Techno-economic assessment – OCC chain to permanent storage and utilisation

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Authorisation

This document requires the following approvals:

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Executive summary

The purpose of this task of the EverLoNG project was to perform a techno-economic assessment of full-chain onboard carbon capture (OCC). The governing assumption made in this work was that the transport and storage scenarios should be based on existing and/or planned infrastructure to the degree possible. There are several transport and storage projects under development and some even in the construction phase, but none are currently in operation. The location of these projects formed the basis of the full-chain OCC case studies. Further, selecting Port of Rotterdam as Sleipnir's unloading port is natural is this is the homeport of the crane vessel. An LNG tanker is also likely to frequent Port of Rotterdam as it is an important port for LNG trade.

Several transport and storage scenarios were subjected to a techno-economic assessment for OCC. For the European-based permanent storage alternatives the results indicate that cost of accessing the infrastructure for transport and storage could be between 80 – 150 EUR/tonne CO_2 captured. The lowest cost is associated with the storage scenario with the least transport elements which reduce the complexity of the chain. The OCC transport and storage assessment performed in EverLoNG indicates that utilising nearby storage infrastructure is the less costly alternative, with reference to Aramis versus Northern Lights. However, this is potentially dependent on the mode of transport needed to reach the storage infrastructure. Transporting the CO_2 to Northern Lights necessitates an export terminal, a CO_2 cargo ship, and import terminal, and a pipeline to the offshore injection site. Each step is also associated with CO_2 conditioning. For storage in Aramis, only the pipeline is needed, resulting in a significantly less complex transport and storage chain. A significant part of this cost is the storage cost, assumed to be 40 EUR/tonne for storage in an offshore aquifer. The cost of storage used in the current study was a guestimate based on available data for Aramis and Northern Lights. It is likely that the cost of storage will become lower as more storage project are developed and implemented. Please note that the results are only valid under the assumptions made.

A potential alternative to permanently storing the CO_2 is to utilise it. The utilisation of CO_2 captured through OCC to produce e-fuels like methanol and methane was explored. However, a relatively recent amendment to Directive 2003/87/EC dictates that the CO_2 captured needs to either be permanently stored or permanently bound in a product for the captured CO_2 to be claimed as allowances under EU ETS.

The techno-economic assessment of transport and storage chains for OCC developed in EverLoNG were governed by Port of Rotterdam layout, operational restrictions, and CO_2 infrastructure plans. Still, the general approach should still be adaptable to other ports.

There is a need of a strategy for portside infrastructure development in an OCC start-up phase. The first projects being commercialised will likely yield small volumes delivered at different parts of a port (depending on the type of vessel). A gradual development of port-side infrastructure is needed, and it is likely that at least parts of the infrastructure utilised in an initial phase could be temporary installations.

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1 Introduction

ACT is an international initiative to establish CO_2 capture, utilization, and storage (CCUS) as a tool to combat global warming. EverLoNG is an ACT (Accelerating CCS technologies) project that aims to encourage implementation of OCC (onboard carbon capture) by demonstrating its use on LNG-fuelled ships. The project has optimised the technology and considered how to best integrate OCC into existing ship and port infrastructure. A graphical representation of the EverLoNG project and its' scope is shown in Figure 1.

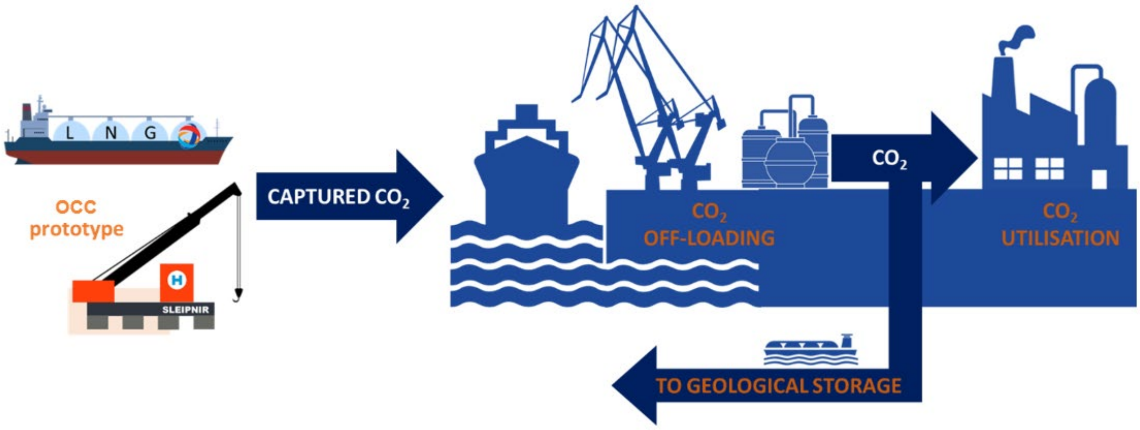

Figure 1. The scope of the EverLoNG project.

This document serves as a joint delivery of Tasks 4.3 and 4.4 in the EverLoNG project. Here, the (techno-economic assessment (TEA) of full-chain onboard carbon capture (OCC) to either permanent storage or utilisation is presented. The governing methodology of the TEA is provided in a separate deliverable, D4.3.1 "TEA and LCA framework document for EverLoNG case studies" [1]. Relevant parts of this document are rendered here to ease the readability.

2 Full-chain case development

The logistics involved in OCC cases could differ significantly from traditional CO_2 capture in industrial settings, primarily due to the anticipated lower volumes from OCC (for each individual vessel) and the possible unpredictability regarding the offloading of captured CO_2. Certain vessels operate on a charter basis, indicating that they do not follow a fixed route, and the ports they visit can change from one charter to another. This is generally the case for LNG carriers. To develop representative and realistic full-scale chains, it is important to know the CO_2 volumes captured between each offloading, the number of days between each offloading, and at which port the unloading takes place. After the CO_2 has been received and intermediately stored at the port, it needs to be transported to its destination, either for utilisation or permanent storage.

The two vessels that form the basis of the full-chain assessment in EverLoNG are a semi-submersible crane vessel from Heerema and a new-built LNG carrier. The on-board CO_2 capture, liquefaction, and intermediate storage is detailed in the EverLoNG deliverables D4.3.1 TEA and LCA framework document for EverLoNG case studies" [1] and D4.3.3 "Economic evaluation: SBCC as a standardized decarbonization solution [2]. For the full-chain assessment, their assumed operational profile and expected CO_2 volumes have been used as a starting point for the full-chain assessment. Please note that SBCC (ship-based carbon capture) was replaced by OCC (onboard carbon capture) during the project execution.

The captured CO_2 needs to be unloaded at a suitable location from where it can be transported to a sink, either permanent storage or utilisation. The CO_2 unloading should take place when the vessel calls at port as part of their normal operation.

For Sleipnir, the port selection seems to be straight-forward as the home port of the vessel is Port of Rotterdam. However, due to the nature of being a crane-vessel it will move to different locations, potentially all over the world, depending on the assignments. Due to this, the vessel might only call its home port in between assignments and for regular maintenance. However, to develop a full-chain case study for Sleipnir it was assumed that the captured CO_2 would be unloaded at a fixed location, most likely a port. Still, as the feasibility of this is somewhat uncertain due to the potential infrequent calls, offshore unloading of the CO_2 directly to a CO_2 cargo vessel should be explored in later projects.

For the LNG tanker, selecting a port is also challenging, as this type of vessel may not operate between the same ports on every journey. Consequently, for the purpose of creating a predictable full-chain case study, it was decided that the LNG tanker would follow a fixed route.

An additional aspect that came up over the course of the project was the CO_2 volumes to be handled at each unloading versus the total volumes that the unloading facility could handle each year. The cost of CO_2 infrastructure is highly dependent on the volume of CO_2 handled per year. Therefore, developing a CO_2 infrastructure that will only handle CO_2 from one vessel will have a low utilisation degree and result in excessively high CO_2 handling cost. This can be illustrated by considering the two vessels studied in EverLoNG. The crane vessel Sleipnir normally has a six-week operational profile. Over the course of a year, it is therefore expected to unload CO_2 approximately nine times, with an expected 4 500 t CO_2 unloaded each time. The total CO_2 volume handled each year then becomes 40 500 t, assuming the CO_2 is unloaded at one location. To limit the effect that the CO_2 unloading can have on the normal port operation, the CO_2 should be unloaded efficiently into a suitable onshore facility. This results in a somewhat over-dimensioned receival facility that includes onshore intermediate storage tanks that can receive 4 500 t CO_2 at one time but sitting idle when the vessel is not in port. The story is similar for the LNG tanker, here the assumed operational profile is based on a predictable LNG transport from an export port to an import port, with 11 roundtrips per year. This indicates that it calls each port 11 times a year. Further it is assumed that 2 500 t CO_2 is captured from port to port and that the CO_2 is unloaded at both ports. This results in a total annual CO_2 volume of approximately 28 000 t. An assessment into the potential CO_2 volume when assuming full utilisation of the onshore receival facility was conducted. With several ships with OCC sharing the infrastructure, this resulted in a volume close to 450 000 tonne CO_2 for both case studies.

2.1 Unloading port and sink assessment

To develop a full-chain for handling the CO_2 captured onboard the vessels, an assessment of suitable unloading ports and sinks (either permanent storage or utilisation) was undertaken. A governing assumption for the assessment was that the port should be in Europe and that they should be located where there are existing or concrete plans for a larger CO_2 infrastructure. One such port is Port of Rotterdam. Several CO_2 handling infrastructure initiatives are under development in Europe that could be relevant for Port of Rotterdam, i.e., Porthos, Northern Lights, and Aramis. The storage project

Porthos could potentially have been a suitable sink for the CO_2 captured onboard as the infrastructure currently under construction will pass through Port of Rotterdam. According to Fraters (2023) Porthos is expected to store 2.5 Mt CO_2 per year for 15 years from 2026 [3]. The planned infrastructure of the project is further described on the Porthos website [4]. However, the Porthos project is, based on information about the current project, at full capacity and therefore not likely a suitable sink for EverLoNG. The Aramis project will cooperate with Porthos on the onshore infrastructure (pipeline and conditioning plant). The offshore pipeline from shore to the offshore injection site will have an annual capacity of 22 Mt at maximum capacity [5]. An investment decision is expected in 2025 and start-up in 2028. The Aramis onshore infrastructure, the import terminal, will also be able to receive liquid CO_2 from CO_2 cargo ships. An alternative to storage in Aramis, is storage in the Northern Lights project. Here, an import terminal at Øygarden in Norway is under construction. The terminal can, when operational, receive CO_2 cargo ships transporting liquid CO_2 from emitters in Europe. The CO_2 is then pumped and heated before it is transported by a pipeline to an offshore injection site for permanent storage in an aquifer [6, 7]. The Northern Lights project is expected to be operational by 2024, the initial capacity of the infrastructure is 1.5 Mt CO_2 per year with plans to increase the capacity as the demand grows [8].

As previously mentioned, the homeport of Sleipnir is Port of Rotterdam, making this port the best choice for unloading the captured CO_2 for the present study. As the LNG vessel has a more generic approach, and no fixed route, it was decided that the import terminal would be Port of Rotterdam with the export terminal being Port Arthur in Texas USA. The rationale behind this was that Port of Rotterdam already has an LNG terminal with a significant throughput. Similarly, Port Arthur is an established export terminal for LNG. For Port Arthur, any CO_2 unloaded is foreseen to join up with existing CO_2 infrastructure found in the vicinity of the port, mainly the Denbury Green Pipeline which transports CO_2 for EOR (enhanced oil recovery) today.

A map showing the most important locations at Port of Rotterdam is provided in Figure 2. These locations are, home quay of Sleipnir, the LNG terminal and the foreseen site for unloading of CO_2 from the LNG tanker, the planned Aramis CO_2 export terminal, and the planned backbone pipeline transporting CO_2 from relevant local industrial sources to the export terminal site. The CO_2 unloading sites and the planned onshore infrastructure were used to develop the Port of Rotterdam onshore CO_2 handling infrastructure for the CO_2 captured onboard the vessels.

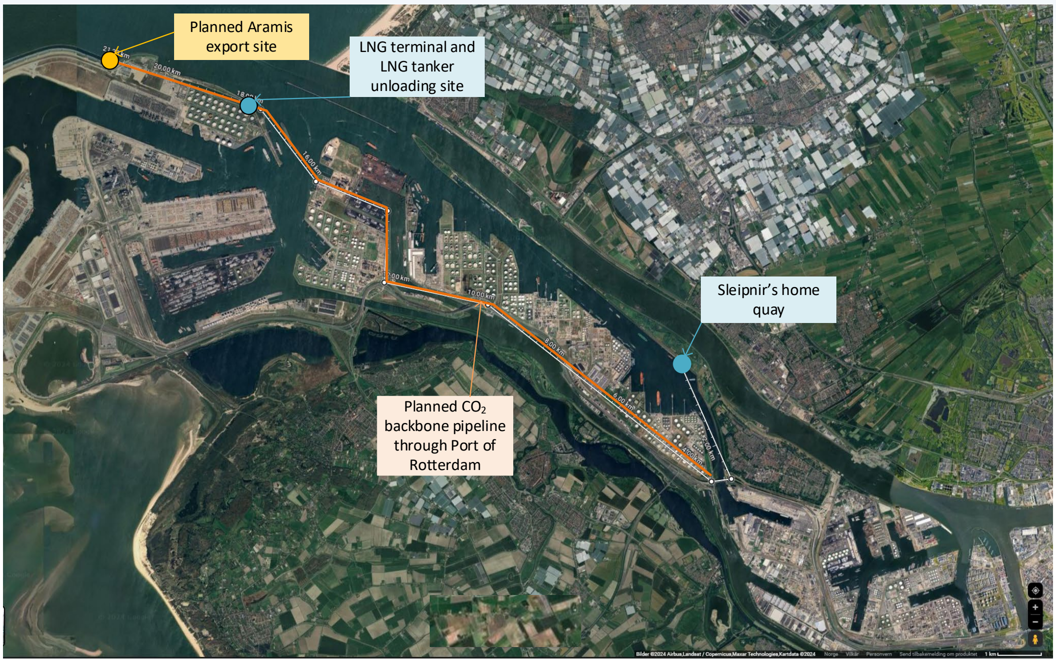

Figure 2. Important locations at Port of Rotterdam ©Google Maps.

It was decided to include both Aramis and Northern Lights as possible permanent storage sinks for CO_2 for both vessels when the CO_2 is unloaded at the Port of Rotterdam, these options are illustrated in Figure 3.

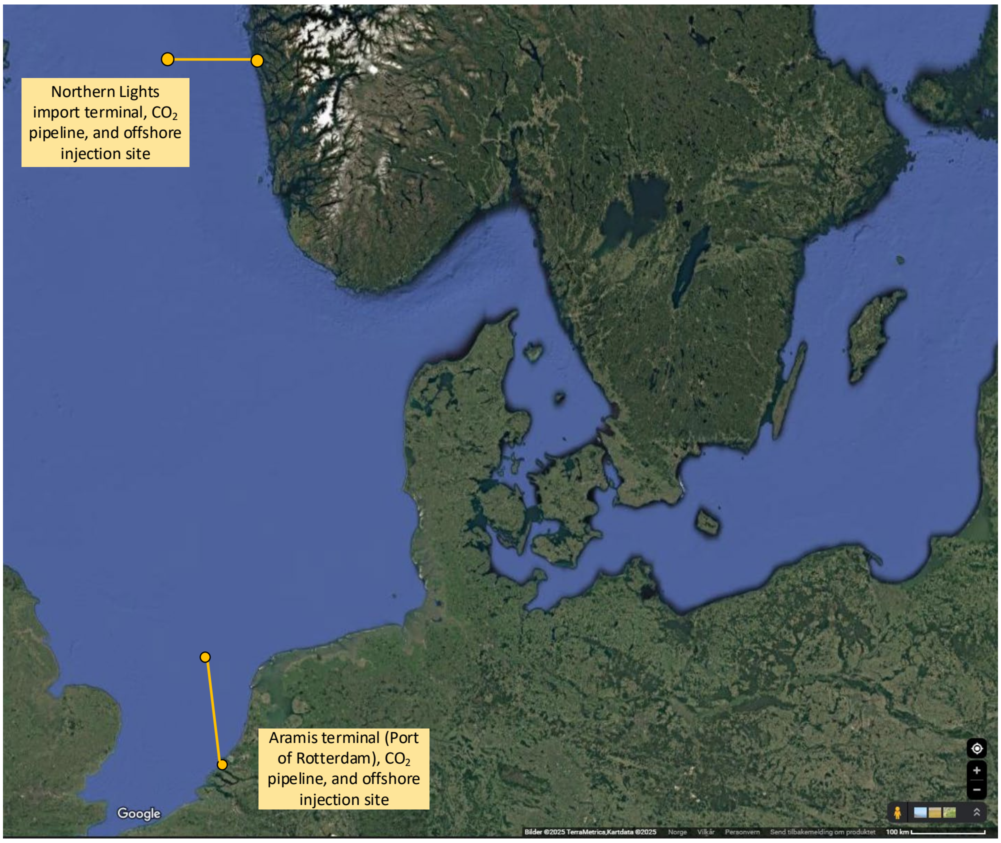

Figure 3. Aramis and Northern Lights ©Google Maps.

A simpler approach was adopted for Port Arthur, here the captured CO_2 is transported from the receival facility to join up with the Denbury Green Pipeline via a connecting pipeline.

An alternative to permanent storage of CO_2 could be utilisation for some purpose. Originally in the EverLoNG project the utilisation routes were production of synthesised fuel or chemicals and direct use in greenhouses. Over the course of the project, the focus on utilisation was reassessed due to several factors with the major one being that captured CO_2 should stay captured. This decision was further strengthened by amendments made to relevant European Union law. One such amendment was the inclusion of maritime emissions in the EU ETS from January 2024 [9]. The implementation is gradual and in the initial phase, ships ≥ 5 000 GT would need to account for 40 % of 2024 emissions reduction in 2025, 70 % of 2025 emissions reduction in 2026, and 100 % from 2027 onwards. This EU Action covers 50 % of emissions for voyages that start or ends outside of the EU, and 100 % of emissions for voyages within the EU. The vessels studied in EverLoNG are assumed to be covered by the EU ETS scheme and the fate of the captured CO_2 becomes important when reporting emissions, as not all utilisation pathways result in reduced emissions. Additionally, a relatively recent amendment to Directive 2003/87/EC dictates that the CO_2 captured needs to either be permanently stored or permanently bound in a product for the captured CO_2 to be claimed as allowances under EU ETS [10].

When assessing CO_2 utilisation pathways, it is important to keep in mind the above aspects of EU law and the implications it will have for the ship owner's ability to reach the desired emission reduction targets. Talus and Maddahi (2024) provides a comprehensive overview of carbon capture and utilisation under EU law [11].

In the EverLoNG project it was assumed that the CO_2 is utilised for fuel production, either methanol or methane. Both normally has a very short time frame in which the CO_2 is removed from the atmosphere as the CO_2 is released again as soon as the fuel is consumed.

With reference to the above discussion, a limited investigation into utilisation was undertaken for CO_2 unloaded at the Port of Rotterdam. Here the CO_2 is foreseen transported by pipeline to the industrial site Botlek near the port at which point the CO_2 is assumed sold for utilisation. The plant utilising the CO_2 is assumed to produce either methanol or methane to be used by a third party.

2.2 Case descriptions

Based on the assessment of unloading ports and sinks, the following full-chain CCUS cases was defined:

- Case 1 – Sleipnir CO_2 storage
  - Case 1a – Northern Lights
  - Case 1b – Aramis
- Case 2 – Sleipnir CO_2 utilisation
  - Case 2a – Methanol (Port of Rotterdam)
  - Case 2b – Methane (Port of Rotterdam)
- Case 3 – LNG tanker CO_2 storage/EOR
  - Case 3a – Port of Rotterdam/Northern Lights and Port Arthur/EOR
  - Case 3b – Port of Rotterdam/Aramis and Port Arthur/EOR

- Case 4 – LNG tanker CO_2 utilisation
    - Case 4a – Port of Rotterdam/methanol and Port Arthur/EOR
    - Case 4b – Port of Rotterdam/methane and Port Arthur/EOR

3 Transport and sink techno-economic assessment

The OCC full-chain CCUS cases studied in the EverLoNG project are developed for the purpose of assessing the techno-economic aspects of transporting CO_2 captured onboard a vessel to a sink. However, as these volumes are relatively small the following overreaching assumptions are made when performing the study:

- The CO_2 captured onboard a vessel should as soon as possible enter a larger CO_2 transport and sink network
- Increasing the utilisation degree of the port receival facility is necessary to reduce the cost

The base data for the study are presented in Table 1. As mentioned above, focus should be on achieving a high utilisation degree of the port receival facility.

Table 1. The base data for the full-chain EverLoNG cases.

	Sleipnir	LNG tanker
Type of vessel	Crane vessel	LNG tanker
Type of operation	6-weeks operation	Roundtrip – port to port
Unloading port(s)	Port of Rotterdam	Port of Rotterdam Port Arthur (USA)
Roundtrip duration, days		33
Calls per port per year	9	11
CO_2 volume unloaded per port call, t	4 500	2 500
Annual CO_2 volume unloaded per port, t/year	40 500	27 800
Annual CO_2 design capacity*, t/year	450 000	450 000

*100 % utilisation with continuous flow of CO_2 into the transport and storage chain.

With the two vessels studied in the EverLoNG project, it is the receival facility at the LNG terminal (the facility for the LNG tanker) that should have the greatest potential of achieving full utilisation. This is due to LNG being an established trade. Still, there is a limitation due to the port occupancy associated with LNG cargo loading/unloading. An assessment was made with reference to the LNG tanker studied in EverLoNG and it was found that at full occupancy close to 450 000 t CO_2 could be unloaded per year.

For Sleipnir, achieving a high occupancy is not feasible as there are relatively few crane vessels in operation and because they can occupy the quay several weeks, if not months, at a time. Still, it is assumed here that the facility could be shared with other vessels. The calculation on the potential CO_2 capacity of the receival facility is therefore based on the volume of the intermediate storage tanks and an assumed continuous feeding of the CO_2 into the transport and storage chain. This also gave a potential annual CO_2 volume of 450 000 t.

3.1 Methodology

The methodology of the techno-economic assessment performed in EverLoNG is detailed in D4.3.1 and the reader is therefore referred to this document for details [1].

All the transport scenarios are modelled in the CO_2LOS cost tool [12], a cost estimation tool for calculating cost of CO_2 transport chains consisting of both pipeline and ship. The tool was developed in CO_2LOS phase III and IV, and is owned by SINTEF AS and Brevik Engineering AS. In addition to calculating the cost of CO_2 transport chains, it also provides technical design data.

In the EverLoNG full-chain OCC cases, the CO_2LOS tool is used to estimate the cost of offshore CO_2 transport pipelines and the CO_2 cargo vessels. For the onshore facilities including onshore CO_2 transport pipelines, intermediate storage, and CO_2 conditioning, the tool provides the key design data, for dimensioning the equipment. When needed, Aspen Plus v11.1 was used to perform supplementary simulations. The cost data is from Aspen Process Economic Analyzer v11. All cost data is adjusted to 2023 numbers. All infrastructure with the exception of storage and EOR.

Reliable CO_2 storage cost data is challenging to find in open literature. The storage cost data available is often outdated, based on data from the US, and/or combined with transport cost [13, 14]. Two of the most advanced transport and storage projects in Europe, Northern Lights and Aramis, cost data are available [15, 16]. However, also here transport and storage cost are combined, making it challenging to identify the expected storage cost. A best guestimate would be that the cost should be in the range of 27 – 45 EUR/t CO_2 stored, assuming that the storage is operating at design capacity. A somewhat conservative value of 40 EUR/t is therefore assumed for storage in Northern Lights and Aramis. For more information about storage and transport cost for Northern Lights and Aramis, please see EverLoNG D4.3.1 [1].

For the utilisation route to methane and methanol, the CO_2 is delivered to the site at which the production takes place. It is further assumed that the methane/methanol production facility is a separate company than the vessel owner and that the owner of the utilisation plant will need to pay for the delivered CO_2. The price of CO_2 is however difficult to predict as this will likely be decided through negotiations between the seller and the buyer. In the case of CO_2 captured in the current case studies, the price needs to at least cover the cost of capture and transport to the utilisation site. Further, for the vessels studied here it is also assumed that 100 % of emissions is included for voyages within the EU/EEA (European Economic Area) and 50 % for voyages operating to and from the EU/EEA [9].

The current (first quarter 2025) EU ETS price is around 70 EUR/t, in 2023 the average price was approximately 90 EUR/t [17]. As the price has fallen from its record high price in 2023, a price of 70 EUR/t is assumed here.

In the case of utilising the CO_2 for EOR, it is assumed that the cost of feeding the CO_2 into an EOR project in the US is 14 EUR/t. According to Melzer (2012) [18] it is expected that more than 90 – 95 % of the CO_2 purchased for EOR is trapped in the reservoir. Some CO_2 will be produced with the oil, but this CO_2 will to a large degree be reinjected into the reservoir. In the EverLoNG project is therefore assumed that 95 % of the CO_2 injected is retained in the reservoir.

3.2 Scope

In addition to covering transport of the captured CO_2 to sink, the scope is expanded to also include the receival facility. The reason for this is that the intermediate storage volume and the conditioning for the next transport step will vary depending on the case. Therefore, the generic receival facility presented in EverLoNG D2.1.3/D4.4.1 "CO_2 Offloading, Storage Facility and Solvent Reclaiming Facility" [19] has been adapted and recalculated for the different case studies. The scope of each case study is presented in Figures 4 – 9. The individual chain elements that are relevant for the transport and storage chain are discussed in more detail in Section 3.2. It is also worth noting that the chain elements described are applicable for more than one case.

3.3 Technical description of chain elements

Receival facility

The receival facility could have different configurations depending on the several factors like distance to other CO_2 infrastructure and how the CO_2 is transported in the next step of the chain. In the EverLoNG project, the receival facility is assumed to include onshore intermediate storage tanks with sufficient capacity to store all CO_2 captured onboard. Depending on the utilisation degree of the intermediate storage tank facility, a BOG (boil-off gas) system could be needed. To prepare the CO_2 for further transport, the CO_2 will likely need conditioning. The conditioning will depend on the operating conditions but will likely include pumping to transport pressure and heating to above 0 °C.

It is assumed that the CO_2 quality is according to the desired specifications for further transport and storage, no additional purification of the CO_2 received from the vessel is included.

Onshore pipelines – connecting and backbone pipeline

The current infrastructure design assumes that the capture CO_2 is unloaded at some distance from a larger CO_2 handling infrastructure. It is currently foreseen that the CO_2 is transported from the receival facility to an export terminal or to a utilisation site through onshore pipelines.

The pipeline is foreseen to follow existing pipeline corridors if available. For the EverLoNG case studies, it is assumed that such corridors are established and that there is sufficient capacity for a CO_2 pipeline.

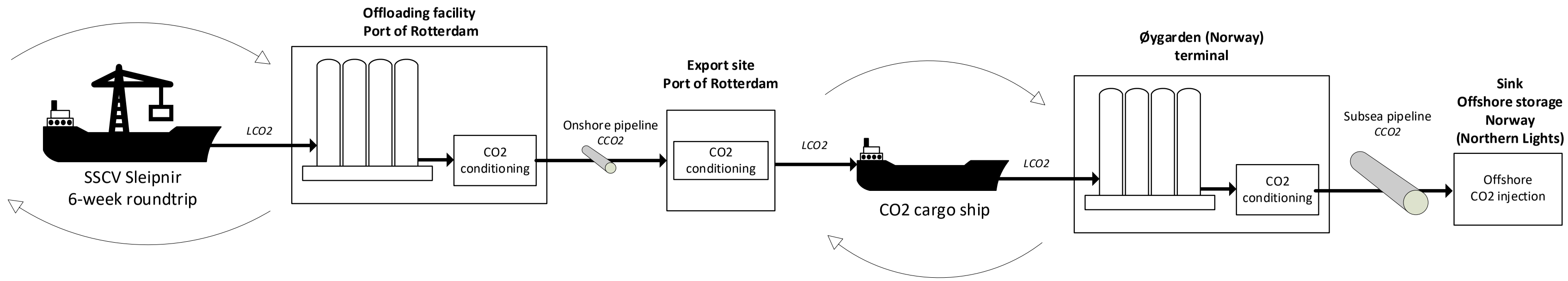

Figure 4. Illustration of Case 1a.

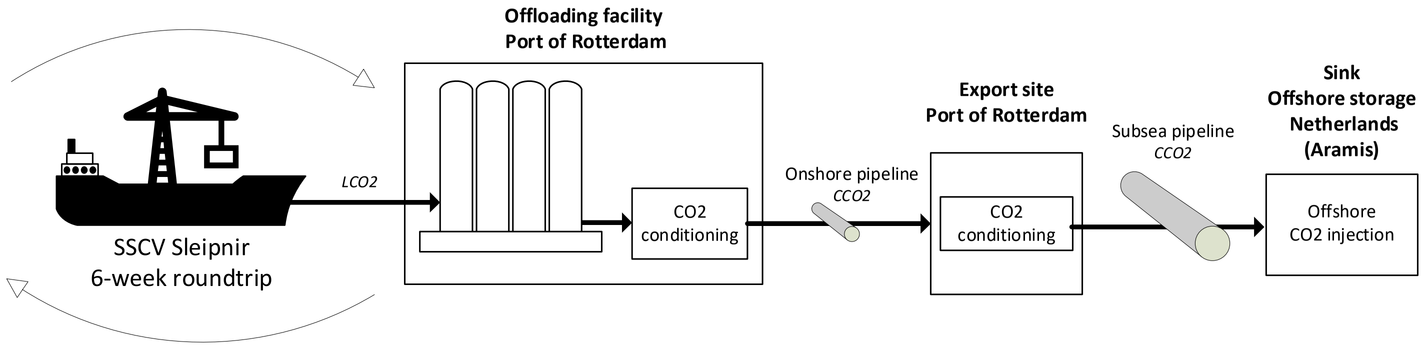

Figure 5. Illustration of Case 1b.

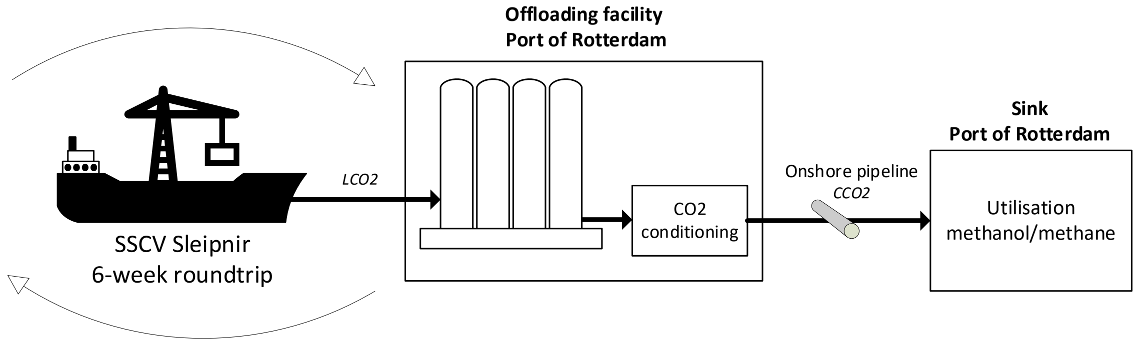

Figure 6. Illustration of Case 2a and b.

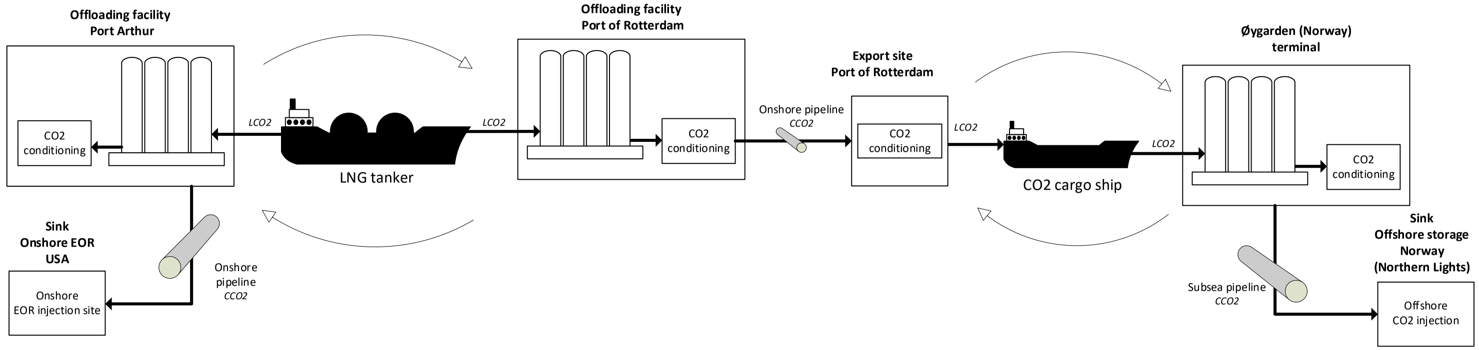

Figure 7. Illustration of Case 3a.

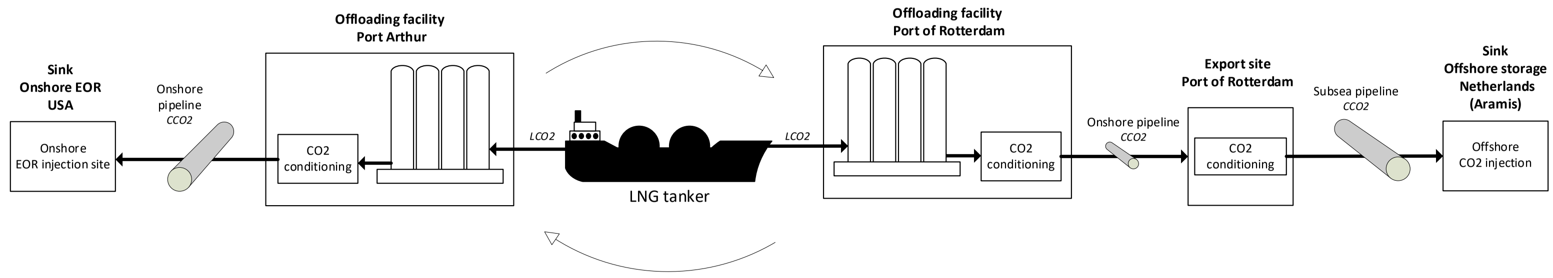

Figure 8. Illustration of Case 3b.

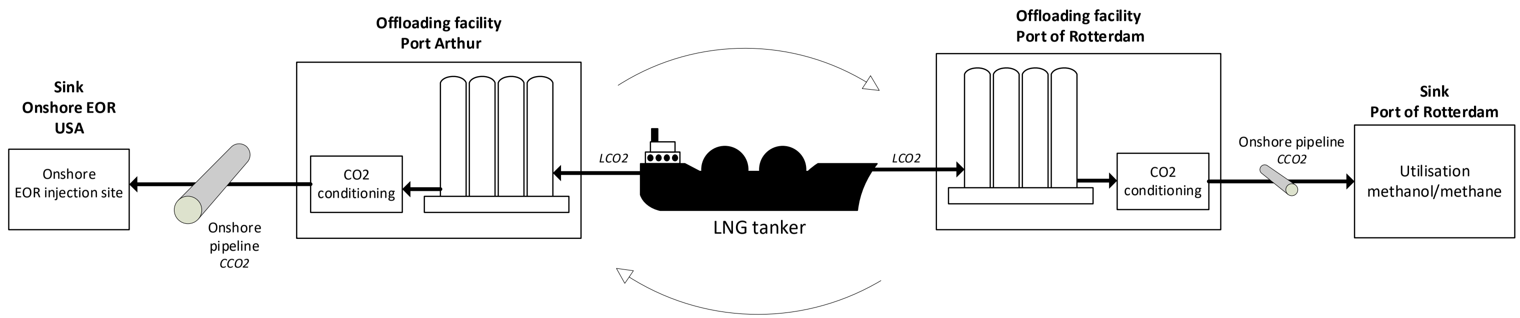

Figure 9. Illustration of Case 4a and b.

Onshore Port of Rotterdam

The planned backbone pipeline through Port of Rotterdam in the Porthos project is reported to have the following key design features extracted from [4]:

- The operational pressure is 35 bar
- The pipeline will be placed in an existing pipeline corridor which is between 10 and 45 m wide
- The pipeline diameter is approximately 1 080 mm (42 inches)
- The onshore length of the pipeline is 30 km
- The reported capacity of the pipeline is 2.5 Mt annually

There is no information about operating temperature, and therefore ambient temperature is assumed. The velocity in the pipeline is assumed to be 1 m/s.

The length of the connecting pipeline and the need to connect to the backbone pipeline will be case specific. The diameter of the connection pipeline is assumed to be 450 mm.

Onshore Port Arthur

For Port Arthur it is assumed that the CO_2 is transported through a 300 mm connecting pipeline to the Denbury Green Pipeline for transport to a suitable EOR injection site. Only the connecting pipeline is calculated in the EverLoNG project. The operating pressure of the connecting pipeline is assumed to be 120 bar, the length is 25 km, and the CO_2 velocity is 1 m/s.

Export site

The captured CO_2 arrives at the Port of Rotterdam export site at a pressure of 35 bar and ambient temperature. The design of the export site will depend on the next step of the chain, as the CO_2 is either transported by ship to Northern Lights or to the Aramis injection site by offshore pipeline. The design capacity of the export terminal is such that it matches the capacity of the backbone pipeline through Port of Rotterdam, i.e., 2.5 Mt annually.

Northern Lights

Transport of CO_2 to the Northern Lights infrastructure is done by CO_2 ship operating at a pressure of 15 barg and a temperature of -28 °C. This means that the CO_2 must be liquefied. The liquefaction process selected here includes further pressurisation of the CO_2 from 35 bar and then expansion down to transport pressure. The liquid CO_2 is then stored in intermediate storage tanks awaiting the CO_2 cargo ships arrival for transport to the Northern Lights import terminal.

Aramis

The operating pressure of the Aramis offshore pipeline is expected to be 150 bar. The CO_2 coming arriving at the export site through the onshore pipeline is therefore conditioned, compressed and pumped, to reach the pressure needed.

Sink

This segment covers the rest of the elements needed to reach permanent storage or the utilisation site.

Northern Lights

The CO_2 collected from the Port of Rotterdam export terminal is shipped to the import terminal of Northern Lights located in Øygarden on the West coast of Norway. At the CO_2 cargo vessels arrival, the CO_2 is pumped to shore and intermediately stored in onshore storage tanks. The CO_2 cargo vessel then returns to Port of Rotterdam. It is assumed that a vessel like the Northern Lights 7 500 t vessels is used. Figure 10 shows a recent picture of a delivered CO_2 cargo vessel, Northern Pioneer, at the terminal in Øygarden.

The next step of the Northern Lights chain is conditioning of the CO_2 to pipeline operating pressure with the final step being transport through an offshore pipeline to the injection site. The conditioning step consists of pumping and heating of liquid CO_2. The length of the transport pipeline is reported to be 100 km, and the operating pressure of the pipeline is assumed to be 120 bar.

Aramis

The CO_2 leaves the export terminal at Port of Rotterdam through an offshore pipeline and transported to the offshore injection site. The pipeline is assumed to have an operating pressure of 120 bar, a length of 200 km, and a CO_2 transport velocity of 1 m/s. The design capacity of the pipeline is 7.5 Mt which is in line with the first phase of the Aramis project [5].

Figure 10. Northern Pioneer at CO_2 facilities in Øygarden. Photo by Ruben Soltvedt [20].

EOR – Port Arthur

The CO_2 from the connecting pipeline is assumed to enter the Denbury Green Pipeline for transport to an EOR injection site. The pipeline transport distance and operating conditions is not specified and assumed to be outside of scope.

Utilisation – Port of Rotterdam

As specified in Section 2.1.1, the CO_2 utilisation site is assumed located within the Botlek industrial site. CO_2 is assumed to be transported from the receival facility through dedicated pipelines. The pipeline distance will vary depending on the case. The operating condition is assumed to be the same as for the connecting and backbone pipelines previously described.

The methanol and methane production capacity of the plant is assumed to be 100 kt per year [20]. The CO_2 needed is taken from Prussi et al. [21] and calculated to be 148.3 kt for the methanol and 270.0 kt for methane.

3.4 Case specific design data

In this section, the technical details of each case are provided. The design data are summarised in Table 2 and 3, for Sleipnir and LNG tanker cases, respectively. It is worth noting that the design capacity of the chain elements varies throughout the chain. The reason for this approach is to design a chain that would be analogue to the existing plans of Northern Lights and Aramis. It should also be noted that in the case of ship transport to Northern Lights, only one ship is included in the assessment. The annual transport capacity of one 7 500 t CO_2 cargo ship operating between Port of Rotterdam and the Øygarden import terminal is around 410 000 t. This is less than the capacity needed for the full utilisation degree, where the CO_2 volume is 450 000 t. However, it is assumed that more than one CO_2 cargo ship will be in operation, but it will not affect the design of the terminals.

Table 2. The design data for Sleipnir cases.

	Case 1a	Case 1b	Case 2a	Case 2b
Receival facility – Port of Rotterdam				
CO_2 handling capacity, Mt/year	0.45			
Net storage capacity per tank, m^3	636			
Number of tanks	9			
State of CO_2 received, bara/°C	15/-28		-	-
Length and diameter of connecting onshore pipeline, km/mm	3.6/450		-	-

Length and diameter of backbone onshore pipeline, km/mm	24/1080	-	-	-
Length and diameter of onshore pipeline to utilisation, km/mm	-	-	30/450	
Operating condition of pipeline, bar	35		35	
Calculated total pressure drop, bar	0.2		0.5	
Pump delta P, bar	19.2		19.5	
Heat exchanger delta T, °C	36		36	
Export site – Port of Rotterdam				
CO_2 handling capacity, Mt/year	2.5		-	-
CO_2 condition of next step	Liquid CO_2	Compressed CO_2	-	-
Number of tanks (similar to receival facility tanks)	20	-	-	-
CO_2 transport to storage				
To/from	Port of Rotterdam to Øygarden	Port of Rotterdam to offshore injection site	-	-
Mode of transport	Ship	Offshore pipeline	-	-
CO_2 cargo vessel size, t	7 500	-	-	-
Operating condition, bara/°C	15/-28	120/ambient	-	-
CO_2 handling capacity, Mt/year	0.41 (one ship)	7.5	-	-
Offshore pipeline length and diameter, km/mm	-	200/700	-	-
Calculated pressure drop, bar	-	17	-	-
Import terminal - Øygarden				
CO_2 handling capacity onshore facilities, Mt/year	0.41	-	-	-
Number of tanks (similar to receival facility tanks)	12	-	-	-
CO_2 handling capacity offshore pipeline, Mt/year	1.5	-	-	-

Length and diameter of offshore pipeline, km/mm	100/300	-	-	-
Operating condition of pipeline, bar	80	-	-	-
Calculated total pressure drop, bar	27	-	-	-
Pump delta P, bar	91	-	-	-
Heat exchanger delta T, °C	17	-	-	-
CO_2 utilisation Port of Rotterdam				
CO_2 consumed, Mt/year*	-	-	0.15	0.27

*Please note that the handling capacity is different than the CO_2 consumed as the CO_2 volume for utilisation is limited by the methanol and methane production capacity assumed to be 100 kt annually.

Table 3. The design data for the LNG tanker cases.

	Case 3a	Case 3b	Case 4a	Case 4b
Receival facility – Port of Rotterdam				
CO_2 handling capacity, Mt/year	0.45			
Net storage capacity per tank, m^3	636			
Number of tanks	5			
State of CO_2 received, bara/°C	15/-28			
Length and diameter of connecting onshore pipeline, km/mm	2.4/450		-	-
Length and diameter of backbone onshore pipeline, km/mm	-	-	-	-
Length and diameter of onshore pipeline to utilisation, km/mm	-	-	50/450	
Operating condition of pipeline, bar	35		35	
Calculated total pressure drop, bar	0.05		0.5	
Pump delta P, bar	19.05		19.5	
Heat exchanger delta T, °C	36		36	

Export site – Port of Rotterdam				
CO_2 handling capacity, Mt/year	2.5		-	-
CO_2 condition of next step	Liquid CO_2	Compressed CO_2	-	-
Intermediate storage tanks (similar to receival facility tanks)	20	-	-	-
CO_2 transport				
To/from	Port of Rotterdam to Øygarden	Port of Rotterdam to offshore injection site	-	-
Mode of transport	Ship	Offshore pipeline	-	-
CO_2 cargo vessel size, t	7 500	-	-	-
Operating condition, bara/°C	15/-28	120/ambient	-	-
CO_2 handling capacity, Mt/year	0.41 (one ship)	7.5	-	-
Offshore pipeline length and diameter, km/mm	-	200/700	-	-
Calculated pressure drop, bar	-	17	-	-
Import terminal - Øygarden				
CO_2 handling capacity onshore facilities, Mt/year	0.41	-	-	-
Intermediate storage tanks (similar to receival facility tanks)	12	-	-	-
CO_2 handling capacity offshore pipeline, Mt/year	1.5	-	-	-
Length and diameter of offshore pipeline, km/mm	100/300	-	-	-
Operating condition of pipeline, bar	80	-	-	-
Calculated total pressure drop, bar	27	-	-	-
Pump delta P, bar	91	-	-	-
Heat exchanger delta T, °C	17	-	-	-
Import terminal – Port Arthur				

CO_2 handling capacity, Mt/year	0.45			
Net storage capacity per tank, m^3	636			
Number of tanks	5			
State of CO_2 received, bara/°C	15/-28			
Length and diameter of connecting onshore pipeline, km/mm	25/300			
Calculated total pressure drop, bar	13.2			
Pump delta P, bar	118.2			
Heat exchanger delta T, °C	17			
CO_2 utilisation Port of Rotterdam				
CO_2 consumed, Mt/year*	-	-	0.15	0.27

*See comment for Table 2.

The main difference between the Sleipnir cases and the LNG tanker full-chain case studies is the location of the receival facility, see Figure 2. The Sleipnir receival facility is located approximately 15 km in a straight line from the planned export terminal at Port of Rotterdam. This results in a need for both a connecting pipeline and access to the backbone pipeline. Alternatively, a dedicated pipeline could transport the CO_2 from the receival facility to the export terminal. This option has not been explored further here. In the case of the LNG tanker, the receival facility is assumed located on the LNG terminal which is adjacent to the planned export terminal. Therefore, the CO_2 is transported through a dedicated pipeline only, and the backbone pipeline therefore not needed. Furthermore, since there would be no need to comply with the operating condition of the backbone pipeline, 35 bar, the CO_2 unloaded at the LNG terminal could be transported in liquid phase via pipeline directly to the export terminal. This alternative could omit the need for intermediate storage tanks and CO_2 conditioning. However, in the current study a prerequisite is that the CO_2 captured onboard a vessel needs to be unloaded as efficiently as possible and to ensure this, a dedicated receival facility is needed.

Another possibility that has not been explored is the use of barges to which the CO_2 could be unloaded directly. Such barges could operate within the port and collect the CO_2 captured onboard vessels and bring it to the export terminal without the need for port-side receival facilities. This solution is however likely only applicable in a roll-out phase. As soon as the volume increases, the number of barges needed could be such that it would affect port operations.

3.5 Cost estimation

The results of the cost estimation of the different transport and sinks scenarios developed for CO_2 captured onboard the crane vessel Sleipnir and an LNG tanker is provided in Table 4 and 5, respectively. The data has reference year 2023 and are presented as EUR/tonne CO_2 captured.

The results are also broken down to show the CAPEX, fixed OPEX, and variable OPEX of each chain segment, see Figures 11 Sleipnir case studies, and Figure 12 for the LNG tanker studies.

The cost presented covers the transport and storage chain of the CO_2 captured onboard the vessels. The cost of capture also needs to be included for the full-chain cost of CO_2 capture from vessels. Additionally, it should be highlighted that the transport and storage cost is based on a fully utilised infrastructure.

Table 4. The transport and storage cost for the Sleipnir cases.

	Case 1a, EUR/tonne CO_2 captured (2023)	Case 1b, EUR/tonne CO_2 captured (2023)	Case 2a, EUR/tonne CO_2 captured (2023	Case 2b, EUR/tonne CO_2 captured (2023
Receival facility at Port of Rotterdam	23.7	23.7	21.8	21.8
Backbone pipeline Port of Rotterdam	3.6	3.6	-	-
Export terminal Port of Rotterdam	17.4	3.2	-	-
CO_2 cargo ship to Northern Lights	25.7	-	-	-
Import terminal Northern Lights	25.5	-	-	-
Offshore pipeline to storage in Northern Lights	11.3	-	-	-
Offshore pipeline to storage in Aramis	-	9.2	-	-
Storage access fee	40.0	40.0	-	-
Onshore pipeline to utilisation	-	-	48.5	26.7
EU ETS (all emissions within EU/EEA)	-	-	70.0	70.0
Total	**147**	**80**	**140**	**118**

The results presented in Table 4 shows that having access to storage infrastructure nearby is beneficial as expected. For the specific cases studied, the reason for this is that shipping the CO_2 for storage in the Northern Lights infrastructure involves more transport steps than the Aramis storage alternative.

The need for intermediate storage tanks along the chain increases the cost, this is especially a cost driving factor for the Northern Lights case studies where such tanks are found at the receival facility, the export terminal at Port of Rotterdam, and at the Northern Lights import facility.

In addition to the two cases where the CO_2 is permanently stored underground, a case where the CO_2 is transported to a facility for methane or methanol production is also assessed. The transport of CO_2 from the receival facility to the utilisation site could be excluded from the cost and become the responsibility of the fuel production plant. However, to ensure predictable operation of the receival facility, the cost of transporting the CO_2 to utilisation is assumed to be within the scope. It should also be noted that the pipeline is will only transport the CO_2 volume specified in Table 2.

The feasibility of utilisation depends on the price the fuel producer is willing to pay for the CO_2. The cost presented in Table 4 is for receival facility and transport only and the cost of onboard capture needs to be included.

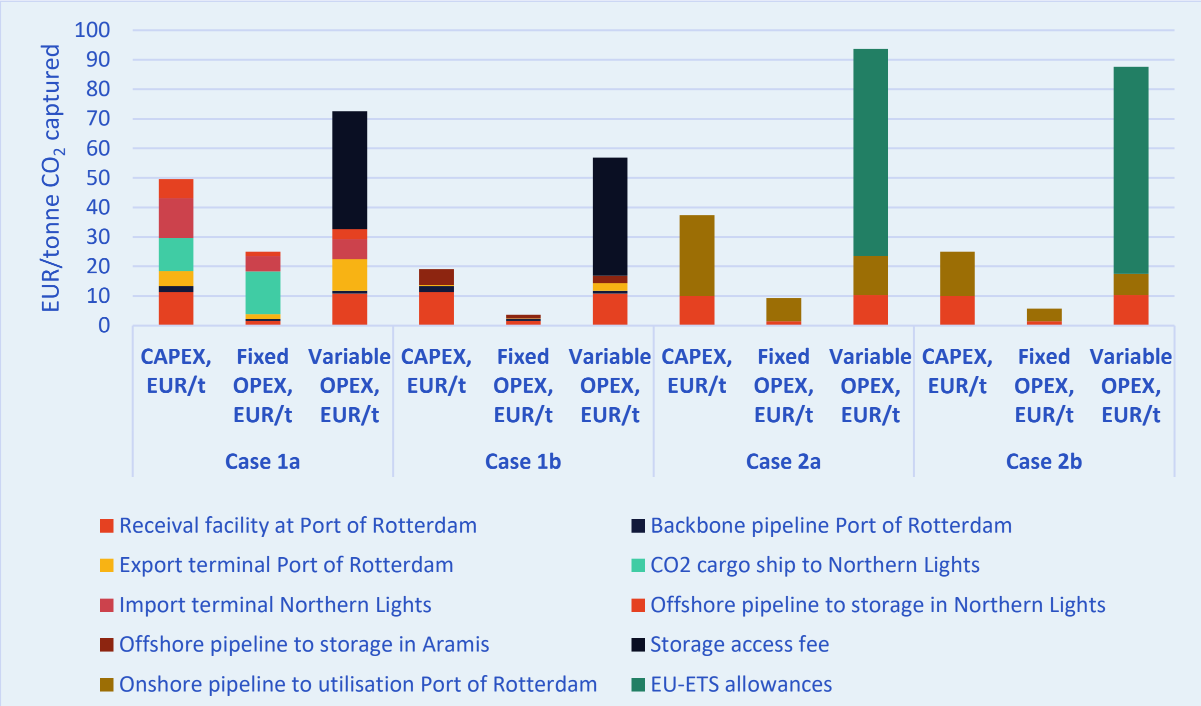

Figure 11. Cost breakdown of the chain elements for the Sleipnir cases.

The cost breakdown in the figure shows the contribution of CAPEX, fixed OPEX and variable OPEX on for each chain segment.

Table 5. The transport and storage cost for the LNG tanker case studies.

	Case 3a, EUR/tonne CO_2 captured (2023)	Case 3b, EUR/tonne CO_2 captured (2023)	Case 4a EUR/tonne CO_2 captured (2023)	Case 4b, EUR/tonne CO_2 captured (2023)
Receival facility at Port of Rotterdam	17.9	17.9	15.8	15.8
Backbone pipeline Port of Rotterdam	-	-	-	-
Export terminal Port of Rotterdam	17.4	3.2	-	-
CO_2 cargo ship to Northern Lights	25.7	-	-	-
Import terminal Northern Lights	25.5	-	-	-
Offshore pipeline to storage in Northern Lights	11.3	-	-	-
Offshore pipeline to storage in Aramis	-	9.2	-	-
Storage access fee	40.0	40.0	-	-
Import terminal Port Arthur	24.9	24.9	24.9	24.9

Transport and EOR (storage) Port Arthur access fee	14.0	14.0	14.0	14.0
Onshore pipeline to utilisation Port of Rotterdam	-	-	80.9	44.4
EU ETS (50 % emissions within EU/EEA)	-	-	35	35
Total	**177**	**109**	**171**	**134**

The same observations that were made for the Sleipnir-based case studies, are applicable for the LNG tanker case studies.

Compared to the Sleipnir cases, the case with the LNG tanker shows a significant increase in cost. The reason for this is because the CO_2 is unloaded at both Port of Rotterdam and Port Arthur. This cost presented in Table 5 is the cost calculated to access shared infrastructure. However, for an LNG tanker that for the scenario studied here unloads 50 % of the captured CO_2 at Port or Rotterdam and the other 50 % at Port Arthur the cost of transport and storage will be averaged. This results in a cost of 88.3, 54.4, 85.5, and 67.0 EUR/t CO_2 transported and stored for the cases presented in Table 5.

It is not clear at this point how the cost of such a case should be presented. Therefore, the cost associated with transport and storage for case 3a, 3b, and 4a/b in cases where the CO_2 is potentially only unloaded at one of the ports. These results are presented in Tables 6 and 7 for Port of Rotterdam and Port Arthur, respectively.

Table 6. The transport and storage cost for the LNG tanker when CO_2 is only unloaded at Port of Rotterdam.

	Case 3a, EUR/tonne CO_2 captured (2023)	Case 3b, EUR/tonne CO_2 captured (2023)
Receival facility at Port of Rotterdam	17.9	17.9
Backbone pipeline Port of Rotterdam	-	-
Export terminal Port of Rotterdam	17.4	3.2
CO_2 cargo ship to Northern Lights	25.7	-
Import terminal Northern Lights	25.5	-
Offshore pipeline to storage in Northern Lights	11.3	-
Offshore pipeline to storage in Aramis	-	9.2
Storage	40.0	40.0
Onshore pipeline to utilisation Port of Rotterdam	-	-
EU ETS (50 % emissions within EU/EEA)	-	-
Total	**138**	**70**

Table 7. The transport and storage cost for the LNG tanker when CO_2 is only unloaded at Port of Arthur.

	Case 3a, EUR/tonne CO_2 captured (2023)	Case 3b, EUR/tonne CO_2 captured (2023)
Import terminal Port Arthur	24.9	
Transport and EOR (storage) Port Arthur	14.0	
Total	**38.9**	

The cost breakdown of the cost data provided in Table 5 is provided in Figure 12 for each chain segment.

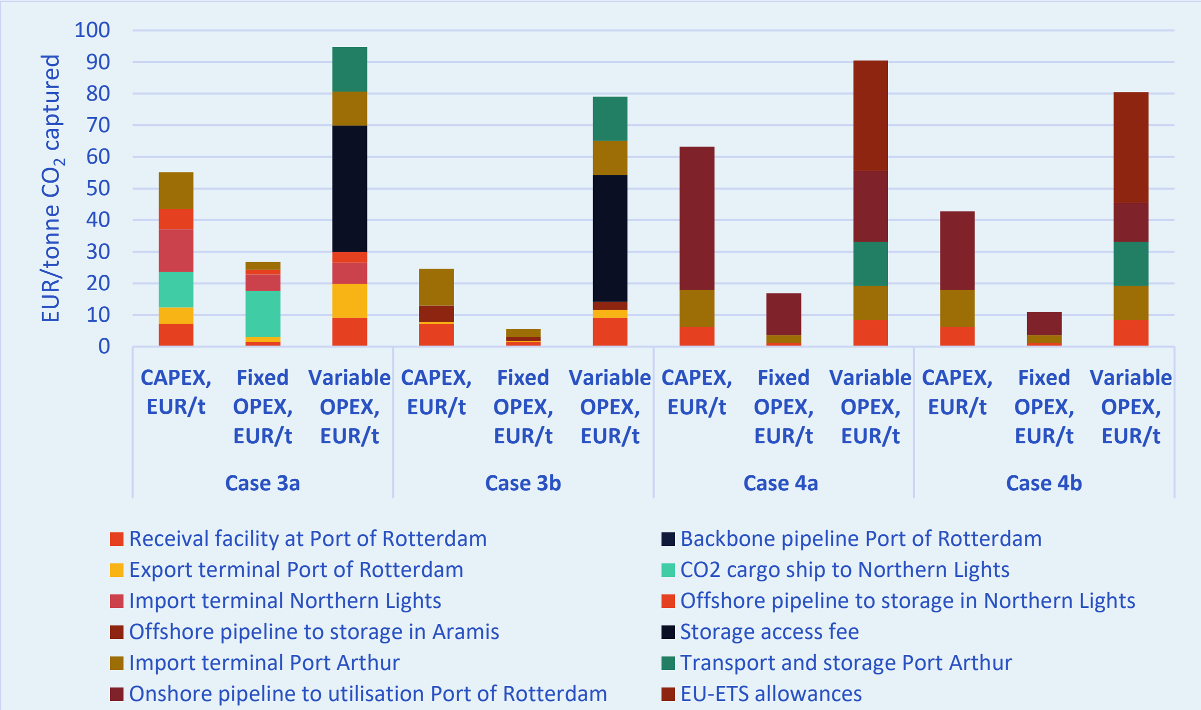

Figure 12. Cost breakdown of the chain elements for the LNG cases.

4 Concluding remarks

The purpose of this task of the EverLoNG project was to perform a techno-economic assessment of full-chain OCC. The governing assumption made in this work was that the transport and storage scenarios should be based on existing and/or planned infrastructure to the degree possible. There are several transport and storage projects under development and some even in the construction phase, but none are currently in operation. The location of these projects formed the basis of the full-chain OCC case studies. Further, selecting Port of Rotterdam as Sleipnir's unloading port is natural is this is the homeport of the crane vessel. An LNG tanker is also likely to frequent Port of Rotterdam as it is an important port for LNG trade.

The most challenging aspect of OCC full-chain assessment was the CO_2 volumes to be handled. The vessels studied would call the port between nine and eleven times a year and unloading 4 500 and 2 500 tonne of CO_2 at each call. The total annual volumes to be handled were close to 40 000 and

30 000 tonne. Building a permanent infrastructure for such small volumes becomes costly. It was therefore decided that the facility to which the vessels unload should be designed for full utilisation degree. The annual design volume of the portside receival facility then became 450 000 tonne. A reduction in utilisation degree will greatly increase the cost of CO_2 handling of the receival facility. The scope of the receival facility is the infrastructure needed to receive the CO_2, condition it, and transport it to a shared infrastructure for further transport to sink.

The OCC transport and storage assessment performed in EverLoNG indicates that utilising nearby storage infrastructure is the least costly alternative, with reference to Aramis versus Northern Lights. However, this is potentially dependent on the mode of transport needed to reach the storage infrastructure. Transporting the CO_2 to Northern Lights necessitates an export terminal, a CO_2 cargo ship, and import terminal, and a pipeline to the offshore injection site. Each step is also associated with CO_2 conditioning. For storage in Aramis, only the pipeline is needed, resulting in a significantly less complex transport and storage chain.

The cost of storage used in the current study was a guestimate based on available data for Aramis and Northern Lights. It is likely that the cost of storage will become lower as more storage projects are developed and implemented.

As already mentioned, it is paramount that the infrastructure developed has a high utilisation degree both from a technical and economic perspective. The economic aspects were discussed above. From the technical perspective, a lower utilisation degree could affect the operation of the infrastructure as the CO_2 then will arrive batchwise and feed into the rest of the chain in the same manner.

The tecno-economic assessment of transport and storage chains for OCC developed in EverLoNG were governed by Port of Rotterdam layout, operational restrictions, and CO_2 infrastructure plans. Still, the general approach should still be adaptable to other ports.

There is a need of a strategy for portside infrastructure development in an OCC start-up phase. The first projects being commercialised will likely yield small volumes delivered at different parts of a port (depending on the type of vessel). A gradual development of port-side infrastructure is needed, and it is likely that at least parts of the infrastructure utilised in an initial phase could be temporary installations.

There is also a significant uncertainty in the role-out of OCC and this will increase the risks associated with infrastructure development. It is paramount that the risk is distributed between the port authorities and the shipping industry.

5 Nomenclature

ACT	Accelerating CCS technologies
CAPEX	Capital expenditure
CCS	Carbon capture and storage
CCU	Carbon capture and utilisation
CCUS	Carbon capture, utilisation, and storage
EOR	Enhanced oil recovery
EU ETS	European Union Emissions Trading System
FEED	Front end engineering design
LNG	Liquefied natural gas

OCC	Onboard carbon capture
OPEX	Operational expenditure
RFNBO	Renewable fuels of non-biological origin
TEA	Techno-economic assessment

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