XODUS

CCUS ENABLING INFRASTRUCTURE STUDY REPORT

Net Zero Technology Centre

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About the contributors

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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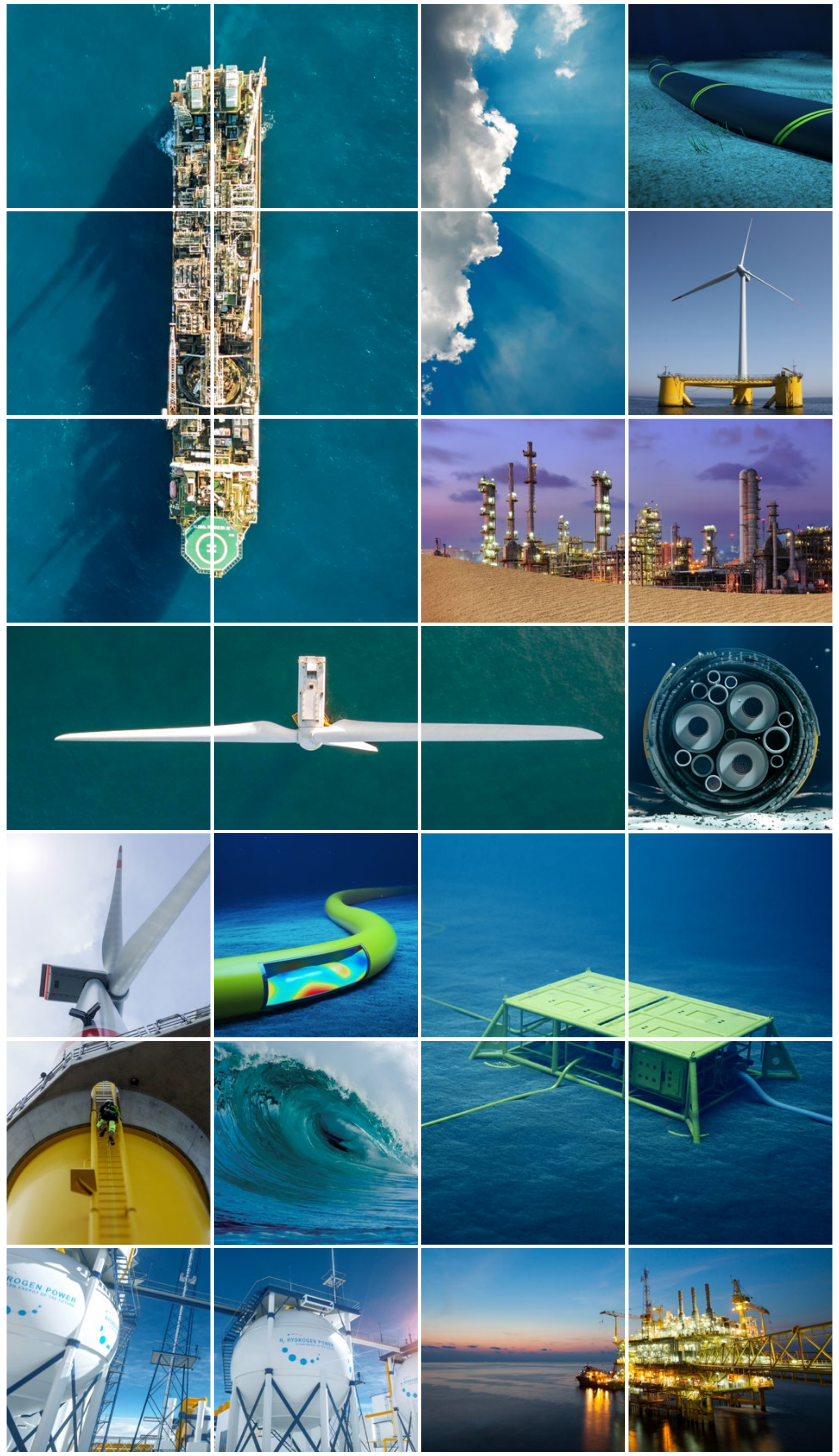

INTRODUCTION

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.

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 report 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 report.

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

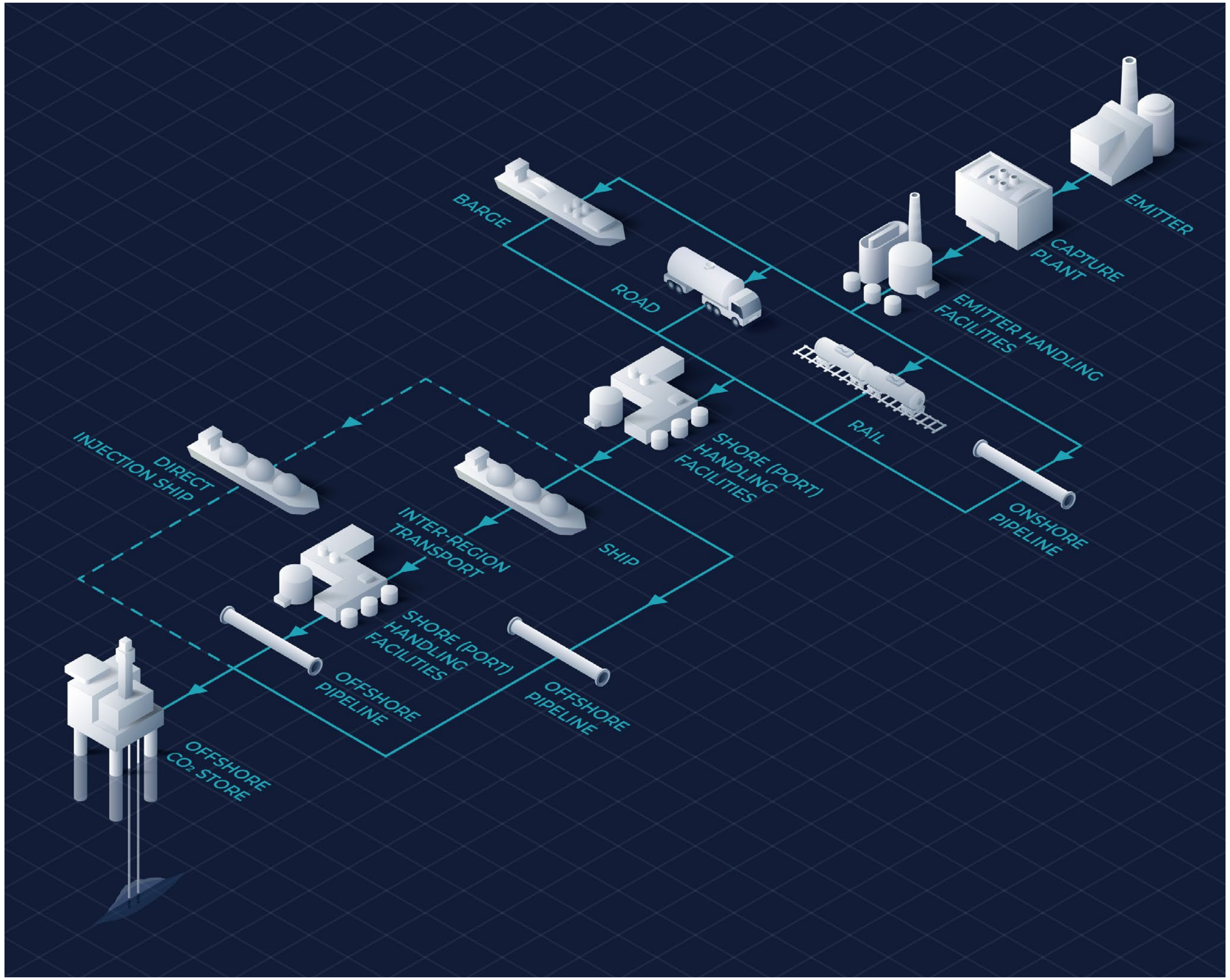

Figure 1 – CO_2 Transport Options

Figure 2 illustrates the geographic spread of identified potential CO_2 stores and potential captured emissions across Europe. The captured emissions points sources in the figure are translated from work carried out by the European Union Joint Research Council [Reference 2].

As is evident from Figure 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 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.

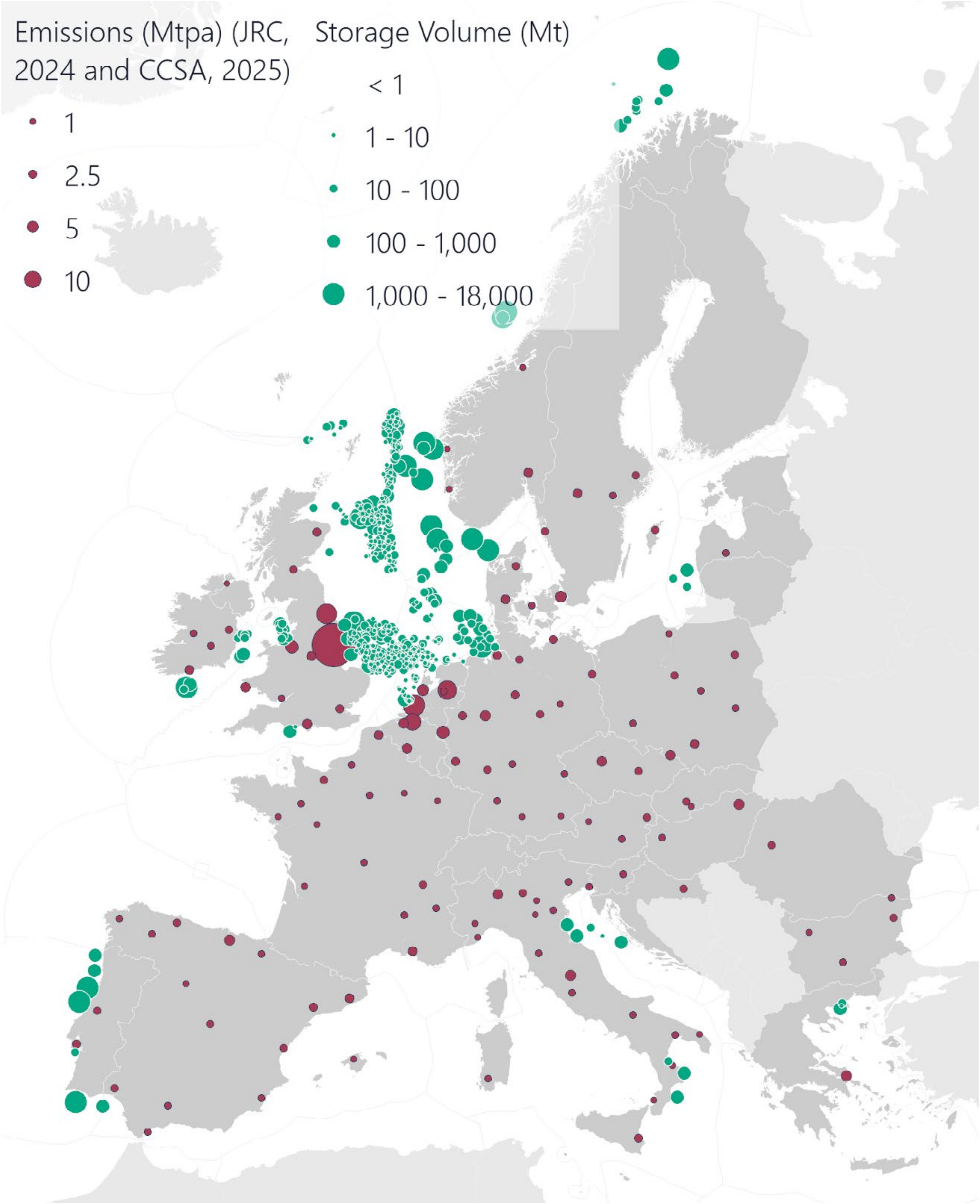

Figure 2 – Predicted Emissions Sources and Offshore CO_2 Stores in 2050

Data sourced from CCSA and JRC [Reference 1, 2], Xodus analysis for UK and Norway: 1. Accelerating a Europe-wide CO_2 storage market, CCSA, 2024, available online at https://www.ccsassociation.org/resources/download?id=6091
2. JRC Publications Repository – Shaping the future CO_2 transport network for Europe, European Commission, 2024, available online at: https://publications.jrc.ec.europa.eu/repository/handle/JRC136833

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 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. The use of road tankers is most suited to relatively low volumes of CO_2 transport.

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.

Rail cars are also a 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 route at scale could be constrained by competition with other rail users due the high utilisation of existing railway networks across Europe.

Ship transport is already being implemented within the CCUS industry with projects such as Northern Lights relying on a fleet of ships to transport captured CO_2 to a 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 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 CO_2) 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.
- Non-pipeline transport 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 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 1 illustrates the estimated most cost-effective method of onshore transport for captured CO_2 for a range of transport volumes and distances:

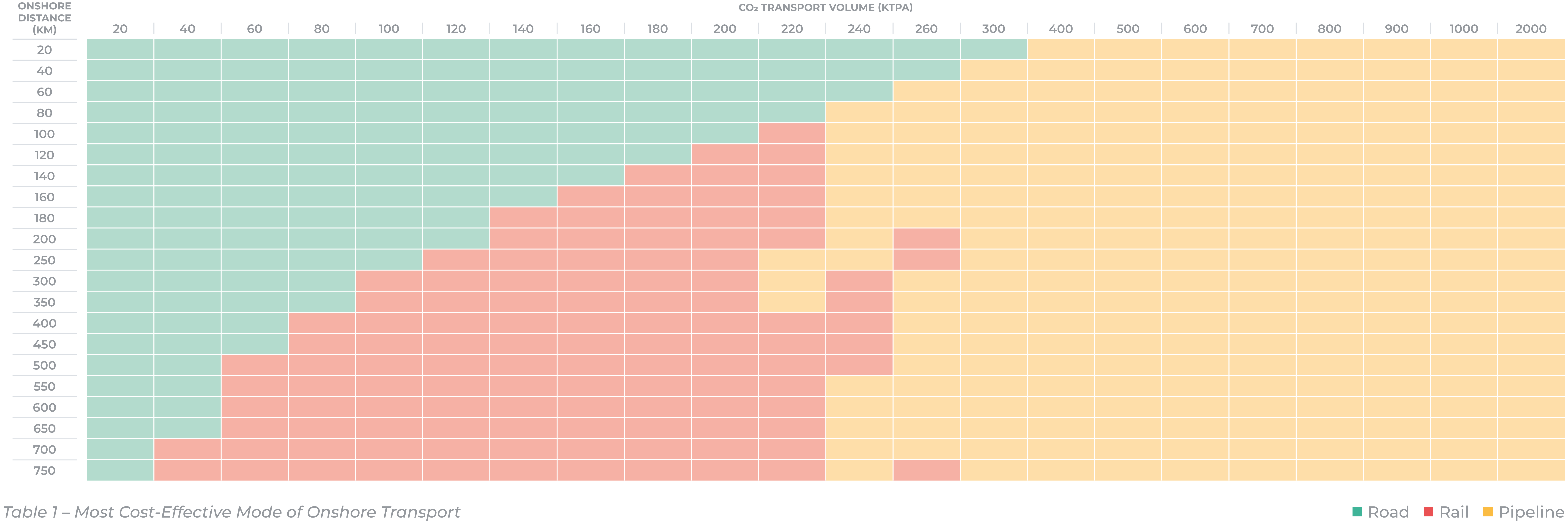

Table 1 – Most Cost-Effective Mode of Onshore Transport

PORT ASSESSMENT

A large number of ports across Europe are suitable for use within a future Europe-wide CO_2 transport chain with up to 60 ports being particularly well located to gather captured CO_2 emissions and route them to offshore geological storage by 2050.

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 assessment is indicative and is based on modelled outputs that don't take into account any existing commercial agreements, memoranda of understanding, or published development plants for emitters, ports or transport and storage operators.

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.

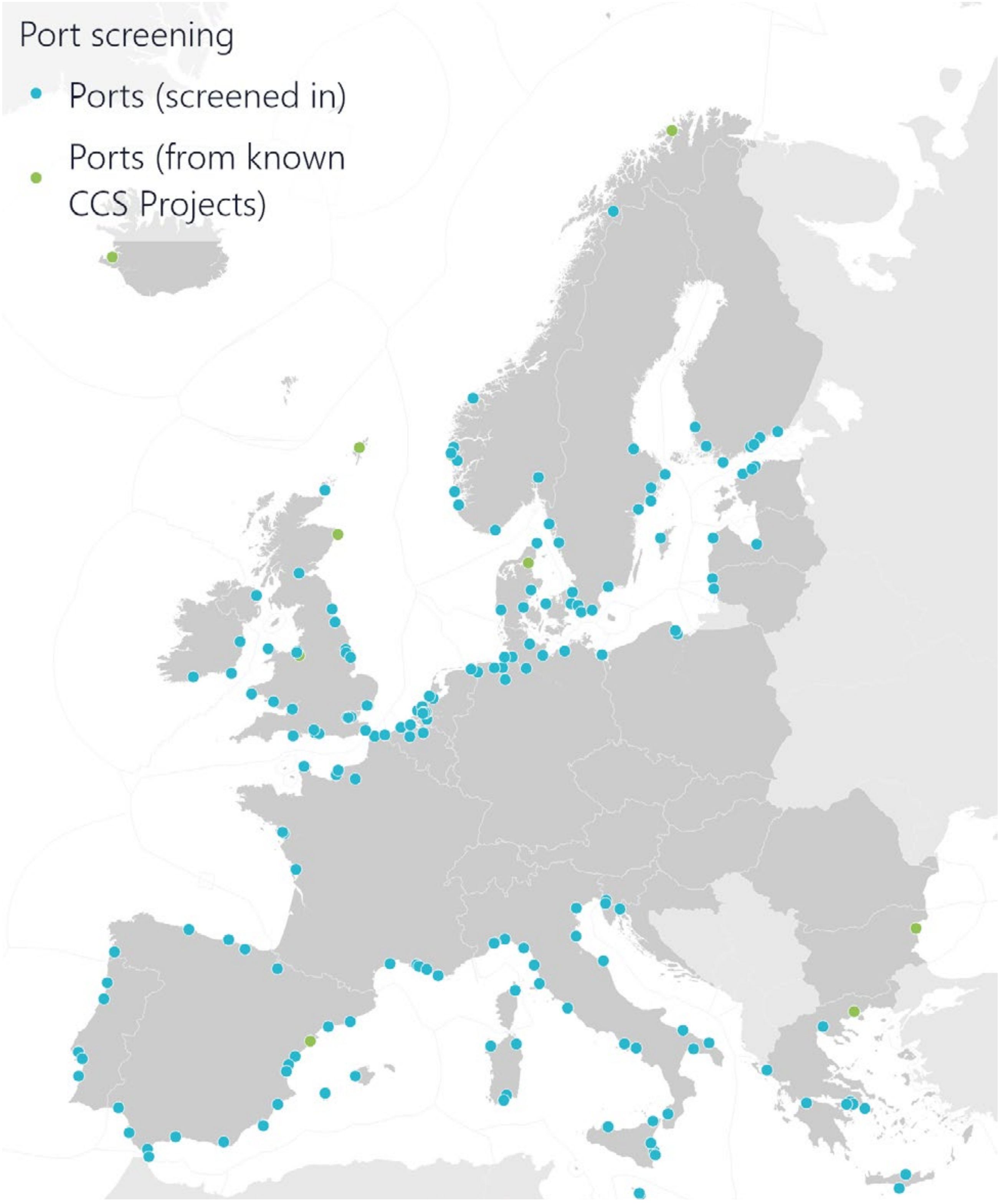

Figure 3 – Screening of Suitable CO_2 Transport Ports

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.

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.

Figure 4 – Evolution of Potential 'Emitter' and 'Store' Ports from 2030 to 2050

CO_2 VOLUME ASSESSMENT

Non-pipeline transport is predicted to play a significant part of a future Europe-wide CO_2 transport chain with up to 33 ports and 65 ships being required by 2050.

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.

This report 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.

Figures 5 and 6 show this evolution in the coming decades and illustrates how emitters would access a storage facility through shipping (maritime regions in blue) or pipeline (pipeline regions in orange), with the expectation that both approaches could co-exist in coastal areas (co-existence regions in green).

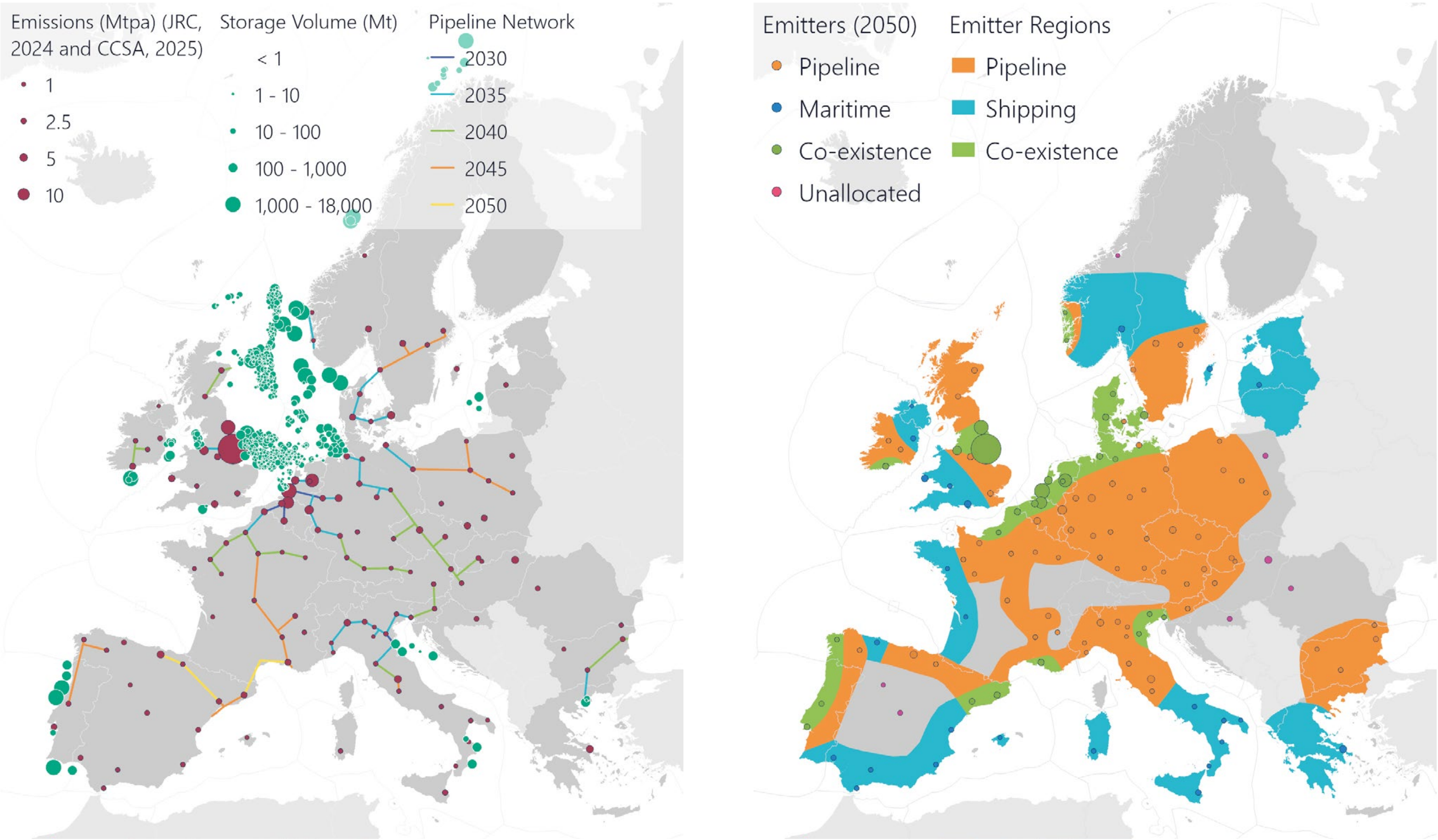

Figure 5 – Prediction of Overall Europe CO_2 Transport Network from 2030 to 2050

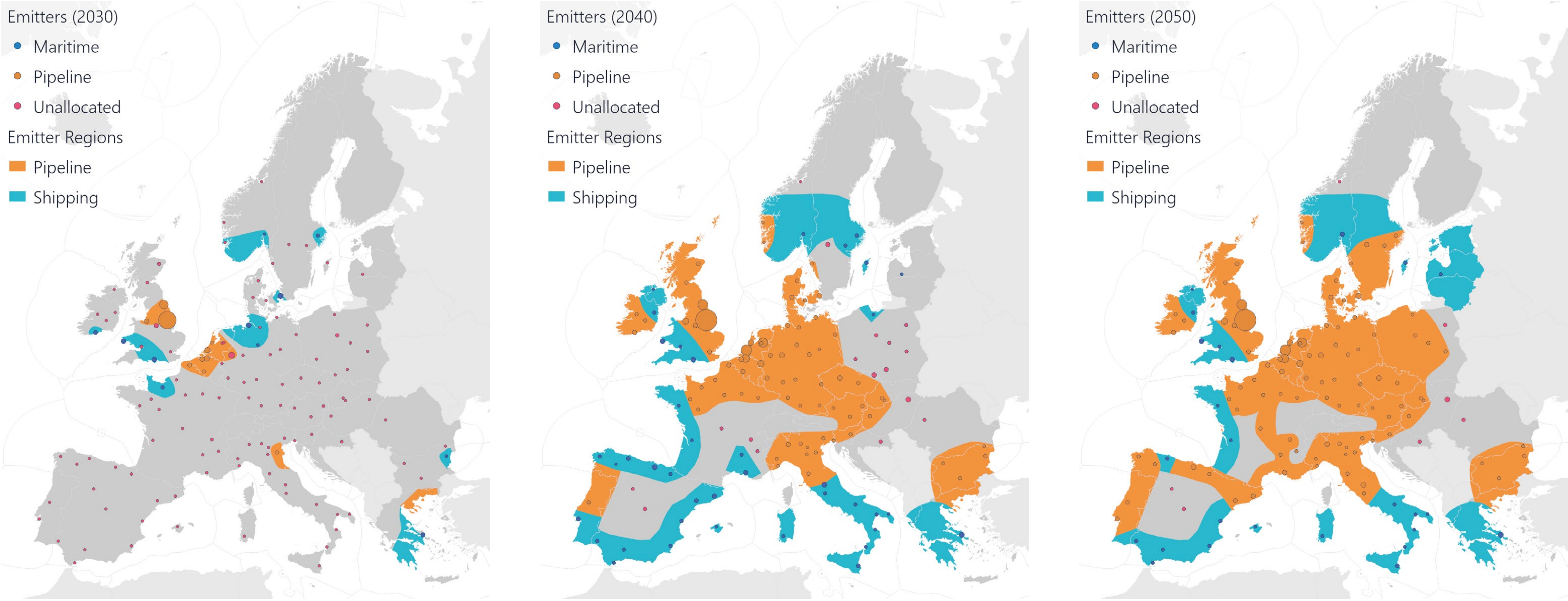

Figure 6 – Predicted Evolution of CO_2 Catchment Regions from 2030 to 2050

Our modelling suggests that, despite the market share for shipping decreasing over time, the estimated volume of CO_2 transported by ship will increase over time, with up to 79MTPA predicted by 2050.

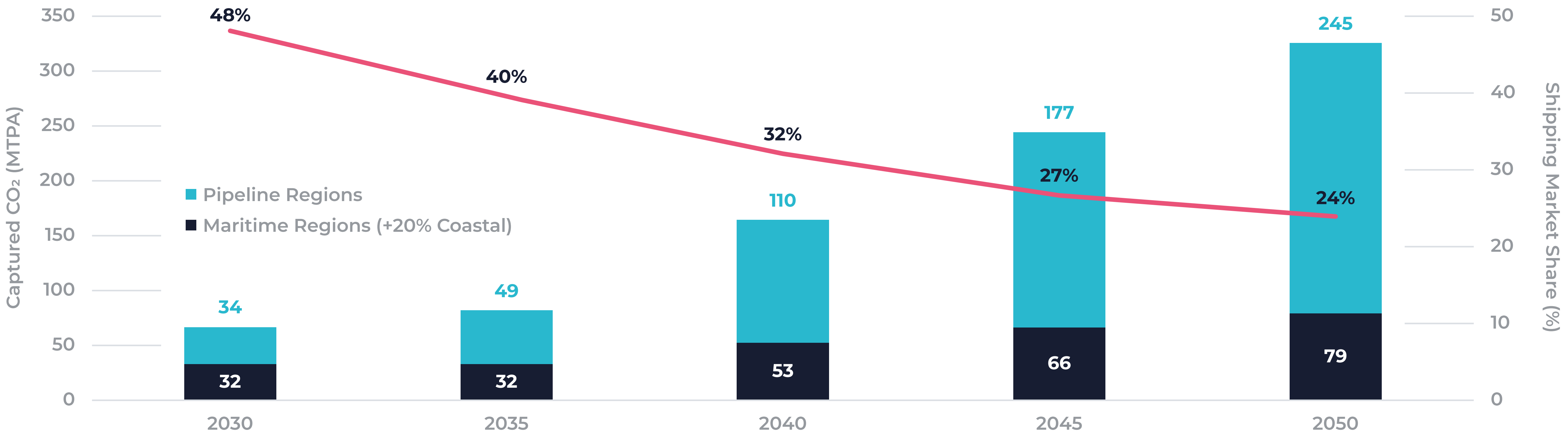

Figure 7 – Predicted CO_2 Shipping Market Share from 2030 to 2050

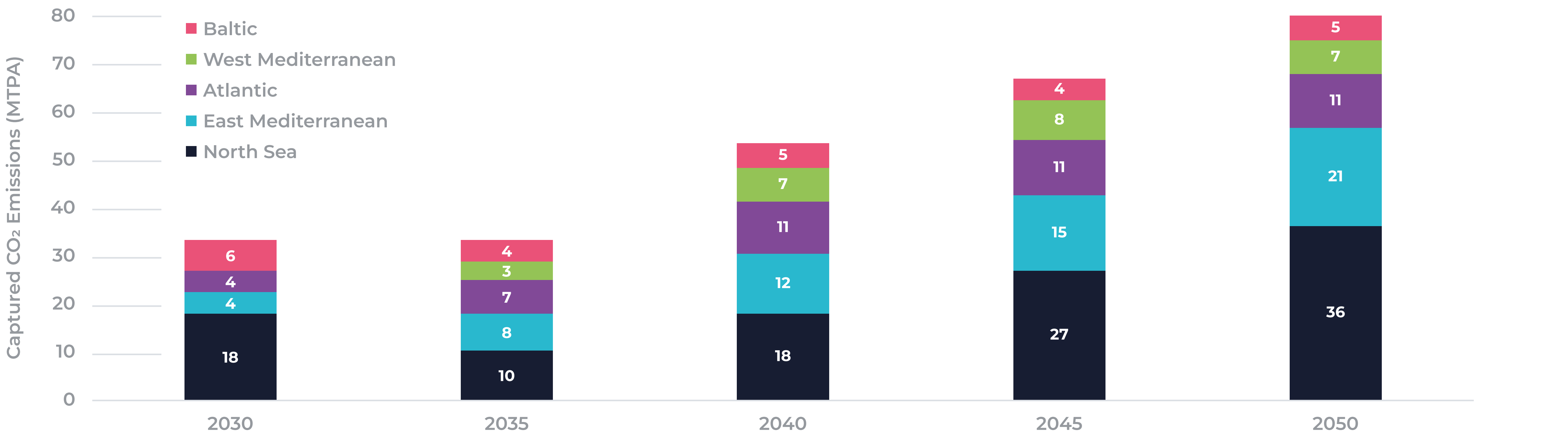

Figure 8 – Predicted CO_2 Shipping Volumes by Region from 2030 to 2050

The modelling 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.

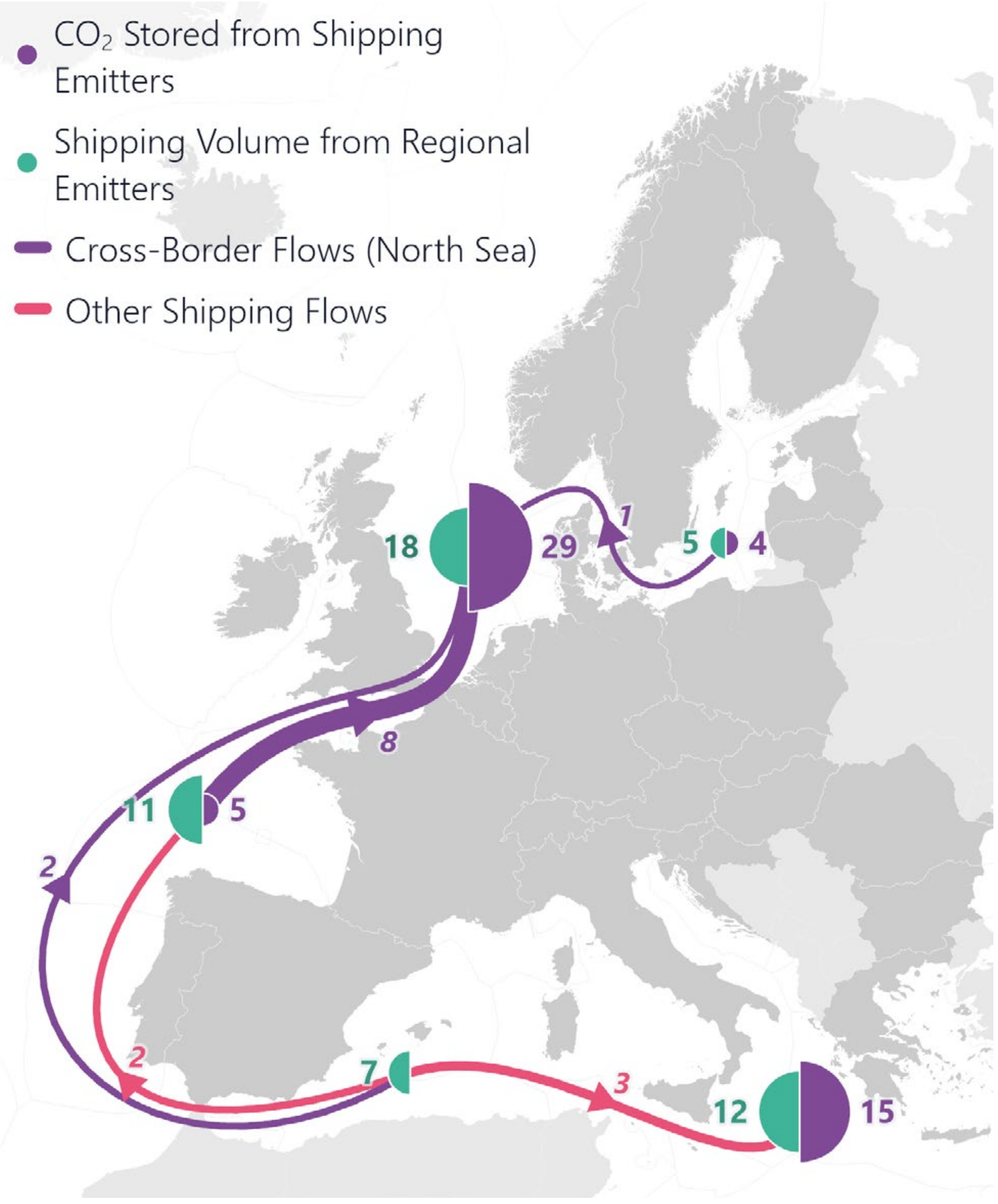

Figure 9 – Predicted CO_2 Shipping & Storage Flows in 2040

The number of ports and ships required to support this transport market is predicted to 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 15,000 tonnes per ship (which is roughly the mid-range of the ship sizes anticipated to be deployed within Europe). The modelling suggests that Europe will operate a limited network of high throughput ports, supported by a smaller set of regional export sites.

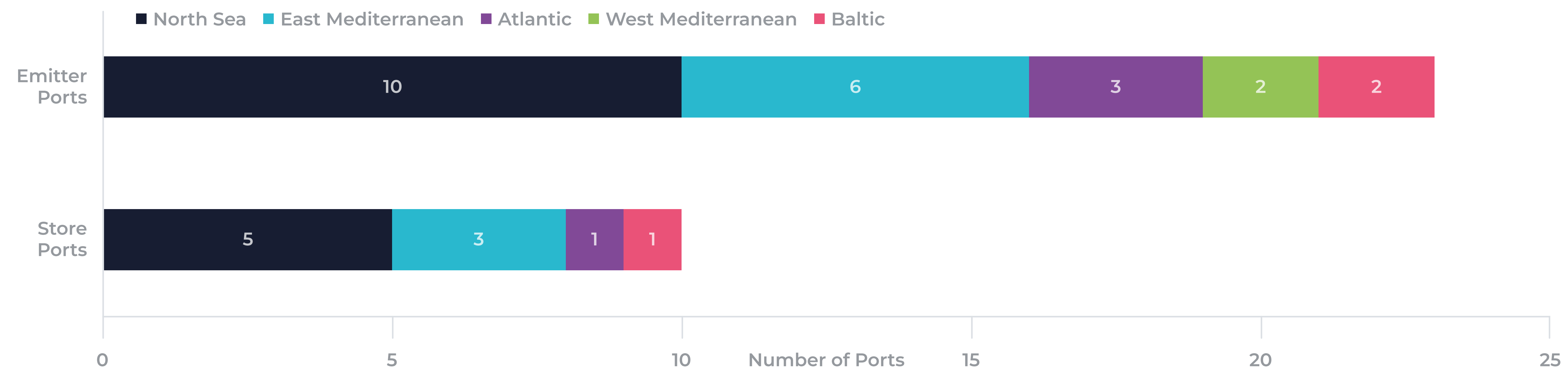

Figure 10 – Predicted Number of Required CO_2 Shipping Ports in 2050

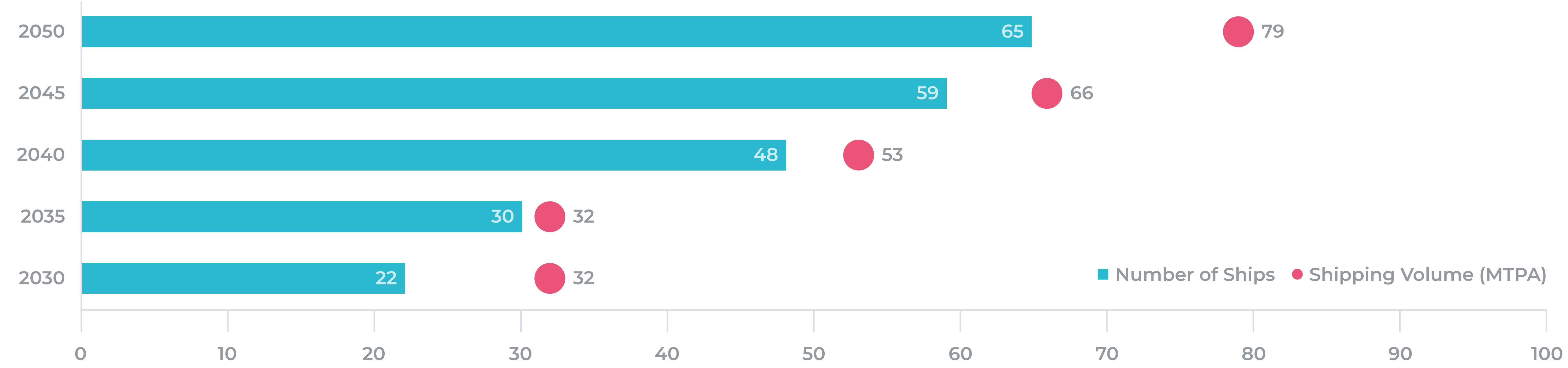

Figure 11 – Predicted CO_2 Shipping Volume and Number of Required CO_2 Ships

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.

KEY OUTCOMES

PROVEN TECHNOLOGIES

Most of the **CCUS transport technology** required for a Europe-wide network **already exists**, largely proven in the LPG sector and in early CO_2 shipping projects such as Northern Lights. The main challenge is scaling and adapting for large-scale CO_2 service.

INVESTMENT

Early shipping and port investments will help unlock offshore storage ahead of building out a large-scale onshore pipeline network for CCUS.

HYBRID NETWORK

The **combination of pipeline and non-pipeline transport** will bring flexibility to the overall CCUS industry. Pipelines will dominate high volume, highly industrialised corridors with shipping essential for flexibility, cross-border flows and helping to decarbonise regions where pipeline networks would not be competitive.

FOCUSED HUBS

We estimate that approximately **33 CO_2 transport ports** will be needed to support a Europe-wide CCUS transport network by **2050**.

SHIPPING

We estimate that a dedicated shipping fleet of approximately **65 CO_2 transport vessels** will be needed to support a Europe-wide CCUS transport network by **2050**.

NORTH SEA OPPORTUNITY

We predict that the **UK, Dutch, and wider sectors of the North Sea** will emerge as Europe's primary **offshore storage region**, with large-scale import from other regions.