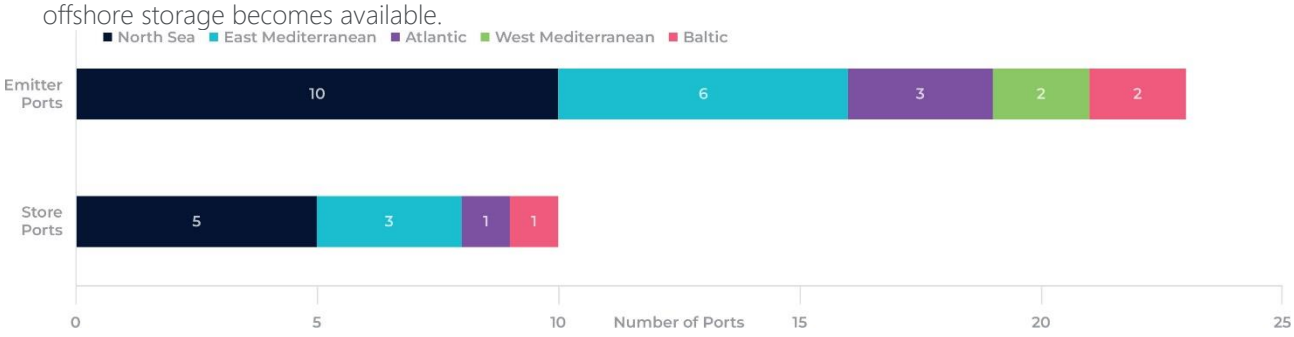


Figure E-9 – Modelled Number of Ports Required in 2050

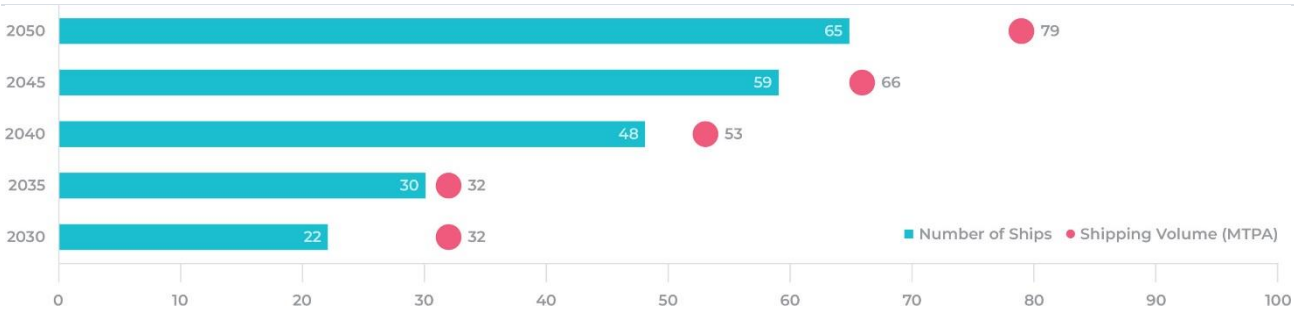


Figure E-10 – Modelled Number of Ships Required

Conclusion

This study shows that CO_2 transport infrastructure is fundamental to scaling up CCUS across Europe, with the UK, Dutch, and wider sectors of the North Sea positioned as a cornerstone of the emerging system. Cost-based modelling indicates that a significant proportion of captured CO_2 will need to be stored offshore, especially in the North Sea, which consistently emerges as Europe's primary storage sink from 2030 to 2050. Shipping-enabled transport is vital for cross-border connectivity, providing early access to storage ahead of pipeline expansion and remaining a structurally important part of a hybrid transport network in the long term. The geographic spread of sources and sinks, along with the scale of future CO_2 flows, makes a dedicated CO_2 shipping fleet essential to unlock Europe's decarbonisation potential.

The modelling suggests that a limited number of high-capacity ports and a scalable fleet can efficiently support international flows, creating a resilient and investable transport system. The North Sea, with its advanced CCUS projects, world-class offshore storage, and robust port infrastructure, is uniquely poised to lead Europe's transition. Early investment in North Sea storage, port facilities, and shipping solutions can set the benchmark for how the UK and Europe connect emitters to storage. With proven technologies, market demand and enabling infrastructure ready, the key task now is to accelerate deployment.

1 INTRODUCTION

Carbon Capture, Utilisation and Storage (CCUS) is a core element of decarbonisation and climate change plans in Europe and beyond. Previous studies carried out by Xodus in conjunction with the Carbon Capture and Storage Association (CCSA) have highlighted that transport and storage of captured carbon dioxide (CO_2) across borders within the European Union/European Economic Area and the United Kingdom (UK) is crucial to effective and timely emissions reduction [Reference 1].

The previous work highlighted that non-pipeline transport would be a key element in enabling cost effective transport of CO_2 from emitters to safe and secure storage sites. This project has concentrated on the infrastructure required to transport CO_2 to offshore storage sites as they currently make up the majority of currently identified CO_2 stores in Europe. Consideration of direct injection was deemed to be outside the scope of this study.

Figure 1-1 illustrates the high-level options available to gather and transport CO_2 from emitters to offshore storage sites:

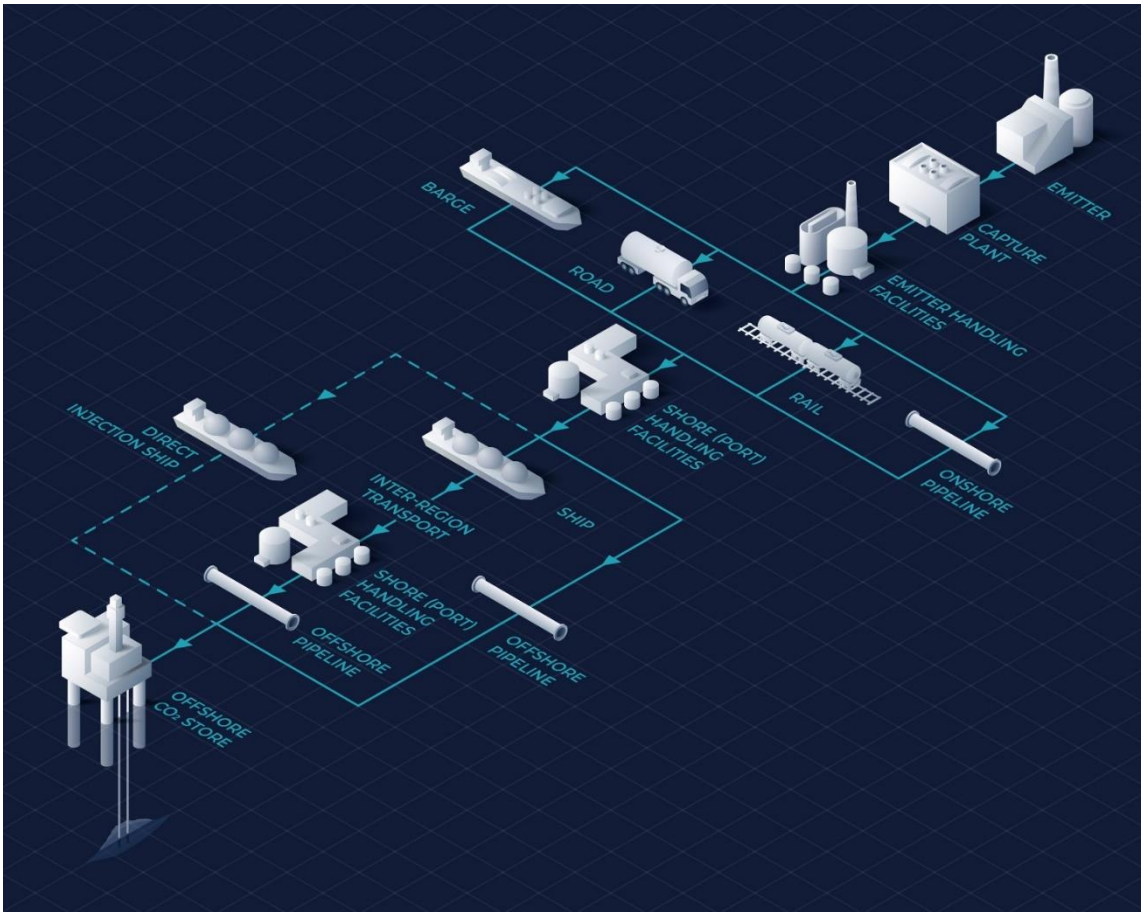


Figure 1-1 – CO_2 Transport Options

It was identified that further work was necessary following completion of the previous project to understand and estimate the scope and scale of non-pipeline infrastructure that would be required across Europe as the overall CCUS industry matures.



The Net Zero Technology Centre (NZTC) commissioned Xodus to undertake a study reviewing the following three main areas to gain insight into the potential for non-pipeline CO_2 transport within Europe:

- Technology Assessment: Assessment of the likely CO_2 storage and treatment infrastructure likely to be required for non-pipeline transport, including a high-level understanding of capital investment requirements for port infrastructure.
- Port Assessment: Assessment of the scale and suitability of existing port infrastructure across Europe (including the UK) needed to support gathering of CO_2 emissions from local industry and transport of those emissions to ports located nearby cost-efficient offshore CO_2 stores.
- CO_2 Volume Assessment: Assessment of the potential volumes of CO_2 emissions that may be transported between countries within Europe via ship at 10-year time intervals from 2030 to 2050, with these volumes forming the basis for estimating the required number of ports and ships.

This report summarises the findings of the study work carried out on behalf of the NZTC.

2 TECHNOLOGY ASSESSMENT

2.1 Introduction

Transport of captured CO_2 from emitters to secure stores is a key element of the overall CCUS industry. The significant majority of potential CO_2 storage sites identified across Europe are located in offshore subsurface reservoirs, a significant distance away from major sources of emissions in various onshore locations across the continent. Figure 2-1 illustrates the overall range of options considered for transport of CO_2.

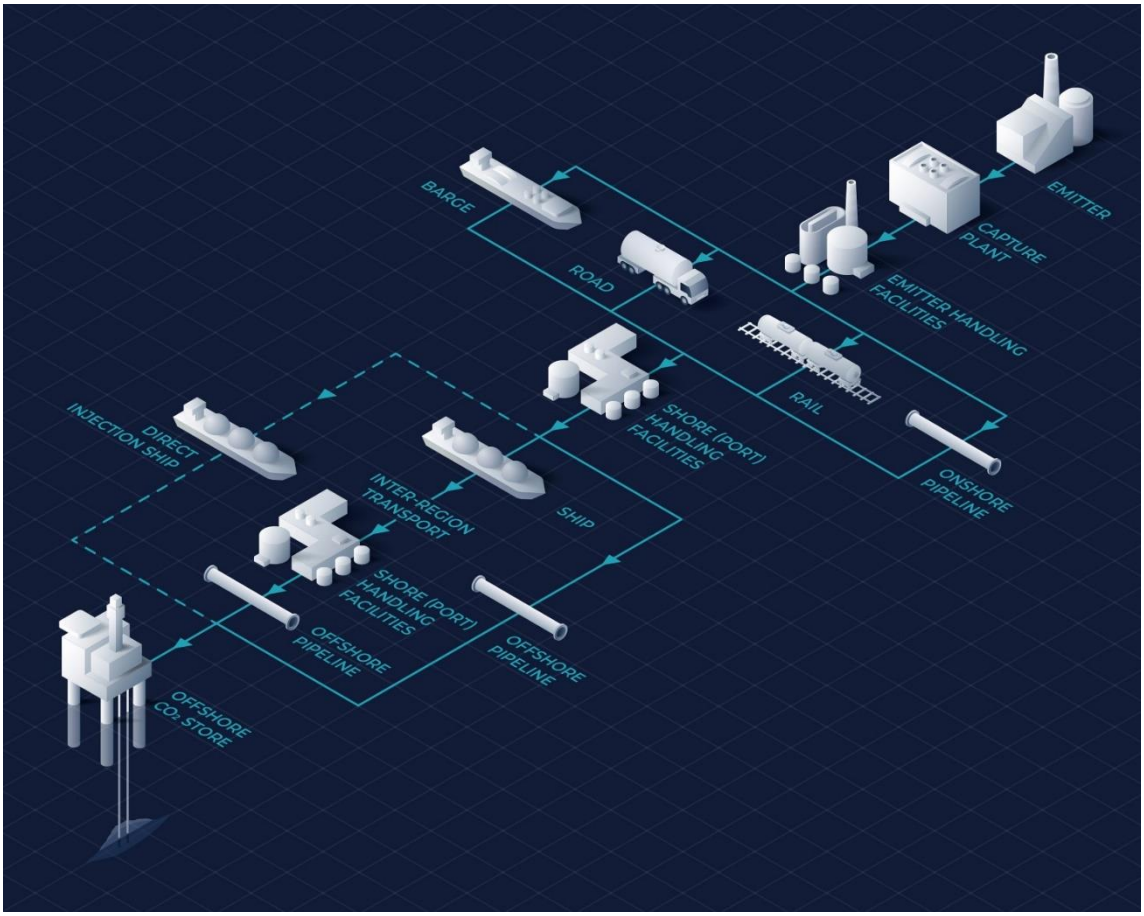


Figure 2-1 – CO_2 Transport Options

As this study is focused on the potential requirements for infrastructure to enable CO_2 transport from emitters to offshore storage sites, this section discusses the technology elements required to enable that transport and highlights particular challenges or technology advancements required to enable the overall transport chain.

The study has also developed capital and operating cost estimates for "typical" elements of the transport chain.

2.2 Transport Methods

Export of CO_2 via pipeline to an offshore store is an area of the CCUS transport chain that has been developed over the past 15-20 years and is relatively well understood in industry. Early examples like the Snøhvit project in Norway have been operating in this way for many years, as well as recent start-up operations such as Northern Lights and ongoing developments including the Northern Endurance Partnership in the UK and Porthos and Aramis in the Netherlands.

As a result of this established track record, this study has focused on the aggregation, and onshore and offshore transport methods available to take captured CO_2 from source to port, then transported by ship, as illustrated by Figure 2-2.

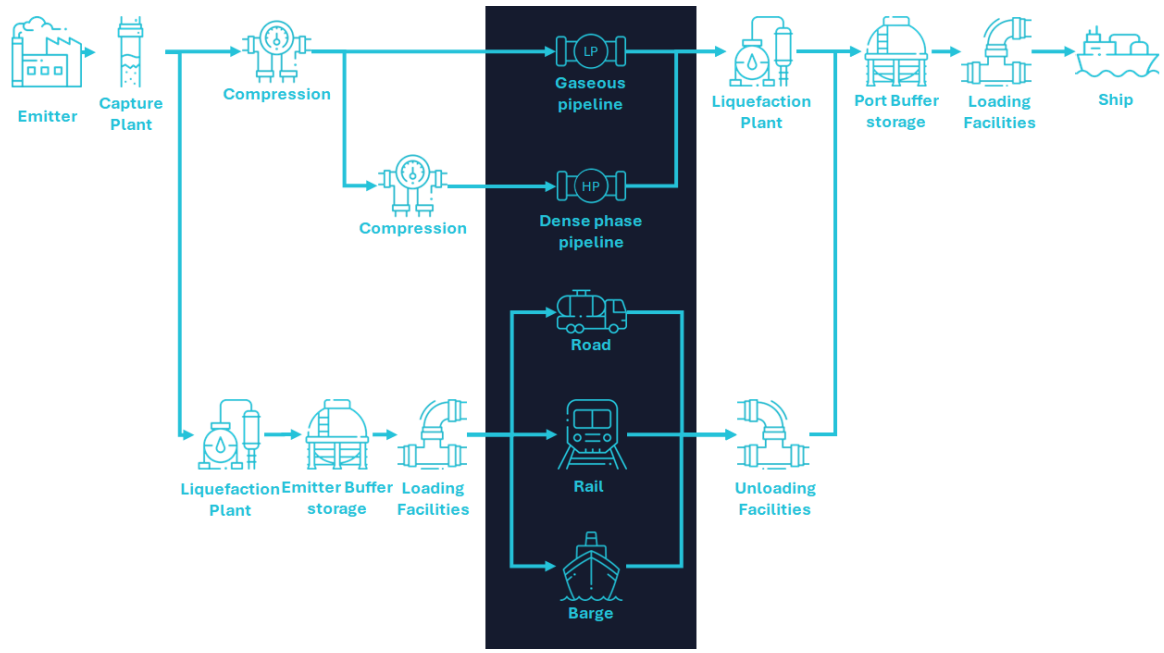


Figure 2-2 – Transportation Options for Gathering Emissions and Enabling Export via Ship

As can be seen from the above figure, there are four main options for onshore transport of captured CO_2 emissions:

- Pipeline (in gaseous or "dense" phase).
- Road (in liquid phase)
- Rail (in liquid phase)
- Barge (in liquid phase)

While pipeline transport remains the most dominant and commercially established method for transporting gases such as natural gas and CO_2 across large distances, it bears significant limitations including large upfront capital investment and long construction periods. As an alternative, non-pipeline transport (NPT) via road, rail or barge along Europe's extensive transport network offers a flexible solution that circumvents the need for dedicated pipeline infrastructure.

2.2.1 Pre-Transport Requirements

The facilities required for preparing CO_2 prior to transport via pipeline or NPT are markedly different.

In general, the facilities required for pipeline transport are limited to pressure boosting equipment (compression for gaseous phase transport, i.e. up to a transport pressure of circa 30barg, and then further compression/pumping for dense phase transport, i.e. above a transport pressure of circa 80barg). The technologies associated with pressure boosting of CO_2 at scale have been in use in industry for many years. While there are key differences in terms of specific mechanical components with the equipment (e.g. seals), the overall requirements for pressure boosting are well understood and the technology focus for this type of equipment in CO_2 service is more around improving efficiency and scaling existing technologies rather than developing new technologies.

In contrast, NPT methods such as road, rail, or barge transport require significantly more complex equipment to prepare CO_2 prior to transport. The following items would typically be required for NPT methods:

- Liquefaction Plant: Converts captured CO_2 into liquid form for transport.
- Emitter Buffer Storage: Temporary storage at the emitter site before loading to aid logistics.
- Loading Facilities: Infrastructure for transferring stored CO_2 to transport vehicle
- Transport Vehicle:
  - Road Transport: Vacuum-insulated and pressure-controlled road tankers.
  - Rail Transport: Vacuum-insulated and pressure-controlled rail tank wagons.
  - Barge Transport: River barges for inland waterway transport with pressurised cryogenic cargo tanks
  - Ship Transport: Ships for offshore transport of CO_2 between ports with pressurised cryogenic cargo tanks.

Effective NPT of CO_2 whether by road, rail, river or sea, presents additional technical challenges compared to transport via pipeline systems. To ensure safe, efficient and cost-effective operations, three core challenges must be addressed:

1. Maintaining Appropriate CO_2 Conditions – Ensuring stable phase (typically liquid) through temperature and pressure control.
2. Managing Composition – Impurities can alter the phase envelope, complicating liquefaction and transport.
3. Handling Boil-Off Gas (BOG) – Preventing pressure build-up, product loss and safety hazards through CO_2 being boiled off due to heat ingress from the surrounding atmosphere during storage and transit.

Each of these factors must be incorporated into the design and operation of NPT systems to ensure reliability, safety and cost-effectiveness.

2.2.2 Road Transport

For small scale emitters or pilot carbon capture projects, road tankers can offer a practical and flexible transport option, particularly in regions where permanent pipeline or rail infrastructure is not yet available. Road tankers provide flexibility in routing and scheduling, making them suitable for early-stage deployment or for emitters located in remote or dispersed regions.

Emitters must capture CO_2 to a sufficiently high purity to ensure efficient and safe transportation. Even minor impurities can significantly alter the CO_2 phase envelope, making it critical to maintain the CO_2 in a single phase, ideally liquid, during transport. However, it is important to strike a balance between specifying very high purity CO_2 to limit the cost and complexity of transport tanks versus the amount of equipment and processing needed at emitters to achieve that high purity. This is a critical factor that is further discussed across all transport options in section 2.4.

Selecting the appropriate transport condition is a key consideration. Options include:

- Medium Pressure (MP) systems, which require liquefaction equipment and transport at sub-zero (cryogenic) temperatures.
- High Pressure (HP) systems, which rely on compression and cooling and transport at near ambient temperatures.

Each approach involves trade-offs in terms of infrastructure requirements, safety and phase stability. Liquefaction systems demand significant investment, power consumption and operational expertise, which may be prohibitive for smaller emitters. High-pressure (HP) transport systems require tankers capable of withstanding significantly higher operating pressures, leading to thicker and heavier pressure vessels on the road tankers. This added weight reduces payload capacity due to limits on the overall weight that vehicles are allowed to be on roads. This leads to HP systems transporting less CO_2 per trip than MP systems and being less efficient for large-scale operations.

Regardless of the chosen transport condition, a loading facility will be needed for safe filling and unloading road tankers. In some cases, small-scale intermediate storage is likely to be needed as the capture of CO_2 will tend to be continuous and road tankers will be loaded in batches. These infrastructure requirements add further complexity to road-based CO_2 transport, especially for emitters operating at limited scale or in remote locations.

CO_2 road tankers are currently in operation at a small scale and are typically vacuum-insulated, designed to maintain CO_2 in liquid form under controlled pressure and temperature conditions. A standard European road tanker used for CO_2 transport generally has a capacity of around 20 to 25 tonnes, depending on national weight limits and road regulations.

Many European countries face congestion on key freight corridors, particularly near industrial hubs and ports. Adding significant tankers could increase traffic congestion and increase emissions. In addition, the availability of qualified tanker drivers across Europe has been a growing concern, with shortages reported in several member states. These factors may limit the scalability of road-based CO_2 transport, especially if multiple projects are deployed simultaneously.

Road transport also requires dedicated infrastructure at the unloading points, including unloading systems, venting / pressure control equipment and safety zones. While road transport plays an important role in early CCUS

deployment and small-scale emitters who are not located near major CCUS infrastructure, it is unlikely to represent a large proportion of the transport industry in the longer term.

The main advantage of road transport is the extensive existing road network, which provides access to most locations and broadens the range of emitters that can participate in CCUS. However, road transport alone cannot accommodate the volumes produced by most emitters. A typical tanker's 20–25 tonne capacity makes it impractical for large industrial sources without deploying a large fleet, which is further constrained by urban congestion and road safety considerations. Figure 2-3 shows an estimate of the number of trucks required for a given rate and distance. As an example, an emitter with 200 thousand tonnes per annum (KTPA) and delivery distance of 200km, Xodus estimated a fleet size of around 12 tankers would be required. Transport volumes above approximately 200-300 KTPA, for any distance other than very short distances (less than 100 kilometres) will require a fleet size, which becomes unreasonable (assumed to be anything larger than approximately 1 tanker per hour loading during dayshift, which equates to a fleet size of 12).

Onshore Distance (km)	CO_2 Transport Volume (KTPA)																					
	20	40	60	80	100	120	140	160	180	200	220	240	260	300	400	500	600	700	800	900	1000	2000
20	2	2	2	3	3	3	4	4	4	5	5	5	6	6	8	10	11	13	15	16	18	35
40	2	2	3	3	4	4	4	5	5	6	6	6	7	8	10	12	14	16	18	20	22	43
60	2	2	3	3	4	4	5	5	6	6	7	7	8	9	11	14	16	19	21	24	26	51
80	2	3	3	4	4	5	5	6	7	7	8	8	9	10	13	16	19	21	24	27	30	58
100	2	3	3	4	5	5	6	7	7	8	9	9	10	11	14	18	21	24	27	31	34	66
120	2	3	4	4	5	6	7	7	8	9	9	10	11	12	16	20	23	27	31	34	38	74
140	2	3	4	5	6	6	7	8	9	10	10	11	12	14	18	22	26	30	34	38	42	82
160	2	3	4	5	6	7	8	9	9	10	11	12	13	15	19	24	28	32	37	41	46	90
180	2	3	4	5	6	7	8	9	10	11	12	13	14	16	21	26	30	35	40	45	50	98
200	3	4	5	6	7	8	9	10	11	12	13	14	15	17	22	28	33	38	43	48	54	106
250	3	4	5	6	8	9	10	11	13	14	15	16	18	20	26	32	39	45	51	57	63	125
300	3	4	6	7	9	10	12	13	14	16	17	19	20	23	30	37	45	52	59	66	73	145
350	3	5	6	8	10	11	13	15	16	18	19	21	23	26	34	42	50	59	67	75	83	165
400	3	5	7	9	11	12	14	16	18	20	22	23	25	29	38	47	56	66	75	84	93	184
450	4	6	8	10	12	14	16	18	20	22	24	26	28	32	42	52	62	72	83	93	103	204
500	4	6	8	10	13	15	17	19	22	24	26	28	30	35	46	57	68	79	90	102	113	224
550	4	6	9	11	14	16	18	21	23	26	28	31	33	38	50	62	74	86	98	110	123	244
600	4	7	9	12	15	17	20	22	25	28	30	33	36	41	54	67	80	93	106	119	132	263
650	4	7	10	13	16	18	21	24	27	30	32	35	38	44	58	72	86	100	114	128	142	283
700	5	8	11	14	17	20	23	26	29	32	35	38	41	47	62	77	92	107	122	137	152	303
750	5	8	11	14	18	21	24	27	30	34	37	40	43	50	66	82	98	114	130	146	162	322

Figure 2-3 – Number of Road Tankers Required

Safety is also a concern when transporting CO_2 by road, as the CO_2 will be transported pressurised or at very low (cryogenic) temperature. This could pose risks to public health and infrastructure in the event of a road accident. These risks exist for small scale CO_2 road transport that is already in operation, but the likelihood of an incident would be increased with a greater number of tankers being in operation.

Overall, road transport faces scalability constraints due to small transport volumes, safety hazards and technical complexities. These challenges underscore the need for alternative long-term carbon transport strategies, including rail, barge and shipping options.

2.2.3 Rail Transport

Rail transport of captured CO_2 offers a compelling alternative to road transport. In general, many industrial hubs are serviced by an interconnected network of railways to enable transport of goods to and from those areas. The mechanical elements of rail transport are very similar to road transport but with the potential to transport higher volumes of CO_2 with higher availability and faster transit times than road.

As per transport by road, rail is particularly suited for smaller emitters or areas without pipeline access. It can provide flexibility and cost-effectiveness during early project phases or pilot-scale operations.

Transporting CO_2 by rail requires specialised cryogenic tank wagons designed to maintain liquid CO_2 under controlled pressure and temperature conditions that are functionally the same as the tanks on MP road transport.

A typical rail tank wagon has a storage capacity of approximately 50 to 70 cubic metres (equivalent to 54-76 tonnes of MP CO_2), with an overall length of 12 to 15 metres and a diameter of around 2.5 to 3 metres. These dimensions are compatible with standard rail infrastructure across Europe, allowing for integration into existing freight networks. In addition to fixed tank wagons, rail transport may also utilise ISO tank containers designed for cryogenic service. These intermodal tanks, typically mounted within a 20-foot frame, are built to international standards and can be transferred between rail, road, and sea transport modes. ISO tanks offer flexibility for cross-border logistics and can be particularly useful where multimodal transport is required.

The infrastructure required at the dispatch and receiving ends of a rail transport system is also similar to that for road transport (i.e. loading/unloading facilities, temporary storage tanks, temperature and pressure control facilities, etc.). The key difference is that multiple rail tanks can be transported by a single train compared to one tank per road tankers. This leads to rail being able to transport more CO_2 than an equivalent road tanker per trip.

The key challenge with rail transport is the availability of the existing railway network to handle significant quantities of additional traffic. Many railways across Europe have very high utilisation levels and adding a significant number of new freight trains to those systems may be logistically challenging. Equally, cross-border transport of CO_2 via rail may also be challenging due to differing regulations and technical requirements across the railways in separate countries. However, it should be noted that this concern is already encountered within the existing freight train industry across Europe.

Rail transport would benefit significantly from the extensive industrial rail infrastructure already in place across Europe. Many major CO_2-emitting sites are directly connected to freight rail networks, and several are already equipped for handling pressurised or liquefied gases such as LPG. This existing infrastructure would allow for relatively rapid deployment of CO_2 transport operations without major track upgrades. However, the scalability of rail transport is constrained by the limited volumetric capacity of individual tank cars. This study has assumed a rail tank storage capacity of 56 tonnes (80% of full storage volume) of CO_2, meaning that even modest daily transport volumes would require dozens of rail tanks per day. For regional-scale decarbonisation efforts, where multiple millions of tonnes of CO_2 may need to be moved annually, the number of trains required would potentially lead to intense congestion which would interrupt existing freight movements.

Overall, while rail offers geographic flexibility and leverages existing infrastructure, its capacity constraints and infrastructure requirements pose challenges for scaling. Despite its limitations, the relatively low infrastructure requirements of rail transport could enable it to be a practical and complementary option that could be integrated alongside other transport methods as part of a diversified carbon transport strategy.

Notably, several major European ports are already developing the infrastructure required to receive CO_2 transported by rail. Wilhelmshaven and Rotterdam are among the most advanced, with initiatives such as CO2next at Rotterdam actively responding to interest from inland emitters seeking export routes to offshore storage sites. These developments suggest that a nascent rail-to-port CO_2 logistics chain is beginning to take shape, which could provide a practical near-term pathway for emitters without direct pipeline access.

2.2.4 Barge Transport

Transporting captured CO_2 via major European rivers, such as the Rhine or Danube, offers a promising alternative to road or rail, potentially reducing congestion and lowering the overall carbon footprint of transport. Major rivers have long served as industrial transport corridors, and the Rhine, in particular, flows through some of Europe's most carbon-intensive regions—connecting industrial hubs in Germany, the Netherlands, France and Switzerland before terminating in Rotterdam. Several terminals along this corridor are already in various stages of assessing or developing CO_2 barge reception capabilities (including CO2next at Rotterdam), driven in part by requests from inland emitters. This makes it a good candidate for CO_2 barge transport.

Similar to road and rail, the CO_2 would need to be liquefied and stored in intermediate storage tanks adjacent to the river. Barges would collect CO_2 at designated river terminals equipped with loading infrastructure. Barges could pick up cargoes from multiple emitters on their route to the final storage port prior to pipeline export to offshore stores.

CO_2 transport barges will require specialised equipment to safely store and manage liquefied CO_2, including:

- Cryogenic storage tanks for CO_2 containment.
- Pumping systems for offloading to elevated facilities.
- Boil-off gas (BOG) management systems.

The transport of CO_2 via barge can be considered to be analogous to transport via ship, which is discussed in section 2.2.5. As such, no significant technology barriers are expected for barge transport of CO_2.

River terminals must be equipped with cryogenic loading facilities. Small-scale pipelines may be needed to connect emitters to these terminals. For this assessment, a loading rate of 1,500 m^3/hour—consistent with ship-loading benchmarks—has been assumed. With an estimated maximum barge capacity of 4,000 m^3, loading would take approximately three hours per vessel. While acceptable for most inland terminals, this requirement implies the need for multiple loading bays or staggered scheduling to accommodate higher traffic volumes, representing a significant infrastructure challenge.

Barge size is another critical consideration. Taking the Rhine as an example, barges typically measure ~100 m in length and 15–17.5 metres in width, which may restrict navigation on tributaries such as the Main, Neckar, and Ruhr which house significant industrial steel and cement hubs. Seasonal variations in river depth and flow further complicate navigability.

Barge transport offers a low-carbon, scalable alternative for moving CO_2 from inland emitters to coastal hubs, leveraging existing river networks and industrial infrastructure. However, its feasibility depends on significant investment in loading facilities, navigability assessments, and operational planning to manage capacity and scheduling constraints. Despite these challenges, barge transport could play a key role in a diversified European CO_2 transport strategy alongside pipelines, road, and rail.

2.2.5 Ship Transport

CO_2 has a long-established track record of being transported by ship in small quantities for the food and beverage industry. There are currently four small ships engaged in food/beverage grade operation carrying high purity liquefied CO_2 in small parcels of around 2,000 cubic metres (m^3).

As the CCUS industry develops, ship transport of CO_2 is predicted to be an important part of the transport and storage chain, particularly where transport by pipeline is not feasible of economic. Several sources estimate that 800-900 CO_2 transport ships may be required worldwide by 2050 [Reference 5].

The technologies required for ship transport of CO_2 are analogous to those required for the existing and extensive liquified petroleum gas (LPG) shipping industry:

- Pressure vessels ("cargo tanks") for storing liquid CO_2 at above atmospheric pressure and below ambient temperature.
- Loading and unloading piping systems for transferring CO_2 to and from the ship, including pumps suitable for cryogenic liquids installed within the storage pressure vessels.
- Refrigeration/reliquefaction systems to ensure that the stored CO_2 is maintained at a constant pressure and temperature during transport.

The major differences between shipping of LPG and CO_2 are centred around the combination of pressure and temperature at which the liquids are stored and how this is maintained by the refrigeration/reliquefaction systems.

Three "levels" of pressure/temperature are currently being proposed for ship transport of liquid CO_2:

- Low Pressure (LP): 8barg and -55°C.
- Medium Pressure (MP): 18barg and -30°C.
- Elevated Pressure (EP): 48barg and ambient temperature.

The LP level is very similar to typical design conditions for semi-refrigerated LPG ships, but the MP and EP levels represent significantly higher cargo tank design pressures than LPG systems, leading to the tanks needing thicker walls and therefore being heavier than LPG system equivalents.

The overall naval design of ships that carry CO_2 will be essentially the same as small or mid-size LPG carriers and established technology can therefore be used for this element of ship construction. The cargo tank design technology is covered by the requirements of the International Gas Carrier code [Reference 2].

The primary difference for CO_2 tanks (even for LP service) compared to LPG tanks is that the cargo containment must be designed for a slightly lower storage temperature (-55°C) than LPG (typically -48°C) and the cargo density that is around twice that for LPG. These factors add up to tanks that need thicker walls and are heavier and, due to the limitations imposed by the applicable design codes will generally require more tanks to keep the thicknesses within the allowable limits. To help combat this, a number of suppliers of the low temperature steels used in cargo tank fabrication have been developing carbon manganese grades that are suitable for design temperatures down to -55°C but still retain the necessary mechanical properties related to strength to minimise the impact of the increased pressure required for CO_2 transport.

LPG ships with "semi-refrigerated" cargoes that are equivalent to the LP CO_2 conditions have traditionally been limited to cargo capacities of circa 22,000m^3 with ships carrying larger cargoes (e.g. 35,000m^3 to 90,000m^3) tending to be "fully-refrigerated" with "prismatic" cargo tanks designed for low pressures in the region of 0.4barg. This type of cargo tank would not be suitable for transporting CO_2 due to their low design pressure. Equipping ships of this size with pressure vessel cargo tanks instead of prismatic tanks would result in significant differences in ship design and significantly higher construction costs for CO_2 ships versus LPG ships.

The refrigeration/reliquefaction system required for CO_2 shipping will be markedly different than for a LPG ship. LPG ships tend to draw the boil off gas (BOG) generated within the cargo tanks by heat ingress from the ambient surroundings and then compress it and condense it to a liquid at about 40°C using seawater as a cooling medium before returning the liquid back to the cargo tank. It is not possible to utilise the same system for CO_2 liquefaction as the condensing temperature is above the "critical temperature" of CO_2. As a result, a different approach is required.

The most common proposed by industry is to provide another cooling medium (e.g. Ammonia) to condense at a temperature significantly below 40°C. The cooling medium is vaporised in this process and then compressed and condensed using seawater as its cooling medium in a closed refrigeration loop. This is analogous to the "cascade refrigeration" systems used for ships that transport ethane/ethylene (that have storage temperatures down to -103°C) and is proven technology.

An alternative may be to draw liquid from the cargo tanks at -55°C and then cool that further using another closed refrigeration loop before spraying the cooled CO_2 back into the cargo tanks. This is likely to require two cascaded closed refrigeration loops to provide a cold enough temperature to chill the CO_2 drawn from the cargo tanks and is not currently being considered widely in industry. It is however proven technology and could be applied to CO_2 ships if required.

It should be noted that, for shorter transport journeys, there is the potential to not provide a refrigeration / reliquefaction system at all on CO_2 ships and simply let the CO_2 warm up during transit before discharging at a receiving port. This would require higher cargo tank design pressures to enable the increase in storage pressure that would naturally occur as the CO_2 warms up, which could be limited by increasing the degree of insulation around the cargo tanks to limit the heat ingress from ambient surroundings. This would reduce the complexity and cost of CO_2 ships but would limit the ship's flexibility in being able to transport CO_2 on longer/different routes.

Ships are starting to be delivered to service this growing market including the three 7,500m^3 ships delivered for the Northern Lights project during 2024 and 2025 (Northern Pioneer, Northern Pathfinder, and Northern Phoenix) plus one 22,000m^3 ship for Capital Clean Energy Carriers (Active) with the Capital Clean Energy Carrier ship being designed to handle both CO_2 and LPG. This highlights that the base technologies required for ship transport of CO_2 are established and well proven with the focus being on evolving those technologies to improve efficiency and reduce capital and operating cost.

2.3 Port Infrastructure Requirements

The main requirements for a port within the CO_2 transport chain is to temporarily store CO_2 received from a range of transport methods (e.g. pipeline, road, rail, barge, or ship) prior to exporting the CO_2 either via pipeline to an offshore store or via ship to another port that will then enable export to an offshore store via pipeline.

Establishing port infrastructure for CO_2 involves far more than simply loading and unloading transport vessels (road, rail, barge, or ships). Although the jetty facility is broadly similar to those used for importing or exporting other cryogenic fluids, it serves as a critical interface for transferring liquefied CO_2 from onshore systems to marine carriers. Both ends of the transport chain, export and import terminal, require specialised systems designed to handle cryogenic CO_2 safely and efficiently. The exact configuration depends heavily on the next step in the CCUS transport chain, whether it is permanent geological storage, further processing or temporary buffering at a regional hub.

Typical components include:

- Liquefaction facilities: Convert gaseous CO_2 into liquid form for marine transport.
- Intermediate storage tanks: Store liquefied CO_2 and maintain its temperature and pressure.
- Pumps and compressors: Control flow rates and pressures during transfer operations.
- Heaters: Condition CO_2 during unloading or re-pressurisation.
- Marine Loading Arms (MLAs): Engineered for cryogenic service to ensure safe and flexible ship-to-shore transfer.
- Metering systems: Provide accurate measurement of CO_2 volumes and flow rates, ensuring traceability and compliance to relevant regulations.
- Venting systems: Safely release excess pressure or BOG during storage and transfer (see subsection 2.3.3).
- Recirculation pipework: Enable temperature and pressure control to maintain phase stability.
- Drain drums: Collect liquid CO_2 from MLAs after loading/ unloading residues during operation.
- Power supply: Support pumps, compressors, heaters and control systems

The following sections provide some more detail on the critical components.

2.3.1 Liquefaction Facilities

Liquefaction is a fundamental process in CCUS infrastructure, enabling the conversion of gaseous CO_2 into liquid form suitable for storage and marine transport. The process typically involves a cooling system typically comprising of a primary liquefier and a sub-cooler, supported by a closed-loop refrigeration cycle as described for ship transport in section 2.2.5.

Ammonia is widely preferred as the refrigerant due to its high latent heat of vaporisation which allows for significantly lower mass flow rates, reduced refrigerant inventory, and smaller equipment sizes compared to alternatives like propane, ethane, or nitrogen.

Typical liquefaction systems include

- Multistage Compressor
- Heat Exchangers
- Condensers
- Refrigerant Storage Drum
- Knock out drums

Liquefaction plants can be configured with modular trains, e.g. 0.5MTPA trains, to provide operational flexibility including turndown capability and capacity for future expansion. However, increasing the number of trains generally results in higher capital expenditure. While liquefaction technology is well-established, the scale required for CCS applications typically exceeds that used in conventional industrial processes.

2.3.2 Intermediate Storage

Intermediate CO_2 storage systems are a vital component of CCS port infrastructure, acting as a buffer between liquefaction and marine transport. These systems maintain liquid CO_2 under controlled conditions, typically at medium pressure (15-20barg) and low temperatures (around -30°C), to ensure phase stability and optimise density for efficient handling.

In some cases, high-pressure (HP) storage (typically 35-50barg and 0°C to 15°C) is considered to reduce storage volume requirements and align with dense-phase pipeline systems. However, HP storage demands more robust materials with thicker walls and more complex safety systems.

Two common vessel types are used:

- Spherical tanks: Offer uniform pressure distribution and are suitable for large volumes. Typically stick built on site.
- Bullet tanks: Modular, cost effective and easier to fabricate off-site. Increasingly preferred for CCUS projects due to ease of integration.

Storage vessels are constructed from materials such as carbon steel with enhanced low-temperature toughness to prevent embrittlement during depressurisation. Systems typically include

- Recirculation pumps: Maintain cold temperatures.
- Export pumps: Transferring the CO_2 from the intermediate storage tank to the barge/ship.
- BOG compressors: Manage vapour pressure and prevent contamination of the stored CO_2.

Storage capacity is generally sized to exceed the volume of a standard shipping parcel, with additional buffer capacity included to accommodate shipping delays and operational downtime.

2.3.3 BOG Management

BOG management is a critical aspect of CO_2 storage and export systems. BOG is generated primarily due to ambient heat ingress into cold storage tanks, causing partial vaporisation of liquid CO_2. Generation rates depend on storage pressure, insulation performance, tank surface area and environmental conditions. Bullet tanks, due to their larger surface area, typically produce more BOG than spherical tanks.

Additional BOG sources include:

- Tank filling operations.
- Vapour displacement during barge/ship loading.
- Barge/Ship offloading, where vapour may be returned to the terminal.
- BOG is also produced during tank filling and may be received from ships during offloading. During loading operations, vapour displacement from the ship's cargo tanks can result in significant BOG volumes.

Typical BOG handling systems include:

- Knockout drums
- Compressors
- Aftercoolers
- Reliquefication units

All of the above equipment items are proven technology for handling CO_2.

2.3.4 Marine Loading Arms

Marine Loading Arms (MLAs) are required for transferring liquefied CO_2 at cryogenic temperatures to and from ships/barges due to their mechanical reliability and ability to handle both liquid and gaseous phases. Typical MLA sizes range from 8 to 12 inches in diameter, with loading rates commonly between 800 and 1,500m^3/hour, depending on configuration. To meet vessel turnaround targets, multiple arms are often installed in parallel.

The use of marine loading arms is established technology in the LPG and other cryogenic gas transport industries with no major functional differences to those required for CO_2 transfer.

2.3.5 Vent

Venting systems are a key component of CCUS infrastructure, designed to safely manage the controlled release of CO_2 during equipment depressurisation, maintenance activities, emergency shutdowns, or abnormal operating conditions. These systems typically comprise knockout drums to separate entrained liquids; vent stacks to enable dispersion to atmosphere at elevated locations, and flow control mechanisms to regulate discharge rates and ensure safe atmospheric dispersion. CO_2 vapour is heavier than air and tends to accumulate in low-lying areas, meaning that venting systems must be strategically located and integrated with gas detection, ventilation, and safety zoning strategies to protect personnel and equipment. Dedicated vent systems are required for both CO_2 and any refrigerant gas, each incorporating separate knockout drums, vent headers, and stack assemblies.

2.4 System Wide Considerations

As described in the preceding sections, similar systems (e.g. storage tanks, reliquefaction systems, loading/unloading facilities) are required throughout the proposed transport chain for CO_2.

As a result, there are a number of factors that are common in each step of the chain that need to be thought about from an overall system perspective even though the equipment and processing steps required across the whole system are generally established and proven technology.

The transport of captured CO_2 does represent unique challenges, including:

- The impact of CO_2 composition and purity throughout the transport chain.
- Accurate transfer and metering of CO_2 as it is transported from emitters to store.

2.4.1 Composition Impacts

There has been a large amount of industry discussion around the impact of varying compositions on the implementation of CCUS. CCUS does represent a slightly different challenge to the transport of food/beverage grade CO_2 or other pressurised gases in that it will tend to gather CO_2 from a range of sources, all of which will have different purities based on what industrial process the CO_2 is being captured from and what technology is being used to enable the capture.

However, it should be noted that the overall purity of CO_2 from the majority of capture processes being considered by industry is high at over 95% CO_2 being in the captured stream. Typical impurities include water, carbon monoxide, "non-condensable" gases (e.g. hydrogen, helium, oxygen, nitrogen, argon, methane, etc.), oxides and sulphides (e.g. SOx, NOx, H_2S, etc.), and trace elements carried over from the capture process (e.g. amines, ammonia, glycol, etc.).

Each of these impurities can cause a range of issues:

- Water: Potential for forming corrosive acids when combined with CO_2 (plus impurities) as well as the potential for forming ice/hydrates at low temperatures.
- Carbon monoxide: Toxicity issues (although that effect is dominated by CO_2 itself).
- Non-condensable gases: Issues with maintaining temperature and pressure of CO_2 stored in the transport chain as well as ancillary effects on materials of construction (in particular hydrogen and oxygen).
- Oxides and sulphides: Potential for forming corrosive acids when combined with water as well as ancillary effects on materials of construction.
- Trace elements from capture processes: Potential for making corrosive situations worse by affecting the likelihood of liquid water forming and impacting corrosive mixture effects.

Any impurity in CO_2 will impact the temperatures and pressures that a transport system can realistically operate at. As an example, a larger amount of "non-condensable" gases will result in higher design pressures for equipment generally being required throughout the whole transport chain to ensure that the CO_2 is safely handled. Equally, impurities tend to affect at what temperature and pressure range CO_2 can be converted from gas to liquid.

The impact of impurities for pipeline transport is relatively well understood and is generally focused on what the materials of construction need to be for the pipeline system and how to ensure that CO_2 is either a gas or a liquid (or dense phase gas) throughout the pipeline operating range. As a result, these impacts are not discussed in this report.

However, the impact of impurities in non-pipeline transport is less well understood and needs to consider wider implications than materials of construction or CO_2 phase behaviour.

Two main areas need to be considered:

- Where facilities are located to ensure that captured CO_2 meets the requirements for final transport to a store.
- How non-condensable gases are handled during the transport chain.

Where to put treatment facilities

As discussed in the previous sections, various temperature and pressure regimes are possible for non-pipeline transport, ranging from low temperature and comparatively low pressure up to ambient temperatures and high pressure. The equipment required to store and condition CO_2 at the emitter prior to these transport steps can vary significantly depending on the conditions that CO_2 will be transported at and what materials of construction are used for storing and handling the CO_2 during transport.

At one extreme, emitters could be required to do minimal processing or handling of their captured CO_2 resulting in the need for transport to be at ambient temperature/high pressure but may also require corrosion resistant materials for the storage and handling systems during transport to protect against the possible presence of liquid water and corrosive acids (which naturally occur when CO_2 is combined with water). This would minimise the extent and cost of the facilities required at emitters but would increase the cost of the transport facilities and would result in the need for more facilities at the receiving port to ensure the CO_2 is suitable for intermediate storage and export to pipeline or ships.

At the other extreme, emitters could be required to install facilities to "clean up" their captured CO_2 so that it is suitable for all elements of the transport and storage train, resulting in the potential requirement for significant levels of equipment at each emitter.

A balance needs to be struck between these two extremes to ensure that the overall cost and complexity of CCUS is minimised and the transport and storage system is flexible and resilient to small changes in composition.

Handling of non-condensable gases

The majority of NPT options involve maintaining CO_2 at a comparatively low pressure and a temperature below ambient conditions by using refrigeration/reliquefaction systems to make up for heat ingress to storage tanks from surroundings.

This process generally uses compressors to draw "boil off gas" from storage tanks (on road tankers, rail cars, in barges, or in ships) and then condense the gas before returning the resulting liquid back to the storage tanks. During this process, non-condensable gases will tend to accumulate over time in the condenser in the refrigeration/reliquefaction loop. This will continuously increase the pressure at which the boil off gas can be condensed. There are systems available to reduce this effect, but it is unavoidable in any system that tries to condense boil off gas that contains non-condensable gases.

Over time, this will result in the need to vent small amounts gas from the condenser in the refrigeration/reliquefaction loop to atmosphere, which will inevitably contain trace amounts of CO_2 as well as non-condensable gases. Accounting for this potential emission of captured CO_2 to atmosphere is something that the industry needs to understand in more detail to ensure that the purpose of CCUS (i.e. reducing the amount of CO_2 that is emitted to atmosphere) is fulfilled.

Another impact associated with non-condensable gases is how they are handled when transferring CO_2 between NPT methods. Gas will generally be evolved from cargo tanks when unloading CO_2 as the pressure in the tank will naturally drop as liquid is pumped out of the tank. This gas will have a greater proportion of non-condensable gases in it than the liquid CO_2 that is unloaded from the cargo tank. When that cargo tank is next filled, the gas within the cargo tank will need to be handled effectively. The traditional method employed for this within the LPG industry is to ensure there is a "vapour return" connection on the cargo tank that allows the gas displaced by the liquid filling the cargo tank to be transferred to the facility exporting the liquid CO_2 to the cargo tank. This method minimises the amount of non-condensable gas that can accumulate in the cargo tank. If vapour return isn't supplied, non-condensable gases will tend to accumulate in the cargo tanks as they go through numerous cycles of unloading and filling leading to a greater need to vent those gases to atmosphere from the refrigeration/reliquefaction unit during transport.

Experience in the LPG industry has shown that there are sometimes issues with vapour return systems not being used due to concerns that the cargo tank gas could "contaminate" the systems of the facility exporting CO_2 to the tank. It is important that this behaviour is not carried over into the CCUS industry to ensure that non-condensable gases are handled appropriately and their impact metered effectively throughout the transport chain.

2.4.2 Transfer and Metering

Metering the handover of CO_2 along the whole transport chain for CCUS (whether that is via pipeline or via NPT) is essential to ensure fiscal accountability and regulatory compliance. In Europe, metering systems must align with frameworks such as the EU Emissions Trading System (EU ETS) and national carbon storage regulations.

Metering and analyser challenges in the UK CCUS industry centre on the difficulty of accurately measuring CO_2 across changing phases, potential high financial exposure from small errors and the need for specialised instrumentation that can cope with dense-phase CO_2 behaviour. These issues are well-recognised by regulators and measurement specialists, but they remain a major technical hurdle for transport and storage operators.

CO_2 behaves unpredictably across the pressure/temperature ranges experienced with transport and storage systems, resulting in CO_2 shifting between gas, liquid, supercritical, and two-phase states. These rapid property changes make flow measurement far more complex than for natural gas or oil. CO_2's unique behaviour under different property states and process conditions can create significant measurement uncertainty. This can result in high financial exposure from small metering errors. CO_2 storage will be tied to emissions accounting and carbon trading, and it is therefore essential that robust metering systems are deployed. However, many existing flow meters were designed for hydrocarbons, not dense-phase CO_2. These meters can have difficulty maintaining single-phase flow, are sensitive to impurities (e.g., O_2, N_2, H_2S) and calibration can be challenging due to a lack of test facilities for CO_2.

Two main issues are associated with the metering requirements for CCUS:

- Accurately determining the levels of impurities in captured CO_2.
- Metering CO_2 at elevated pressures (dense phase CO_2).

As described in the previous section, captured CO_2 can contain a wide range of trace impurities, quite often at very low levels. Providing effective metering that can accurately measure the levels of impurities likely to be encountered in captured CO_2 is a technology area that needs more research and development. Some of the entry specifications being produced for CCUS projects (e.g. the maximum level of water allowed) are proving to be difficult to measure and assure in practice. This will become more pronounced as CCUS projects develop into receiving captured CO_2 from a range of sources.

Another technology development area is the measurement of CO_2 at elevated pressures. A large number of the proposed CCUS projects involve storing CO_2 at pressures above the "critical pressure" of the CO_2 mixture due to the geological location of the proposed store and the pressure within that store. This results in the need to transport CO_2 to the store above its critical pressure. Metering captured CO_2 (and its impurities) at these elevated pressures is a known issue for industry and significant research has been put into determining the most appropriate

The CCUS sector is still developing common specifications for sampling systems, calibration gases and analytical accuracy requirements. This lack of harmonisation complicates procurement and regulatory compliance.

Regulators recognise ongoing technical issues and note that "numerous technical issues remain" in CCUS deployment, including measurement challenges that affect project readiness and investment decisions. Measurement is central to the CCUS business model as accurate metering and analysis underpins transport and storage network charging, emissions verification and cross-chain risk allocation.

2.5 Cost Estimate

2.5.1 Overview

The study developed costs for various elements in the transport chain (including pipelines, road tankers, rail tanks, and port infrastructure) to feed into the CO_2 volume assessment described in section 4. The shipping costs used in the CO_2 volume assessment were taken from the previous work carried out by Xodus on behalf of the CCSA [Reference 1].

Barge transport was not included in the assessment or examined in the cost estimate as it will be very specific to each emitter and where their captured emissions will be routed to as well as the impact that picking up additional captured CO_2 during the voyage would have on the unit cost of transport.

The following sections describe the basis and results of the cost estimating process used for each element of the transport chain.

2.5.2 Port Infrastructure Costs

The capital cost of developing port and jetty infrastructure for CO_2 export is highly sensitive to several project-specific factors:

Existing Jetty Infrastructure

- Reusing existing piles, decks, and access structures can significantly reduce capital costs.
- New-build jetties require extensive marine works, piling, dredging, and environmental permitting.

Ship Size

- Larger vessels require deeper berths, longer loading durations, and larger marine loading arms (MLAs).
- Smaller vessels may reduce jetty footprint but increase operational frequency and complexity.
- Ship size also affects the storage requirements.

Distance from CO_2 Source or Storage

- Longer distances between the jetty and the CO_2 capture or storage facility increase:
  - Pipework length and insulation
  - Structural steel and civil works
  - Pumping power and control systems

CO_2 Transport Rate

- Higher throughput (e.g. 5MTPA versus 1MTPA) may require:
  - Additional MLAs and metering systems
  - Larger headers and buffer storage.
  - More robust safety and control systems
- Some infrastructure costs are fixed and do not scale linearly.

Table 2-1 illustrates the potential impacts that design decisions can have on the capital costs for a CO_2 transport port.

PARAMETER	IMPACT ON CAPITAL COST	NOTES
Existing Infrastructure	Reuse of jetty piles, decks, and access ways can significantly reduce capital cost.	New builds require extensive marine works and permitting.
Berth Depth & Dredging	Shallow sites may require dredging, increasing marine construction costs.	Deep natural berths reduce capital cost.
Ship Size	Larger ships require deeper berths, longer MLAs, and more robust mooring systems.	Smaller ships may reduce infrastructure but increase operational cycles.
Containment Mode	LP versus MP affects pipe sizing, insulation, material selection, and safety systems.	MP typically preferred for export; LP may be used for storage.
Distance from Port Infrastructure	Longer distances increase pipework, structural steel, insulation, and pumping needs.	Affects civil works and control system complexity.
CO_2 Capture Rate	Higher throughput requires more MLAs, metering, and redundancy.	Some infrastructure costs are fixed and do not scale linearly.
Environmental Constraints	Protected zones or SEZs may limit layout and increase permitting complexity.	May require alternative layouts or mitigation measures.
Flexibility & Scalability	Designs allowing future expansion (e.g. ammonia or LNG export) may increase initial CAPEX.	Trade-off between upfront cost and long-term adaptability.

Table 2-1 – Potential Impacts on Capital Cost Estimates

The cost estimate presented in this report has been developed by Xodus for an example project to adapt an existing industrial site and develop a facility with a 5MTPA CO_2 transport rate. This size and type of facility was deemed to be appropriate to create a baseline capital and operating cost per tonne of CO_2 transport given previous work by Xodus indicated that the economies of scale when developing port infrastructure level out above 2-3MTPA [Reference 1]. Table 2-2 provides an estimate of the major equipment items, whilst Table 2-3 provides the estimated CAPEX.

ITEM	ESTIMATED COST (£ MILLION)	NOTES
Liquefaction	65	5 x 1MTPA liquefaction trains to provide turndown capabilities.
Intermediate Storage	9	Onshore Storage Assumed to be 36,000tonnes. Estimate Based on 9 x 4000tonne bullets. Carbon Steel fabrication
Marine Loading Arms	5	Assumes 10-inch diameter, and 3 arms required.
Road Tanker Unloading Facility	0.5	3 systems in parallel. From Que$tor
Rail Loading Facility	0.6	3 systems in parallel. From Que$tor
Jetty Structure	21	Single jetty with 3MLAs. From Que$tor
Process Equipment	7	Includes pumps, vaporisers, BOG management system, vent.
Control & Instrumentation	5	Metering system, Control systems

Table 2-2 – Indicative Costs for Major Equipment for an example 5MTPA Port Facility

ITEM	ESTIMATED COST (£ MILLION)	NOTES
Procurement	200	Includes Major Equipment Items, electrical, instruments, structural, civils, valves etc
Fabrication And Construction	70	Based on a UK based project
Engineering & Project Management	47	15% of Procurement, fabrication and construction.
Owners Cost	31	10% of Procurement, fabrication and construction.
Insurance and Certification	12	4% of Procurement, fabrication and construction.
Contingency	62	20% of Procurement, fabrication and construction.
Total	**422**	

Table 2-3 – Indicative Estimated CAPEX for an example 5MTPA Port Facility

Table 2-4 presents the estimated annual operating costs (OPEX) for a 5MTPA transport port.

COMPONENT	ESTIMATED COST (£ MILLION)	NOTES
Liquefaction	22	Assumed MP conditions. UK electricity Costs.
Jetty Facility	2	Assumed 3 MLAs
Port Infrastructure	10	Includes Operating Personnel and Inspection & Maintenance
Total	**34**	

Table 2-4 – Operating Expenditure Estimate for an example 5MTPA Port Facility

Taking the combined capital and operating cost estimates above and assuming an overall operating life of 20-years for the port facility, the projected cost per tonne of transported CO_2 was estimated to be £11/tonne.

2.5.3 Land Transport Costs

Basis

A series of calculations were performed to evaluate the relative costs of CO_2 transport via road, rail, or pipeline. This evaluation considered the distance of transport, in addition to the annual rate of CO_2 that could be transported over these distances for each mode of transport.

Road Transport

Table 2-5 shows the parameters utilised to determine the road transport costs per year of operation.

PARAMETER	VALUE
CO_2 volume per road tanker (tonnes)	18
Average road tanker speed (miles per hour / kilometres per hour)	40 / 64
Loading/unloading times (hours)	1
Road tanker cost (£)	127,500
Road tanker lifespan (years)	15
Road tanker fuel consumption (litres/100kilometres)	30
Estimated diesel cost (£/litre)	1.45
Driver Employment Cost (£/year)	45,000

Table 2-5 - Parameters for Road Transport of CO_2

Rail Transport

Table 2-6 shows the parameters utilised to determine the rail transport costs per year of operation.

PARAMETER	VALUE
CO_2 volume per rail car (tonnes)	83
Average rail speed (miles per hour / kilometres per hour)	50 / 81
Rail Track costs (£/km)	10
Loading/unloading times (hours)	1
Rail car cost (£)	127,500
Rail car lifespan (years)	15
Fuel consumption per rail car per tonne of CO_2 (litres/100kilometres/tonne)	0.473
Estimated diesel cost (£/litre)	1.45
Freight Train Driver Employment Cost (£/year)	60,000

Table 2-6 - Parameters for Rail Transport of CO_2

Pipeline Transport

For pipeline transport, a general cost of £130,000 per inch diameter of pipeline, per kilometre was assumed (£/inch-kilometre), with an assumption of a new direct route to the desired location. This was based on a review of installed onshore pipeline costs for various projects in Europe and worldwide and aligns well with the overall assumptions used by national gas infrastructure firms for the development of natural gas pipeline networks in Europe. For each given annual volume of CO_2 transport calculated, a corresponding pipeline diameter was determined to enable evaluation of the cost of the required pipeline.

2.5.4 Results

The costs of CO_2 transport were determined using the provided basis for a range of transport distances and annual CO_2 volumes. These results have been recorded in Table 2-7, indicating greater costs with warmer colours. From these calculated costs, a summary is shown in Table 2-8 to show the most cost-effective mode of transport for a given transport distance and annual CO_2 volume, where an assumption was made that road transport cases requiring more than 8 road truckers would be less preferable to rail or pipeline alternatives.

Onshore Distance (km)	Road Transport Costs (£/tonne) CO_2 Transport Volume (KTPA)																					
	20	40	60	80	100	120	140	160	180	200	220	240	260	300	400	500	600	700	800	900	1000	2000
20	7.39	4.18	3.11	3.38	2.90	2.58	2.81	2.58	2.40	2.58	2.43	2.31	2.46	2.26	2.26	2.26	2.15	2.17	2.18	2.12	2.13	2.10
40	8.37	5.16	5.16	4.36	4.52	4.09	3.79	3.96	3.73	3.88	3.70	3.56	3.68	3.66	3.56	3.49	3.45	3.42	3.40	3.38	3.36	3.33
60	9.34	6.14	6.14	5.33	5.49	5.07	5.22	4.93	5.07	4.85	4.97	4.80	4.90	4.85	4.69	4.73	4.64	4.67	4.61	4.64	4.60	4.56
80	10.32	8.72	7.11	7.11	6.47	6.58	6.20	6.31	6.40	6.15	6.24	6.04	6.13	6.04	5.99	5.96	5.94	5.83	5.83	5.83	5.83	5.77
100	11.30	9.69	8.09	8.09	8.09	7.55	7.63	7.69	7.38	7.45	7.51	7.29	7.35	7.23	7.13	7.19	7.13	7.08	7.05	7.09	7.06	7.00
120	12.27	10.67	10.13	9.07	9.07	9.07	9.07	8.66	8.71	8.74	8.48	8.53	8.57	8.42	8.42	8.42	8.32	8.33	8.34	8.28	8.30	8.23
140	13.25	11.65	11.11	10.84	10.68	10.04	10.04	10.04	10.04	10.04	9.75	9.77	9.80	9.83	9.72	9.66	9.61	9.58	9.56	9.54	9.53	9.46
160	14.23	12.62	12.09	11.82	11.66	11.55	11.48	11.42	11.02	11.02	11.02	11.02	11.02	11.02	10.86	10.89	10.80	10.74	10.78	10.73	10.76	10.70
180	15.20	13.60	13.06	12.80	12.64	12.53	12.45	12.40	12.35	12.32	12.29	12.26	12.24	12.21	12.16	12.12	11.99	11.99	11.99	11.99	11.99	11.93
200	19.39	16.18	15.11	14.57	14.25	14.04	13.89	13.77	13.68	13.61	13.55	13.51	13.46	13.40	13.29	13.36	13.29	13.25	13.21	13.19	13.23	13.16
250	21.83	18.62	17.55	17.02	17.34	17.02	16.79	16.62	16.84	16.70	16.58	16.48	16.65	16.48	16.37	16.31	16.37	16.33	16.29	16.27	16.25	16.21
300	24.27	21.06	21.06	20.26	20.42	19.99	20.14	19.86	19.64	19.78	19.60	19.72	19.58	19.56	19.46	19.39	19.46	19.41	19.38	19.35	19.33	19.30
350	26.71	25.11	23.50	23.50	23.50	22.97	23.04	23.10	22.79	22.86	22.63	22.70	22.76	22.65	22.54	22.48	22.43	22.49	22.46	22.43	22.41	22.38
400	29.15	27.55	27.01	26.74	26.58	25.94	25.94	25.94	25.94	25.94	25.94	25.68	25.70	25.73	25.62	25.56	25.52	25.58	25.54	25.52	25.49	25.43
450	34.80	31.59	30.52	29.99	29.67	29.45	29.30	29.19	29.10	29.03	28.97	28.92	28.88	28.81	28.70	28.64	28.60	28.57	28.62	28.60	28.58	28.51
500	37.24	34.03	32.96	32.43	32.75	32.43	32.20	32.03	32.25	32.11	31.99	31.89	31.81	31.89	31.79	31.72	31.68	31.65	31.63	31.68	31.66	31.59
550	39.68	36.47	36.47	35.67	35.83	35.40	35.10	35.27	35.05	35.19	35.02	35.14	34.99	34.98	34.87	34.81	34.76	34.73	34.71	34.69	34.74	34.68
600	42.12	40.52	38.91	38.91	38.91	38.38	38.46	38.11	38.20	38.27	38.04	38.11	38.17	38.06	37.95	37.89	37.85	37.81	37.79	37.77	37.76	37.73
650	44.56	42.96	42.42	42.16	42.00	41.36	41.36	41.36	41.36	41.36	41.06	41.09	41.11	41.14	41.03	40.97	40.93	40.90	40.87	40.86	40.84	40.81
700	50.21	47.00	45.93	45.40	45.08	44.87	44.71	44.60	44.51	44.44	44.38	44.33	44.29	44.22	44.12	44.05	44.01	43.98	43.96	43.94	43.92	43.89
750	52.65	49.44	48.38	47.84	48.16	47.84	47.61	47.44	47.31	47.52	47.40	47.31	47.22	47.31	47.20	47.14	47.09	47.06	47.04	47.02	47.01	46.94

Onshore Distance (km)	Rail Transport Costs (£/tonne) CO_2 Transport Volume (KTPA)																					
	20	40	60	80	100	120	140	160	180	200	220	240	260	300	400	500	600	700	800	900	1000	2000
20	15.58	10.62	8.97	8.14	7.64	7.31	7.08	6.90	6.76	6.65	6.56	6.49	6.42	6.92	6.68	6.54	6.89	6.80	6.74	7.09	7.03	7.85
40	21.24	16.28	14.62	13.80	13.30	12.97	12.74	12.56	12.42	12.31	12.22	12.15	13.03	12.88	12.64	13.28	13.16	13.07	13.72	13.66	14.30	16.70
60	26.90	21.94	20.28	19.46	18.96	18.63	18.40	18.22	18.08	17.97	19.19	19.08	18.99	18.85	18.61	19.55	19.43	20.38	20.30	21.24	21.18	25.76
80	32.55	27.60	25.94	25.12	24.62	24.29	24.05	23.88	23.74	25.29	25.16	25.05	24.96	24.81	26.01	25.82	27.06	26.95	28.20	28.12	29.37	35.42
100	38.21	33.26	31.60	30.78	30.28	29.95	29.71	29.54	31.41	31.25	31.12	31.01	30.92	30.77	32.28	33.79	33.64	35.18	35.08	36.62	38.16	47.27
120	43.87	38.92	37.26	36.44	35.94	35.61	35.37	37.57	37.37	37.21	37.08	36.98	36.88	38.86	38.55	40.36	42.19	42.05	43.90	45.73	45.65	58.46
140	49.53	44.58	42.92	42.10	41.60	41.27	43.79	43.54	43.34	43.18	43.05	42.94	42.85	45.13	47.17	46.94	49.06	51.19	53.32	53.22	55.36	72.43
160	55.19	50.23	48.58	47.76	47.26	46.93	49.75	49.50	49.30	49.14	49.01	48.90	51.59	51.40	53.74	56.13	55.94	58.38	60.81	63.25	65.79	85.20
180	60.85	55.89	54.24	53.42	52.92	56.06	55.72	55.46	55.27	55.11	54.98	57.98	57.86	57.67	60.32	63.00	65.71	68.43	71.15	74.00	73.89	98.53
200	66.51	61.55	59.90	59.07	58.58	62.02	61.68	61.43	61.23	61.07	64.39	64.25	64.13	63.93	66.89	69.88	72.89	75.92	78.94	82.10	85.12	115.55
250	80.66	75.70	74.05	73.22	77.41	76.93	76.59	76.34	80.44	80.23	80.06	79.92	79.80	83.71	87.35	91.06	94.81	98.57	106.41	110.16	113.93	155.74
300	94.81	89.85	88.20	93.04	92.32	91.85	91.51	96.37	96.11	95.90	95.73	100.53	100.38	100.14	109.34	113.77	118.25	127.61	132.09	136.60	145.78	205.17
350	108.96	104.00	102.35	107.95	107.23	106.76	112.37	112.04	111.78	111.58	117.14	116.96	116.81	122.20	127.30	138.00	143.40	154.07	159.31	169.99	175.25	255.27
400	123.11	118.15	116.50	122.86	122.14	121.67	128.05	127.71	127.46	133.78	133.57	133.40	139.68	139.40	151.57	163.98	169.88	182.07	194.25	200.24	212.55	309.99
450	137.26	132.30	138.96	137.77	137.05	144.16	143.72	143.39	150.47	150.22	150.01	157.05	156.88	163.75	177.37	191.26	197.89	211.58	225.27	239.09	252.78	376.14
500	151.41	146.45	153.87	152.68	151.97	159.84	159.39	167.23	166.91	166.65	174.46	174.25	182.03	181.71	196.86	212.26	227.43	242.62	257.82	273.15	288.36	440.71
550	165.55	160.60	168.78	167.59	176.13	175.51	184.07	183.66	183.34	191.90	191.66	200.19	199.99	208.34	225.22	241.83	258.49	283.69	300.52	317.22	333.93	518.34
600	179.70	174.75	183.69	182.50	191.80	191.18	200.51	200.10	209.41	209.10	218.39	218.15	227.43	227.06	254.83	272.92	291.07	318.70	336.88	355.09	382.54	592.82
650	193.85	188.89	198.60	197.41	207.48	206.86	216.94	216.53	226.60	226.30	236.35	236.11	246.15	255.98	275.83	305.53	325.18	355.07	374.76	404.48	424.32	671.94
700	208.00	215.89	213.51	224.08	223.15	233.92	233.38	244.18	243.80	254.60	254.31	265.10	264.87	286.79	307.73	339.67	371.81	392.97	424.94	457.05	478.27	766.27
750	222.15	230.80	228.42	239.76	238.82	250.36	249.81	261.38	272.91	272.56	284.10	283.83	295.36	307.04	341.15	375.33	409.73	432.39	466.64	501.02	535.27	855.29

Onshore Distance (km)	Pipeline Transport Costs (£/tonne) CO_2 Transport Volume (KTPA)																					
	20	40	60	80	100	120	140	160	180	200	220	240	260	300	400	500	600	700	800	900	1000	2000
10	8.67	5.42	4.34	3.25	3.47	2.89	2.48	2.17	1.93	2.60	2.36	2.17	2.00	1.73	1.30	1.04	1.16	0.99	0.87	0.77	0.69	0.43
20	17.34	13.01	11.56	8.67	6.94	5.78	7.43	6.50	5.78	5.20	4.73	4.34	4.00	3.47	2.60	2.77	2.31	1.98	1.73	1.93	1.73	1.04
30	32.52	19.51	17.34	13.01	10.41	13.01	11.15	9.76	8.67	7.80	7.09	6.50	6.00	5.20	5.20	4.16	3.47	2.97	3.25	2.89	2.60	1.56
40	43.36	26.01	23.12	17.34	13.87	17.34	14.87	13.01	11.56	10.41	9.46	8.67	8.00	9.25	6.94	5.55	4.62	4.96	4.34	3.85	3.47	2.43
50	65.04	43.36	28.91	21.68	26.01	21.68	18.58	16.26	14.45	13.01	11.82	10.84	10.01	11.56	8.67	6.94	7.23	6.19	5.42	4.82	4.34	3.04
60	78.04	52.03	34.69	26.01	31.22	26.01	22.30	19.51	17.34	15.61	14.19	13.01	16.01	13.87	10.41	8.32	8.67	7.43	6.50	5.78	6.24	4.16
70	91.05	60.70	40.47	30.35	36.42	30.35	26.01	22.76	20.23	18.21	22.07	20.23	18.68	16.19	12.14	12.14	10.12	8.67	7.59	8.09	7.28	4.86
80	104.06	69.37	46.25	52.03	41.62	34.69	29.73	26.01	23.12	20.81	25.23	23.12	21.35	18.50	13.87	13.87	11.56	9.91	10.41	9.25	8.32	5.55
100	130.07	86.72	57.81	65.04	52.03	43.36	37.16	32.52	28.91	34.69	31.53	28.91	26.68	23.12	21.68	17.34	14.45	12.39	13.01	11.56	10.41	6.94
120	156.09	104.06	104.06	78.04	62.44	52.03	44.60	39.02	46.25	41.62	37.84	34.69	32.02	27.75	26.01	20.81	17.34	17.84	15.61	13.87	12.49	9.37
140	182.10	121.40	121.40	91.05	72.84	60.70	52.03	60.70	53.96	48.56	44.15	40.47	37.35	32.37	30.35	24.28	24.28	20.81	18.21	16.19	17.00	10.93
160	208.12	138.75	138.75	104.06	83.25	69.37	59.46	69.37	61.66	55.50	50.45	46.25	42.69	37.00	34.69	27.75	27.75	23.78	20.81	21.58	19.42	12.49
180	234.13	156.09	156.09	117.07	93.65	78.04	66.90	78.04	69.37	62.44	56.76	52.03	48.03	52.03	39.02	31.22	31.22	26.76	23.41	24.28	21.85	14.05
200	260.15	173.43	173.43	130.07	104.06	86.72	99.10	86.72	77.08	69.37	63.07	57.81	66.70	57.81	43.36	34.69	34.69	29.73	30.35	26.98	24.28	15.61
250	433.58	216.79	216.79	162.59	130.07	144.53	123.88	108.40	96.35	86.72	78.83	72.26	83.38	72.26	65.04	52.03	43.36	37.16	37.94	33.72	34.69	21.68
300	520.30	390.22	260.15	195.11	156.09	173.43	148.66	130.07	115.62	104.06	94.60	108.40	100.06	86.72	78.04	62.44	52.03	52.03	45.53	46.25	41.62	26.01
350	607.01	455.26	303.51	227.63	182.10	202.34	173.43	151.75	134.89	121.40	137.96	126.46	116.73	101.17	91.05	72.84	60.70	60.70	60.70	53.96	48.56	36.42
400	693.73	520.30	346.86	260.15	277.49	231.24	198.21	173.43	154.16	173.43	157.67	144.53	133.41	115.62	104.06	83.25	80.93	69.37	69.37	61.66	55.50	41.62
450	780.44	585.33	390.22	292.67	312.18	260.15	222.98	195.11	173.43	195.11	177.37	162.59	150.09	130.07	117.07	93.65	91.05	89.19	78.04	69.37	70.24	46.83
500	867.16	650.37	433.58	325.19	346.86	289.05	247.76	216.79	240.88	216.79	197.08	180.66	166.76	144.53	130.07	104.06	101.17	99.10	86.72	77.08	78.04	52.03
550	953.88	715.41	476.94	357.70	381.55	317.96	272.54	238.47	264.97	238.47	216.79	198.72	183.44	158.98	143.08	133.54	111.29	109.01	95.39	95.39	85.85	57.23
600	1,040.6	780.44	520.30	520.30	416.24	346.86	297.31	325.19	289.05	260.15	236.50	216.79	200.11	208.12	156.09	145.68	121.40	118.92	104.06	104.06	93.65	62.44
650	1,127.3	845.48	563.65	563.65	450.92	375.77	322.09	352.28	313.14	281.83	256.21	234.86	216.79	225.46	169.10	157.82	131.52	128.84	112.73	112.73	101.46	67.64
700	1,214.0	910.52	607.01	607.01	485.61	404.67	346.86	379.38	337.23	303.51	275.91	252.92	233.47	242.80	182.10	169.96	141.64	138.75	136.58	121.40	109.26	72.84
750	1,300.7	975.56	650.37	650.37	520.30	433.58	371.64	406.48	361.32	325.19	295.62	270.99	300.17	260.15	195.11	182.10	151.75	148.66	146.33	130.07	117.07	78.04

Table 2-7 – Estimated Costs for Onshore CO_2 Transport (£/tonne)

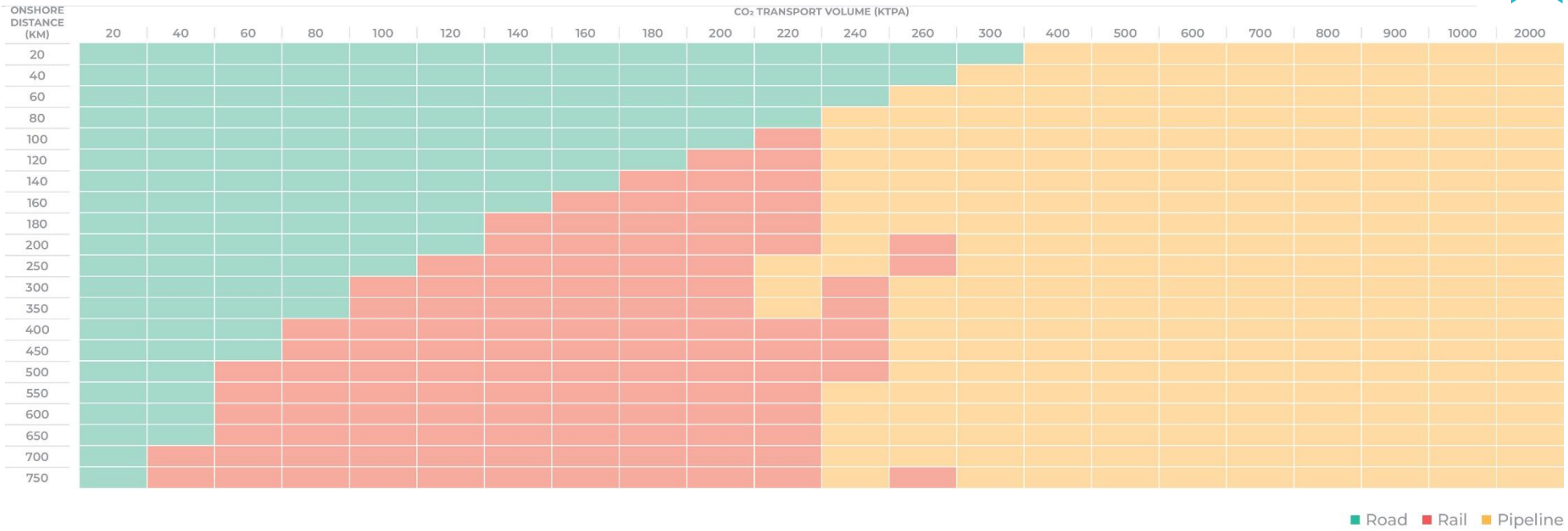


Table 2-8 – Most Cost-Effective Mode of Onshore Transport Matrix

2.6 Key Findings from Technology Assessment

The key findings from the technology assessment are as follows:

- Most of the technologies required to enable a Europe wide CCUS transport network are established and proven, either in analogue industries (particularly the LPG transport industry) or directly in CO_2 service. There is a need to evolve those technologies in terms of scale and adapt them to CO_2 service at scale, but there are already examples of the technologies being used in industry, especially through the advent of the Northern Lights CCUS project.
- Non-pipeline transport does present a realistic alternative to pipeline transport for gathering captured CO_2 emissions prior to export to offshore storage sites:
  - Road tankers are particularly suited to small emitters who are located at a distance from established CO_2 infrastructure. The transport of CO_2 by road is already established and CCUS can scale the use of CO_2 tankers quite readily. The use of road tankers is most suited logistically to relatively low volumes of CO_2 transport.
  - Rail cars are also a potential route for non-pipeline transport using established technologies. They offer the potential to transport higher volumes of CO_2 than road tankers over longer distances but the implementation of this transport route at scale could be constrained by competition with other rail users due the high utilisation of existing railway networks across Europe.
  - Barge transport could be considered for transport of CO_2 where emitters are located alongside major rivers. The size and scale of barges required to deliver effective CO_2 transport is likely to limit their use to major rivers, but there is the opportunity to service multiple emitters with common barges. Technologies from the LPG industry (where barges are used) will need to be adapted for use on CO_2 service but the theory of this has already been proven through the delivery of ship-based CO_2 handling systems.
  - Ship transport is already being implemented within the CCUS industry with projects such as Northern Lights relying on a fleet of ships to transport some of the emissions stored by the project to their gathering port. The technology required for these ships is analogous to that widely used for decades within the LPG industry for the transport of "semi-refrigerated" liquefied gases. CO2next are also planning to construct an open-access shipping terminal for liquid CO_2 at the Maasvlakte in Rotterdam.
- Pipeline transport is the most cost-effective method for onshore transportation of CO_2 at high volume and over long distances (See figure below) but has a comparatively long lead time to implement due to planning and consenting requirements involving multiple stakeholders (typically many different landowners and regulators across long pipeline routes).
  - Long term operating costs of pipelines are also comparatively lower than non-pipeline transportation options.
- Non-pipeline transport does introduce technology challenges in additional to those that apply to pipeline transport of CO_2:
  - The handling of non-condensable gas impurities in captured CO_2 needs careful consideration across the full transport chain as the facilities required to maintain the comparatively low temperatures and pressures required for efficient non-pipeline transport of CO_2 may lead to conditions where gas needs to be periodically vented to atmosphere.
  - Composition requirements across the transport chain need to be considered as a whole to ensure that the most efficient balance is struck between the scope and scale of facilities required throughout the chain



rather than enforcing potentially overly strict composition requirements on all emitters feeding into the chain.

- Metering and analysis of CO_2 is known to be a challenging area and is the subject of significant research and testing. Non-pipeline transport may have the potential to make this even more critical due to the multiple transfers between steps in the transport chain (e.g. emitter to land transport method to gathering port to ship transport to receiving port to pipeline to store).

3 PORT ASSESSMENT

3.1 Introduction

Figure 3-1 illustrates the geographic spread of identified potential CO_2 stores [Reference 4] and potential captured emissions across Europe [Reference 3].

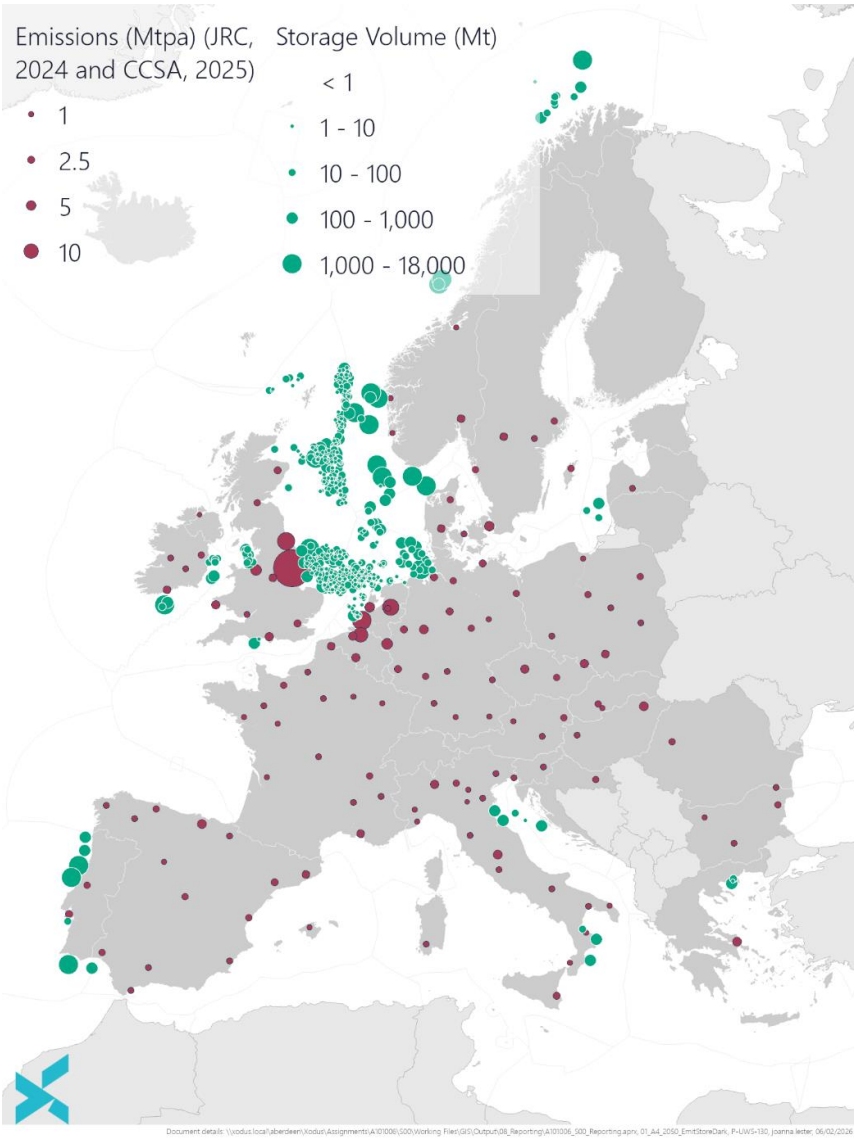


Figure 3-1 – Predicted Emissions Sources in 2050 and Identified Offshore CO_2 Stores.
Data sourced from CCSA and JRC [Reference 1, 3], Xodus analysis for UK and Norway.

As is evident from Figure 3-1, there are a range of potential emitters across Europe who are located significant distances away from potential stores. Ports will be critical parts of the overall infrastructure required to gather CO_2 from emitters and transport it to safe offshore stores.

The following three steps were followed to gain insight into which of the port locations across Europe may be best suited to provide services to the CCUS industry as it matures.

- Port identification and location: The suitability of all existing ports across Europe to handle the size and scale of ships likely to be used for transport of CO_2 was assessed to arrive at a screened down list of ports for further evaluation.
- Port scoring: The proximity of the screened down list of ports to predicted future captured CO_2 emissions was used to determine how useful they could be in gathering emissions prior to onward transport to stores.
- Port evaluation: Ports in each geographic area across Europe were then assessed to further screen down to a shortlist of ports that could potentially be utilised for CO_2 transport.

The assessment did not concentrate on the facilities provided at individual ports or the detail of whether those facilities could be adapted in future to provide CO_2 handling services as it was agreed that this would be the focus of further work outside the scope of this study. Nor did the assessment take into account existing plans and MoUs that emitters, ports and T&S entities have in place. See Section 3.4 for further information on port evaluation.

3.2 Port Identification and Location

The first element of this work identified that there are circa 850 functioning ports across Europe, as illustrated in Figure 3-2.



Figure 3-2 – All Ports in Europe

CO_2 has a long-established track record of being transported by ship in small quantities for the food and beverage industry. There are currently four small ships engaged in food/beverage grade operation carrying CO_2 in small parcels of around 2,000 cubic metres (m^3).

As the CCUS industry develops, ship transport of CO_2 is predicted to be an important part of the transport and storage chain, particularly where transport by pipeline is not feasible of economic. Several sources estimate that 800-900 CO_2 transport ships may be required worldwide by 2050 [Reference 5].

Ships are starting to be delivered to service this growing market including the three 7,500m^3 ships delivered for the Northern Lights project during 2024 and 2025 (Northern Pioneer, Northern Pathfinder, and Northern Phoenix) plus one 22,000m^3 ship for Capital Clean Energy Carriers (Active). The size and scale of these ships is very similar to that used extensively in the semi-refrigerated liquefied petroleum gas (LPG) industry for decades with the Capital Clean Energy Carriers ship designed to be able to carry CO_2 or LPG.

As a result, the port logistic capabilities (e.g. jetty size, available draft, etc.) required to handle CO_2 ships of this size are well understood within the shipping industry.

This study determined that a useful method for screening down the ports across Europe to those that could handle the likely size of ships required for CO_2 transport, would be to examine whether the existing ports are used to handling ships of the size required for the LPG industry (from 3,500m^3 up to 60,000m^3).

This was achieved by utilising a "port call database" that tracked all ship movements into and out of ports across Europe covering the entirety of 2024. The database recorded over 1.3 million ship movements across the circa 850 ports identified for the study.

The port calls for the range of ship sizes (i.e. 3,500m^3 to 60,000m^3 carrying capacity) likely for CO_2 transport were filtered out from the port call database to understand the frequency that the existing ports already handle ships of this size. This data was then used to estimate an "equivalent volume" of CO_2 that could have been handled by the existing ports if the ships of the appropriate size were to be carrying CO_2 rather than the cargoes they would have delivered to the ports.

The overall annual equivalent volume of CO_2 for each port was then used to screen down the list of 850 ports to a more manageable number for further consideration. Setting a minimum limit of approximately 3 million m^3 per year yielded a screened down list of circa 200 ports. Previous work [Reference 1] has indicated that the economies of scale when building the facilities for CO_2 handling ports levels out above 2-3MTPA of CO_2.

The resulting screened list was then reviewed and any ports associated with ongoing proposed CCUS projects (e.g. the Acorn Project in the UK) that were missing were added into it to yield the ports illustrated in Figure 3-3:



Figure 3-3 – Screened Ports in Europe

3.3 Port Scoring

Figure 3-4 illustrates the options considered by this study for transport of captured CO_2 from emitters to offshore storage sites. Consideration of direct injection was deemed to be outside the scope of this study.

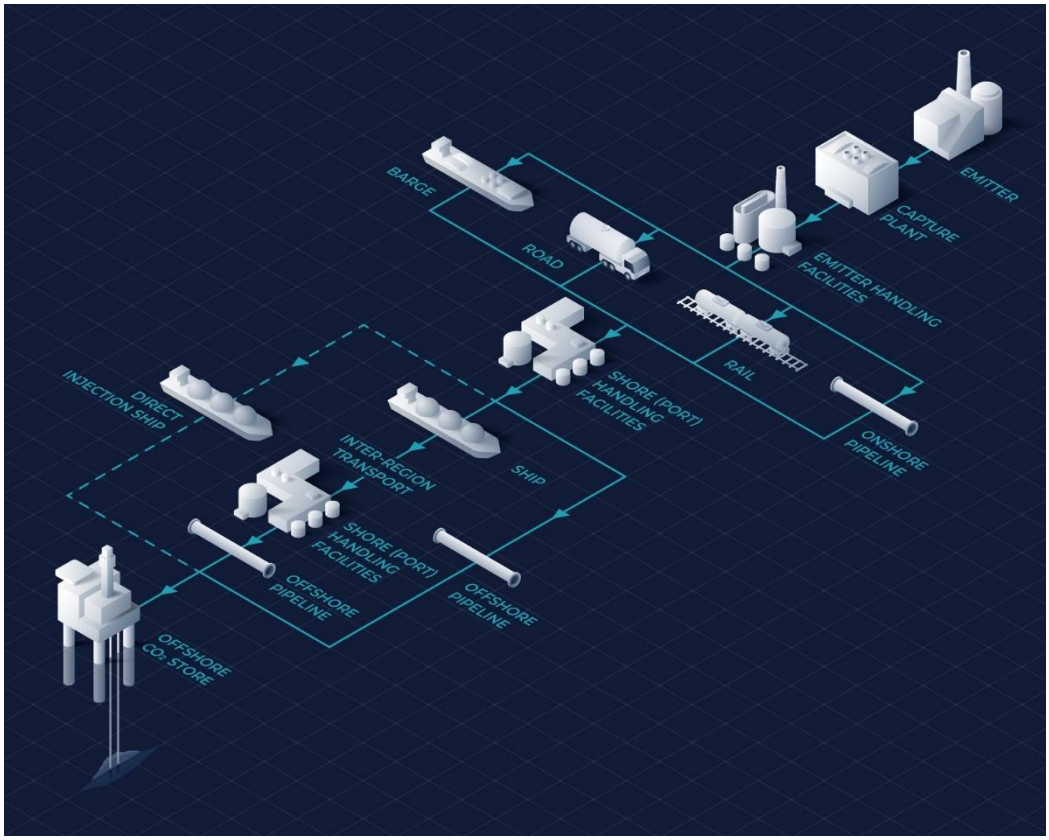


Figure 3-4 – CO_2 Transport Options

Ports can serve one or both of the following roles in Figure 3-4:

- Gathering captured CO_2 from a range of emitters that do not have a local store prior to export via ship to a remote region for offshore storage (Emitter ports).
- Receiving CO_2 from ships and other transport measures prior to export to an offshore store via pipeline (Store ports).

Recognising these two roles, the study developed a methodology for scoring and ranking the screened ports across Europe based on their suitability for CO_2 handling. This included their current ability to treat, temporarily store and transport CO_2 from nearby emitters, manage imported CO_2 from remote sources and export CO_2 to nearby stores (via pipeline).

The scoring methodology was developed to give each port an "emitter score" and a "store score". The emitter score is based on the proximity of each port to emitters and the volume predicted from those emitters (in 10-year intervals from 2030 to 2050). Similarly, the store score is based on the proximity of each port to identified CO_2 stores and the volume capability of those stores.

3.3.1 Emitter Score

The emissions data for this study was sourced from EDGAR (Emissions Database for Global Atmospheric Research) Community GHG Database, developed through a collaboration between the European Commission, Joint Research Centre (JRC), and the International Energy Agency (IEA) [Reference 3]. The dataset includes components such as IEA-EDGAR CO_2, EDGAR CH_4, EDGAR N_2O, EDGAR F-GASES, based on version EDGAR_2025_GHG (2025) published by the European Commission, JRC.

The data utilised in this study from the EDGAR Community GHG Database predicts how much CO_2 will be captured and where, in 10-year intervals from 2030 to 2050.

The "emitter" score for each port was then determined by dividing the predicted capture rate from each source in the EDGAR database by the distance of that emitter to the port being examined. This enabled the study to understand both the proximity of ports to emissions sources and the potential scale of emissions that could be routed to those ports.

A similar process was carried out to evaluate the "store" score of each of the ports in the screened list. Data from the CO2Store database [Reference 4] was used to provide the potential size and location of identified offshore CO_2 stores across Europe. The "store" score for each port was then determined by dividing the predicted store size from each source in the CO2Store database by the distance of that store to the port being examined. This enabled the study to understand both the proximity of ports to stores and the potential scale of CO_2 that could be routed from those ports to stores.

3.4 Port Evaluation

Internal project team workshops assessed the "emitter" score of all the ports and refined the screened list down to the ports with the highest scores per region (as determined by the size and number of predicted emitters) for each time step. Where two or more ports were in close proximity with similar scores, the decision was made to select the port with the highest score, ensuring the selection process remained data driven.

The workshops also assessed the "store" score of all the ports and refine the screened list down to the ports with the highest scores per region (as determined by the size and number of identified stores). The "store" score review was only performed at a single time step as the identified store list within the CO2Store database is currently static and does not change at different time steps.

The output of the workshops for the "emitter" and "store" scores is illustrated in Figure 3-5 (2030), Figure 3-6 (2040) and Figure 3-7 (2050):

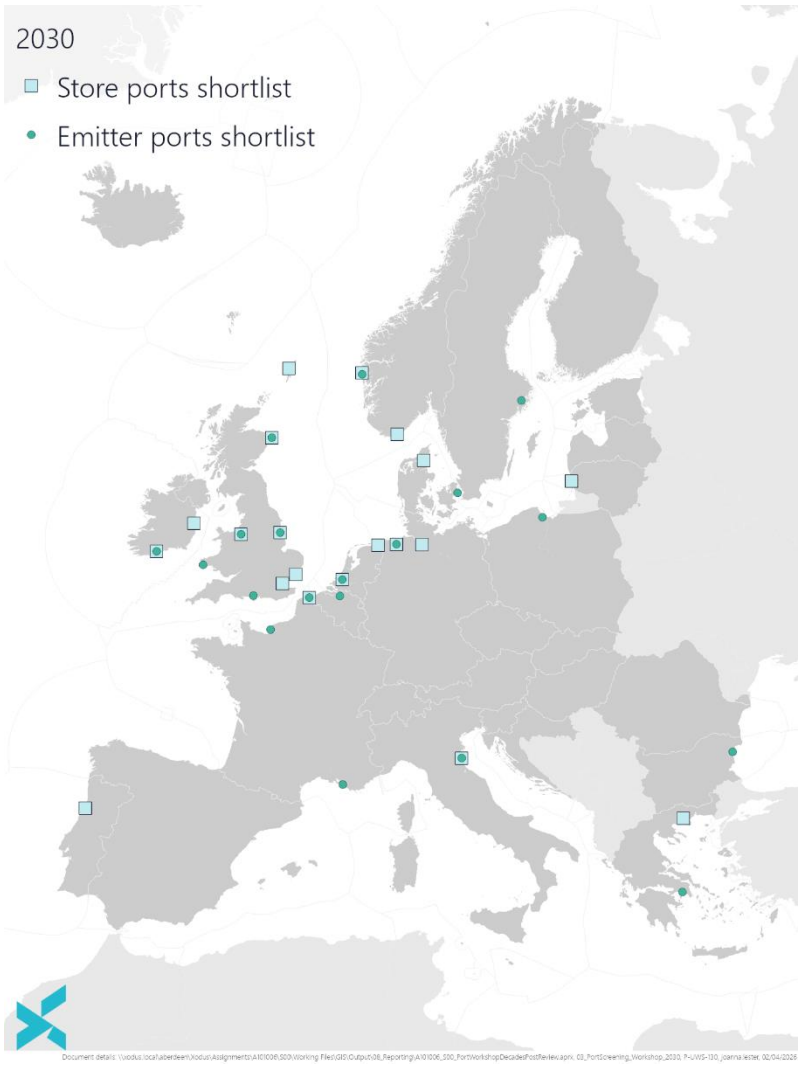


Figure 3-5 – Shortlisted "Emitter" and "Store" Ports in 2030

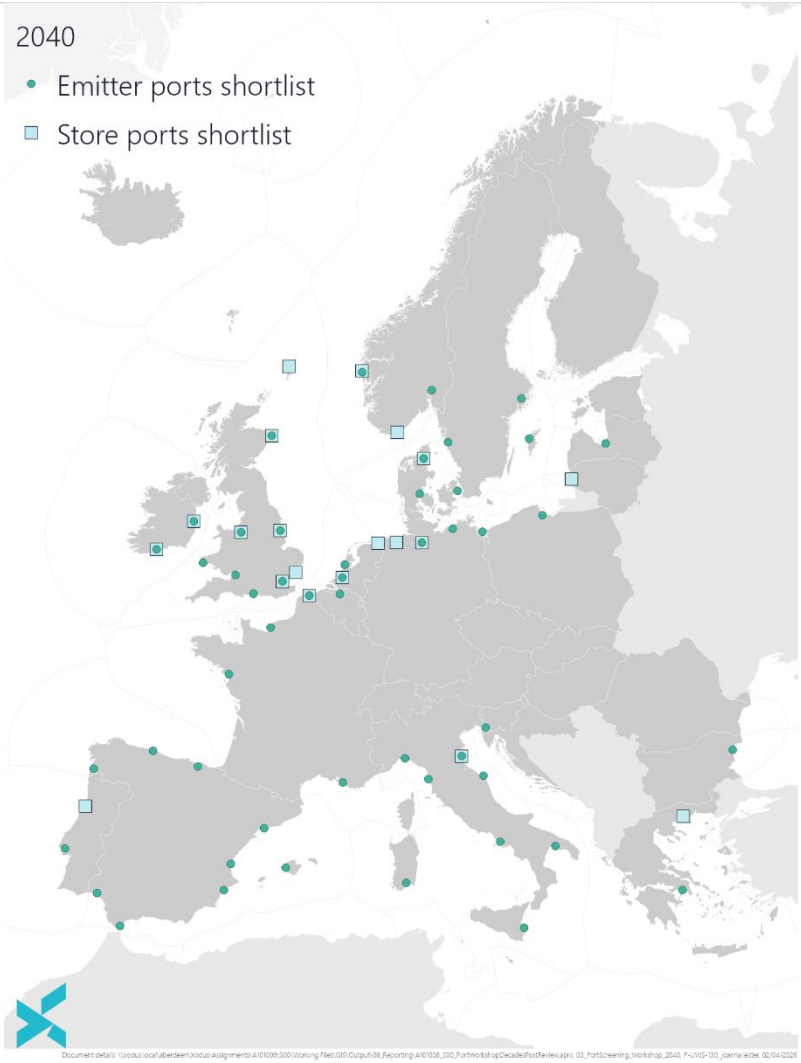


Figure 3-6 – Shortlisted "Emitter" and "Store" Ports in 2040

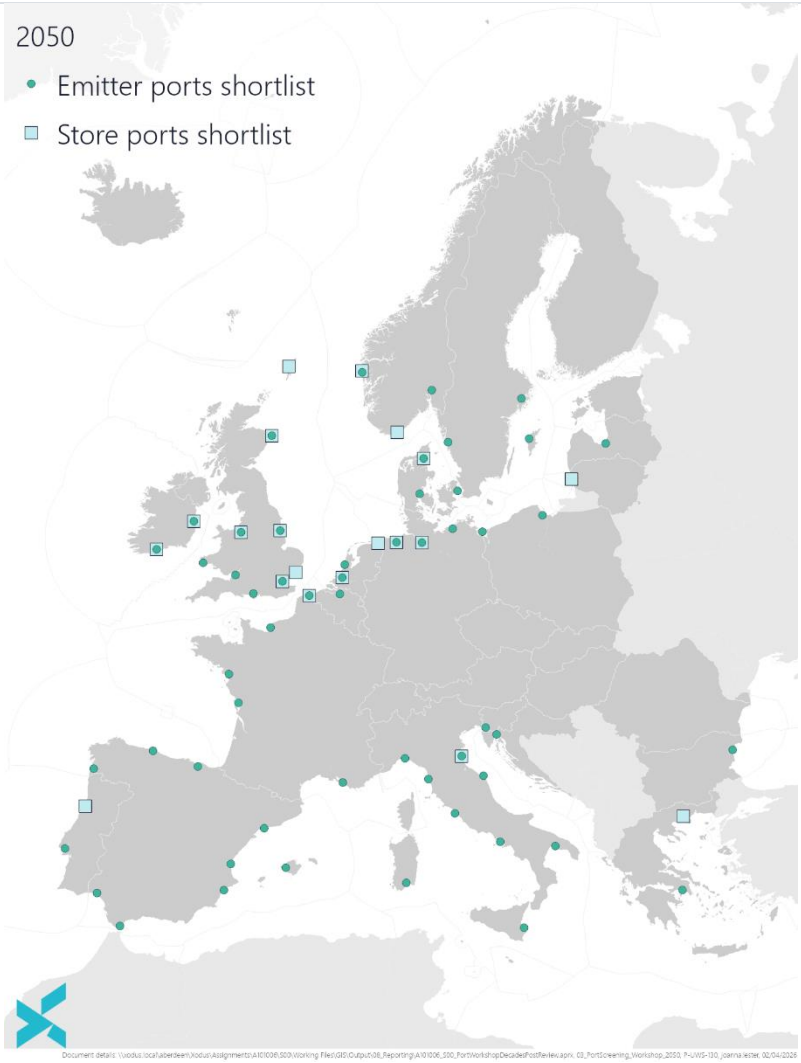


Figure 3-7 – Shortlisted "Emitter" and "Store" Ports in 2050

The range of ports identified in the above figures was then reviewed to determine whether there should be any further consideration of the capabilities of those ports and whether they are potentially suitable for handling CO_2 in the future. The review noted that the shortlisted ports all tended to involve areas with significant industrial infrastructure and major transport links, which would tend to include the factors that could be considered when assessing whether ports are suitable for future handling of CO_2. No other significant industrial ports that have proximity to either stores or emitters were found, so the study concluded that there was no requirement to apply additional factors to "promote" ports into the shortlist.

The overall number of shortlisted "emitter" and "store" ports is summarised in Table 3-1:

EMITTER PORTS			STORE PORTS
2030	2040	2050	
19	50	53	19 (12 dual-purpose emitter/store ports)

Table 3-1 – Port Evaluation Results

3.5 Key Findings from Port Assessment

The key findings from the port assessment are as follows:

- All operating ports across Europe were assessed to investigate their potential suitability for handling CO_2 transport. Approximately 850 ports were screened down to circa 200 ports by comparing the size and types of ships currently handled with those expected to be required for CO_2 shipping.
- An analysis was carried out to compare the proximity of shortlisted ports to projected CO_2 emissions over time, and to identified offshore CO_2 storage sites. This analysis highlighted which ports are best positioned to function as either:
    - Emitter ports – aggregating CO_2 from onshore emitters for export.
    - Store ports – receiving aggregated CO_2 flows for onward transport to offshore storage sites.
- The modelling indicated that by 2050, approximately 53 Emitter ports and 19 Store ports could be suitable for use. Of these, 12 of the Store ports were also suitable as Emitter ports, resulting in a total number of 60 ports assessed to be suitable for use as part of a Europe-wide CO_2 transport chain by 2050.
- Many of the identified "dual-purpose" emitter/store ports are located in highly industrialised areas such as the Port of Rotterdam, Teesside and Liverpool Bay.
- The number and distribution of suitable ports aligned well with the findings of the CO_2 Volume Assessment in section 4, which used a top-down approach based on project shipping demand and typical port sizes required for economies of scale.
- No additional weighting or modifying factors were needed to "promote" ports with known CCUS interest, as the methodology naturally scored them highly due to their location in heavily industrialised regions with strong transport networks and significant potential for future CO_2 capture.

4 CO_2 VOLUME ASSESSMENT

4.1 Introduction

The following sections quantify the role of CO_2 shipping within Europe's emerging CCUS network from 2030 to 2050 by applying a cost-based modelling framework to every major European emitter, estimating whether pipeline or shipping offers the lowest-cost route to offshore storage as infrastructure develops over time.

The analysis proceeds in four stages:

1. Estimate the total volume of captured CO_2 in Europe consistent with EU, UK and Norwegian decarbonisation trajectories.
2. Assess the most cost-efficient transport mode for each emitter, either pipeline or shipping, based on onshore transport costs, pipeline rollout, distance to ports, and distance to storage basins, using a least-cost algorithm.
3. Identify and define Europe's "maritime regions", where shipping is modelled to become the dominant mode of transport, and quantify shipping volumes by region.
4. Allocate shipped volumes to receiving storage basins and determine the resulting port and vessel requirements.

This modelling provides a top-down forecast of the European CO_2 shipping market, including shipping market share, regional shipping flows, cross-border dependencies, and the approximate size / number of ports and vessels required to support the market by 2050. Table 4-1 summarises the work carried out in this analysis and highlights which section addresses each element of the work.

Note on Modelling Outputs – The analysis in this section is based on modelled outcomes generated through algorithmic assessment and data inputs. Results are indicative and are intended to support comparative analysis rather than provide definitive forecasts. The model excludes existing commercial agreements, memoranda of understanding, and development plans for emitters, ports, or transport and storage operators. Any representation of emitters, ports, or CO_2 flows reflects a least-cost allocation within the study's dataset and does not imply commercial intent or preferred configurations.

TOPICS	STEPS	OUTCOME
Section 4.2 Shipping Volume	Quantifies captured CO_2 quantities in Europe from 2030–2050. Uses cost-based modelling to determine whether each emitter selects a shipping or pipeline transport option. Incorporates multiple modelling steps: onshore transport cost (road/rail/truck), potential pipeline infrastructure, and analysis of catchment areas between ports and pipelines.	Range of CO_2 shipping quantities at each decade from 2030 to 2050, with associated transport market share
Section 4.2 Shipping Regions	Uses the cost-modelling outcomes to identify regions where emitters are more likely to select shipping to access storage. Defines five shipping regions: North Sea, Atlantic, Baltic, West Mediterranean, East Mediterranean.	Breakdown of CO_2 shipping quantities per maritime region
Section 4.3 Storage Regions	Allocates each region's shipping volume to the storage basin most likely to receive it (e.g., Atlantic emissions → North Sea storage).	Quantities of CO_2 delivered to receiving (import) ports in each storage region.
Section 4.4 Cross-Border Considerations	Identifies the share of shipping flows that rely on, or benefit from, cross-border transport agreements.	Shipping quantities requiring cross-border coordination and agreements.

TOPICS	STEPS	OUTCOME
Section 4.5 **Port Estimate**	Top-down assessment of the number of emitter ports and store ports required to handle projected volumes.	Estimated number of ports required to support CO_2 shipping.
Section 4.6 **Ship Estimate**	Top-down assessment of the number of ships that will be required to transport CO_2.	Estimated number of vessels required to support CO_2 shipping.

Table 4-1 – Summary of CO_2 Volume Assessment Analysis Scope

4.2 Shipping Volume

This section estimates how much CO_2 within Europe is likely to be transported by ship rather than by pipeline between 2030 and 2050 according to the model. The analysis uses a cost-based modelling framework applied to every major emitter cluster in Europe at each time step, determining the most economical connection to offshore storage at that point. The results underpin the definition of shipping regions, shipping market share, and the allocation of volumes to storage basins.

The modelling builds on the European Commission's JRC CCUS scenario [Reference 3], which provides emission trajectories and pipeline infrastructure assumptions. Three adjustments were made in this assessment:

1. Slower Ramp-Up of Capture and Transport
   Instead of a steep increase to 2040 followed by a plateau, our model assumes a phased adoption, reaching peak volumes toward 2050. UK and Norwegian projections are based on Xodus' own datasets and CCSA insights.
2. Modified Pipeline Deployment
   The original JRC backbone shows an extensive build-out. We apply our own cost-driven, incremental pipeline expansion, reflecting commercial conditions under which pipeline development becomes viable.
3. Offshore-Only Storage
   All CO_2 is assumed to be stored offshore, aligning with the majority of European policy and permit frameworks and enabling consistent comparison between pipeline and shipping pathways.

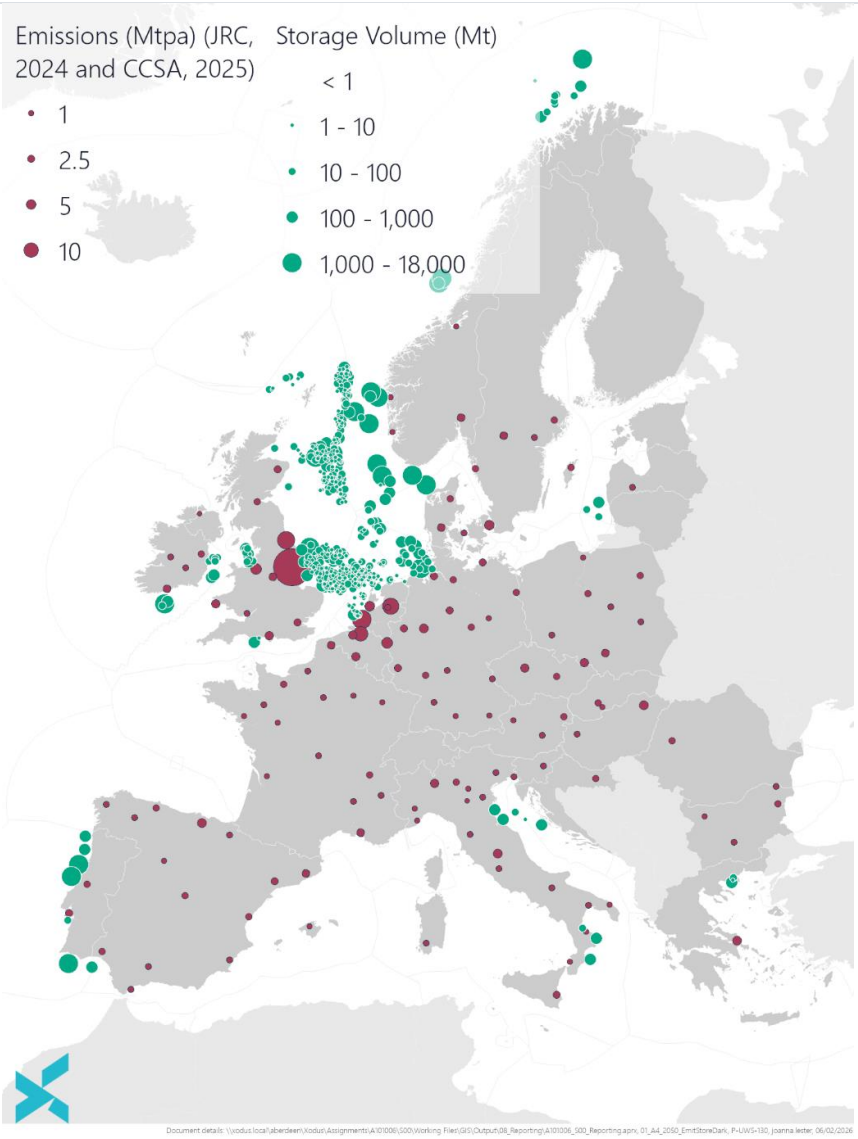
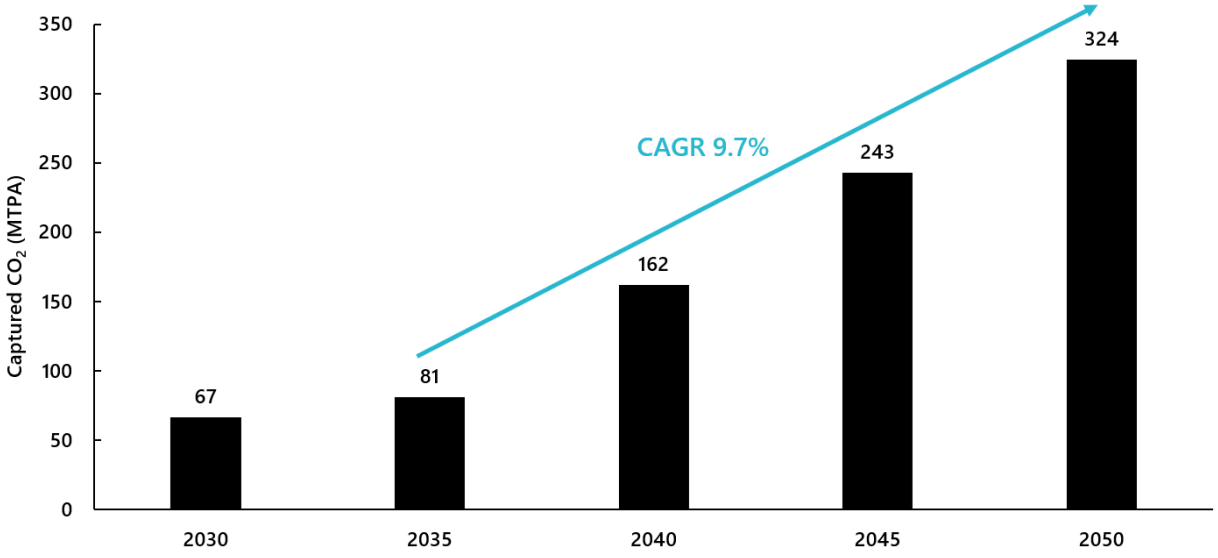


Figure 4-1 - Map of projected annual CO_2 capture volumes in 2050.
Data sourced from CCSA and JRC [Reference 1, 3], Xodus analysis for UK and Norway.

4.2.1 Captured CO_2 Emissions Estimate

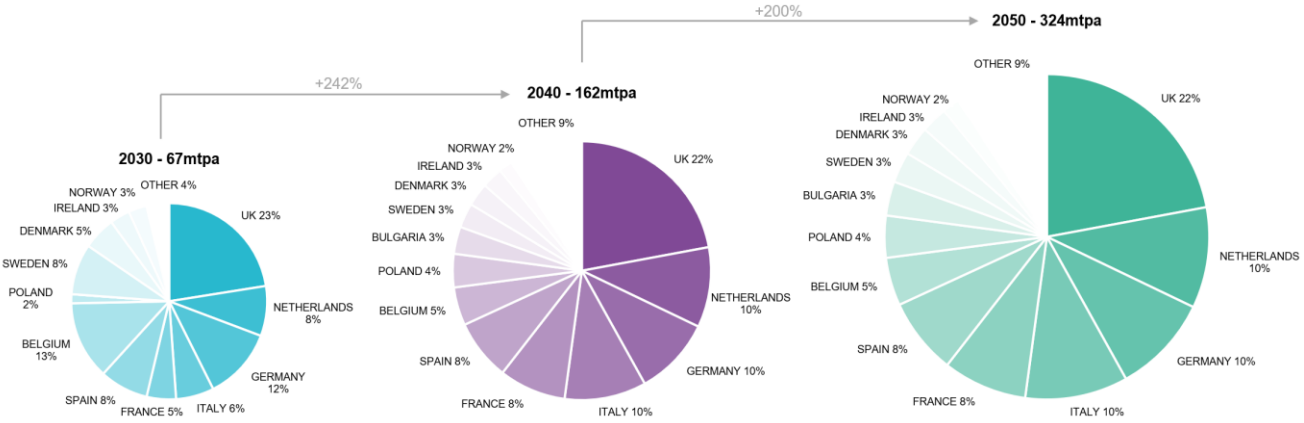
A steady increase in CCUS CO_2 capture rate was modelled across Europe, rising from 67MTPA in 2030 to 324MTPA by 2050 as shown in Figure 4-2.



Source: JRC for the EU, Xodus analysis for the UK and Norway.

Figure 4-2 – Captured CO_2 Between 2030 and 2050

Growth is relatively modest to 2035, before accelerating at a compound annual growth rate (CAGR) of 9.7% onwards as CCUS deployment broadens across major emitter clusters under a phased, cost-driven rollout aligned with infrastructure availability. Captured CO_2 emissions are concentrated in a small number of countries, with the UK, the Netherlands, Germany and Italy accounting for around 50% of captured emissions across 2030, 2040 and 2050 as shown in Table 4-4.



Source: JRC for the EU, Xodus analysis for the UK and Norway.

Figure 4-3 - Emissions Volume breakdown at each decade

The UK is modelled to consistently represent the largest share, reflecting the scale and maturity of its industrial CCUS clusters, particularly HyNet and East Coast Cluster. The Netherlands and Germany also contribute material volumes, driven by large industrial emissions in the Rotterdam and Rhine-Ruhr regions. Other countries contribute smaller but increasing volumes as CCUS deployment broadens beyond early-mover hubs.

Several countries, such as Switzerland, Finland, Croatia, are not included in the JRC database of captured carbon emissions. As such they were not considered as part of this modelling exercise.

4.2.2 Allocation of CO_2 to Shipping or Pipeline

Each emitter has been assigned a transport pathway based on the estimated lowest cost route to offshore storage. The calculated total transport cost used in the analysis combines onshore transport (truck, rail, or pipeline) and shipping transport where applicable. This can be categorised into four main approaches:

APPROACH		EXAMPLES
1.	**Co-location to Port with CO_2 Store**	An emitter located near a port such as Rotterdam uses a short pipeline to connect to an offshore CO_2 storage system (e.g. Aramis or Porthos).
2.	**Land Transport to Port with CO_2 Store**	An emitter located 100 kilometres inland sends CO_2 by truck to a port for onward transport by pipeline to an offshore store.
3.	**Land Transport to Export Port, then Transfer to Port with CO_2 Store**	An emitter located near a port without nearby storage (e.g. Nantes) sends CO_2 by truck to the port, which is then transported by ship to a port with CO_2 store (e.g. Rotterdam).
4.	**Land Transport to Pipeline, then Onward to Port with CO_2 Store**	An emitter near an established pipeline transport sends CO_2 by truck or spur line to a pipeline hub, which is then connected to a port with Storage (e.g. Rotterdam). The cost includes three components: truck transport, onshore pipeline transport, and onward connection to the offshore store.

Table 4-2 – Approach to Lowest Transport Cost Modelling

The following key assumptions were used in the modelling:

- Shortest route was used for all land-based transport distance calculations.
- Shipping costs were derived using distance and a minimum viable volume threshold of 1MTPA.
- Truck transport distance was capped at 200 kilometres to reflect fleet size constraints at higher volumes.
- Pipeline costs were based on Xodus' cost database, applied to a custom pipeline layout that expands gradually to 2050.

These assumptions allowed realistic competition between transport modes without artificially favouring either pipeline or shipping.

The analysis suggested that the establishment of a growing network of onshore pipelines for CO_2 transport across Europe was justified over time as illustrated in Figure 4-4.

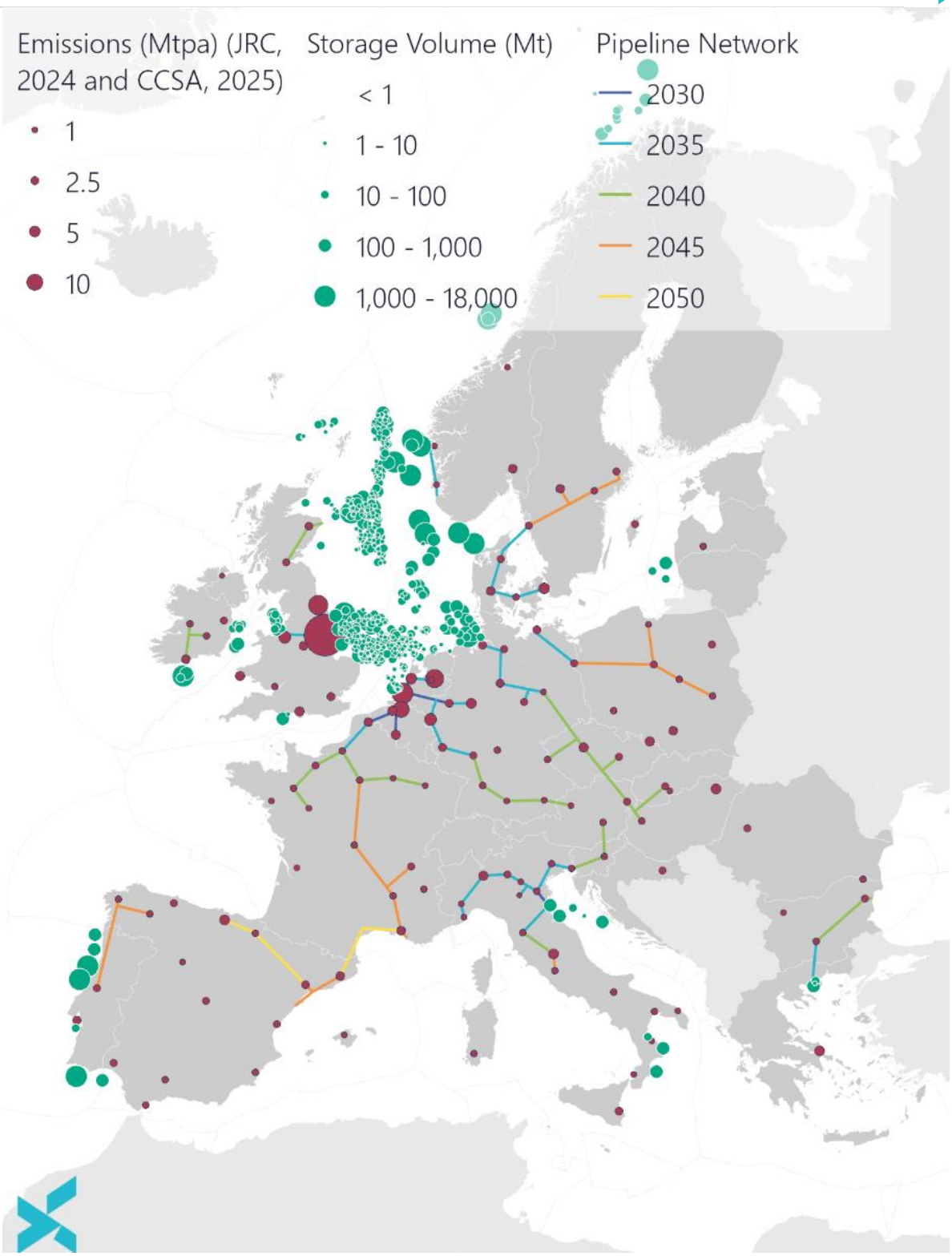


Figure 4-4 – Xodus Pipeline Design from 2030 to 2050.

The resulting modelled pipeline network develops gradually from 2030 to 2050, forming a partial backbone that connects major industrial clusters where volumes justify investment and originating from ports with access to storage, such as Rotterdam or Ravenna. In the model, regions with multiple medium-scale emitters become pipeline-dominated earlier, while more dispersed or coastal regions continue to rely on shipping throughout the period.

4.2.3 Shipping and Pipeline Regions Over Time

The output of the allocation analysis is illustrated in Figure 4-5 where each emitter has been allocated to a transport mode in each model year. The results suggest:

- Pipeline-dominated regions emerge where backbone expansion reaches major industrial hubs.
- Shipping-dominated regions persist in coastal, peripheral, or late-maturing areas.
- Highlighted in dark grey is where the modelling indicates there would be regions where emitters are too distant from any port/pipeline option to select a commercially attractive option under the model constraints.

As the pipeline network expands, some currently shipping-dependent regions are modelled to transition to pipelines, but this shift varies significantly by geography and storage availability.

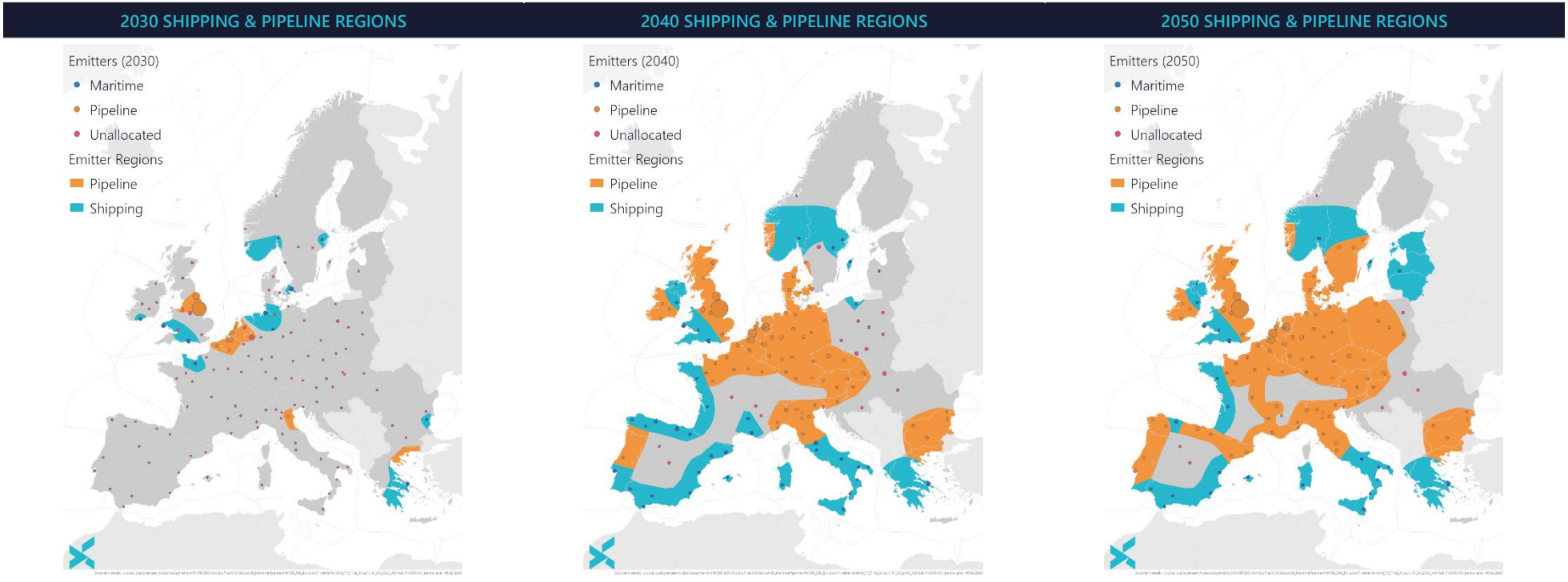


Figure 4-5 – Modelled Evolution of Pipeline and Shipping CO_2 Catchment Regions Over Time

4.2.4 Co-Existence of Shipping and Pipeline Transport Routes

While the model enables competition between transport modes on a cost basis, it would otherwise tend toward a binary outcome at the level of individual emitters and regions as infrastructure matures.



In practice, this understates the extent to which shipping and pipelines are likely to co-exist, particularly in coastal and river-connected regions where multiple transport options remain commercially and strategically valuable.

Several factors support the persistence of hybrid shipping–pipeline systems:

Resilience and Optionality

Shipping provides an alternative route to storage, reducing dependence on single pipeline assets and improving resilience during outages, maintenance, or capacity constraints. It also allows variable or seasonal volumes to be accommodated without oversizing pipeline infrastructure.

Phased Development

Shipping can be deployed at smaller scale and earlier in the market lifecycle, enabling access to storage ahead of full pipeline build-out. As volumes grow, the model suggests pipelines anchor baseload flows, while shipping continues to serve marginal or flexible volumes.

Trading

Shipping enables cross-border and inter-cluster CO_2 movements, supporting a more connected and tradable CCUS market. Coastal regions can act as aggregation and redistribution nodes, redirecting CO_2 between storage sites as availability and commercial conditions change.

Risk Diversification and Contracts

Hybrid systems diversify technology and demand risk. Pipelines require high upfront capital and long-term volume certainty, while shipping allows modular capacity additions. Once established, long-term capture/shipping contracts and sunk investments mean shipping is unlikely to be fully displaced by later pipeline capacity.

River connected regions (e.g., Rhine corridor) are also modelled to retain a persistent shipping component due to the availability of barge transport and the concentration of emitters along inland waterways and could see a similar dynamic.

A visualisation is shown in the 2050 map where coastal regions, may retain these dual shipping and pipeline options for CO_2 transport. To reflect realistic market behaviour, 20 percent of coastal emissions within 200 kilometres of a port have been assigned to shipping in the analysis.

4.2.5 Shipping Market Share

The analysis allocated the overall shipping quantities into broad maritime regions rather than showing an allocation by ports and defined five maritime regions (Baltic, Atlantic, Western Mediterranean, Eastern Mediterranean and North Sea).

The analysis has assessed two potential options for captured CO_2 being transported by ship across these regions:

1. All emitters located in "maritime" regions are allocated to ship transport.
2. As (1) but with 20% of emitters located within 200 kilometres of a port also being allocated to ship transport.

The modelled outcomes from these two options are illustrated in the figures below:

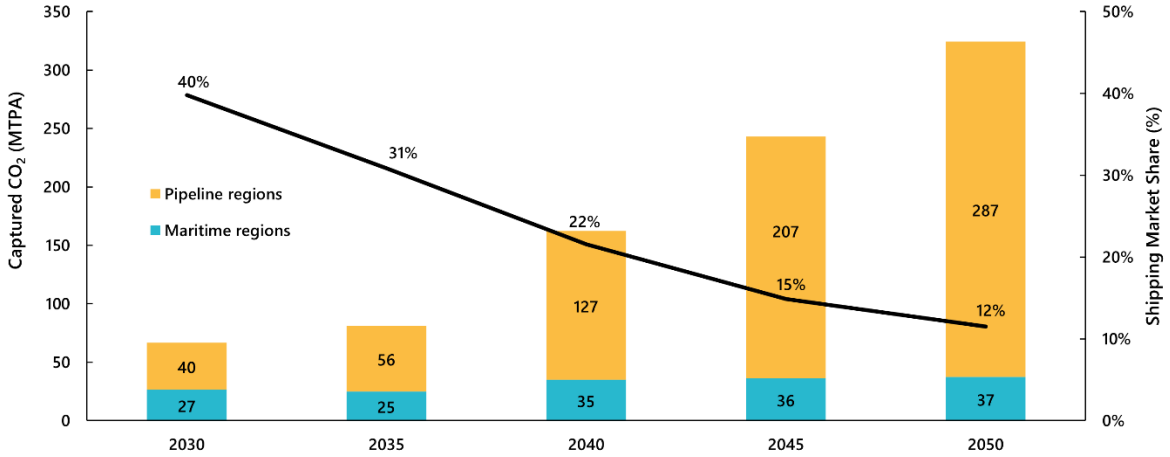


Figure 4-6 – Option 1: Shipping Market Share Capturing Only Maritime Regions

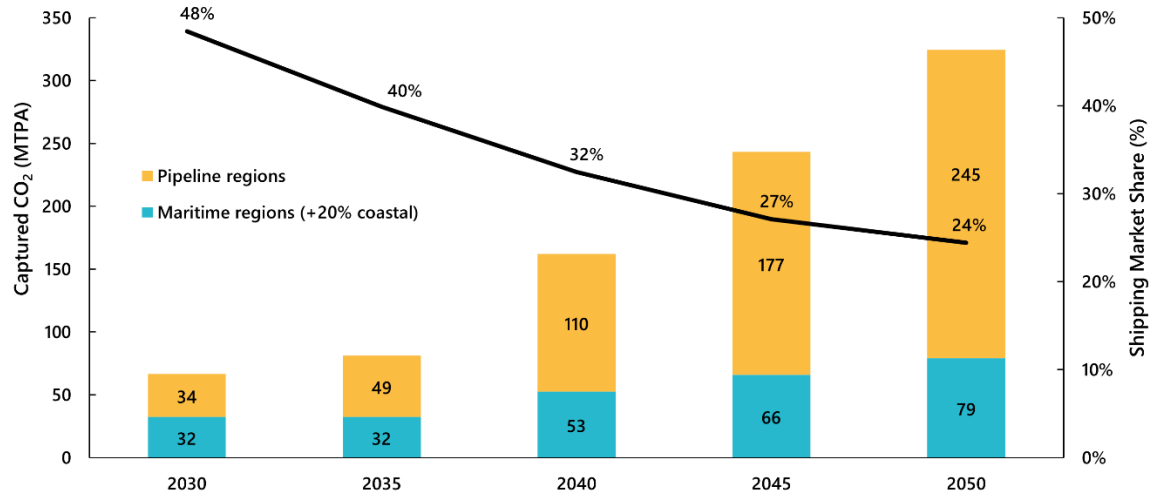


Figure 4-7 – Option 2: Shipping Market Share with 20% Coastal Region Emitters Included

In the early years for both options, shipping is modelled to account for close to half of total CO_2 transport, reflecting its flexibility and ability to serve dispersed emitters before dedicated pipeline infrastructure is in place. As pipeline deployment progresses, increasing captured emissions are modelled to come online in clusters close to ports with access to offshore storage, creating sufficient scale to justify investment in pipeline networks and driving a gradual shift toward pipeline-dominated regions.

In parallel, new captured emissions is modelled to emerge in more geographically dispersed areas, such as western France, Spain and southern Italy, where distances between emitters and limited proximity to storage make pipelines less viable, reinforcing the role of shipping.

The two options presented above are an approximate range of the total quantity of emissions that are modelled to be transported by ship over the period examined.

Key model findings

- Shipping consistently captures 12–24% of total European captured CO_2 emissions across all time periods.
- By 2050, this equates to around 37–79MTPA.
- Shipping remains structurally essential even with extensive pipeline deployment.
- Pipelines dominate high-density corridors and short-distance flows.
- Shipping continues to serve dispersed coastal clusters, regions without early pipeline access, and areas where pipelines are not cost-competitive.

Shipping therefore provides flexibility, cross-border connectivity, and system resilience, particularly for late-developing storage regions.

4.3 Shipping Regions

Figure 4-8 illustrates the quantity of CO_2 that is predicted to be exported via ship from emitters in each of the defined maritime regions over time based on the upper end estimate of total emissions transported by ship from section 4.2.

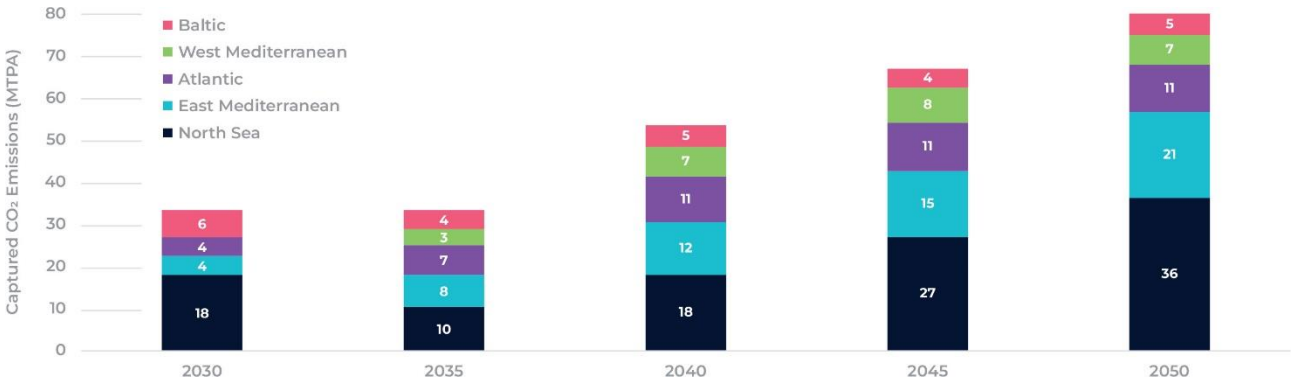


Figure 4-8 – CO_2 modelled to be transported by ship by maritime region

[1] *The apparent reduction in the number of North Sea Store ports between 2030 and 2035 is a function of the modelling methodology. The scaling factor increases by 50% over this period, while assumed shipping volumes decline as pipeline capacity expands. This outcome reflects the mechanics of the model rather than a forecast of an actual reduction in port activity or availability.*

The analysis then estimated which regions the above "exported" emissions would be shipped to for final storage. The key objective of this analysis was to understand:

- How much imported CO_2 each storage region could handle.
- How these flows could evolve over time as storage availability changes.

This framework allowed the study to model shipping demand at a regional level and supports the subsequent port-sizing and ship quantity analyses in sections 4.5 and 4.6.

The allocation of where ship transported CO_2 is exported to was based on quantitative analysis form past work as well as a repartition of volume based on overall distance to store. Table 4-3 details the methodology used for allocating the CO_2 shipping destinations for each region.

REGION	ALLOCATION
Baltic	In the early period (2030), all captured emissions transported by ship in the Baltic region are assumed to be exported to the North Sea due to the absence of local storage. From the 2040s onwards, emerging storage projects/ports enable the region to progressively retain a share of its own volumes, reducing reliance on exports to other regions by 2050.
Atlantic	The Atlantic region exhibits the most complex dynamics. In the early period, all captured volumes are assumed to be exported to the North Sea. From around 2040, storage capacity comes online in Portugal and Ireland, enabling the Atlantic region to retain a share of its own captured emissions. These Atlantic stores also begin to capture a portion of Western Mediterranean captured emissions, for example, routing southern Spanish emissions to storage in Portugal. For emissions exported to the North Sea, storage allocation is assessed using a cost-based approach. Storage cost data from the previous Xodus study on cross-border carbon shipping are applied across European stores [Reference 1]. The stores can be grouped into broader locations such as UK or Dutch SNS giving an aggregate capacity at an average price as all Atlantic emissions would need to pass through the channel to access the North Sea), the distance calculation is added to compare options. Potential Market Share of Atlantic Volume Storage Region: Market Share UK SNS: 58% Other UK: 16% Netherlands/Germany: 26% Based on the model, Norwegian stores are not expected to take capture volumes from Atlantic region due to additional shipping distance while there are nearer North Sea stores. This is a feature of the modelling algorithm.
Western Mediterranean	All captured emissions transported by ship in the Western Mediterranean are assumed to be initially exported to the North Sea or the East Mediterranean (e.g. Adriatic Italy or Greece). As storage capacity becomes available in Portugal from around 2040, a portion of these volumes is redirected to Atlantic storage.
Eastern Mediterranean	The East Mediterranean accommodates all locally captured emissions transported by ship within the region, supported by proximity to suitable storage sites such as the proposed Prinos project and the Ravenna project.
North Sea	While the same allocation approach used in other regions could have been applied, captured emissions in the North Sea are instead allocated pro rata to their region of origin, reflecting the relatively small cost differentials across the basin. Cross-border flows within the North Sea are therefore expected to be driven by trading opportunities, available capacity and marginal cost differences, rather than by a rigid allocation rule

Table 4-3 – Allocation Assumptions for Captured CO_2 Transport

The methodology described above was then used to allocate the destination of ship transported CO_2 for each region as shown in Figure 4-9:

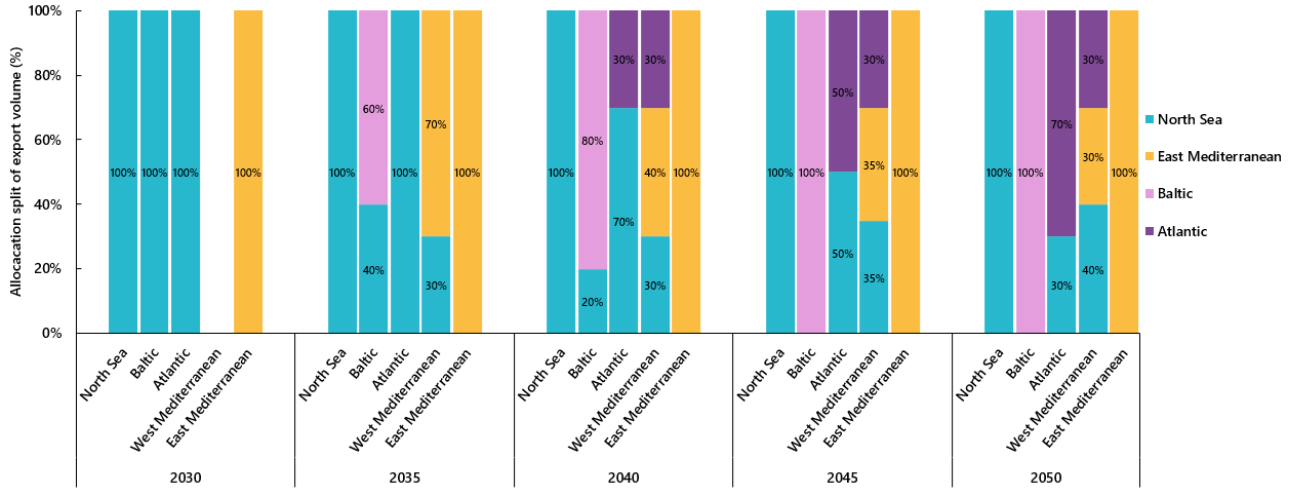


Figure 4-9 – Destination for Ship Transported CO_2 for Each Maritime Region

The above methodology results in the following results from the analysis:

	CO_2 EMISSIONS TRANSPORTED BY SHIP (MTPA)				
Region	2030	2035	2040	2045	2050
North Sea					
- Transported within region	18	10	18	27	36
- Exported from region	-	-	-	-	-
- Imported to region	10	10	11	10	7
Baltic					
- Transported within region	-	2	4	4	5
- Exported from region	6	2	1	-	-
- Imported to region	-	-	-	-	-
Atlantic					
- Transported within region	-	-	3	6	8
- Exported from region	4	7	8	6	3
- Imported to region	-	-	2	1	-
Western Mediterranean					
- Transported within region	-	-	-	-	-
- Exported from region	-	3	7	8	7
- Imported to region	-	-	-	-	-
Eastern Mediterranean					
- Transported within region	4	8	12	15	21
- Exported from region	-	-	-	-	-
- Imported to region	-	2	3	3	2

Table 4-4 – Distribution of Captured CO_2 Emissions Transported by Ship

Figure 4-10 illustrates the modelled flow of CO_2 between and within regions for 2040.

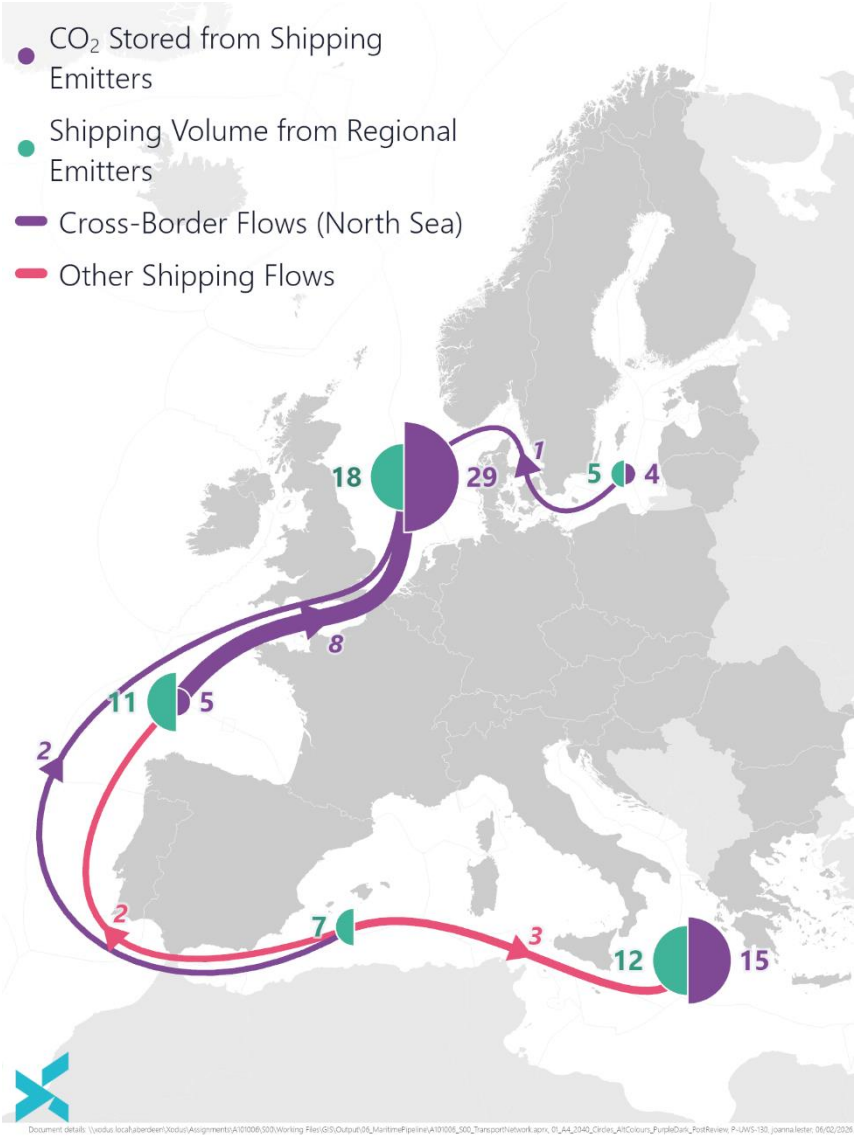


Figure 4-10 – Modelled Maritime CO_2 Shipping Flows: Import and Export Volumes Across European Shipping Regions in 2040.

The key modelling observations that can be drawn from this analysis are:

- North Sea is Europe's Primary CO_2 Sink
  The North Sea is the dominant receiving region, particularly for captured emissions exported from the Atlantic and West Mediterranean regions.
- West Mediterranean Remains Fully Export-Dependent
  The West Mediterranean region is the only area without early local storage, meaning all its early captured CO_2 is modelled to be transported to other basins. This continues through to 2050.
- Post-2040 Atlantic Shift Toward Self-Sufficiency
  As storage is modelled to open in Portugal and Ireland (post-2040), the Atlantic region becomes partially self-sufficient and begins to handle captured emissions exported from the West Mediterranean region.

4.4 Cross Border Considerations

As shown in the analysis detailed above, cross-border CO_2 shipping is a core feature of the European transport system, as many emitters must access storage located in other countries. The analysis suggests that the North Sea will remain the primary cross-border receiving region, consistently receiving CO_2 from the Atlantic, West Mediterranean, and Baltic regions. This reflects the concentration of planned and active offshore storage hubs in the UK, Norway, and the Netherlands.

Regions without early local storage, particularly the Atlantic and West Mediterranean regions, are expected to depend most heavily on cross-border routes until new basins (e.g. Portugal, Ireland, Adriatic/Greece) become available. Even as new sites come online, long-term contracts and storage capacity constraints mean that cross-border flows remain significant.

Overall, cross-border shipping drives the need for aligned regulations, liability frameworks, and port-to-port interoperability, ensuring CO_2 can move seamlessly between jurisdictions and into shared offshore storage hubs.

4.5 Port Estimate

The output of the analysis into the distribution of shipped CO_2 across the regions presented in section 4.3 enables a high-level estimate of the number of ports required in each region and how this could evolve over time.

This estimate has been developed by assuming a typical throughput for ports that export CO_2 via ship to other storage areas (emitter ports) with a separate typical throughput assumed for ports that receive CO_2 exported from other areas (store ports).

Economies of scale are a key factor in modelling the number and distribution of ports required across Europe. Cost modelling carried out in previous work by Xodus suggested that the unit cost of port infrastructure decreases significantly as throughput increases from small scale facilities to approximately 2-3MTPA [Reference 1]. Below this range, each additional tonne of annual capacity reduces average costs noticeably, creating a strong incentive in the model to gather CO_2 at shared export hubs rather than developing multiple smaller terminals.

Beyond roughly 3MTPA, the marginal benefit of additional scale is modelled to become modest. For larger ports, handling 4MTPA or more, the model suggests that the incremental reduction in unit cost per tonne of transported CO_2 is limited. Consequently, there is little economic justification for very large emitters to transport CO_2 over substantially longer distances solely to join an already large terminal. This economic signal supports consolidation, but not unlimited concentration.

These scaling effects suggest that regions with a very high emitter density, such as the Benelux area, could realistically support multiple export ports or terminals located within short distances of each other, because each could operate within the efficient 2-3MTPA range. In contrast, regions with more dispersed emissions, such as France, Spain, or southern Italy, are modelled to be more likely to consolidate around a smaller number of ports. This could be supported by short onshore collection pipelines that gather CO_2 from regional emitters, even when volumes are insufficient to justify full integration into a wider pipeline backbone.

The economies of scale are modelled to be less influential for ports that import CO_2 from ships for onward transport via pipeline to offshore storage sites. Their primary role is to optimise both pipeline-fed and shipping-fed emissions arriving for offshore storage. In our analysis, these ports are sized to be in the region of 8MTPA, which is equivalent to receiving around 530 ships per year (i.e. circa 10 per week) assuming an average vessel cargo of 15,000tonnes. This reflects the scale of throughput expected at major storage-facing terminals, particularly in the North Sea.

Table 4-5 and throughput ranges below reflect the capacity assumptions per port used to derive the overall number of ports required in Europe.

	CAPACITY PER PORT (MTPA)				
	2030	2035	2040	2045	2050
Emitter Port	2.5	2.5	3.5	3.5	3.5
Store Port	2	3	6	7	8

Table 4-5 – Assumed Handling Capacity Per Port

The modelling provides a high-level estimate of how many ports will be required across Europe to handle future CO_2 shipping demand. By combining aggregated shipping volumes with realistic scaling effects for export and import terminals, the analysis indicates that around 20–30 ports are needed continent-wide[1].

Modelled export port requirements vary by region, driven by the number of coastal emitters, their distance to storage, and the economies of scale associated with larger facilities. In contrast, major receiving regions, most importantly the North Sea, would be expected to benefit from consolidation, as a small number of high-capacity hubs can accommodate large volumes efficiently.

Overall, the model findings suggest that Europe will operate a limited network of high-throughput ports, supported by a smaller set of regional export sites, with port requirements evolving over time as pipelines expand and new offshore storage becomes available.

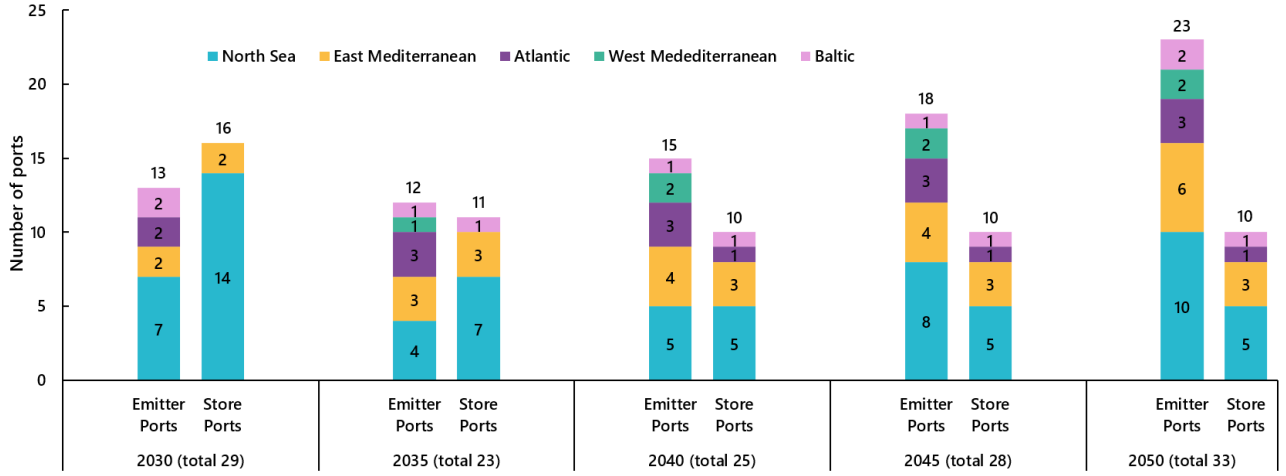


Figure 4-11 – Modelled Number of Ports Required

[1] *The apparent reduction in the number of North Sea Store ports between 2030 and 2035 is a function of the modelling methodology. The scaling factor increases by 50% over this period, while assumed shipping volumes decline as pipeline capacity expands. This outcome reflects the mechanics of the model rather than a forecast of an actual reduction in port activity or availability.*

4.6 Ship Estimate

The CO_2 shipping distribution analysis can also be used to develop a high-level estimate of the number of ships required over time within Europe to support the CCUS industry.

As previously discussed, it is anticipated that the cargo carrying capacity that will be deployed within Europe will range from circa 7,500m^3 to 22,000m^3. The following assumptions were used to calculate the number of ships required:

- Average ship cargo size: 15,000tonnes
- Average ship cruising speed: 15knots
- Ship onloading/offloading duration: 12hours
- Port mobilisation/demobilisation duration: 1-day
- Ship utilisation: 85%

The above assumptions, combined with the total quantity of CO_2 and the average trip distance estimated in the analysis of inter and intra-region shipping carried out in section 4.3 were used to estimate the number of ships required as shown in Table 4-6.

	2030	2035	2040	2045	2050
Shipping volume (MTPA)	32	32	53	66	79
Average distance (kilometres)	387	782	763	715	619
Number of 15,000 tonne ships required	**22**	**30**	**48**	**59**	**65**

Table 4-6 – Estimated Number of Ships Required

The above analysis suggests that there is likely to be a significant number of ships required to service the CCUS industry within Europe that increases over time but levels out in 2045-50. For context, the Northern Lights project has already put three 7,500m^3 ships into service and have recently placed orders for four 12,000m^3 ships that will be delivered within 3 years (i.e. one project is predicted to have 7 ships in service ahead of 2030). The established LPG shipping industry typically orders circa 120 ships per year worldwide.

This implies that there is capacity in the shipbuilding market to supply the number and scale of ships required to support the CCUS industry within Europe.

4.7 Key Findings from CO_2 Volume Assessment

Table 4-7 summarises the key findings of the CO_2 Volume Assessment modelling.

MARKET FORECAST	
2030	
Shipping Volume	• 40 – 48% of total European CO_2 CCUS transport • 27 – 32 MTPA of shipping volume
Infrastructure requirements	• 20 – 30 ports are needed across Europe • 20 – 25 CO_2 ships are needed to support the industry
Shipping Flow	• The North Sea emerges as dominant storage region, receiving all shipping flows from the North Sea, Atlantic and Baltic regions. • Mediterranean CO_2 shipping volumes remain limited relative to Northern Europe, reflecting the earlier stage of market development and infrastructure build-out, particularly in the Western Mediterranean.
2040	
Shipping Volume	• 22 – 32% of total European CO_2 CCUS transport • 35 – 53 MTPA of shipping volume
Infrastructure requirements	• 20 – 30 ports are needed across Europe • 40 – 50 CO_2 ships are needed to support the industry
Shipping Flow	• The Atlantic region both exports to the North Sea and imports from the Western Mediterranean, acting as the only European corridor with simultaneous import–export flows.
2050	
Shipping Volume	• 12 – 24% of total European CO_2 CCUS transport • 37 – 79 MTPA of shipping volume
Infrastructure requirements	• 20 – 30 ports are needed across Europe • 60 – 70 CO_2 ships are needed to support the industry
Shipping Flow	• The North Sea is the largest storage region for shipped volume and receive volume from the Atlantic and Baltic region. • The East Mediterranean is also a large market with 30% of the activity

Table 4-7 – Key Findings of CO_2 Volume Assessment Analysis

The analysis shows that there is a significant and consistent need for transport of CO_2 by ship between emitters and stores across Europe that will grow from 2030 to 2050. The scope and scale of the infrastructure required is challenging but is within that developed for analogue industries (e.g. the LPG or LNG industries) if the economic drivers for its development are in place.

5 CONCLUSIONS

Figure 5-1 illustrates the high-level options available to gather and transport CO_2 from emitters to offshore storage sites:

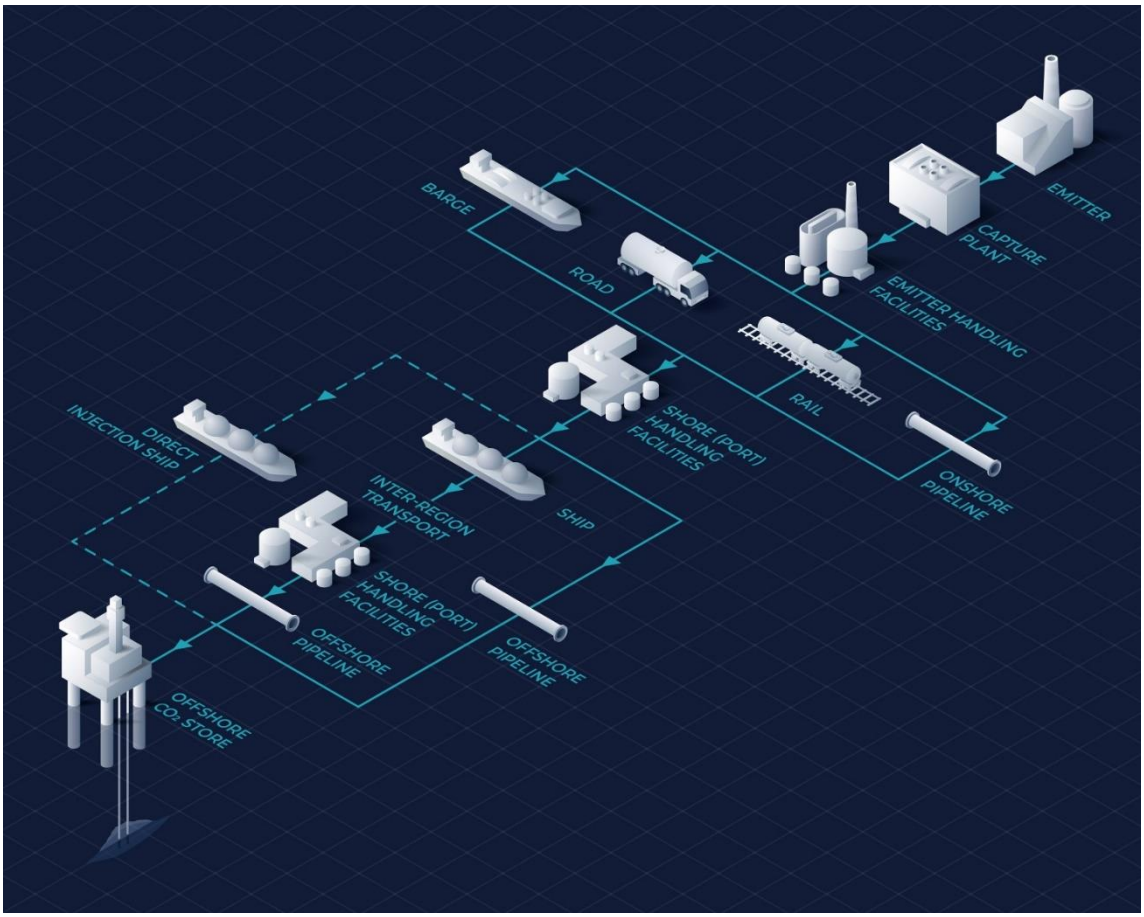


Figure 5-1 – CO_2 Transport Options

This study reviewed the following three main areas to gain insight into the potential for non-pipeline CO_2 transport within Europe:

- Technology Assessment: Assessment of the likely CO_2 storage and treatment infrastructure likely to be required for non-pipeline transport, including a high-level understanding of capital investment requirements for port infrastructure.
- Port Assessment: Assessment of the scale and suitability of existing port infrastructure across Europe (including the UK) needed to support gathering of CO_2 emissions from local industry and transport of those emissions to ports located nearby cost-efficient offshore CO_2 stores or to other ports located near to cost-efficient offshore CO_2 stores.
- CO_2 Volume Assessment: Assessment of the potential volumes of CO_2 emissions that may be transported between countries within Europe via ship and pipeline at 10-year time intervals from 2030 to 2050, with these volumes forming the basis for estimating the required number of ports and ships.

The key findings from the study are as follows:

Technology Assessment

- Most of the technologies required to enable a Europe-wide CCUS transport network are established and proven either in analogue industries (particularly the LPG transport industry) or directly in CO_2 service. There is a need to evolve those technologies in terms of scale and adapt them to CO_2 service at scale, but there are already examples of the technologies being used in industry, especially through the advent of the Northern Lights CCUS project.
- Non-pipeline transport does present a realistic alternative to pipeline transport for gathering captured CO_2 emissions prior to export to offshore storage sites:
  - Road tankers are particularly suited to small emitters who are located at distance from established CO_2 infrastructure. The transport of CO_2 by road is already established and CCUS can scale the use of CO_2 tankers quite readily. The use of road tankers is limited economically and logistically to relatively low volume of CO_2 transport over short distances.
  - Rail cars are also a potential route for non-pipeline transport using established technologies. They offer the potential to transport higher volume of CO_2 than road tankers over longer distances but the implementation of this transport route at scale could be constrained by competition with other rail users due the high utilisation of existing railway networks across Europe.
  - Barge transport could be considered for transport of CO_2 where emitters are located alongside major rivers. The size and scale of barges required to deliver effective CO_2 transport is likely to limit their use to major rivers, but there is the opportunity to service multiple emitters with common barges. Technologies from the LPG industry (where barges are used) will need to be adapted for use on CO_2 service but the theory of this has already been proven through the delivery of ship-based CO_2 handling systems.
  - Ship transport is already being implemented within the CCUS industry with projects such as Northern Lights relying on a fleet of ships to transport some of the emissions stored by the project to their gathering port. The technology required for these ships is analogous to that widely used for decades within the LPG industry for the transport of "semi-refrigerated" liquefied gases.
- Pipeline transport is the most cost-effective method for transporting CO_2 at high volume and over long distances but has a comparatively long lead time to implement.
- Non-pipeline transport does introduce technology challenges outside those that apply to pipeline transport of CO_2:
  - The handling of non-condensable gas impurities in captured CO_2 needs careful consideration across the full transport chain as the facilities required to maintain the comparatively low temperatures and pressures required for efficient non-pipeline transport of CO_2 may lead to conditions where a small amount of non-condensable gas (e.g. nitrogen, hydrogen, etc., plus trace amounts of CO2) will need to be periodically vented to atmosphere..
  - Composition requirements across the transport chain need to be considered to ensure that the most efficient balance is struck between the scope and scale of facilities required throughout the chain rather than enforcing potentially overly strict composition requirements on all emitters feeding into the chain.
  - NPT requires transfer of CO_2 between transport and storage at multiple points in the chain which can increase CO_2 losses due to small amounts being vented to atmosphere during each transfer process.
  - Metering and analysis of CO_2 is known to be a challenging area and is the subject of significant research and testing. Non-pipeline transport may have the potential to make this even more critical due to the multiple transfers between steps in the transport chain (e.g. emitter to land transport method to gathering port to ship transport to receiving port to pipeline to store).

Port Assessment

- All operating ports across Europe were assessed to investigate their potential for use in handling CO_2 transport.
- Approximately 850 ports were screened down to circa 200 ports by examining the size and scale of ships they currently handle compared to those that would likely be required for CO_2 ship transport.
- An analysis of the relative proximity of the 200 ports to predicted captured CO_2 emissions over time and identified offshore CO_2 storage sites to assess where ports may be ideally located to service both gathering of CO_2 from onshore emitters for export (termed "emitter ports") to remote transport hubs and gathering of those exported CO_2 flows for onward transport to offshore stores (termed "store ports").
- There was no need to apply modifying factors to the analysis to "promote" ports known to have an interest in CCUS or to have significant existing infrastructure that could be adapted to CO_2 transport as the ports assessed as being ideally located for CCUS service are generally in highly industrialised areas with extensive transport infrastructure and the potential for industrial capture of CO_2 emissions to be established in future.
- The analysis indicated that approximately 53 ports could be suitable for use as emitter ports by 2050 with 19 ports deemed to be suitable for use as store ports. 12 of the store ports were also assessed to be suitable for use as emitter ports resulting in a total number of 60 ports assessed to be suitable for use as part of a Europe-wide CO_2 transport chain by 2050.
- A large number of the identified "dual-purpose" emitter/store ports are in highly industrialised areas such as the Port of Rotterdam, Humberside, and Liverpool Bay.
- The scale and number of ports assessed provided good agreement with the number and spread of required CO_2 ports predicted by the CO_2 Volume Assessment in section 4, which performed a top-down analysis based on demand for CO2 transport by ship and a typical size of CO_2 transport port based on economies of scale.

CO_2 Volume Assessment

Key conclusions from the modelling analysis:

- CO_2 shipping could be a structurally essential component of Europe's CCUS network. Cost-based modelling confirms shipping's material role from 2030–2050, complementing rather than being displaced by pipelines as networks mature.
- Shipping modelled to handle a significant and persistent share of captured CO_2, around 40–48% (27–32 MTPA) of CO_2 transport in 2030. While this percentage decreases as pipelines expand, shipping still accounts for 12–24% by 2050 (~37–79 MTPA), reflecting sustained demand from dispersed, coastal, and late-developing capture regions.
- A hybrid pipeline–shipping system seems the most realistic long-term outcome. Pipelines dominate high-volume, short-distance corridors, while shipping remains essential for flexibility, resilience, phased deployment, and variable volume flows. Even pipeline-connected coastal regions see shipping serving a meaningful share of demand.
- The North Sea is modelled to be the dominant European CO_2 storage sink, receiving imports from the Atlantic, Baltic, and Western Mediterranean regions throughout 2030–2050 due to scale, maturity, and cost-competitive offshore storage.
- Cross-border transport is fundamental to the CCUS market. Many regions will rely on storage in other countries, particularly before 2040. Cross-border shipping thus becomes a defining feature, driving the need for aligned regulatory frameworks, port interoperability, and long-term international agreements.
- A relatively small number of ports could efficiently serve the European shipping market. Economies of scale suggest that around 20–30 ports (by 2050) are sufficient, with high-throughput receiving hubs (notably in the North Sea) supported by regional export ports.

- A dedicated CO_2 shipping fleet of substantial scale is expected to be required but achievable. The market grows from 20–25 ships by 2030 to 60–70 ships by 2050, a scale well within the capabilities of the established LPG shipbuilding and operations sector.
- Overall, CO_2 shipping represents a durable, investable market. The modelling suggests that non-pipeline transport is not just a transitional solution but a long-term element of European CCUS infrastructure, underpinning flexibility, enabling early deployment, and supporting a geographically diverse storage network.

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