Roadmap for a European offloading network

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Executive summary

The maritime sector emits approximately 1000 Mt CO_2 yearly, which accounts for nearly 3% of global emissions caused by humans. Several CCS projects are under construction and planning, and potential CO_2 storage sites, primarily in Northern Europe, are expected to start operation in 2025/2026.

While onboard CO_2 capture (OCC) has significant potential for decarbonizing the shipping industry, its implementation faces substantial challenges. These include cost, the variability of shipping operations, logistical barriers at ports, and technical requirements for CO_2 purity and solvent handling. Addressing these issues will require coordinated efforts across the maritime and CCS sectors, large investment in infrastructure, and the development of flexible, standardized solutions tailored to the needs of diverse vessels and ports. Without these measures, large-scale adoption of OCC will face significant hurdles.

Being one of the first ports to handle ships with onboard capture facilities poses a challenge, but also an opportunity. Ships that have investigated in OCC need ports to receive the CO_2 captured. The infrastructure that should be in place is the logistic route for CO_2 to be transported to storage or utilization. Ideally there should be a close correspondent to an CCS or CCU infrastructure at port, where the volumes of CO_2 would be high. In addition, a possibility to scale up the volume of CO_2 coming from the ships is desired. It is assumed that the cost for port infrastructure will be reduced due to the economy of scale.

The implementation of OCC represents a viable decarbonization measure that can be deployed immediately, as demonstrated in the EverLoNG project. However, several challenges must be addressed to enable its widespread adoption. Port infrastructure remains a critical bottleneck, with current facilities often unable to accommodate the specific requirements of CO_2 offloading and further transport. The relatively low volumes of CO_2 captured per ship, combined with long intervals between offloading and unpredictable volumes due to short-term contracts, add logistical complexity to the process. To overcome these challenges, initial initiatives should concentrate on large ports with existing infrastructure for CO_2 handling and transport. Additionally, the development of flexible offloading systems capable of accommodating various ship types and sizes is essential to ensure seamless integration of OCC into port operations. These steps are critical to realizing the potential of OCC as a key component of maritime decarbonization efforts.

Towards 2035

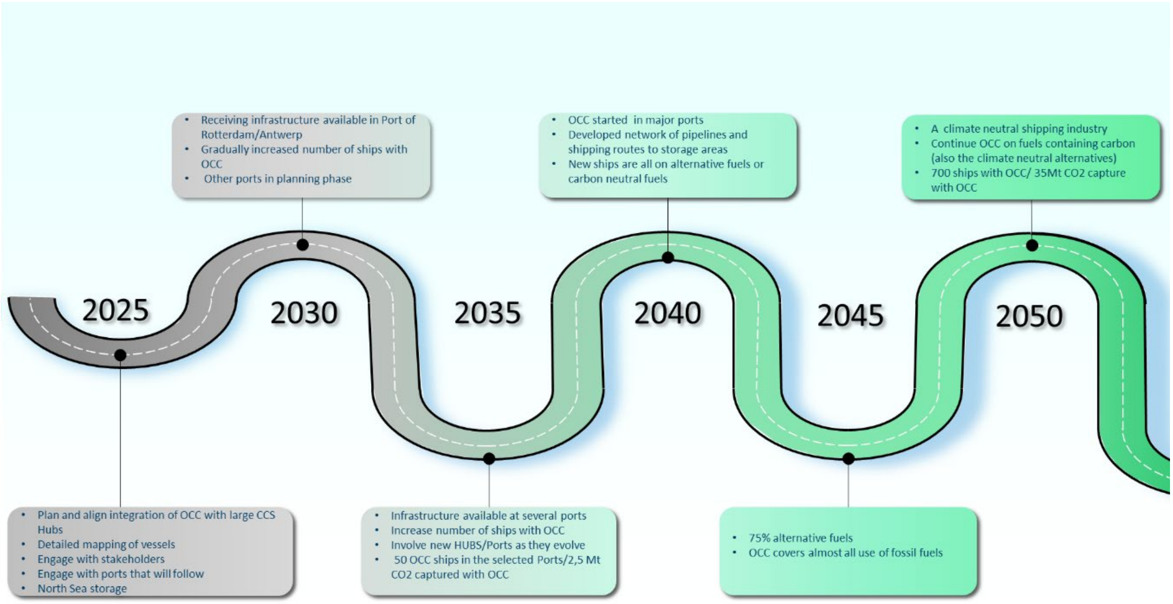
Early implementation of OCC should focus on regions with established or developing CCS infrastructure, particularly major European ports which are near CCS hubs. If OCC captures 50% of maritime CO_2 emissions from these ports, it could reduce Europe's shipping emissions by 8.5% (approximately 10-11 Mt/year). Standardization and logistics must be addressed, including CO_2 collection and transport systems. By 2035, the goal in the roadmap is to have 50 OCC-equipped ships capturing 2.5 million tons of CO_2 annually, with a few ports prepared to handle these operations.

Towards 2050

The expansion of OCC will depend on the adoption of alternative fuels such as ammonia, hydrogen, methanol, and methane. If fossil fuels remain in use, OCC will be essential for climate neutrality. By 2040, all major ports should have developed OCC infrastructure, and by 2045, nearly all fossil-fuel-powered ships should be equipped with OCC. If alternative fuels with carbon content (e.g., green methanol) become dominant, OCC could enable negative emissions through permanent CO_2 storage.

By 2050, the roadmap envisions 700 OCC-equipped vessels capturing 35 million tons of CO_2 annually. However, the final impact will depend on the pace of alternative fuel adoption, shipping industry growth, and regulatory developments. A detailed roadmap from 2025 to 2050 outlines key milestones for OCC implementation alongside broader decarbonization strategies, but is highly uncertain, and requires large investments and cooperation between stakeholders, ship owners and ports.

OCC implementation is feasible, but port infrastructure and logistics must be developed to facilitate widespread adoption. The suggested roadmap for OCC implementation to 2050 is showed below:



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1 Introduction

ACT (Accelerating CCS Technologies) is an international initiative to establish CO_2 capture, utilisation, and storage (CCUS) as a tool to combat global warming. EverLoNG is an ACT funded project that aims to encourage implementation of OCC by demonstrating its use on LNG-fuelled ships. The project has optimized and tested the technology and considered how to best integrate OCC into existing ship and port infrastructure. Demonstration of the technology on two different types of ships for nearly 2000 hours have been executed, and investigation on the integration of OCC at the ship. The project has also investigated the possible offloading alternatives and had several workshops and webinar with the industry stakeholders. Information from this work has been aligned and used in the development of this roadmap. A graphical representation of the EverLoNG project and its' scope is shown in Figure 1.

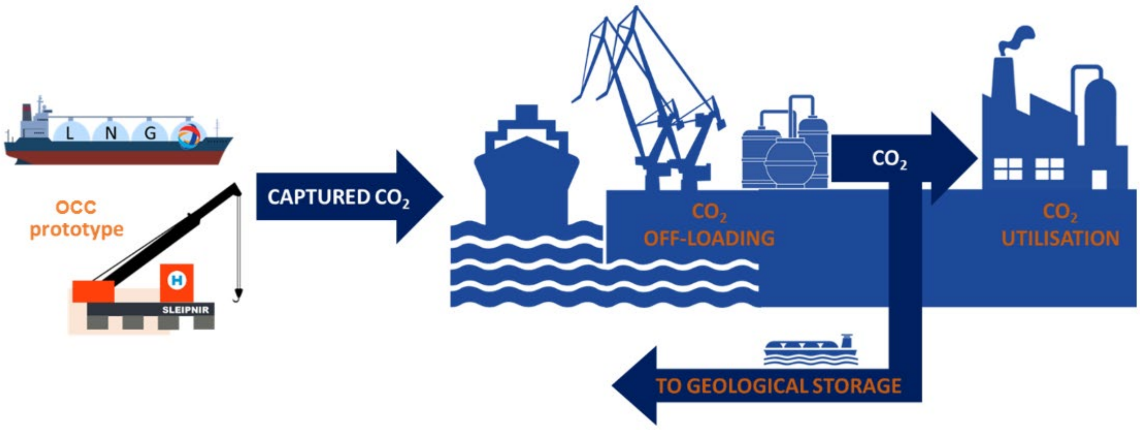

Figure 1 The scope of the EverLoNG project

This report serves as a roadmap towards developing a European CO_2 offloading network. The focus of the report is on the current situation and the development of an offloading network in Europe towards 2035. Beyond this, a possible further network development towards 2050 has been undertaken. The current and future European and global regulation and trends in the maritime sector forms the basis of the roadmap development.

1.1 Scope

There are several technological solutions that may reduce emissions from the maritime sector which are currently being explored. These are ship propulsion optimisation, fuel-shift, operational optimalizations and Onboard Carbon Capture (OCC). Ship optimisation includes improved engine efficiency, operation profile optimisation, wind assistance solutions, and air lubrication. Even so, retrofitting ships with alternative propulsion will only reduce fuels consumption and consequent emissions in a range of 5 to 20 %. For more information about alternatives to OCC, see e.g., CO2LOS III Final Report [1].

The focus in this report is on OCC and the importance of developing an efficient offloading network that can enable large-scale implementation of such a technology, while also considering the effect of other relevant emission reduction measures.

For OCC to contribute to emission reduction in a large scale, the captured CO_2 must be permanently removed from the atmosphere. There will therefore be limited focus on CO_2 utilisation pathways, as the CO_2 emission reduction potential will depend on the specific utilisation pathway adopted.

2 Regulations and trends in the maritime sector

An important aspect when developing a roadmap for a European offloading network is the current regulations that govern the maritime sector. In this chapter, the current and future regulations and trends are presented, and implications discussed.

In the Fourth Greenhouse Gas Study (2020) by the International Maritime Organization (IMO) emission projections towards 2050 were presented [3]. One of the scenarios indicated that the emissions from the maritime sector in 2050 could be as high as 130 % compared to 2008 [3]. According to Statista, CO_2 emissions due to international shipping to and from ports within the European Economic Area (EEA) was close to 130 $MtCO_2$ in 2022 [4]. Please note that the emissions are the total CO_2 emitted from ships with ports of call also outside of Europe.

2.1 Regulations and trends

The maritime sector operating within the EU, is from January 2024 for first time included into the EU-ETS. The implementation is gradual, and in the initial phase ships ≥ 5 000 Gt would need to acquire the sufficient allowance *"to cover 40% of their fleets' 2024 tank-to-wake (TtW) carbon dioxide (CO_2) emissions in 2025"*, 70 % of 2025 emissions in 2026, and 100 % from 2027 onwards. This EU Action covers 50 % of emissions for voyages that start or ends outside of the EU, while 100 % of emissions for voyages between ports and at berth [2]. The EU ETS covers CO_2, CH_4 and N_2O emissions, but the two latter only from 2026. In March 2025, the ETS is approx. 70 €/tCO_2, but has been varying between 20 €/tCO_2 to 100 €/tCO_2 within the last 5 years.

Alternative emission reduction measures are also likely to be implemented and to a degree reduce the need for OCC. An alternative or complementary to OCC is fuel switch. The FuelEU Maritime Regulation should facilitate for a fuel-switch in the maritime sector to renewable and low-carbon fuels. This regulation is a part of the "Fit for 55" package where the EU aims at a net reduction in greenhouse gas emissions of 55 % by 2030 compared to 1990 and climate neutrality by 2050 [5]. According to EU prospects this will in turn increase the incentive of renewable and low carbon fuels, the reduction on GHG fuels will increase gradually starting at 2% in 2025 to 80% in 2050, see Figure 2

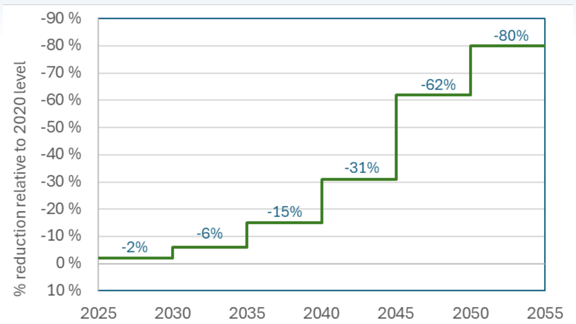

Figure 2. EU projection maritime fuels reduction, modified from [6]

In 2023, the IMO strategy on reduction of GHG (greenhouse gas) emissions from ships from 2018 was amended [7]. This amendment was made to further strengthen IMO's contributions towards the Paris Agreement. The IMO has very ambitious plans on cutting GHG emission towards 2050, it considers a final goal of Net Zero GHG emissions. The route contemplates increase energy efficiencies, design of new ships and retrofitting of current ones, setup regulations and mechanisms to reduce the CO_2 emissions per transport work, thus setting categories (A-E) and forcing to action vessels with a high-than average emissions by work (e.g. emissions by tonnage transported), and the introduction of Net Zero GHG emissions fuels as hydrogen, ammonia, also biofuels and ethanol.

The IMO goals are:

-2030 goals: 40% reduction per transport work compared to 2008 – 5% uptake zero emissions fuels and striving for 10%.

-2040 goals: indicative check point 70% reduction of the total annual GHG but striving for 80%.

-2050 goals: Net Zero GHG emissions.

Traditionally, the IMO has looked at CCS beneath the seabed, also focusing on geoengineering to promote Ocean CO_2 capture. Just recently, the IMO is looking at onboard carbon capture (OCC) by considering several technologies and how its regulation might be accommodated within IMO's regulatory framework.

In general, very strong regulations are in effect by the EU, while prospects are clearly defined by organisations as IMO, as main maritime actors have also their own projections. Undoubtedly, the main target is the gradual reduction of the use of fossil fuels, thus the need for OCC will be decrease to zero if shipping where to achieve its ambitious goal.

3 Port - ship integration

Ports play a crucial role in advancing onboard carbon capture (OCC) technology. There is a pressing need for new infrastructure, both regarding CO_2 operations of unloading, loading and storage, but also for solvent handling. Expanding OCC capabilities entail a variety of technical and logistical challenges that must be effectively addressed to enable widespread adoption. The figure below provides an overview of the necessary infrastructure at port to support vessels equipped with onboard carbon capture with amine technology. The captured CO_2 needs to be offloaded, and also the solvent required to capture the CO_2 should be offloaded, reclaimed, and loaded to the ship again. Both handling new solvent and disposal of used solvent is infrastructure that is needed at port.

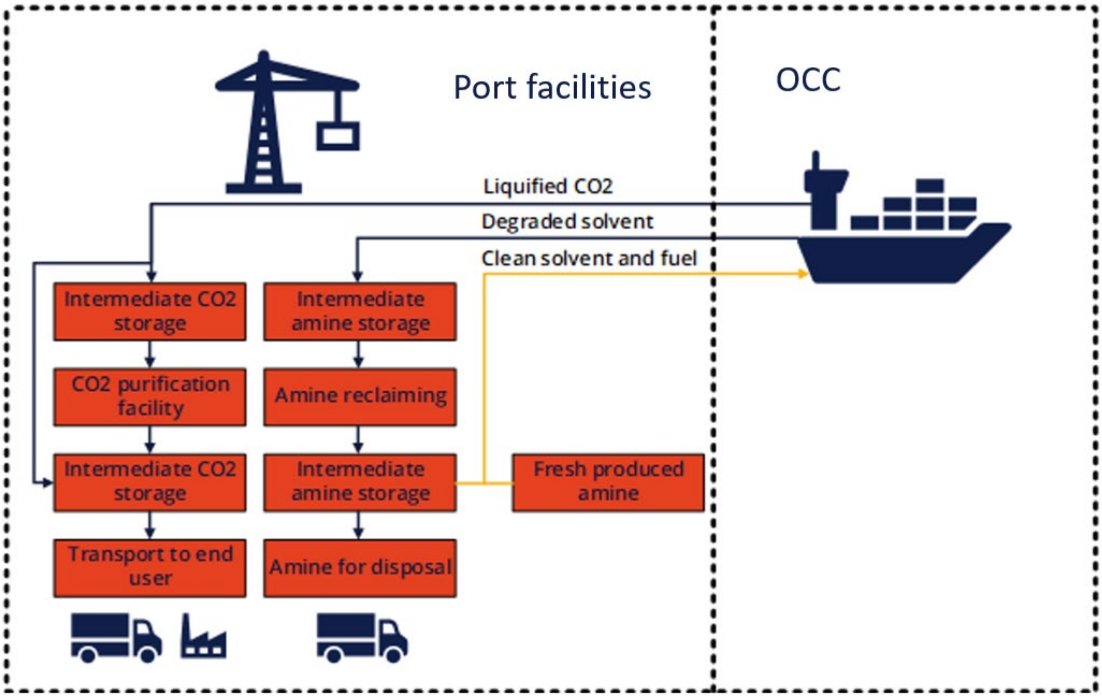

Figure 3. Infrastructure at port

3.1 Offloading strategies and interaction between ships and ports

CO_2 capture from ships will typically be in a range of 1000- 5000 tonnes per voyages [8] depending on the ships size, capture rate and travel distance. This chapter focuses on the transfer from the onboard storage to port, and can mainly be divided in two, ship-to-ship or ship-to-shore. By ship to ship, the CO_2 is offloaded to "collector" ship, designed to lay a side of the OCC ship, and receive CO_2. After the tankers in the receiving ship is full, the "collector" ship will go to a separate offloading quay and offload. One of the benefits with this solution, is that the OCC ships does not have to go to a dedicated CO_2 quay to offload CO_2 but can offload CO_2 at the same quay and time as the main cargo. The "collector" ship may go to different types of OCC ships and can reduce the need for infrastructure at quay to collect the CO_2 into one intermediate storage. An alternative to offloading to a ship, is to offload direct to the quay. This alternative is mainly the solution for smaller ports with few quays.

The project has investigated different types of offloading the CO_2 from the ship, see deliverable 2.1.1 Offloading alternatives in the EverLoNG project. The CO_2 may be pumped out from the onboard storage with hoses or loading arms, or the onboard storage itself can be transferred from the ship to shore. Container swap, where the CO_2 is stored in ISO container sized tanks at the ship, can be offloaded from the ship to the shore by large cranes that are design for cargo handling. For OCC at container ships, that system requires no extra infrastructure for offloading the CO_2. It may also be easy to perform transfer with trucks, railways or other ships. There might be challenges with the number of valves if a large number of containers are needed.

Another alternative for offloading is to store the CO_2 in large storage tank(s) and offload it through process piping and/or flexible hoses. This concept is operational today both for CO_2 and other gases like LNG. The gas is pumped direct to shore or via a collecting ship that serves as a transit to the storage tanks in the port. To maintain the pressure and temperature in the onboard tanks when the CO_2 is offloaded, a return line with CO_2 in gas phase is included in the system.

A third method for offloading is skid mounted storage tanks that can be placed onboard in a let-down area. When the ship arrives to the port, the storage tank is lifted to shore and replaced with an empty or near empty tank to remain the pressure/temperature. These tanks may be larger and with an optimal design for the CO_2 handling compared to the standard ISO tankers.

3.2 Ports with CO_2 infrastructure under development

The port infrastructure needs to be sized according to the varying load coming from offloading the ships, and that is a much larger design than a steady CO_2 flow. This increase both the cost and complexity of the infrastructure. Designing the port receiving facility for one ship alone, will require a large CO_2 infrastructure that is operating discontinuously, dependant on how often the ship will offload their CO_2. Two large ports in Europe, Port of Antwerp-Bruges and Port of Rotterdam, have already suggested plans for their CCUS infrastructure, in both short- and long-term perspective. These ports have focused their infrastructure as a HUB, mainly for CCS/CCU projects from land-based industry. CO_2 from OCC may be one of the sources for such a HUB.

The Antwerp@C CO_2 Export Hub (https://www.fluxys.com/en/projects/antwerp-export-hub) is a large-scale carbon capture and export project led by Air Liquide, Fluxys Belgium, and the Port of Antwerp-Bruges. The initiative has (per Dec 2024) received €144.6 million in EU funding under the Connecting Europe Facility for Energy (CEF-E) to develop shared CO_2 transport and export facilities.

Port of Antwerp is Europe's second largest seaport with more than 300-line services to over 800 destinations ensure global connectivity. The Port of Antwerp annually handles around 240 million tonnes of international maritime freight and is home to Europe's largest integrated chemical cluster. The project Antwerp@C CO_2 Export Hub will establish an open-access infrastructure to collect, transport, liquefy, and export captured CO_2 from industrial sites within the Antwerp port platform. The captured CO_2 will be transported through a dedicated pipeline network to a shared terminal, where it will be liquefied and stored before being loaded onto ships for cross-border transport to offshore permanent storage sites. The terminal will feature a CO_2 liquefaction unit, buffer and storage tanks, and marine loading facilities, making it one of the first and largest multimodal CO_2 export hubs in the world. It is possible also to include CO_2 loads from ships entering the port.

The Port of Antwerp-Bruges will provide land and quay infrastructure to support the facility. The project's first phase will have an initial export capacity of 2.5 million tonnes per year (Mtpa), with ambitions to expand to 10 Mtpa by 2030. This initiative is part of the broader Antwerp@C project, which includes major industrial players such as BASF, Borealis, ExxonMobil, INEOS, and TotalEnergies, with the goal of reducing CO_2 emissions in the Antwerp port area by 50% by 2030. The infrastructure is designed to be scalable and modular, enabling further CCS adoption in the region.

As one of the first large-scale multimodal CO_2 export facilities, the Antwerp@C CO_2 Export Hub represents a major milestone in Europe's efforts to establish a sustainable carbon capture and storage network.

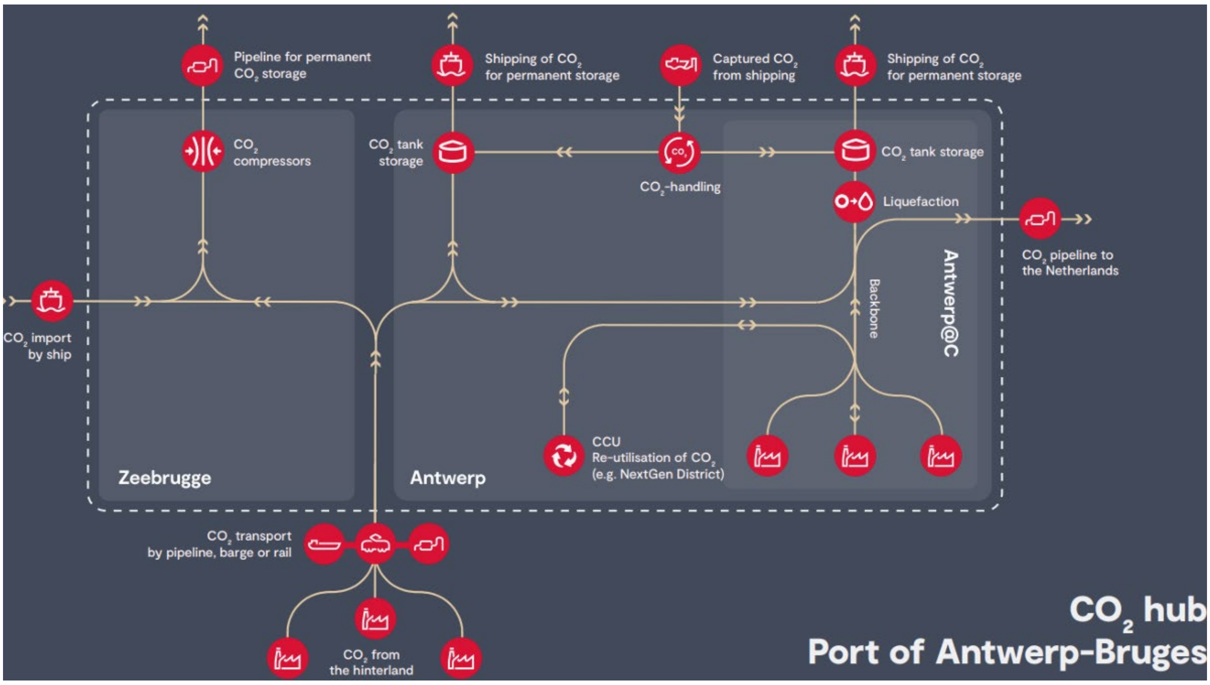

Figure 4 Planned CO_2 hub in Port of Antwerp-Bruges.

Porthos, which stands for Port of Rotterdam CO_2 Transport Hub and Offshore Storage, is a project that intends to provide infrastructure to energy intensive industries in the Port of Rotterdam and possibly to industries in the Antwerp and North Rhine Westphalia areas at a later stage. The project will link the CO_2-capture facilities and the existing Organic Carbon dioxide for Assimilation of Plants (OCAP) pipeline with a new onshore pipeline which will drive the aggregated CO_2 into a CO_2-hub in the Port of Rotterdam, and subsequently via an offshore pipeline in a depleted gas field 20 km off the coast for permanent storage. It is foreseen that stored CO_2 from ships arriving the port may also have access to this infrastructure. As the distances are large in this port, the location of the quay for CO_2-offload is of importance regarding the cost for accessing the Porthos infrastructure [9].

3.3 Port/ship challenges

Onboard Carbon Capture represents a promising solution for decarbonizing shipping, yet it faces several critical challenges. These challenges arise from the unique characteristics of the shipping industry as operational unpredictability, ships low yearly emission volumes, logistical complexities with long time between offloading and unpredictable routes and time in actual service, and the demanding requirements for CO_2 handling and storage. Some of these challenges are discussed below:

- **Diversity in ship operations and infrastructure**

The global shipping industry comprises a wide variety of vessels with differing sizes, designs, cargo types, engine types, and fuel consumption patterns. This diversity complicates the design and standardization of OCC systems, as each vessel may require tailored solutions to meet its specific operational needs. Additionally, many shipping routes and schedules are highly dynamic due to short-term charter agreements, leading to unpredictable routes, cargo types, and CO_2 volumes. These operational uncertainties make it challenging to optimize OCC systems for individual ships and integrate them into existing shipping practices.

- **Low CO_2-emission volumes per ship**
  The relatively low yearly volumes of CO_2 captured per ship compared to industrial CCS pose challenges for further transport and storage. Unlike large industrial emitters that generate high, consistent CO_2-emission volumes, individual ships produce smaller quantities, which may not justify the cost or complexity of regular CO_2 offloading. Long intervals between port calls exacerbate this issue, making efficient collection and storage infrastructure essential.

- **Port infrastructure and flexibility**
  Large shipping ports are highly diverse, with multiple terminals catering to different vessel types and cargo operations. Developing flexible CO_2 receival facilities that can handle various ship designs, volumes, and offloading intervals is essential but challenging. Additionally, ports must integrate OCC operations without disrupting existing routines, which requires careful planning of activities and investment in adaptable infrastructure.

- **CO_2 infrastructure and logistics**
  Access to CO_2 infrastructure, such as pipelines, intermediate storage, or transport facilities, is critical for OCC's success. Almost all ports lack this infrastructure, as carbon capture and storage (CCS) is not yet well-developed. Large-scale deployment of OCC would require significant expansion of port facilities and downstream handling networks, potentially delaying implementation.

- **CO_2 quality and stream purity**
  Strict purity requirements for CO_2 streams create technical challenges for OCC. Mixing CO_2 streams from different vessels, which may vary in composition due to operational or system differences, could result in non-compliance with storage or utilization standards and the need of purification processes. This challenge is particularly relevant for ports handling multiple ships with different capture technologies or fuel types.

- **Absorbent reclaiming and compatibility**
  Onboard carbon capture systems utilize various solvents, such as amine-based solutions or newer advanced formulations, each with distinct requirements for regeneration, disposal, and maintenance. The lack of standardization across solvent types and capture technologies makes integration across multiple ships challenging, as the port cannot have several different solvents available at quay.

- **Large-scale deployment considerations**
  If OCC were adopted on a large scale, the cumulative challenges would become even more pronounced. Ports would need to scale up infrastructure to accommodate increased CO_2 volumes, manage diverse vessel requirements, and maintain high levels of operational efficiency. Coordination between shipping companies, port authorities, and CO_2 transport and storage operators would be critical to ensure smooth operations.

- **Handling chemicals at the port**
  The ports need to condition and purify both the CO_2 and solvent, and the process plant for this requires personnel with the needed expertise.

All these challenges should be addressed to roll out large scale of OCC. The following roadmap takes these challenges into account and shows how one possible way to start the OCC technology.

4 Port selection

4.1 Port selection criteria

It is not expected that all ports will need to develop or should be required to provide infrastructure for receiving CO_2 captured through onboard carbon capture (OCC) technology. The decision to establish such facilities will depend on various factors, including the strategic and logistical feasibility of implementing CO_2 reception infrastructure at a given port. Several key criteria are being considered in selecting suitable ports for this purpose:

- **Proximity to CO_2 Transport and Storage Networks**: Ports that are located near existing or planned CO_2 transport infrastructure, such as pipelines or shipping routes dedicated to CO_2 transport, and permanent storage facilities (e.g., geological storage sites) will be more viable candidates. Close integration with these networks will facilitate efficient handling and long-term sequestration of captured CO_2.

- **Port Size and Economic Significance**: The relevance of a port for CO_2 reception may be assessed based on its overall size and economic activity. Metrics such as total maritime traffic volume, throughput (measured in tonnes or TEUs for container ports), and the port's role in regional or global trade networks will be considered. Larger, high-traffic ports are more likely to serve as key hubs for CO_2 reception due to economies of scale and greater operational capacity.

- **Strategic Planning and Commitment**: The port's own vision and strategic development plans regarding CO_2 infrastructure will play a crucial role in selection. Ports that have already committed to sustainability initiatives, decarbonization strategies, or partnerships with industries involved in carbon capture and storage (CCS) may be prioritized. Existing plans for infrastructure investment, policy frameworks, and willingness to collaborate with stakeholders will also be taken into account.

- **Frequency of OCC-Compatible Vessel Calls**: Ports with a high frequency of visits from ships that are expected to adopt onboard carbon capture technology will be more suitable candidates. This includes considering current and projected vessel traffic patterns, the proportion of ships operating on routes where OCC is likely to be implemented, and engagement with shipping companies exploring OCC adoption. The potential demand for CO_2 offloading services will be a determining factor in infrastructure investment decisions.

By evaluating ports against these criteria, authorities and industry stakeholders can ensure that CO_2 reception infrastructure is strategically developed in locations where it will be most effective and economically viable. The EverLoNG project has developed a Port readiness tool that may give an indication of what parameters that should be in place to develop a port with the required infrastructure for receiving CO_2 from ships.

4.2 Major European ports

4.2.1 Main European ports by tonnage

Information regarding ports is highly dynamic and undergoes significant changes from year to year, reflecting the variable nature of maritime transport. For instance, in 2024 the Port of Antwerp-Bruges grew (TEU) over 4% which did double the growth of Rotterdam. At the same time there are several attributes under which ports could be ranked, total tonnage, miles per container transport, cash flow, etc. Unarguably, the main European ports across attributes are the ports of Rotterdam, Antwerp-Bruges and Hamburg all with over 100 000 ktons cargo tonnage in 2024.

According to Eurostat [10] it is Rotterdam and Antwerp-Bruges that are by far the largest ports in Europe. The main European ports based on throughput (10 largest by gross weight, 2022) are listed in Table 1 [11]]. A total of 37.5% of ship cargo (gross weight) in the EU is handled in the 10 largest ports. For large containers or liquid bulk, the share is around 45-55%, while the share for other types of goods is closer to 20-25%. The Gross weight is the total incoming and outgoing goods. For Rotterdam the incoming amount is approximately 70% of the total (Outgoing 30%). The total CO_2 emissions for each port are not only related to the transport volume or tonnage, but also to the type of vessels, fuel type and transport distance, and calculations can be complicated due to the complexity of global logistics. EU MRV and Eurostat statistics are the most relevant for such calculations. This is described further under 4.2.2. The map and bar diagram below shows the location of the ports and cargo mix.

Table 1 The 10 main European ports and their annual throughput [11] Reference year 2022.

Ports /Area	Gross weight (Mt) 2022 (Ref: Eurostat)	Dry bulk (Mt)	Liquid bulk (Mt)	Large Containers (Mt/MTEU)	Breakbulk (Mt) (Ro-Ro and other goods)
1. Rotterdam (NL)	426	77	212	107	31
2. Antwerp-Bruges (BE)	254	17.1	90	109	38
3. Hamburg (DE)	103	26	10	66	1
4. Amsterdam (NL)	96	44	45	1	6
5. Algeciras (ES)	81	1.4	27.3	46.7	6.6
6. HAROPA (Le Havre and Rouen) (FR)	79	14.3	40.8	22.2	1.7
7. Marseille (FR)	67	11.5	39.4	11.2	4.9
8. Trieste (IT)	64	4.1	41.7	7	11.2
9. Valencia (ES)	64	2.3	5.8	45.5	10.4
10. Gdansk (PL)	63	21.1	25	14.9	2
Total 10 ports	1297	219	537	430	113
Total EU	3461	788	1276	786	611
Percentage of EU total	37.5	27.8	42.1	54.8	18.5

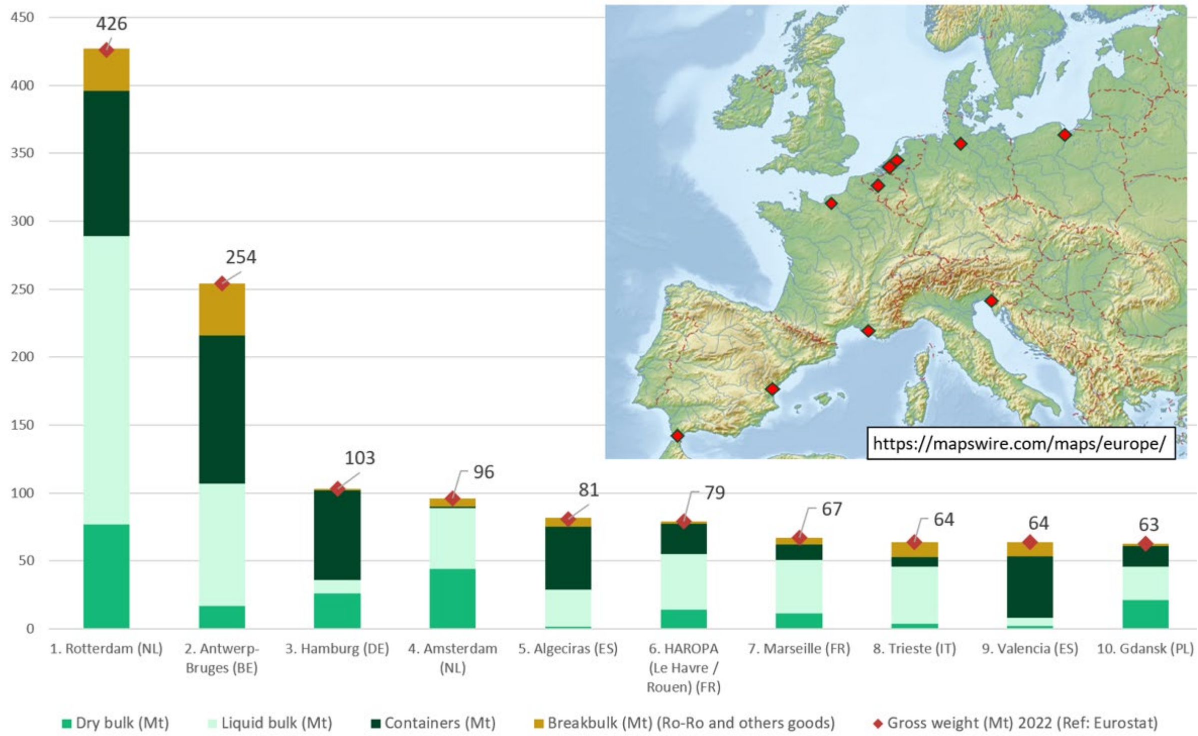

Figure 5. Location and cargo mix for the 10 largest European ports by Gross weight [11, 12].

4.2.2 Main European ports by CO_2 emission volumes

The CO_2 emission related to maritime transport is the sum of the emissions due to fuel combustion during the intercontinental voyage, travel between EU-ports, and the activities at berths. Data for the CO_2 emissions related to each port and the ships that are transiting are not consistently found in reports, however some good indications can be found in the annual report [13] from the European Commission on CO_2 Emissions from Maritime Transport, which gives data from ships entering and leaving EEA ports, collected under the monitoring, reporting and verification (MRV) system for CO_2 emissions from maritime transport adopted in 2015 ("EU Maritime MRV Regulation"). An overview can also be found in the report "EU Ports` Climate Performance, a briefing report from the organisation "Transport & Environment"[14]. Both sources summarise the total CO_2 emissions related to maritime transport to about 125Mt. The ten ports with the largest CO_2 emissions, including emission from the voyage of the ships calling to the port and emissions related to berth, loading, unloading and refuelling. The 10 ports with largest emissions of CO_2 are not the same as those with the largest gross weight of cargo (see Table 1 and Figure 5.) Rotterdam, Antwerp and Hamburg are still on rank 1, 2 and 3 but the rest of the list is somewhat different. In table 2, the CO_2 emissions from the 10 ports covering about 35% of the total emissions are shown. More than 100 other ports have emissions between 0.225- 1.8 Mt/year each. In addition, there are still 90 more ports between 0.1 and 0.225 Mt. this is illustrating that it is a massive task to develop the necessary infrastructure and logistics to for OCC in all ports of a certain size.

Table 2. The ten ports EU/EEA with the largest CO_2 emissions related to ships to the port [14]

Ports /Area	Total CO_2 emissions related to ship transport for each port (Mt /year)
1. Rotterdam (NL)	13.7
2. Antwerp-Bruges (BE)	7.4
3. Hamburg (DE)	4.7
4. Algeciras (ES)	3.3
5. Barcelona (ES)	2.8
6. Piraeus (EL)	2.7
7. Valencia (ES)	2,7
8. Bremerhaven (DE)	2.3
9. Marseille (FR)	2.3
10. Amsterdam (NL)	2.1
Total 10 ports	44
Total Europe*	125
10 ports (% of Europe* total)	35%

* Covers countries under EU MRV (including EEA) and UK MRV (MRV= monitoring, reporting and verification).

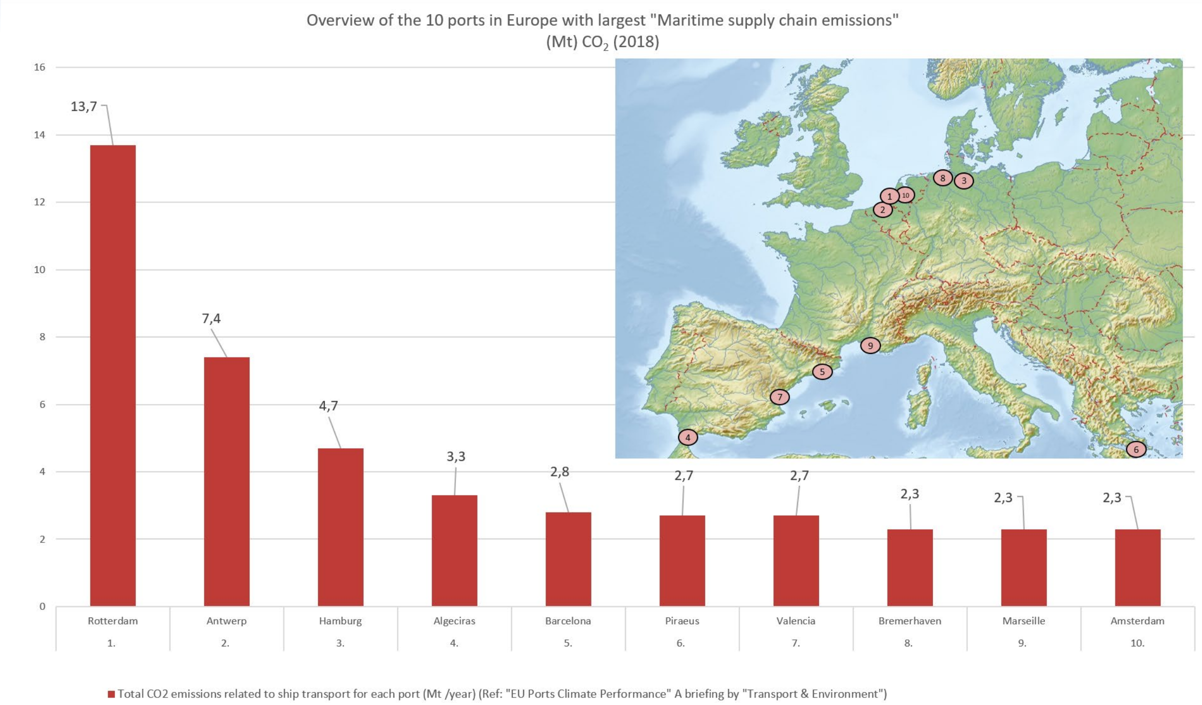

Figure 6. Location of Ports with the largest "Maritime supply chain emissions" of CO_2 in Europe. CO_2 emissions in Mt [14]

4.3 Large scale CO_2 storage infrastructure plans

The opportunities for CO_2 storage exist in many locations in Europe, they are mapped thoroughly since 1990. Most storage sites are related to saline aquifers and depleted hydrocarbon fields [15]. The volumetric storage potential is strongly related to sedimentary basins (nature of the geological formation) and is therefore not equally distributed. The potential of CO_2 storage in Northern Europe, in a wide band stretching from the United Kingdom across to the Baltic states and towards the North Sea are much larger than further south. The largest emission sites are also clustered from the UK and through Benelux, Germany, Poland and towards Romania in the south-east. It can be observed that vast emitters are located not far from these potential storage sites.

According to an overview from 2024 [16] there are 43 CO_2 storage projects in Europe with an expected capacity of approximately 140 $MtCO_2$/yr by 2030. Most of them are clustered in and around the North Sea Basin in the United Kingdom, Norway, Denmark and the Netherlands. Most of the projects are still under development but are planned to start operation during 2025-2030 followed by significant expansion from 2030 onward. Building the necessary infrastructure will be done stepwise, projects and storage sites can be interlinked with CO_2 transport, pipelines and ship from onshore to offshore facilities. There are however high uncertainties on what projects that will be realised, infrastructure development, capacity and timelines.

4.3.1 Projected CO_2 storage projects near major European ports

For OCC - the storage projects located near and connected directly to the largest European ports are of particular interest. Since the CO_2 volumes from OCC will be relatively small, compared to CO_2 volumes from land-based industry and energy sector, successful OCC will rely on the infrastructure available. An overview of existing and planned CO_2 storage projects on the southern part of the North Sea is presented in table 3.

Table 3: Existing and planned CO_2 storage projects on the southern part of the North Sea [16](Sorted after operation start-up)

	Country	Name	Year	CO_2 Capacity (Mt/year)	Expanded CO_2 capacity (Mt/year)	Expansion year
1	Denmark	Greensand	2023	1.5	8.0	2025
2	UK	Net Zero Teesside	2026	2.0	-	-
3	The Netherlands	Porthos	2026	2.5	2.5	NA
4	The Netherlands	Aramis	2029 [27]	5.0	22.0	TBD
5	UK	Bacton Thames Net Zero initiative	2027	6.0	10.0	2030
6	The Netherlands	L10 CCS	2027	5.0	9.0	2028
7	UK	Zero Carbon Humber	2027	5.0	8.0	2030
8	Norway	Havstjerne	2028	3.0	8.0	2030
9	UK	Poseidon (UK)	2029	1.5	10.0	2030
10	Norway	Poseidon (NO)	2030	5.0	-	-
11	Denmark	Bifrost	2030	3.0	16.0	2032
12	UK	Viking CCS	2030	10.0	15.0	2035
13	UK	Orion	2031	1.0	6.0	2035

There is several CCS projects planned at or near Port of Rotterdam and Port of Antwerp. The projects Porthos, Aramis and L10 CCS in the Netherlands are among the first and also among those that plan for highest capacity. The onshore facilities will be located at entrance to the Port of Rotterdam. Porthos can be regarded as the first stage [17] and construction is ongoing. Operation is expected to start in 2026 and is already fully booked. 2.5 Mt of CO_2 will be captured from a cluster of industries in Port of Rotterdam (Air Liquide, Air Products, ExxonMobil and Shell) and sent through the Porthos infrastructure and stored under the North Sea.

The Aramis project [18] is complementary to Porthos and can utilize some of the same infrastructure. Aramis includes a new HUB –CO_2next- from which CO_2 will be transported by offshore pipelines to a distribution platform in the North Sea. The CO_2next HUB is "open access" and will receive CO_2 from pipelines and ships. The CO_2 will then be distributed to injection platforms. Final investment decision across the value chain remains but is expected during 2025 or 2026. Maximum expected storage capacity is 22 Mt/year [19]. L10CCS is one of the largest storage sites that will be connected to Aramis. Timeline is also in line with Aramis (2020-2029) [20].

At Port of Antwerp the Antwerp@C projects is developed. This project is about creating a HUB for CO_2 handling in Antwerp. It includes capture of CO_2 from the very large local industry cluster (under the Kairos@C project) but will also collect and handle CO_2 coming to the Port via river, rail and road transport. Further transport can be realized by ship transport to offshore storage abroad. It is also planned for pipeline that can link Antwerp@C directly to the project in the Port of Rotterdam [21].

4.3.2 Other ports with or projected CO_2 storage infrastructure in Europe

For OCC to have a real impact on the CO_2 emissions and climate change it need to be adopted in several ports.

As shown in Table 1 and 2, the Ports of Hamburg, Amsterdam, HAROPA and Bremerhaven, located also near the North Sea, are all among the 10 largest ports either with tonnage or marine CO_2 emissions. Three are CCS initiatives related to these, and it is likely that a network for CCS will develop in and around the North Sea.

Short description of projects in addition to the Ports of Rotterdam and Antwerp- Bruges that have been presented in chapter 3 is presented below:

- The North Sea Port is a cross-border Port area stretching 60 km from Vlissingen in Netherlands to Gent in Belgium. It is not far from Antwerp (approx. 50 km), but closer to the North Sea. Investments in CCS in the area are ongoing 27. The fertilizer company Yara International ASA is currently building the first cross border CCS project in Sluiskil, central in the North Sea Port area. Starting from 2026, 800 ktCO_2 will be captured from Yaras ammonia plant per year and shipped to storage in the Norwegian Northern Lights storage project [23, 24].

- Port of Zeebrugge (Belgium) are planning a CO_2 HUB together with the company Equinor. They are working on what is named CO_2 Highway Europe, see Figure 7. The intention is to connect Belgium to storage sites at the Norwegian continental shelf, more specific to the Smeaheia storage site. A 1000 km pipeline from Zeebrugge to Smeaheia is planned and with a capacity of 18 Mt per/year after 2030 (Phase1) and later increase to 27 Mt/year (Phase2).The pipeline can also be connected to the Port of Dunkirk further south in France to also transport CO_2 from the planned CO_2 network in that area [25]

- Port of Dunkirk (France) is in the North of France, close to the Belgium border. As mentioned for Zeebrugge a branch of the CO_2 pipeline is planned to Dunkirk to be able to handle CO_2 also from the industry in Northern France. The industry in the Dunkirk area account for 20% of the CO_2 emissions in France and there is a need for the industry in the area to have CCS infrastructure available to decarbonize. Capacity in the initial phase is 3Mt/year to 5.5 Mt/year. Commissioning is planned in 2029 [26].

- Port of Wilhelmshaven and Port of Hamburg are located in Germany and only recently CCS/CCU has been accepted as a tool for climate mitigation action [27]. Projects are due to this under development and is less mature than e.g. in the Netherlands. That said, it is clearly a large potential for transport of CO_2 by river and rail to the Port of Hamburg [28].In the Port of Wilhelmshaven there are initiatives for a CO_2 HUB that can be an important link for the industry on mainland Europe to the storage sites in the North Sea. Germany, Switzerland, Austria, Czech Republic and Eastern France are Countries mentioned for future connection to a Wilhelmshaven HUB [29].

Port of Zeebrugge and Equinor has launched the Smeaheia/CO_2 Highway Europe [30].

Figure 7. The Smeaheia/CO_2 Highway Europe [30], Equinor ©

5 Roadmap

The projection of a roadmap for OCC must be closely linked to the general guidelines of CCS and CCU infrastructure projects. The emissions from land-based activities are much greater than those from the maritime sector, and the development of the extensive infrastructure needed for energy and the industrial sector is being developed on these sectors' terms. At the same time, the emissions from ship traffic are also significant and make up about 3-4% of the total (in the EU27), about the same as from air traffic. Forecasts also indicate that ship traffic will increase by 2050 and that the proportion of greenhouse gas emissions will increase to 10% if effective actions are not taken. All sectors must contribute if the climate targets are to be met [31] 32] Development of the infrastructure for CCS has begun, and full-scale storage projects for CO_2 captured from industry are planned to be operational in 2025 [33, 34]. There is still considerable uncertainty related to how quickly and how extensive the CCS infrastructure will be in the coming years. The outlined roadmap, therefore, describes the most important elements that must be considered and provides a tentative timeline for how OCC can be developed in parallel with the development of CCS and the reduction of emissions from the maritime sector in general towards 2035 and 2050.

5.1 Towards 2035

Introduction of OCC should start where the effect is greatest and where there is high certainty that a CCS infrastructure will be available between 2025 and 2035. In this respect, Europe has a very good starting point in that the two largest ports, Rotterdam and Antwerp. They have both CCS HUBs under planning and development and suggested pipeline routes to storage areas in the southern part of the North Sea. The investment in the Port of Rotterdam, which is connected to the Aramis CCS project, along with the Port of Antwerp's investment in Antwerp@C, allows for simultaneous development of OCC.

If 50% of the maritime CO_2 emissions linked to these two ports were captured and stored, this would amount to 8.5% of all maritime emissions in Europe. (Total approx. 10-11 Mt/year). Figure shows that 70% of the emissions are related to 50 ports and that 36% is related to the 10 largest ports which are listed in Table 2.

Projecting realistic scenarios leading up to 2035, requires detailed evaluation of ships that have the best potential for implementation. Large ships with long sailing routes that traffic those ports regularly, and which do not have plans or opportunities for conversion to non-fossil fuels must be included in plans for OCC. Smaller ships should also be surveyed to get a full overview. Such a detailed review will clarify the real potential for OCC related to these ports.

The authorities in Port of Rotterdam and Port of Antwerp could take the lead towards OCC and engage with players in the maritime industry and other stakeholders. This includes the major shipping companies, the CCS HUBs under development, suppliers of CCS technology and equipment relevant to OCC and classification societies.

- The volume of CO_2 captured on each ship is relatively small for a voyage or roundtrip, and delivery of CO_2 to the HUB and services needed should be handled without the need for going to a separate quay for these tasks.
- Collection and feeder service to be developed for each port for intermediate transport and storage to the central HUB. Such ideas are also referred by others [35].
- Standardization of capture, conditioning, storage and unloading technology might be necessary.

Other nearby planned HUBs and large ports may also be involved to be able to maintain the necessary degree of standardization when network expands (e.g. Dunkirk, Zeebrugge, Amsterdam, Eemshaven, Wilhelmshaven)

The proposed roadmap anticipates a fleet of 50 ships with OCC by the year 2035. The emissions captured per ship will vary significantly, however, assuming an average of 50,000 tons of CO_2 per ship per year, the total CO_2 captured would amount to 2.5 million tons. This projection aligns with the anticipated storage capacities that are expected to be available by 2035. It is assumed that a few ports have the infrastructure ready by then, and that they can handle this number of ships with OCC.

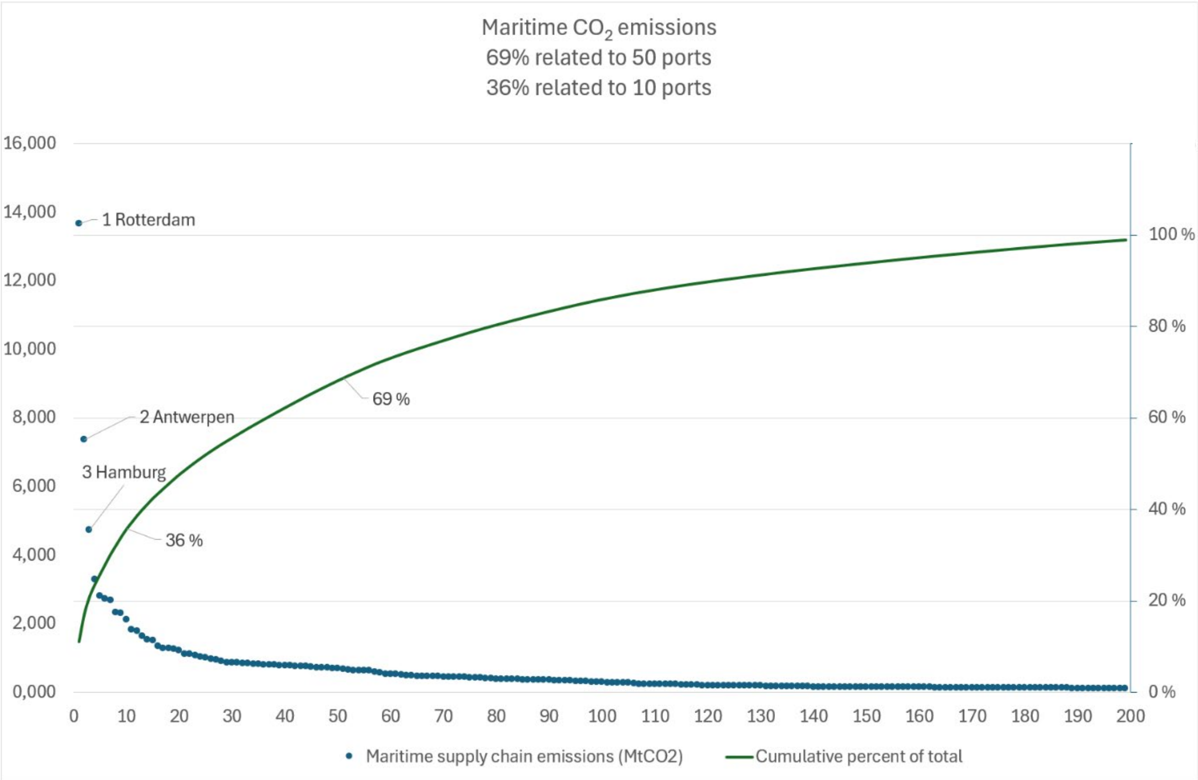

Figure 8: Plot showing the 199 Ports with total of approx. 122 Mt/year maritime CO_2 emissions (EU/EEA/UK MRV). The 50 largest covers close to 70 %. Plot based on [14].

5.2 Towards 2050

The evolution from 2035 to 2050 will depend greatly on the development and deployment of alternative and CO_2 neutral fuels. There are several alternatives here: ammonia, hydrogen, methanol and methane. Both technology and the regulations for safe onboard use need to be mature to have widespread use. An estimated timeline show maturity for most technologies around 2030 [36] The production of climate-friendly variants will depend on access to sustainable biomass, access to renewable electricity, or fossil energy with CCS. In any case, very large investments will be required for the alternative solutions to prevail. The fuel-mix that is valid in the market in 2050 is very hard to predict. If fossil fuels are still part of the market, OCC will be necessary to achieve climate neutrality. OCC can also be used on flue gas from climate-neutral fuels with carbon content (e.g. green methanol) and will then be able to contribute with negative emissions if CO_2 goes to permanent storage. DNV has prepared a set of different scenarios in a report showing forecast for the mix of fuels in the shipping industry[36].

In the most optimistic case, in terms of greenhouse gas emissions, all fossil fuels are phased out in 2050. This would be in line with the updated ambitions of the IMO from 2023 [2]. Then there would be no need for OCC after 2050 to be climate neutral. The less optimistic scenarios look at a fuel mix where approximately 50% of the fuel is still fossil. By 2050, the maritime sector could be positioned somewhere in the middle, with approximately 25% of fossil fuels still present in the market, necessitating the use of OCC.

In addition to the above-mentioned scenarios for phasing in alternative fuels and phasing out fossil fuels there is also a need to pay attention to the total transport work that is expected by ships in 2050. An increase of transport work is expected but predictions of growth are within a large span. IMO predictions (2020) span between 40% and 115% growth, according to a DNV report from 2022 [36]. In the same report, DNVs updated projection is close to 30% growth during 2022 -2050. The projection include assumptions for how the different segments will develop and it is expected changes due to reduction in transportation of fossil fuels, but also an increase of transport of alternatives impacting transport by Liquid and Gas tankers. The total growth of shipping may increase the challenge in reaching the ambitions both for 2035 and 2050.

Wider adoption of OCC needs to take place not later than 2035. Around 2040 all major ports should have developed the needed infrastructure within port and shipment to storage to facilitate OCC. Volume of OCC depends on the phasing in of alternative and climate neutral fuels.

In 2045 almost all ships with fossil fuel should have implemented OCC. Depending on the fuel mix OCC should be mandatory after 2050 for fossil fuel and can be an option for climate neutral fuels (e.g. biofuel, e-methanol) with a potential for negative emissions if the CO_2 is stored permanently.

By the year 2050, the roadmap envisions a fleet of 700 vessels equipped with OCC operating in European ports. This initiative is projected to result in the capture of 35 million tons of CO_2 annually. However, this outcome remains highly uncertain and will be contingent upon the advancement and implementation of additional decarbonization measures, such as fuel switching, engine optimization, and electrification, among others. A suggested roadmap for the development and implementation of OCC from 2025 to 2050 is shown in Figure .

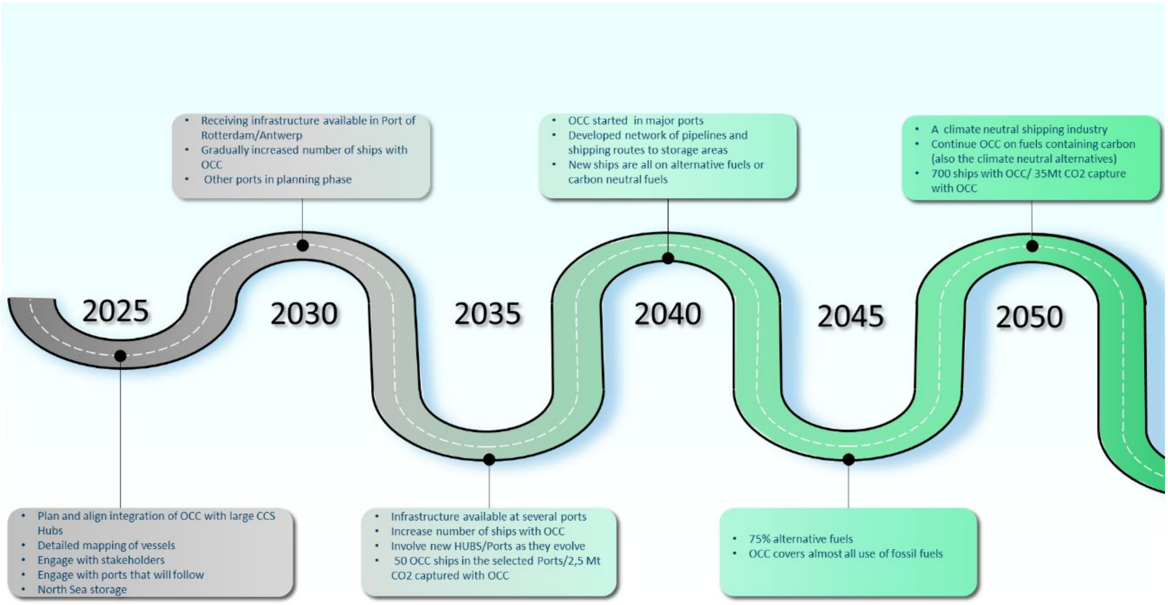

Figure 9: Illustration of main elements in The Roadmap

6 Concluding remarks

The implementation of Onboard Carbon Capture (OCC) as a decarbonization measure is feasible today, as demonstrated by the EverLoNG project. However, several challenges must be addressed for widespread adoption. One major issue is the lack of suitable port infrastructure to handle captured CO_2, making offloading difficult. Additionally, the low volumes captured per ship create economic challenges for transport and storage, especially given the long intervals between offloading and the unpredictable nature of CO_2 volumes due to short-term contracts. To overcome these obstacles, the focus should be on large ports with existing or potential infrastructure for CO_2 transport and storage. A flexible offloading system capable of accommodating different ship sizes and types would also be beneficial. Furthermore, improving logistics for CO_2 handling and fostering policy support through standardization and incentives could facilitate the broader adoption of OCC technology.

A roadmap for OCC must align with the broader development of carbon capture and storage (CCS) and carbon capture and utilization (CCU) initiatives. While maritime emissions account for 3-4% of total EU emissions—comparable to aviation—they are projected to rise to 10% by 2050 without intervention. Given that all sectors must contribute to climate targets, OCC development should progress alongside CCS infrastructure and the development of climate neutral fuels.

Towards 2035

Early implementation of OCC should focus on regions with established or developing CCS infrastructure, particularly major European ports like Rotterdam and Antwerp, which are near CCS hubs. If OCC captures 50% of maritime CO_2 emissions from these ports, it could reduce Europe's shipping emissions by 8.5% (approximately 10-11 Mt/year). Standardization and logistics must be addressed, including CO_2 collection and transport systems. By 2035, the goal in the roadmap is to have 50 OCC-equipped ships capturing approximately 2.5 million tons of CO_2 annually, with a few ports prepared to handle these operations.

Towards 2050

The expansion of OCC will depend on the adoption of alternative fuels such as ammonia, hydrogen, methanol, and methane. If fossil fuels remain in use, OCC will be essential for climate neutrality. By 2040, all major ports should have developed OCC infrastructure, and by 2045, nearly all fossil-fuel-powered ships should be equipped with OCC. If alternative fuels with carbon content (e.g., green methanol) become dominant, OCC could enable negative emissions through permanent CO_2 storage.

By 2050, the roadmap envisions 700 OCC-equipped vessels capturing about 35 million tons of CO_2 annually. However, the final impact will depend on the pace of alternative fuel adoption, shipping industry growth, and regulatory developments. A detailed roadmap from 2025 to 2050 outlines key milestones for OCC implementation alongside broader decarbonization strategies, but is highly uncertain, and requires large investments and cooperation between stakeholders, ship owners and ports.

7 Nomenclature and definitions

ACT	Accelerating CCS technologies
BE	Belgium
CCS	Carbon capture and storage
CCU	Carbon capture and utilisation
CCUS	Carbon capture, utilisation, and storage
DE	Germany
EEA	European Economic Area
ES	Spain
EU-ETS	European Union Emissions Trading System
FR	France
GHG	Greenhouse gas
GT	Grosse tonne
IMO	International Maritime Organization
IT	Italy
LNG	Liquefied natural gas
MRV	Measurement, reporting and verification
MT	Million metric tonne
MTEU	Million twenty-foot equivalent unit
NL	Netherlands
NO	Norway
PL	Poland
Ro-Ro	Roll on/roll off
OCC	Onboard carbon capture
SE	Sweden
TEU	Twenty-foot equivalent unit

<u>Dry bulk</u>: Cargo carried in bulk in a solid form such as Iron ore and scrap, coal, agricultural (also "other" not specified).

<u>Liquid bulk</u>: Cargo carried in bulk in a liquid form such as Crude oil, mineral oil products, LNG (also "other" not specified).

<u>Break bulk</u>: Cargo transported in parts, not in containers, Roll on/roll off, other general cargo.

<u>Transport work</u> (efficiency metric): The EU MRV (Measurement, reporting and verification) Regulation definition is the voyage distance multiplied with the amount of cargo carried [2].

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