TEA and LCA framework document for EverLoNG case studies

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Executive summary

The EverLoNG project, part of the ACT initiative, focuses on integrating Ship-Based Carbon Capture (SBCC) technology on LNG-fuelled vessels to combat maritime emissions. The project demonstrates the potential for SBCC to significantly reduce maritime emissions while highlighting the associated economic and logistical challenges.

Two case studies are central to this analysis: the Sleipnir semi-submersible crane vessel and a new-built LNG carrier from TotalEnergies. These vessels represent different operational profiles and fuel use scenarios, with CO_2 capture rates reaching up to 95% under optimal conditions. Ports of Rotterdam in The Netherlands and Port Arthur in Houston, US serve as hubs for unloading captured CO_2, which is either permanently stored in projects like Northern Lights and Aramis or utilized for enhanced oil recovery (EOR) or chemical production (methanol/methane).

The TEA evaluates financial metrics, including capital and operational costs for the on-board part, onshore part and the full chain with the necessary assumptions, while the LCA assesses environmental impacts across the CO_2 capture and storage/utilization lifecycle. Key findings will guide the development of scalable SBCC solutions, emphasizing integration with existing port and storage infrastructure.

This document outlines the framework for conducting Techno-Economic Analysis (TEA) and Life Cycle Assessment (LCA) to evaluate the feasibility, costs, and environmental impacts of SBCC implementation.

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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 SBCC by demonstrating its use on LNG-fuelled ships. The project will optimize the technology and consider how to best integrate SBCC into existing ship and port infrastructure. A schematic representation of the EverLoNG project and its scope is shown in Figure 1.

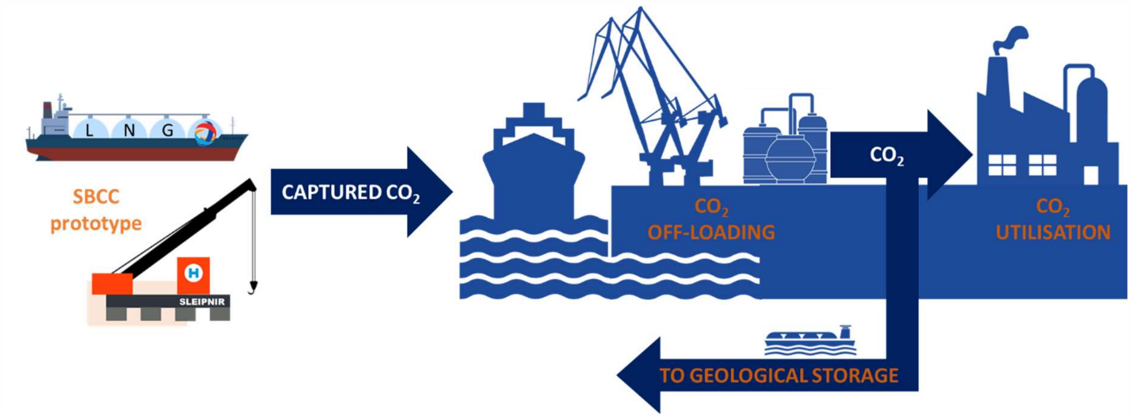

Figure 1: Schematic representation showing the scope of the EverLoNG project

This document serves as the main guideline document for the work done in WP4 of the EverLoNG project, which aimed to perform techno-economic and life cycle assessment on the main case studies considered in the project. Shaped as a framework document, this describes the cases to be studied in detail including the description of appropriate boundary conditions, assumptions and the methodology to evaluate those cases in detail.

The results of the techno-economic evaluation and life cycle assessment are reported in separate documents (LCA D4.1.1, D4.2.1, TEA D3.1.2, D3.1.3, D3.2.3, D3.3.1, D4.3.2, D4.3.3).

Defining the TEA and LCA cases in the EverLoNG project

The logistics in SBCC cases is very different compared with conventional CO_2 capture from an industry, partly due to the lower volumes expected from SBCC (per individual vessel) and the potential uncertainty in the captured CO_2 being offloaded. Some vessels are operated on a chartering basis which means that they do not have a regular route and the ports that they visit may vary from charter to charter. This is typically true 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 final destination, either for utilisation or permanent storage.

The TEA and LCA cases to be studied are introduced in this chapter, aiming to create a clear overview of the boundary conditions on which the TEA and LCA studies are based.

On-board CO_2 capture and liquefaction system

The operational data of both the vessels are provided over ca. 2 years. In this project, MAN/CEAS technical files and/or emissions test reports are then used to get the exhaust gas characteristics and fuel consumption data with respect to the different engine loads that aid in developing the operational and CO_2 emissions profile which are the basis for conceptual design of SBCC technology. After a detailed analysis of the operational data (performed in WP3 of this project), an appropriate size is chosen for the capture system, and the capture and liquefaction processes are simulated in ProTreat® v8.0 and Aspen Plus v14 respectively for this design size. These provide the mass and energy balance results from which the sizing of all equipment is performed. Some additional equipment is sized separately and not modelled in the aforementioned software. The WP3 report (D3.1.2, D3.1.3, D3.2.3, D3.3.1, D4.3.2, D4.3.3) discusses these aspects in detail.

The system boundary for the on-board part is from the exhaust gas from the turbocharger outlet (which is decided based on the analysis of the operational data, shown in WP3 in detail) until the stored CO_2 being offloaded and any spent MEA is reclaimed in the onshore facility. The process flow diagram (PFD) of the CO_2 capture and liquefaction sections are respectively shown in Figure 2 and Figure 3. For the LNG carrier, the PFD shown varies mainly with respect to the number of economizers needed (one for each main engine and one for the auxiliary engines altogether). The exhaust gases are combined before the economizer in the Sleipnir case as opposed to after the economizers for the LNG carrier case.

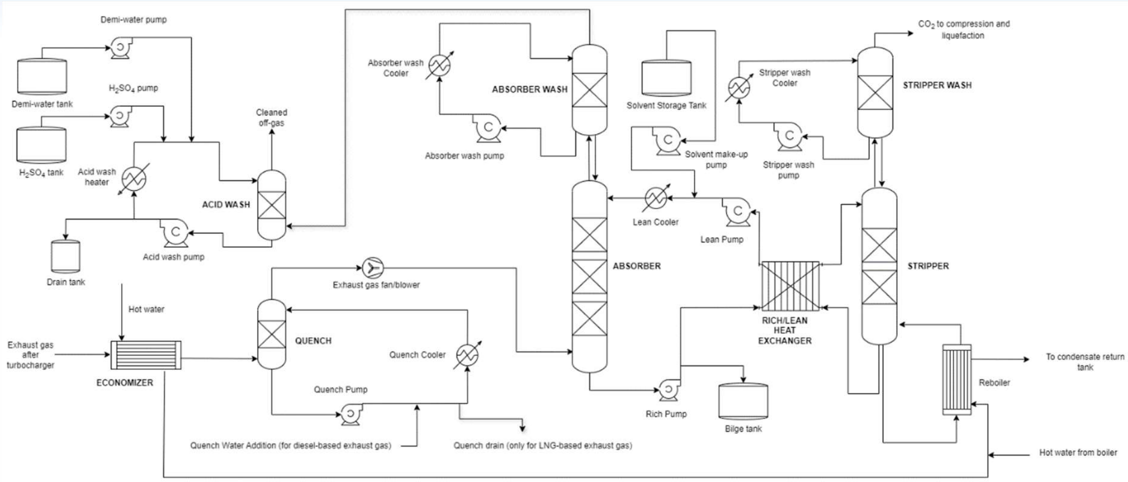

Figure 2: Process flow diagram of the SBCC technology where the system boundary for the on-board starts from the exhaust gases from all the engines exiting the turbocharger outlet combined

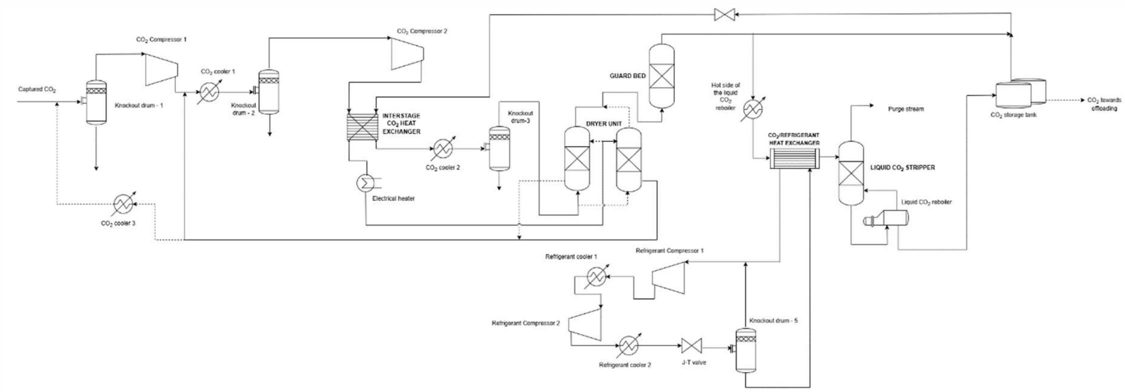

Figure 3: Process flow diagram of the SBCC technology where the system boundary for the on-board ends with the storage tank

Introduction to Sleipnir and TotalEnergies on-board case studies

The EverLoNG project consists of two main case studies, the Sleipnir vessel from Heerema and a new-build LNG carrier from TotalEnergies. The SBCC systems on-board of these vessels are described in detail in the results of WP3 and are briefly summarized in this section.

Sleipnir case study

The Sleipnir is a semi-submersible crane vessel from Heerema. There are 12 main engines on-board of 8 MW each, giving a total installed power of 96 MW. The vessel can sail both on LNG and Diesel fuel, which are separately assessed as a TEA case study. Figure 4 shows the operational profile and corresponding emission profile of the Sleipnir vessel using almost 2 years of hourly averages data (692 days), giving total emissions of 86.6 kton CO_2 emissions in this period. When the operational profile is modified for 100% LNG mode of engine operation, the overall emissions from the vessel reduce to 75.3 kton. The main operation of the Sleipnir is in the 4.5 to 20 MW range. In WP3, it was decided to build the capture systems for 15 MW of equivalent power in a single capture system, meaning that exhaust gases from all the different engines are combined into a single stack. This means that at lower than 15 MW loads, all exhaust gas is treated in the capture system, while at loads higher than 15 MW total load, a percentage of exhaust gas, equal to 15 MW equivalent, is treated in the system.

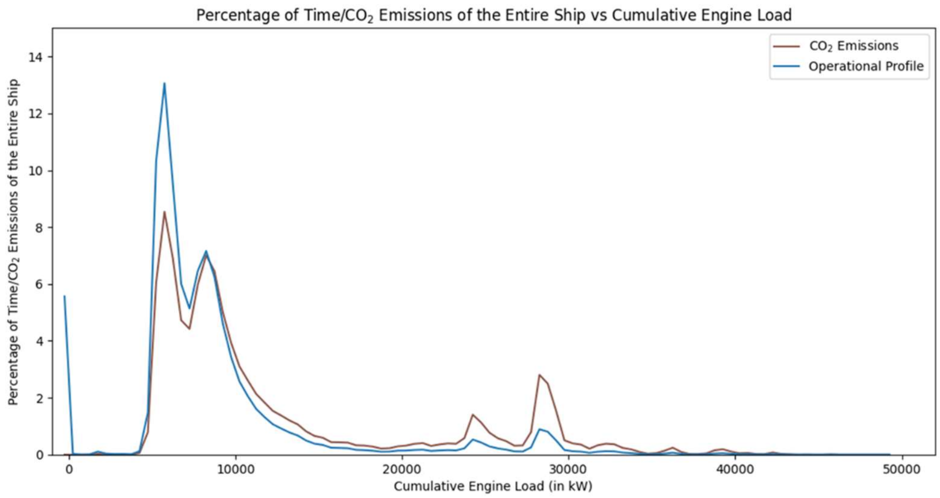

Figure 4: Operational and CO_2 emissions profile of the Sleipnir vessel, as assessed in WP3

The case study is divided in Diesel and LNG (gas) operation separately. The reason for this is that the engine's operation is different for the different fuels, giving different exhaust gas temperatures and CO_2 concentrations (5.28 versus 4.24 vol% respectively for diesel and gas cases). Additionally, it is assumed that heat can be recovered until 135 °C for the LNG case because of the low sulphur content in the LNG-based exhaust gas, while for diesel, the limit is set at 180 °C to avoid crossing the dew point of sulphuric acid formed from the SO_x present in the flue gas. Therefore, it was concluded that for the LNG case, there is sufficient heat available in the exhaust gas to capture all CO_2, and the capture rate of 95% could be achieved, without burning additional fuel for heat in the capture system. For diesel mode, this is not the case, and a maximum capture rate of 77.5% was calculated based on the total amount of heat that can potentially be recovered from the exhaust gas.

The captured CO_2 is compressed and liquefied downstream in a two-stage compression section with the help of an ammonia refrigeration cycle where around 8 ton CO_2/h is liquefied at -26.63 °C and 16 bara. A storage tank capacity of 4000 m^3 was determined considering the offloading period of 6 weeks. The CO_{2eq} avoidance achieved when the operational profile is considered as 50/50 and 100% LNG is respectively 58.1% and 70.5% for the 15 MW design load of the SBCC unit.

The TEA should consider two cases for the Sleipnir vessel: (1) Use the operational profile as evaluated from the obtained data, where Diesel and LNG were used ca. 50/50 and (2) Assume 100% LNG operation.

TotalEnergies LNG carrier case study

For the new-built LNG carrier case study, the effect of implementing different types of engines is included on the total energy balance of the ship with CO_2 capture. The final main engine considered for the LNG carrier case is the MAN 5G70ME-C10.5-GI-LPSCR as it gave the best performance for combined sailing + carbon capture out of all engines analysed (lowest fuel penalty at highest capture rate). Details on this are provided in WP3. The TEA considers one case for the TotalEnergies vessel using the operational data supplied by TotalEnergies for this case.

The TotalEnergies case study is based on a hypothetical new-built LNG carrier. Operational profile for a sister vessel spanning ca. 1.5 years of sailing data was provided at a daily average frequency. This vessel has two main propulsion engines with a maximum continuous rating (MCR) of 12590 kW each giving a total installed power of 25180 kW and 4 auxiliary engines (two engines (large) with an MCR of 3840 kW_e and two engines (small) with an MCR of 2880 kW_e). Additionally, there is also an auxiliary boiler on-board that consumes fuel. All these engines run predominantly on LNG with LSMGO as the pilot fuel. The CO_2 emissions profile for the LNG carrier is shown in Figure 5. Various engine types were elaborated as part of WP3 and an GI engine with a LPSCR system was selected as the engine type to be used. Importantly, for the Sleipnir vessel, the heat availability was never an issue (when considering LNG) and the exhaust gas temperatures available in that case is high enough to go for capture rates >90% whereas for the TotalEnergies case, the capture rate is fixed to be 90%, and the additional heat required for the capture system (next to what is available) is calculated. Also, for both the vessels, methane slip was included in order to determine the $CO_{2,equivalent}$ avoidance from the vessel.

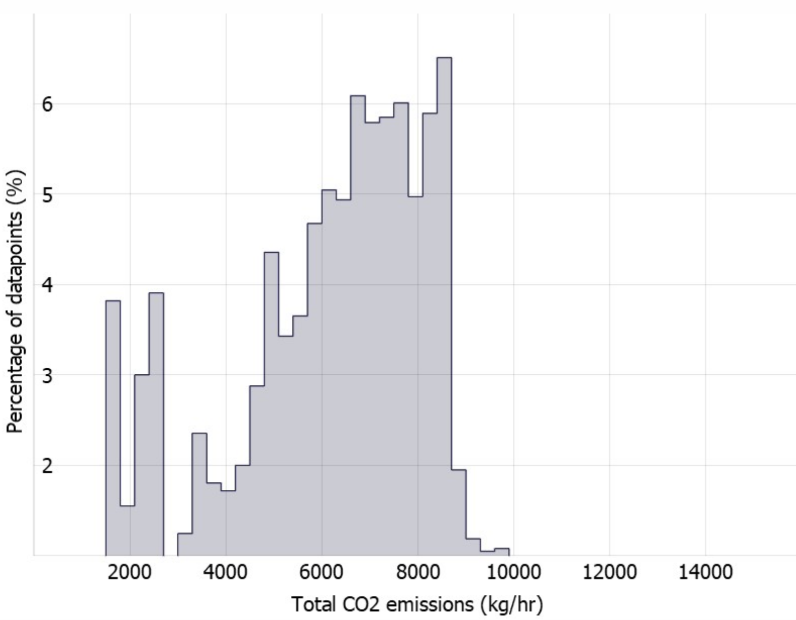

Figure 5: CO_2 emissions profile of the LNG carrier

Associated shop test and emission test reports relevant to the TotalEnergies vessel for the main and auxiliary engines provide the required information on the fuel consumption, exhaust gas flow rates and compositions with respect to different engine loads aiding in the design of the carbon capture system. Based on the operational and emissions profile, the design capacity chosen was that 8000 kg CO_2/h will be processed in the capture system. An assumption is made to combine the exhaust gases from the main engines running parallelly at 61% load and one large and small auxiliary engine at 54.6%

load, and using this as a design point for the capture system. The resulting exhaust gas flow is ca. 144 ton/h with a resultant CO_2 concentration of 3.64 mol%. The details about the conceptual design of the SBCC technology was elucidated as part of WP3.

For a design capacity of 8000 kgCO_2/h processed in the capture system, the amount of CO_2 avoided including and excluding the recapture of additional emissions from burning fuel are 74.7% (67.8 kton) and 67.8% (61.5 kton) respectively. Figure 6 shows the performance curve of the TotalEnergies vessel for the various design capacities giving the data on fuel penalty (%) vs $CO_{2,equivalent}$ avoidance (%) where the additional emissions from burning fuel either being captured or not.

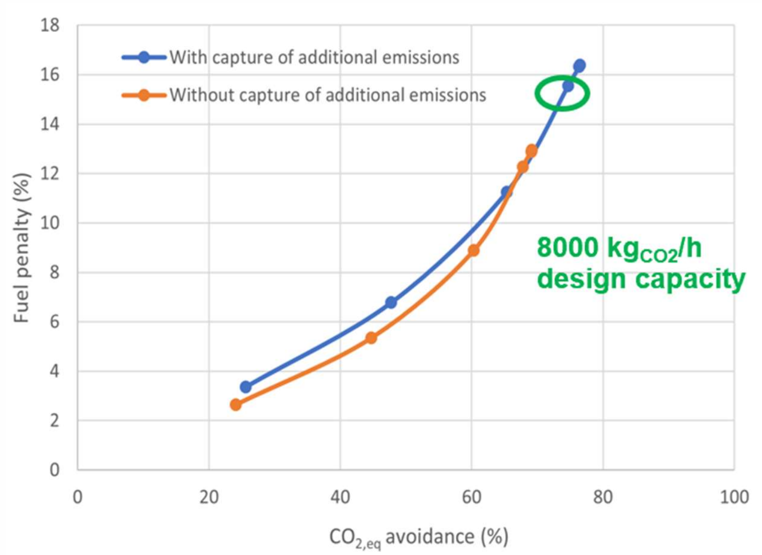

Figure 6: Performance curve of the carbon capture system in the LNG carrier

Port and sink selection

After the CO_2 has been captured and liquefied onboard the vessels, it needs to be unloaded and further be treated in the onshore facility which is then transported to a suitable sink, either for permanent storage or utilisation. The unloading should happen when the vessel calls at port as part of their normal operation. For Sleipnir, the port selection is straight-forward as the home port of the vessel is Port of Rotterdam. For TotalEnergies's LNG tanker, the port selection is slightly more challenging as such a vessel might not travel between the same port in every voyage. It has therefore been decided for the case of developing a predictable full-chain case study, that the LNG tanker will have a fixed route.

The vessel will transport LNG from the U.S. to Europe. Port Arthur, Texas, located roughly 110 kilometres (70 miles) east of Houston, has several operating LNG export facilities, and is within reasonable distance to an existing CO_2 common carrier pipeline. The receiving port in Europe was selected to be the Port of Rotterdam which imports a significant volume of LNG each year. After selecting the two ports, possible options for disposition of CO_2 for each port need to be investigated to complete the CCUS chain. The two ports are discussed separately in the sections below.

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. Porthos is expected to store a 2.5 Mt CO_2 per year for 15 years from 2026[1]. The planned infrastructure of the project is further described here[2]. However, the Porthos project is, based on information about the current project, at full capacity and therefore not a realistic 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[3]. 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.

In the Northern Lights project, CO_2 will be transported in dedicated CO_2 cargo vessels to the import terminal at Øygarden, followed by pipeline transport to an offshore injection site for permanent storage in an aquifer[4,5]. 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[6]. As there are no indications regarding limited capacity, it was decided that this would be the storage base case for CO_2 offloaded at the Port of Rotterdam.

It was decided to include both Aramis and Northern Lights as possible permanent storage sinks for CO_2 from both the vessels when the CO_2 is unloaded in the Port of Rotterdam.

A potential alternative to permanent storage of CO_2 is utilisation. When assessing CO_2 utilisation pathways, it is important to keep in mind that maritime emissions are included in the EU-ETS from January 2024[7]. 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 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.

An alternative or compliment to SBCC is fuel switching. 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

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[1] Fraters, M. (2023, October 18). First CO2 storage project in the Netherlands is launched. Porthos. https://www.porthosco2.nl/en/first-co2-storage-project-in-the-netherlands-is-launched/

[2] Project. (n.d.). Porthos. Retrieved November 17, 2023, from https://www.porthosco2.nl/en/project/

[3] Aramis. 2023. A transport infrastructure for large-scale co reduction. https://www.aramis-ccs.com/files/Aramis-brochure_20230921_ENG.pdf

[4] Equinor. 2019. Northern Lights Project Concept Report. Doc. No. RE-PM673-00001. https://ccsnorway.com/app/uploads/sites/6/2020/05/Northern-Lights-Project-Concept-report.pdf

[5] Equinor. 2020. Northern Lights FEED Report. Doc. No. RE-PM673-00057. Rev. No. 06. https://northernlightsccs.com/wp-content/uploads/2021/03/Northern-Lights-FEED-report-public-version.pdf

[6] Northern Lights – How to store CO2 with Northern Lights. (n.d.). Retrieved November 17, 2023, from https://norlights.com/how-to-store-co2-with-northern-lights/

[7] Reducing emissions from the shipping sector. (n.d.). Retrieved November 17, 2023, from https://climate.ec.europa.eu/eu-action/transport/reducing-emissions-shipping-sector_en

of 55% by 2030 compared to 1990 and climate neutrality by 2050[8]. Such fuels can be made using CO_2 and within this regulation, provisions regarding the origin of this CO_2 are made. This can provide an insight into the attractiveness of CO_2 utilisation and the future perspective. The current provision seems to be that until 2041, fossil CO_2 can be accounted as avoided if it originates from activities under EU-ETS or similar CO_2 pricing schemes. After 2041, the definition of avoided CO_2 will only apply to CO_2 originating from biogenic sources or from direct air capture (DAC)[9].

Port Arthur

The Port Arthur was selected as the U.S. port location since it has several LNG export facilities and there is a CO_2 pipeline which can provide access to storage infrastructure in the region. The U.S. Gulf Coast region, of which Port Arthur is a part, is a hub for CCUS projects due to its large industrial base and existing pipeline networks. The Gulf Coast region also offers numerous geological formations suitable for CO_2 sequestration.

The Denbury Green Pipeline (Green Line or Green Pipeline) was selected as the pipeline to transport CO_2 from the onshore facilities at Port Arthur to the site at which the CO_2 will be sequestered. The Denbury Green Pipeline (recently acquired by ExxonMobil) is a ~500 km (320-mile) pipeline that runs from Texas to Louisiana, passing within 25-40 km of the Port Arthur area. The pipeline can carry up to 23 million cubic meters of CO_2 per day. The Green Pipeline primarily serves enhanced oil recovery (EOR) operations but also has the potential to transport CO_2 for permanent sequestration. Key injection sites for EOR along the Green Pipeline include oil fields in Texas and Louisiana, where the CO_2 is injected for EOR. Denbury is also expanding its CO_2 sequestration portfolio to include dedicated storage sites in Louisiana and Mississippi, where CO_2 will be permanently stored underground[10,11].

Determination of sailing profiles of vessels to be studied

As discussed above, the sailing profiles of the ships are analysed from measured operational data. For application in TEA and LCA, the profiles are referenced to a representative operation case from port to port, then translated into fuel consumption and ultimately into CO_2 and other emissions.

For the LNG tanker this is directly defined by the coming and return voyage of the tanker to deliver LNG from North America to Europe. Thus, the operational profile is scaled to match the voyage duration and distance. In this case, an average speed of 16 knots when sailing is assumed based on the operational profile of the original LNG tanker. This leads to 13.16 days of sailing including the 20% idle times observed in the operational profile leads to 16.45 days operation in total. Of the 3.29 days idle, 2 days are assumed to be spent in port, occupying port facilities, and the remaining 1.29 days are idle waiting time.

[8] Delivering the European Green Deal. (2021, July 14). https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal/delivering-european-green-deal_en

[9] DNV. Analysis of the potential for Norwegian production – Sustainable Aviation Fuel from Non-Biological Feedstocks. 2023. https://avinor.no/globalassets/_konsern/miljo-lokal/miljorapporter/dnv---saf-from-non-biological-feedstocks-in-norway---2023-10-05.pdf

[10] Schnacke, G. CO_2 Enhanced Oil Recovery. The American Oil & Gas Reporter. 2010. https://www.aogr.com/magazine/cover-story/denburys-business-model-demonstrates-feasibility-of-co2-eor-in-mature-field.

[11] ExxonMobil. ExxonMobil completes acquisition of Denbury. 2023. https://corporate.exxonmobil.com/news/news-releases/2023/1102_exxonmobil-completes-acquisition-of-denbury.

On the other hand, the operation of the Sleipnir is not predefined in such a direct way. Different projects lead to various operational profiles, and different shares between crane operation, idle time and sailing time. On average, the Sleipnir is fuelled 8-10 times a year at port. This leads to continuous operations of about 6 weeks at a time, without intermediate fuelling or offloading of CO_2. For consideration in the TEA and LCA, the operational profile of the Sleipnir is thus scaled down to 6 weeks, or 24*7*6 hours.

The cases are focused on Port Arthur for the North American side and the Port of Rotterdam on the European side, as discussed above. Said ports were chosen based on their closeness to CCS infrastructure such as the Dutch Porthos project[12] and the CO_2 offtake 'Green Pipeline'[13] close to Port of Arthur. In addition, both ports are highly frequented and central for their respective regions. Thus, they are likely one of the first movers for handling captured carbon, also from onboard capture. With the Port of Rotterdam being a member of the EverLoNG project, deeper insight into establishing the CO_2 handling and port operations can be achieved for this specific port.

Definition of full-chain case studies

The two vessels, Sleipnir and the TotalEnergies LNG tanker, will both be part of a full-chain assessment covering both CO_2 to permanent storage and utilisation. As mentioned above, Sleipnir will call at Port of Rotterdam every six weeks where it will unload captured CO_2. While the LNG tanker will be loading LNG at Port Arthur and unloading LNG at Port of Rotterdam before it returns to Port Arthur. The LNG tanker will unload the captured CO_2 at both ports. It is also assumed that for Port Arthur that there is no permanent storage alternative, therefore the CO_2 will be sent for use in EOR (enhanced oil recovery). The cases are:

- 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

The cases are illustrated from Figure 8 to Figure 12. Please note that the amine handling is not included. The notations LCO2 and CCO2 stands for liquid and compressed CO_2, respectively.

[12] "Porthos Project," *Porthos* (blog), accessed March 26, 2025, https://www.porthosco2.nl/en/project/.
[13] "Carbon Solutions for a Sustainable Future - Denbury Inc," Denbury, accessed March 26, 2025, https://www.denbury.com/.

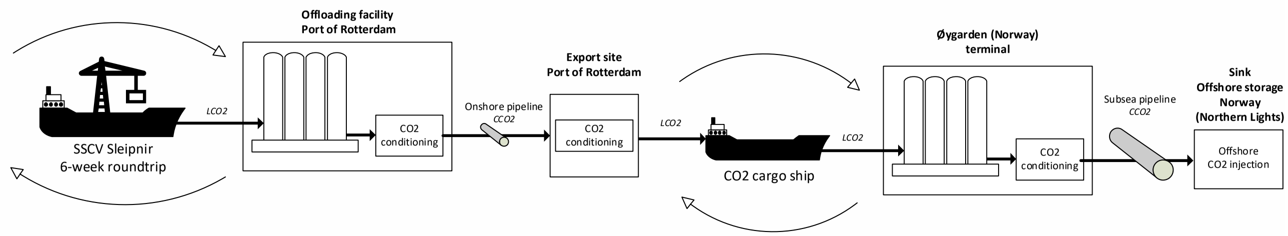


Figure 8: Illustration of Case 1a

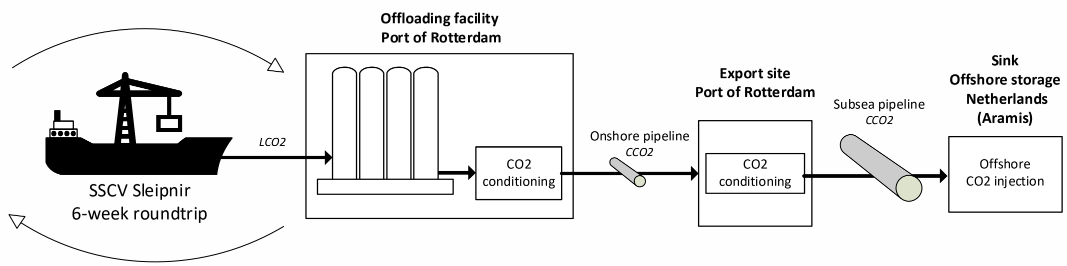


Figure 7: Illustration of Case 1b

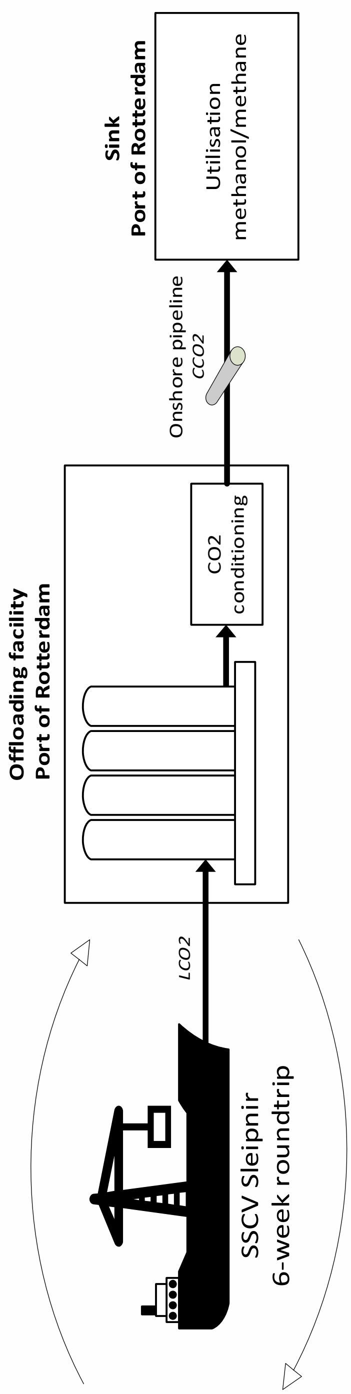


Figure 9: Illustration of Case 2a and 2b

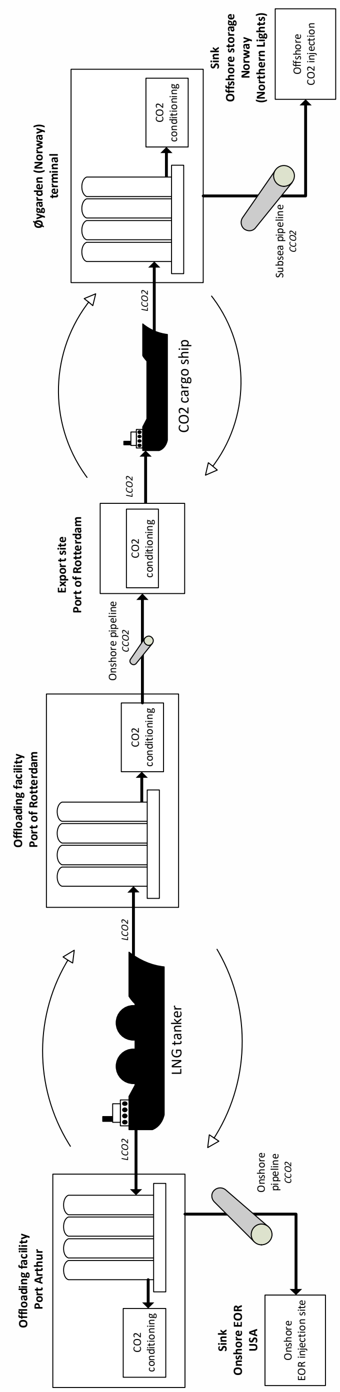


Figure 10: Illustration of Case 3a

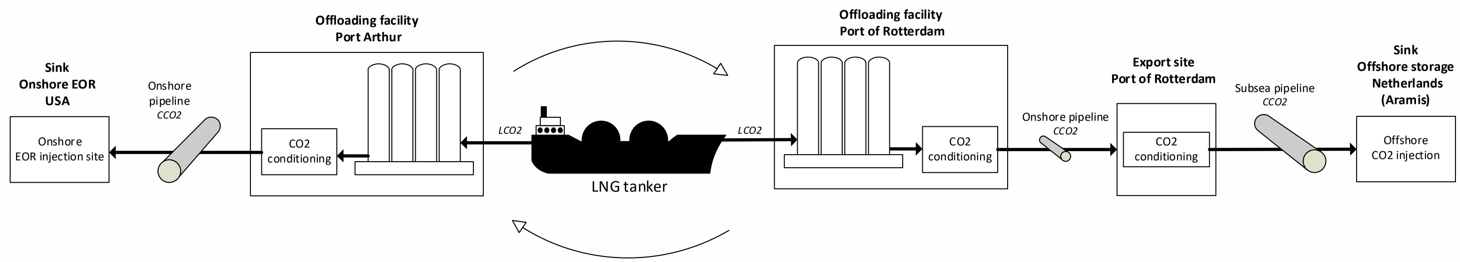


Figure 11: Illustration of Case 3b

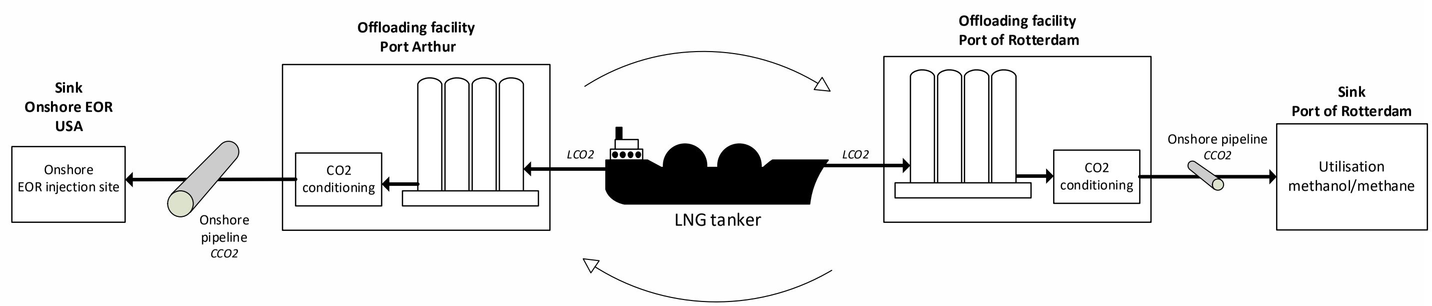


Figure 12: Illustration of Case 4a and 4b

In addition to the cases defined above, additional sub-cases will be included for sensitivity. Currently, two main sensitivity investigations have been identified. A potentially significant cost element in a CCUS chain is the intermediate storage to which the CO_2 is unloaded from the vessels when it calls at the port. It has been discussed whether this element needs to be included in the CCUS chain. The current assessment is that it should be included as it is of utmost importance that the CO_2 can be unloaded when the vessel calls the port. Feeding directly into a pipeline could reduce flexibility and increase the risk. For the approach in EverLoNG, where only a single vessel is assumed, the cost of such infrastructure per ton CO_2 could be very high as it is only utilised a fraction of the time. The two sensitivities are:

i. No intermediate storage infrastructure at unloading port, the CO_2 is feed directly into the transport pipeline
ii. Intermediate storage infrastructure included (as for the base cases) but with an annual CO_2 volume that the intermediate storage infrastructure could handle at 95% regularity, see calculation example in Table 1.

Table 1: The potential annual CO_2 volume handling capacity of an intermediate storage infrastructure

	Unit	**Value**						
No of vessels		1	4	8	10	12	14	16
One vessel no of days roundtrip sailing - 13.16 days one way	days	26.32	26.32	26.32	26.32	26.32	26.32	26.32
One vessel days in port per roundtrip - 2 days per port	days	4	4	4	4	4	4	4
One vessel days idling per roundtrip - 1.29 days per port	days	2.58	2.58	2.58	2.58	2.58	2.58	2.58
One vessel total no of days per roundtrip	days	32.9	32.9	32.9	32.9	32.9	32.9	32.9
No of calls per ship per year	calls/year	11	11	11	11	11	11	11
Total no of calls per year	calls/year	11	44	89	111	133	155	178
No of hours occupying quay in port per call	hours	48	48	48	48	48	48	48
No of hours occupancy per year	hours	533	2 130	4 260	5 325	6 390	7 455	8 520
Percentage occupancy per year		6%	24%	49%	61%	73%	85%	97%
CO_2 volume unloaded on each ship	ton/call	2 500	2 500	2 500	2 500	2 500	2 500	2 500
Total CO_2 unloaded per year	ton/year	27 736	110 942	221 884	277 356	332 827	388 298	443 769

The above calculate volumes show that there should be potential to handle CO_2 from more than one ship. The CO_2 amounts captured range from 2-5kt per unloading, the exact amounts are determined in collaboration with WP3, depending on the operational profile of the respective ship.

Scope and boundary conditions for each section of the analysis

The total scope of the full CCUS chain analysis from onboard CO_2 capture to sink is illustrated in Figure 13. The figure also includes the boundary of each chain segment. The segments of the full-chain are as follows:

- Onboard
  - CO_2 capture, conditioning, onboard storage, and CO_2 unloading pump
  - Spent amine unloading/loading pump
- Port/onshore
  - CO_2 receival facility
  - Amine reclaiming facility
- Sink
  - CO_2 conditioning transport and permanent storage or utilisation

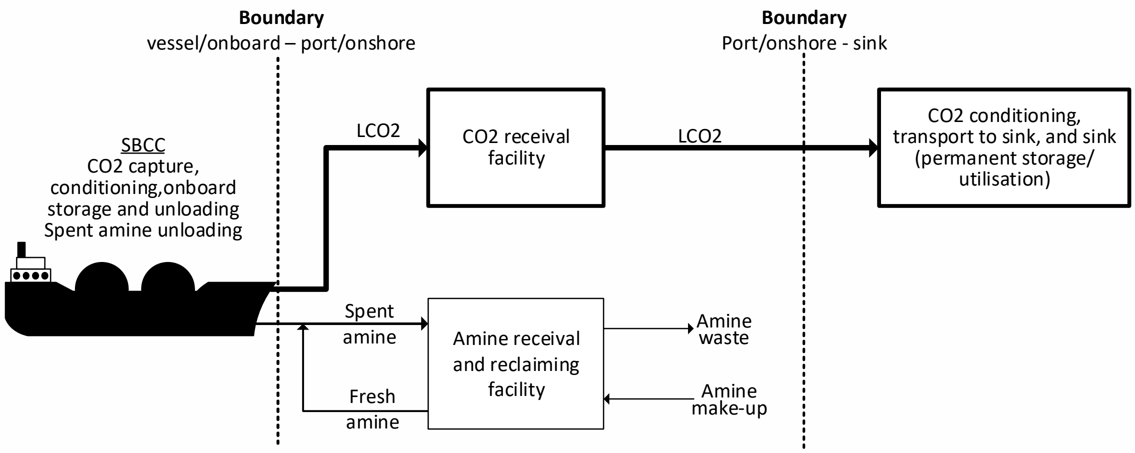


Figure 13: Schematic depicting the system boundary for the onshore facility

Onboard scope

The scope for the on-board section spans from the exhaust gas received by the main engines to the CO_2 being unloaded from the ship from its liquid CO_2 tank, as mentioned before in this document. The equipment shown in Figure 2 and Figure 3 are taken into account in the analysis, including the utilities and generation of those utilities. From the storage tank on-board, the CO_2 is unloaded with the help of a cryogenic pump and a flexible hose, where both these equipments are included as part of the on-board system's CAPEX. Additionally, spent amine to be reclaimed in the onshore facility may be transferred when the ship is in port from the dedicated spent amine tanks. This will be further specified below.

Port/onshore scope

The scope of the port/onshore facilities includes: 1) CO_2 receiving and processing plant and 2) MEA receiving and reclaiming plant.

CO_2 receiving and processing

The onshore CO_2 receiving and processing plant will receive CO_2 pumped off the ship and will process the CO_2 such that it meets CO_2 pipeline transport specifications at the onshore facility boundary. The scope of the CO_2 receiving and processing plant includes receiving liquid CO_2 that is pumped off the ship, intermediate storage, and processing equipment up to the plant boundary where it will connect to the inlet of the pipe that transports CO_2 to the CO_2 pipeline.

Figure 14 provides a block flow diagram for the proposed onshore CO_2 receiving and processing plant to be located at Port Arthur, Texas, USA. Other locations (such as Rotterdam) will be based on the Port Arthur design with necessary adjustments based on the CO_2 export system.

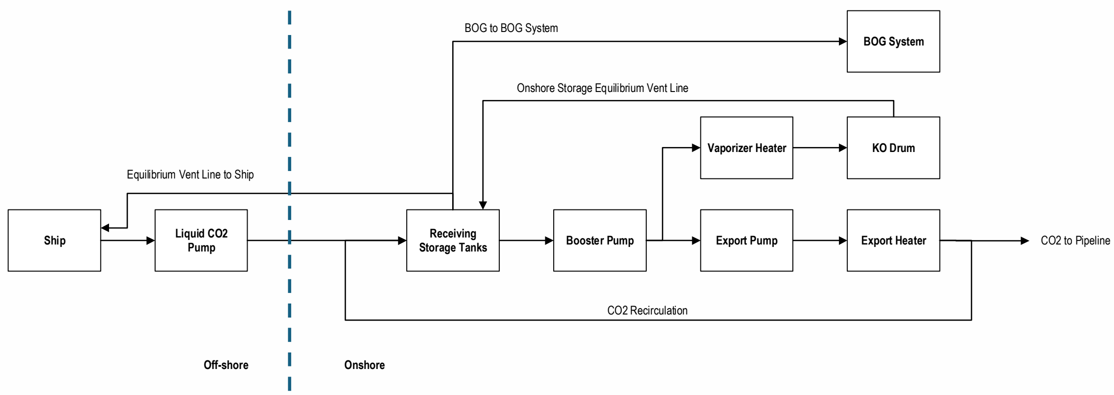


Figure 14: Block diagram of the CO_2 receiving and processing facility

CO_2 quality received at the onshore CO_2 receiving and processing plant is based on the quality of captured CO_2 on board the ship.

CO_2 will be pumped from the ship's CO_2 storage tank(s) via cryogenic pump on the ship to the onshore facility using a flexible hose from the ship to permanent piping onshore. There will be two lines between the ship and the onshore facility: one liquid line to offload CO_2, and one vapor equilibrium vent line to return CO_2 gas to the ship to maintain pressure equilibrium between the ship storage tank and the onshore storage tank. CO_2 offloaded from the ship will enter onshore receiving storage tanks that are sized to store the volume of $CO_{2,}$ including allowance for the minimum tank level (heel) as well as an operating margin and extra buffer space for variances in the frequency of ship arrivals to the port.

Liquid CO_2 from the onshore storage tanks will be pumped to pipeline specifications at the onshore facility boundary. The booster pump downstream of the storage tanks provides a net positive suction head for the export pump, which delivers the liquefied CO_2 to an export heater. The export heater heats the liquid CO_2 to avoid freezing in the pipeline. A fraction of the CO_2 from the booster pump is sent to a vaporizer heater and knockout drum to vaporize a portion of the liquid CO_2 and provide a gaseous equalizing vent line to the intermediate storage tanks. The export system is designed to ensure that the CO_2 meets pipeline specifications.

Due to the time between shipments at the port, a boil-off gas (BOG) system will be included at the facility. A BOG system is needed since a residual volume of CO_2 (20% of tank volume, or the tank heel) will remain in the onshore storage tanks. The CO_2 can be recirculated within the onshore system to maintain the cryogenic temperature of the system between shipments, or a portion of the CO_2 can be used to cool the system prior to LNG shipments. In both cases, a portion of the residual CO_2 is boiled off when it absorbs thermal energy from ambient conditions. This gaseous CO_2 will be directed to the BOG system, where it will be re-liquefied and returned to the storage tanks. This will reduce CO_2 that is vented in the onshore facility.

The expected boil-off rate is calculated at 0.15% per day of the residual CO_2 volume in the tanks after pumping to the pipeline. In scenarios where higher utilization of the onshore facility is projected, the BOG system may be under-utilized, and any CO_2 produced during the interim between ship arrivals will be recompressed with the on-ship BOG system through the equalizing vent line.

MEA receiving and reclaiming

The block diagram of the MEA receiving and reclaiming facility is shown in Figure 15. The spent MEA will be offloaded from the ship using a pump on the ship and a flexible hose connection to an onshore tank truck. The spent MEA will be transported by truck to the spent MEA storage tank at the MEA Receiving and Reclaiming Plant. After reclaiming, the reclaimed MEA will be stored in the reclaimed MEA storage tank at the onshore facility. The reclaimed solvent will be transported by truck to shipside where it will be pumped onto the ship via a flexible hose. The scope of the MEA Receiving and Reclaiming Plant includes receiving the spent MEA, processing the MEA, and sending the reclaimed MEA back to the ship. Waste from the MEA reclaiming facility will be sent to waste disposal, where it will be incinerated.

The spent MEA is reclaimed in a thermal reclaimer to recover 95 weight percent MEA and remove close to 100% of impurities and degradation products. The spent MEA is treated with 30 weight percent caustic solution to neutralize heat stable salts (HSS) to allow them to be removed as sodium salts in the thermal reclaimer. The reclaimer waste, which is mostly solids, is sent to waste storage. The resulting solvent from the reclaimer is around 30 weight percent MEA, with the balance mostly water and some impurities. The reclaimed 30 weight percent MEA solvent is then concentrated in the MEA concentrator to 80 weight percent MEA and 20 weight percent water and is stored in the reclaimed MEA storage tank until ship loading.

The MEA receiving and reclaiming plant has been designed based on the solvent inventories calculated in WP3. The content and concentration of contaminants in the spent solvent is based on WP3 results, and the results of onboard pilot testing done in WP1, for which the actual solvent composition after a few months of operation has been evaluated.

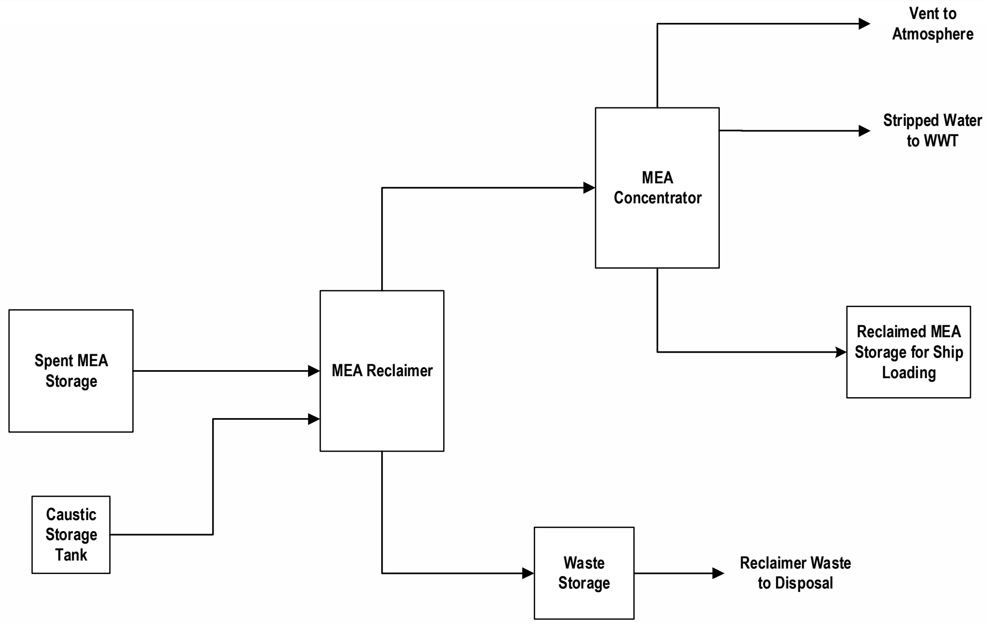


Figure 15: Block flow diagram of the MEA receiving and reclaiming facility

CO_2 transport and storage/utilisation scope

In this segment, the captured CO_2 is transported from the receival facility at port to the sink. The type and location of the sink will dictate the design of the transport segments. The sinks considered in the full-chain case studies are permanent storage in offshore aquifers (Northern Lights and Aramis) and utilisation (methanol, methane, and EOR). For utilisation is assumed that CO_2 unloaded at Port Arthur will be utilised for EOR. While the utilisation route for the CO_2 unloaded at Port of Rotterdam will be for methane and methanol production at a location close to the port. To the degree possible, it is sought to use existing or planned CO_2 infrastructure. The battery limits of the transport and storage/utilisation is as depicted in Figure 16.

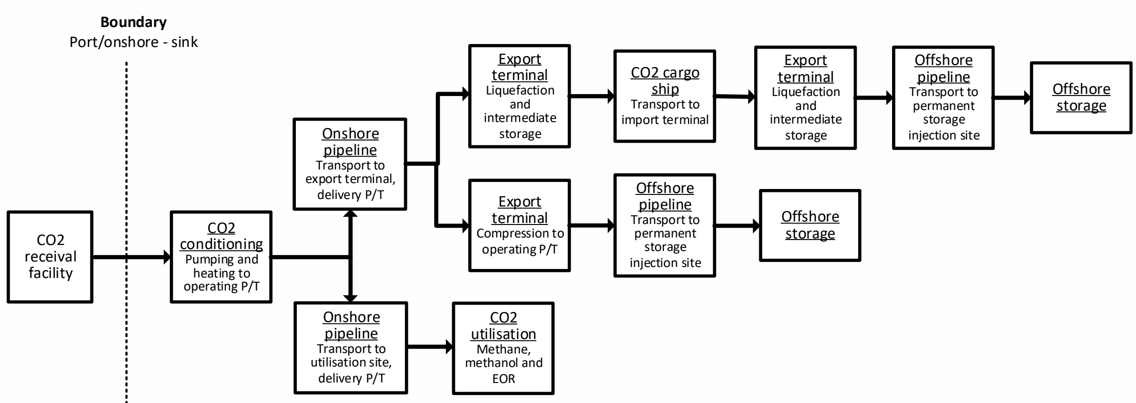


Figure 16: Schematic showing the battery limits of the CO_2 transport and storage/utilisation

Required CO_2 specifications associated to different sinks

The CO_2 will be conditioned before each transport segment to ensure that the CO_2 meets the operational requirements. For the transport and storage projects, Northern Lights[14] and Aramis[15], data on CO_2 specification is available and is shown in Table 2. For Aramis, the specifications are provided for both ship and pipeline, and it is assumed that it is the pipeline specifications that will be relevant in EverLoNG case studies. For EOR, the most important parameters are water and oxygen. In the cases where CO_2 is to be utilised as feedstock for methanol and methane productions, it is the impurities that could lead to catalyst poisoning (and reduced product quality) that are the critical ones. In addition, any impurities that could cause issues in the transport system should be addressed. As the conversion process itself is not the main focus of the case studies and the lack of data on impurity limitations for catalysts, it was decided that the Aramis specifications are adequate. The on-board system should be able to at least generate these purities.

Table 2: Specifications of the CO_2 delivered to the different storage/utilization options

	Unit	Northern Lights[14]*	Aramis[15]* (pipeline)	Methanol/ Methane	EOR[16]
CO_2	mol%	>99.81	>95	Unknown. Seems to be very strict	>95
H_2O	ppm-mol	≤30	<70		630**
N_2	ppm-mol	≤50	<24 000		
O_2	ppm-mol	≤10	≤40		≤10
SO_x	ppm-mol	≤10	-		
NO_x	ppm-mol	≤1.5	≤2.5		
Amine	ppm-mol	≤10	≤10		
NH_3	ppm-mol	≤10	≤3		
CO	ppm-mol	≤100	≤750		
Others?					

*See references for exhaustive list
**30 lbs H_2O/mmscf

Key performance Indicators / Goals

The key performance indicators for the TEA and LCA studies are summarized below.

TEA:

- Onboard capture
  - Specific thermal consumption per ton $CO_{2,eq}$ avoided
  - Specific electricity consumption per ton $CO_{2,eq}$ avoided
  - Amine loss rate

[14] Northern Lights. Liquid CO2 Quality Specifications. Retrieved July 29, 2024, from https://norlights.com/wp-content/uploads/2024/02/Northern-Lights-GS-co2-Spec2024.pdf

[15] CO_2 specifications for Aramis transport infrastructure. (n.d.). Aramis CCS. Retrieved July 29, 2024, from https://www.aramis-ccs.com/news/co2-specifications-for-aramis-transport-infrastructure/

[16] National Petroleum Council. MEETING THE DUAL CHALLENGE - A Roadmap to At-Scale Deployment of CARBON CAPTURE, USE, AND STORAGE. CHAPTER EIGHT – CO2 ENHANCED OIL RECOVERY. 2021. https://www.energy.gov/sites/default/files/2022-10/CCUS-Chap_8-030521.pdf

  - Space requirement
  - On-board $CO_{2,eq}$ avoidance
  - CAPEX per ton CO_2 captured/ $CO_{2,eq}$ avoided
  - OPEX per ton CO_2 captured/ $CO_{2,eq}$ avoided
  - Specific cost per ton CO_2 captured/$CO_{2,eq}$ avoided
- Receival facility
  - Specific electricity consumption per ton CO_2 handled
  - CAPEX per ton CO_2 captured/avoided
  - OPEX per ton CO_2 captured/avoided
  - Specific cost per ton CO_2 captured/avoided
- Transport
  - Specific electricity consumption per ton CO_2 handled
  - Specific fuel consumption per ton CO_2 handled
  - CAPEX per ton CO_2 handled/avoided
  - OPEX per ton CO_2 handled/avoided
  - Specific cost per ton CO_2 captured/avoided
- Storage
  - Specific electricity consumption per ton CO_2 handled
  - CAPEX per ton CO_2 handled/avoided
  - OPEX per ton CO_2 handled/avoided
  - Specific cost per ton CO_2 handled/avoided
- Utilisation
  - Specific electricity consumption per ton CO_2 utilised
  - Specific electricity consumption per ton of product formed
  - Amount of CO_2 avoided compared to using fossil methane/methanol (if sufficient data is available in this project to calculate this)

LCA:

- Impact reduction shares compared to benchmark
  - CO_2 emissions
  - Climate Change CO_2-equivalent emissions of CO_2, CH_4, N_2O, etc.
- Potential burden shifting in other environmental impacts such as resource use, eutrophication and more (based on the EF3.1 impact assessment method).

TEA specific framework

This chapter discusses the detailed TEA framework for the different elements in the full CCU and CCS chains.

Specific on-board framework considerations

Sizing assumptions/specifications of unit operations on-board relevant to the TEA

Any information mentioned in Table 3 applies to both the Sleipnir and the TotalEnergies' case unless stated otherwise specifically.

Table 3: Sizing assumptions/specifications of unit operations on-board relevant to the TEA

Equipment	Parameter	Assumptions/Specifications
Columns		
Quench	Pressure drop	6 mbar for column head + 3 mbar for demister + 3 mbar for liquid distributor + 5 mbar for gas distributor + 1.5 mbar/m of packing height
Absorber/Stripper		
Downstream wash column		
Acid wash column		
Rotating equipment		
*PUMPS**		
Quench pump	Fluid head	Quench column height + 0.5 bar*10m/bar
Lean pump		Absorber column height – (Stripper – Absorber operating pressure)*10m/bar + 0.5 bar*2*10m/bar
Rich pump		6 bar*10m/bar
Absorber wash pump		Absorber column height + 0.5bar*10m/bar
Stripper wash pump		Stripper column height + 0.5bar*10m/bar
Acid wash pump		Total height of quench + acid wash
COMPRESSORS		
CO_2 compressor 1	Isentropic efficiency	85%
CO_2 compressor 2		
NH_3 compressor 1		
NH_3 compressor 1		
Exhaust gas blower	Pressure increase	5 kPa
Heat exchangers		
Quench cooler	Overall heat transfer coefficient	2000 W/m^2/K for liquid-phase heat exchangers and 500 W/m^2/K for gas-phase heat exchangers
Lean cooler		
Water wash cooler		
CO_2 coolers		

NH_3 coolers		
Rich/Lean heat exchanger		
CO_2/NH_3 heat exchanger		
Reboiler		
Liquid CO_2 reboiler		
Interstage heat exchanger		
Seawater heat exchanger		
Tanks		
Solvent storage tank	Headspace	20%
Pipes		
Gaseous CO_2 pipe	CO_2 stream velocity	10 m/s
Liquid CO_2 pipe		2 m/s

*All the pumps have 75% efficiency and are assumed to be at the ground level.

CAPEX calculations

Equipment costs will be calculated using the Aspen Capital Cost Estimator v12 (ACCE) for all units which have been sized. The information described above in the sizing section is used as input in the ACCE. This program gives the equipment costs but additionally gives the direct installed costs. Both values should always be reported, but the direct installed costs are used in the final TEA. The costs of all units are summed to define the total installed costs. The engineering costs for the project can also be retrieved from ACCE once all relevant units have been sizes and costed in the program. Project/Process contingencies are added to the final costs. Since this project considers a feasibility study, it is considered Class 4 accuracy[17], and the accuracy is estimated at –30 to +50%. It is recommended to add 10% process/project contingencies to the total CAPEX to account for any accuracy ranges and/or equipment not considered in the cost estimations. The total CAPEX can be calculated using the equation below. Aspen CCE gives the cost according to March 2019 basis and this will be transformed using manufacturer's price ratio data to year 2023.

Total CAPEX = Installed direct costs + Engineering costs + Project contingencies

[17] Peter Christensen Cce et al., "COST ESTIMATE CLASSIFICATION SYSTEM – AS APPLIED IN ENGINEERING, PROCUREMENT, AND CONSTRUCTION FOR THE PROCESS INDUSTRIES," 2005.

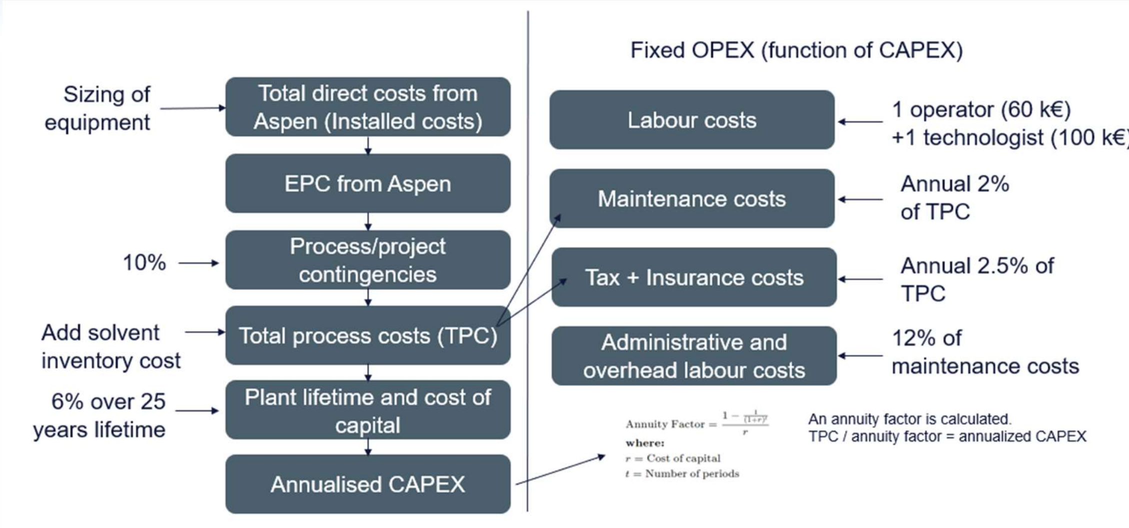


Figure 17: CAPEX and Fixed OPEX framework for the on-board system

The sizing and costing of the equipment will be mostly done following the general TEA framework described above. Because integration systems on ships is very different than typical process engineering equipment, the results of the TEA will be validated using the experience from the consortium members in the EverLoNG project. This means that both the equipment costing, and the installation factors will be validated to ensure proper description of the on-board costs of the SBCC systems.

OPEX calculations

OPEX can be split up between fixed and variable OPEX.

Fixed OPEX mainly considers

- Labour costs: Dependent on part of the chain and country
- Maintenance costs: 2% of total CAPEX per year
- Tax + Insurance costs: 2.5% of total CAPEX per year
- Administrative and overhead labour costs: 12% of maintenance costs

The Fixed OPEX will follow the general Fixed OPEX framework, and the assumptions will be verified with the ship operators and engineering companies in the project.

Variable OPEX mainly consist of utilities and consumables and will be discussed more in detail in the individual sections of the full-chain, as the cost of utilities is dependent on the specific spot where it is used and is likely to vary heavily between different sections of the full-chain.

On-board, almost all energy use is relevant to fuel consumption. Therefore, for the on-board analysis, any electricity or excess heat usage will be provided by burning additional fuel, with the corresponding emission factors and cost of the fuel. The fuel prices are considered based on the suggestions from the two ship owners. Of course, as much as possible heat is recovered from the exhaust gas before any fuel is burned to generate this additional energy. The efficiency of heat or electricity production will differ per ship, as the energy infrastructure is different for the different vessels analysed in this project.

Cooling water systems for the carbon capture system are designed in such a way that the necessary flow can be provided with pumps. Cooling water itself is assumed to be free, because of sailing at open sea.

The amine solvent will degrade over time and solvent will be lost. The TEA will take this degradation and amine loss rate into account based on the on-board performance of the EverLoNG pilot on both vessels. The expected composition of the amine solvent after a certain amount of operation will be provided towards the onshore facilities to reclaim this solvent.

NaOH is added in the quench column to deal with the SO_x present in the exhaust gas. Considering a replacement period of 2 years for the silica gel adsorbent used in the dryers in the liquefaction section, the sorbent replacement costs over the plant lifetime is also included in the variable OPEX.

Table 4: Fixed OPEX components and cost assumptions for the on-board system

Component	Value	Unit
Operator cost	60	60 k€/y per operator * 1 operator
Technologist cost	100	k€/y
Tax + Insurance costs	2.5	% of TPC
Maintenance costs	2	% of TPC
Administrative and overhead labour costs	12	% of maintenance cost

Table 5: Variable OPEX components and cost assumptions for the on-board system

Parameter	Value	Unit	Remarks (if any)
LNG price TotalEnergies case	20	€/MWh	Recommended by TotalEnergies
LNG price Sleipnir case	73.4	€/MWh	Recommended by HMC
Diesel price	60.1	€/MWh	Recommended by HMC
NaOH price	500	€/ton	
MEA price	3000	€/ton	
Silica gel adsorbent price	3900	€/ton	
Sulphuric acid price	1000	€/ton	
Acid wash drain disposal costs	1000	€/ton	

Total cost of capture and annualization methodology for CAPEX for the on-board system

The total cost of CO_2 avoidance of a project can be calculated using multiple methodologies as described in literature[18]. For this project, it is proposed to use the annualization method, since this is an easy-to-use method that allows good distinction between OPEX and CAPEX in the results. For this method, the CAPEX must be annualized. This can be done using the equation below. The total CAPEX is divided by the annuity factor to get the annual CAPEX. The r and t in this equation are respectively

[18] "Full Article: Calculating CO2 Avoidance Costs of Carbon Capture and Storage from Industry," accessed March 28, 2025, https://www.tandfonline.com/doi/full/10.1080/17583004.2018.1553435.

the cost of capital rate/discount rate and the lifetime of the process. Unless stated otherwise a cost of capital of 6%, and a lifetime of the process of 25 years is used in the TEA.

$$Annuity\ factor\ = \frac{1-\frac{1}{(1+r)^t}}{r}$$

Additionally, it is important to note that the CO_2 metric used in the total costs is the amount of CO_2 avoided. This can be calculated using the following equation:

$$CO2\ avoided\ = \frac{CO2\ captured - Additional\ emissions}{Reference\ emissions}$$

$$Cost\ of\ CO2\ capture\ = \frac{Annualized\ CAPEX + Annualized\ OPEX}{CO2\ captured}$$

$$Cost\ of\ CO2\ avoided\ = \frac{Annualized\ CAPEX + Annualized\ OPEX}{CO2\ avoided}$$

When $CO_{2,eq}$ avoided and the cost of $CO_{2,eq}$ avoided needs to be calculated, the above equations could be used but the reference emissions change as methane emissions must be taken into account. The equipment-wise sizing data relevant to the on-board system's TEA is shown in Table 6.

Table 6: Equipment-wise sizing data relevant to the TEA for the on-board capture and liquefaction units

Equipment	Sizing Parameter(s)	Unit
Columns		
Absorber column	Diameter Column height Packing height	m m m
Quench + Acid wash column (not physically connected)		
Wash column		
Stripper column		
Vertical Process Vessels		
Tanks for chemicals ($NaOH/H_2SO_4$)		
Storage tanks	Volume	m^3
Knockout/Flash drums		
Dryer (Adsorber + Regenerator)		
Rotating equipment		
Fan/Blower	Flow rate	m^3/h (or) L/s
Pumps		
Compressors		
Heat Exchangers		
Cooler/heater	Area	m^2

Rich-Lean heat exchanger		
CO_2/NH_3 heat exchanger		
Reboiler		
Seawater heat exchanger		

Specific onshore TEA framework considerations

The onshore TEA will include items within the scope of:

1) the CO_2 Receiving and Processing Plant, from receipt of pumped CO_2 from onboard the ship, to onshore storage to CO_2, and to export to the CO_2 pipeline and
2) the MEA Receiving and Reclaiming Plant, from receipt of the spent MEA at the port facility to reclaimed MEA return to the ship, as outlined in prior sections of this report

While waste disposal is not included in the scope of the MEA reclaiming facility, waste disposal costs for MEA reclaimer waste will be included in cost calculations, as discussed in subsequent sections. Costing methodology for the onshore TEA for the Port Arthur location will be based on the U.S. Department of Energy (DOE) National Energy Technology Laboratory (NETL) Quality Guidelines for Energy System Studies (QGESS) Cost Estimation Methodology for NETL Assessments of Power Plant Performance (NETL-PUB-22580), which is outlined in the following sections[19]. Costs will be reported in 2023 USD for the onshore facility based in Texas.

Onshore facility sizing assumptions and specifications

Table 7 summarizes key sizing assumptions and Table 8 summarizes equipment sizing data for onshore equipment relevant to the TEA. Any information mentioned in these tables apply to both the Sleipnir and the TotalEnergies' case unless stated otherwise.

Table 7: Sizing assumptions relevant to the onshore facility TEA

Equipment	Parameter	Assumptions/Specifications
Vertical Process Tanks		
Intermediate CO_2 Storage Tank	Operating margin	25%
Spent MEA Intermediate Storage Tank		
Caustic Storage Tank		
Reclaimed MEA Storage Tank		
On-site Waste Storage Tote		
Columns		
MEA Reclaimer	Pressure drop	6 mbar for column + 3 mbar for demister + 3 mbar for liquid distributor + 5 mbar for gas distributor
MEA Concentrator		
Pumps		
CO_2 Booster Pump	Head	Provide net positive suction head for CO_2 export pump
CO_2 Export Pump		155 bar x 10m/bar

[19] DOE NETL Quality Guidelines for Energy System Studies Cost Estimation Methodology for NETL Assessments of Power Plant Performance. September 2019. NETL-PUB-22580

MEA Inlet Feed Pump		Reclaimer Height + 0.5 bar*10m/bar
Caustic Metering Pump		Spent MEA Tank Height + 0.5 bar*10m/bar
Reclaimer Reflux Pump		Reclaimer Height + 0.5 bar*10m/bar
Reclaimer Waste Pump		Waste Tank Height + 0.5 bar*10m/bar
Concentrator Feed Pump		Concentrator Height + 0.5 bar*10m/bar
Concentrator Reflux Pump		Concentrator Height + 0.5 bar*10m/bar
Reclaimed MEA Pump		Reclaimed MEA Tank Height + 0.5 bar*10m/bar
Heat Exchangers		
CO_2 Vaporizer Heater	Vapor Fraction	CO_2 vapor fraction = 1.00 at 15 bar
CO_2 Product Export Heater	CO_2 Export Temperature	1.5 ^{o}C

*All the pumps are assumed to be at the ground level.

Table 8: Equipment sizing data relevant to the onshore facility TEA

Equipment	Sizing Parameter(s)	Unit
Columns		
MEA Reclaiming Column MEA Concentrator	Inner diameter Column height Packing height	m m m
Vertical Process Vessels		
Storage Tanks Knockout/Flash Drums	Volume	m^3
Rotating Equipment		
Pumps Compressors	Flow rate Power	m^3/h kW
Heat Exchangers		
Water Cooler/Condenser	Area	m^2
Electric Heater Electric Boiler/Reboiler	Area Power	m^2 kW
Piping		
Piping from Ships to Onshore Storage Tanks Piping to Facility Boundary Piping from Onshore Facility Boundary to CO_2 Pipeline	Length	km

Capital cost framework

The capital cost will be a major equipment-factored estimate based on equipment costs generated from Aspen Process Economic Analyzer (APEA) and Aspen Capital Cost Estimator (ACCE) resulting from Aspen Plus process simulations for the CO_2 receiving and processing facility and the MEA reclaiming facility. These Aspen Plus process simulations will be based on CO_2 and spent MEA volumes, process design parameters, and product specifications from WP3 results.

The five levels of capital costs that are considered in the onshore TEA are based on NETL methodology and are as follows:

Bare Erected Cost (BEC) comprises the cost of process equipment, on-site facilities, and infrastructure that support the plant, and the direct and indirect labour required for its construction and/or installation.

Engineering, Procurement, and Construction Cost (EPCC) comprises the BEC plus the cost of services provided by the EPC contractor. The EPC services include detailed design, contractor permitting, and project/construction management costs.

Total Plant Cost (TPC) comprises the EPCC cost plus project and process contingencies.

Total Overnight Cost (TOC) comprises the TPC plus all other "overnight" costs, including owner's costs. TOC is an overnight cost, expressed in base-year dollars and as such does not include escalation during construction or construction financing costs.

Total As-Spent Capital (TASC) comprises the sum of all capital expenditures as they are incurred during the capital expenditure period for construction including their escalation. TASC also includes interest during construction.

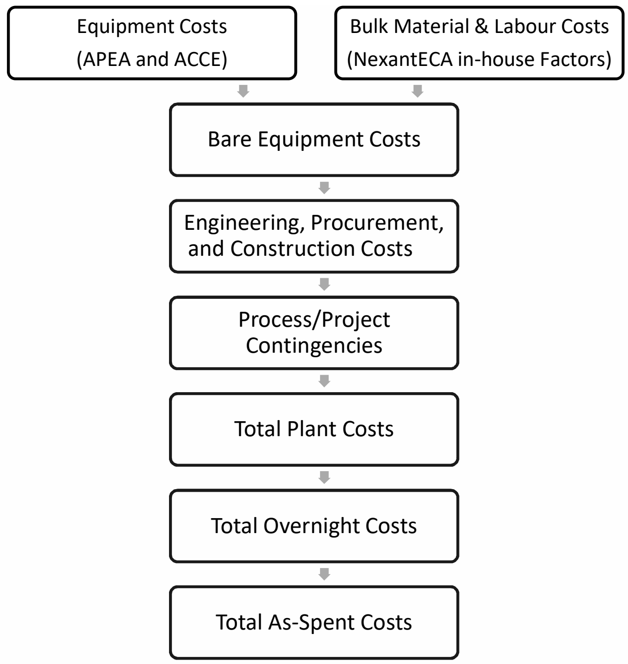
Major equipment capital cost estimates will be developed using the Aspen Process Economic Analyzer v12 (APEA) and Aspen Capital Cost Estimator v12 (ACCE) based on Aspen Plus process simulations for the CO_2 receiving and processing and MEA reclaiming systems. While APEA and ACCE provide equipment costs and direct installed costs, only equipment costs from APEA and ACCE will be used as input in development of the onshore TEA. Since APEA and ACCE costs are generated in 2019 dollars, those costs will be escalated to 2023 dollars. Bulk material and labour costs will be factored from the major equipment cost using NexantECA in-house cost factors. The sum of the major equipment cost and bulk material cost, including shipping cost, will form the total direct cost. Total direct labour cost will be added to the total direct cost to estimate the bare erected cost (BEC).

Engineering, procurement, and construction cost (EPCC) comprises the BEC plus the cost of services provided by the EPC contractor. Project/Process contingencies are added to the EPCC to form the total plant cost (TPC). The Total Plant Cost (TPC) will be calculated using the equation below:

TPC = Installed Direct Costs + Engineering Costs + Project/Process Contingencies

Table 9 shows the CAPEX framework for the onshore facilities.

Table 9: CAPEX framework for the onshore system



The onshore facility also considers Class 4 estimate for the CAPEX. The onshore facility will consider a 20% process contingency since CO_2 storage and MEA reclaiming has been commercially proven and there is less uncertainty with land-based systems compared on the on-board system. The sizing and costing of onshore equipment will be completed using the TEA framework described above. The results of the TEA will be confirmed and validated by the consortium members in the EverLoNG project.

Operating and maintenance cost (O&M) cost framework

The Operating and Maintenance (O&M) costs pertain to those costs associated with operating and maintaining the plant over its expected life.

There are two components of O&M costs: fixed O&M, which is independent of plant operating status, and variable O&M, which is proportional to plant operating level. The variable O&M costs will be estimated based on the capacity factor for the onshore facilities, which is based on ship arrival frequency and time spent at the port. The capacity factor will increase as the number of vessels increases. Table 10 shows the fixed and variable OPEX cost items considered in the onshore TEA framework.

Table 10: OPEX framework of the onshore facility

Fixed OPEX	Variable OPEX
Operating labour	Maintenance material
Maintenance labour	Consumables
Administrative & support labour	Utilities
Property taxes and insurance	Waste disposal

Operating labour cost will be determined based on the number of operators required to work at the plant and average base labour rate, based on the factors shown in Table 11.

Table 11: Fixed OPEX components and the cost assumptions for the onshore facility

Parameter	Value	Unit
Labour rate	48.55[20]	$/hr per operator
No. shifts	2	shifts/day
Labour burden	30	% of base salary
Maintenance material & labour	1.6	% of TPC
Maintenance labour only	40	% of maintenance material + labour
Administrative & support labour	25	% of O&M labour
Taxes + insurance	2	% of TPC

The cost of consumables will be determined based on the individual rates of consumption, the unit cost of each specific consumable commodity, shown in Table 12, and the facilities' annual operating hours. Waste quantities and disposal costs will be evaluated similarly to the consumables.

Table 12: Variable OPEX components and cost assumptions for the onshore facility

Parameter	Value	Unit	Remarks (if any)
Electricity Price	53.7	$/MWh	
NaOH Price	976	$/ton	
Cooling Water Price	0.0318	$/ton	
Waste Disposal Price	49.24	$/ton	For MEA reclaimer waste disposal. Negligible waste generated from CO_2 receiving and processing facility

Owner's costs

Owner's costs include pre-production costs, inventory capital, and other owner's costs such as land and financing costs. Items included as Owner's costs in the onshore TEA, along with relevant assumptions, are:

- Pre-production costs
  - 6 months operating labour
  - 1 month maintenance materials at full capacity
  - 1 month non-fuel consumables at full capacity
  - 1 month waste disposal
  - 2% of TPC
- Inventory Capital
  - 60-day supply of consumables at full capacity
  - Spare parts: 0.5% of TPC
- Other Costs
  - Initial costs for chemicals: assumed 0, initial chemical fills are assumed to be covered in CAPEX, since this will primarily be initial fill for caustic in MEA reclaiming facility
  - Land: assumed 0, since plant will be located within the port facility, no additional land costs
  - Other Owner's costs: 15% of TPC; lumped cost includes preliminary feasibility studies, including Front-End Engineering Design (FEED) study, economic development (costs for incentivizing local collaboration and support) construction and/or improvement of

[20] U.S. Bureau of Labor Statistics. Occupational Employment and Wage Statistics, Texas. 2023

roads and /or railroad spurs outside of site boundary, legal fees, permitting costs, owner's engineering (staff paid by owner to give third-party advice and to help the owner oversee/evaluate the work of the EPC contractor and other contractors), owner's contingency (sometimes called "management reserve" – these are funds to cover costs relating to delayed startup, fluctuations in equipment costs, unplanned labour incentives)

- Financing costs: 2.7% of TPC; covers the cost of securing financing, including fees and closing costs but not including interest during construction or allowance for funds used during construction

CO_2 conditioning and transport, and sink

This section covers the transport of the captured CO_2 from the onshore receival facility to the sink. The main assumption when calculating the different segments in the chain from the onshore/port receival facility to sink is, that to the degree possible, existing or planned CO_2 infrastructure will be utilised. This means that data on operating conditions, routes, dimensions, and CO_2 volume found in open literature will be adopted. Each chain segment will be designed based on a significantly larger annual CO_2 volume than the annual volumes captured onboard Sleipnir and the LNG tanker. A cost of €/tCO_2 will be calculated and this is then assumed to be the tariff for feeding CO_2 into the system. For the parts of the chain where there is no suitable infrastructure planned, the dimensioning CO_2 volume is the actual volumes from Sleipnir and the TotalEnergies LNG tanker. Sinks will be discussed separately in sub-chapter sink.

Conditioning and transport sizing assumptions and specifications

The sizing assumptions and equipment sizing data relevant for CO_2 conditioning and transport is provided in Table 13 and Table 14, respectively. Sink relevant data are handled separately below.

Table 13: CO_2 conditioning and transport sizing assumptions relevant to the TEA

Equipment	Parameter	Assumptions/Specifications
Vertical process tanks		
Intermediate CO_2 storage tank	Operating margin	25%
Rotating equipment		
CO_2 booster pump		Part of onshore scope, see Table 7
CO_2 pipeline export pump		Pressure at inlet and pressure at outlet of pipeline
Other		
CO_2 pipeline onshore	Distance/length	Aerial distance from Google Maps + a topography factor of 20%
CO_2 pipeline offshore	Distance/length	Aerial distance from Google Maps + a topography factor of 15%
CO_2 cargo ship	Size	Northern Lights cargo ship – 7 500 m^3 CO_2

Table 14: Equipment sizing data relevant to the TEA for CO_2 conditioning and transport

Equipment	Sizing Parameter(s)	Unit
Vertical process tanks		

Intermediate CO_2 storage tank	Volume	m^3
Rotating equipment		
CO_2 booster pump	Volume flow Power	m^3/hr kW
CO_2 export pump		
CO_2 unloading/loading pump		
Compressor		
Heat Exchangers		
CO_2 export heater	Area	m^2
Intermediate/after cooler CO_2 compression		
Other		
CO_2 pipeline onshore	Length volume flow Gas velocity	km m^3/hr m/s
CO_2 pipeline offshore		
CO_2 cargo ship	Capacity Saling distance Sailing speed	m^3 km m/s

Before presenting the cost estimation framework it is necessary to define transport chain segments. The scenarios developed consists of the following packages containing conditioning for transport and the transport segment itself.

- Onshore pipeline includes pre-conditioning of the CO_2 to comply with the delivery T/P for the CO_2 (booster stations along the pipeline is currently not foreseen, however if deemed necessary it will be included).
- Offshore pipeline includes pre-conditioning of the CO_2 to comply with the delivery T/P for the CO_2 (the operating pressure of an offshore pipeline is often designed to avoid the need for booster stations).
- CO_2 cargo ship includes pre-conditioning of the operating T/P of the ship and intermediate storage facility at both the export and import terminal.

All the transport scenarios are modelled in the CO_2LOS cost tool[21], a cost estimation tool for calculating cost of CO_2 transport chains consisting of both pipeline and ship. The tool was primarily developed in CO_2LOS phase III. The reference year of the tool is 2020 and inflation adjustment to 2023 is included.

Capital cost framework for CO_2 conditioning and transport

For these chain segments, different cost estimation approaches will be utilised. For any standard equipment needed for CO_2 conditioning along the chain, the previously described capital cost framework will be adopted.

The capital cost of transport pipelines and the CO_2 cargo ship the CO_2LOS cost tool will be used. The basis for the cost calculation of a CO_2 cargo ship is the 7500 m^3 Northern Lights ship. CO_2 cargo ship capital cost consists of light ship cost, cargo tank cost, loading/unloading pump cost (located onboard

[21] CO_2LOS IV: Optimization of CO_2 Transport. Climit. https://climit.no/en/news/co₂los-iv-optimization-of-co₂-transport/

the ship), and loading arm cost (also located onboard the ship). For pipeline, the capital cost elements are the material, engineering & management, and construction cost.

Operating and maintenance cost (O&M) cost framework for CO_2 conditioning and transport

As for capital cost, the operating and maintenance cost of any standard equipment needed for CO_2 conditioning along the chain, the previously described operating and maintenance cost framework will be adopted. The OPEX is split into fixed and variable O&M as previously explained. The personnel policy for CO_2 conditioning, transport, and sink is provided in Table 15.

Table 15: Assumed personnel requirement for CO_2 conditioning and transport

Parameter	Personnel	Remarks
Onshore pipeline including pre-conditioning of the CO_2	1 operator per shift 1 engineer	The possibility of having a common organisation and shared personnel will be assessed for each scenario. The number of shifts and engineers needed will depend on the complexity of the operation on each location.
Offshore pipeline including pre-conditioning of the CO_2	1 operator per shift 1 engineer	
CO_2 cargo ship onshore personnel CO_2 conditioning and intermediate storage	1 operator per shift 1 engineer	
CO_2 cargo ship – onboard crew		Fully manned ship operation is foreseen

As a CO_2 transport chain potentially operates in several countries, country specific labour rate and shift policy are expected. The fixed OPEX components and cost assumptions are provided in Table 16.

Table 16: Fixed OPEX components and cost assumptions for the CO_2 conditioning and transport

Parameter	Value	Unit	Remarks (if any)
Operator [22]	423.4	€/year	1 operator per shift in a three-shift rotation Norway (2023)
Engineer	122.5	€/year	Norway (2023)
CO_2 conditioning			
Tax + Insurance costs	2.5	% of TPC	
Maintenance costs	2	% of TPC	
Administrative and overhead labour costs	12	% of maintenance cost	
Pipeline			
Operating, maintenance, and inspection cost	3 5	€/m	Onshore (pipeline assumed only in established industrial area) Offshore
CO_2 cargo ship			
Crew cost	2.5	% of CAPEX	These costs are assumed to be fixed for a CO_2 cargo ship operating on a predefined route, as is the case here.
Other cost	4.8	% of CAPEX	
Port charge and piloting fee	2.3	% of CAPEX	
Fuel cost, LNG			

[22] ILO Homepage | International Labour Organization. (n.d.). https://www.ilo.org/

			The crew cost, other cost and port charge and piloting fee are only valid for the specified ship size and route.

For any CO_2 condition the variable OPEX consists of utilities, electricity and cooling water, and their unit cost, see Table 17. Further, country specific unit prices are assumed depending on the location of the CO_2 conditioning units. There are no variable OPEX associated with pipeline transport. For a CO_2 cargo ship operating a fixed route as assumed here, all OPEX are assumed to be fixed.

Table 17: Variable OPEX components and cost assumptions for CO_2 conditioning and transport

Parameter	Value	Unit	Remarks (if any)
CO_2 conditioning			
Electricity price[23]	90.0	€/MWh	Norway/Netherlands (2023)
Cooling water price**	0.2	€/ton	

**Seawater/freshwater system is assumed.

Cost framework for sink

Three types of sinks are considered, permanent offshore storage in saline aquifers, utilisation for enhanced oil recovery (EOR), utilisation of CO_2 for methane and methanol production.

Reliable CO_2 storage cost data is challenging to find in open literature. The storage cost data available is often outdated[24], based on data from the US[25], and/or combined with transport cost. Two of the most advanced transport and storage projects in Europe, Northern Lights[26] and Aramis[27], cost data are available. However, also here transport and storage cost are combined making it challenging to identify the expected storage cost. Additionally, for Aramis, the cost is provided on a €/t basis without specifying the cost parameters. With the assumption that 7.5 MTPA is stored, and with an "illustrative accuracy" of ± 25 – 40% for CAPEX and ± 30 - 40% for OPEX, the cost for the gas and liquid route is 90.6 and 112.8 €/t (2024). For Northern Lights, some cost data are available, see Table 18.

Table 18: Available cost data for Northern Lights

Parameter	Value	Unit	Remarks (if any)
CO_2 handling capacity	1.5	Mt/year	Cost reference year 2020
Lifetime	25	years	
No of injection wells	1		
No of ships	2		
Total investment	5975	MNOK	
Total operational cost	370	MNOK	

[23] Electricity price statistics. (n.d.)., from https://ec.europa.eu/eurostat/statistics-explained/index.php?title=Electricity_price_statistics
[24] ZEP. The Costs of CO2 Capture, Transport and Storage – Post-demonstration CCS in the EU.
[25] Smith, E., Morris, J., Kheshgi, H., Teletzke, G., Herzog, H., & Paltsev, S. (2021). The cost of CO2 transport and storage in global integrated assessment modeling. International Journal of Greenhouse Gas Control, 109, 103367. https://doi.org/10.1016/j.ijggc.2021.103367
[26] Innstilling fra energi- og miljøkomiteen om Langskip – fangst og lagring av CO2. (2020, December 16). [Inns]. Stortinget; energi- og miljøkomiteen. https://www.stortinget.no/no/Saker-og-publikasjoner/Publikasjoner/Innstillinger/Stortinget/2020-2021/inns-202021-143s/?all=true
[27] XODUS. 2024 SDE++ Aramis Carbon Capture and Storage Fee Review – Public Summary. https://www.eerstekamer.nl/overig/20240620/sde_aramis_carbon_capture_and/document

Investment cost of additional well	1140	MNOK	
Decommissioning cost	426	MNOK	
Decommissioning cost of additional well	179	MNOK	

Assuming a that one well is sufficient, a project lifetime of 25 years and a rate of return of 7.5%, the cost in €/t becomes ~ 70. It is to be expected that the first well has a higher cost than a potential second well. It is worth noting that the decommissioning cost of the extra well is significantly less than for one. Based on the data provided in the table it is still difficult to isolate the cost associated with storage. A best guestimate would be in range of 27 – 45 €/t_{CO2} stored, assuming that the storage is operating at design capacity.

The primary function of the utilisation cases in this project is to compare such sink alternatives to permanent storage, primarily from an environmental perspective. Still, the economic aspect will be considered on a high level and the economic implications of finding alternative (less cost intensive) sinks for the small and intermittent volumes of CO_2 that is currently the case. The pros and cons of opting for a utilisation route for such small volumes will be assessed.

It is assumed that feeding the CO_2 into an EOR project is free of charge, and therefore only the transport to connect with the EOR infrastructure is included, with the approach as previously described. It could be that it is possible to receive some compensation for the CO_2 when utilised for EOR, however the small intermittent amount delivered into the network might not be desired by the operator. According to Melzer (2012)[28] 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. It should be noted that the processing of the produced oil (and CO_2) is not part of the scope of EverLoNG.

In the case of CO_2 utilised in methane and methanol production, it is assumed that the CO_2 from Sleipnir vessel and the TotalEnergies LNG tanker unloaded in the Port of Rotterdam is transported by pipeline to a plant located within the industrial site Botlek in Rotterdam. The plant produces either methanol or methane. It is further assumed that the production capacity for such a plant is 100 kt per year[29]. The main parameters used for methane (synthetic natural gas) and methanol production are provided in Table 19.

[28] Melzer, L.S. (2012). Carbon Dioxide Enhanced Oil Recovery (CO_2 EOR): Factors Involved in Adding Carbon Capture, Utilization and Storage (CCUS) to Enhanced Oil Recovery. https://carboncapturecoalition.org/wp-content/uploads/2018/01/Melzer_CO2EOR_CCUS_Feb2012.pdf

[29] Martin, P. (2023). Hydrogen-derived “e-methane” plant in Germany taps Norwegian carbon capture company for 400,000 tonnes of CO2 a year. Hydrogeninsight.Com. https://www.hydrogeninsight.com/production/hydrogen-derived-e-methane-plant-in-germany-taps-norwegian-carbon-capture-company-for-400-000-tonnes-of-co2-a-year/2-1-1545317

Table 19: Parameters considered for methane and methanol production

Parameter	Methane (SNG)[30]	Methanol[31]	Unit	Remarks (if any)
Plant capacity	100	100	kt/year	
Specific CO_2 consumed	3.48	1.4	kg/kg product	
CO_2 consumed	348.5	140.0	kt/year	
Specific H_2 consumed	0.63	0.2	kg/kg product	
H_2 consumed	63.1	20.0	kt/year	
Specific water consumed	5.6	1.8	kg/kg product	
Water consumed	557.1	176.6	t/year	
Electricity consumed H_2 production	60	60	kWh/kg H_2	Produced through electrolysis[30]
Energy for synthesis process	0.5	1.0	kWh/kg	
Energy of product, LHV	49.2	19.9	MJ/kg	

[30] Perna, A., Moretti, L., Ficco, G., Spazzafumo, G., Canale, L., & Dell'Isola, M. (2020). SNG Generation via Power to Gas Technology: Plant Design and Annual Performance Assessment. Applied Sciences, 10(23), Article 23. https://doi.org/10.3390/app10238443

[31] Hren, D. T., Bogataj, M., & Nemet, A. (2024). Methanol Production via Power-to-Liquids: A Comparative Simulation of Two Pathways Using Green Hydrogen and Captured CO2. Processes, 12(12), Article 12. https://doi.org/10.3390/pr12122843

LCA specific framework

This chapter discusses the LCA framework for the different elements in the full CCU and CCS chains, focusing on deviations to the TEA approach discussed above. A complete discussion of methodological assumptions is collected in the LCA assessment reports (D4.1.1 & D4.2.1) of the EverLoNG project. The LCA consists of a detailed discussion of the investigated situation in the Goal and Scope definition, collection of environmental data in the Life Cycle Inventory (LCI) followed by Life Cycle Impact Assessment (LCIA) accompanied with interpretation of the findings.

Goal and Scope

The goal of the LCA study is set to compare the environmental impacts of ships operating with and without SBCC, using the two example cases of the Sleipnir and LNG tanker ships. A variety of following CO_2 pathways is included, covering both storage and use cases. A focus is set on the verification of the CO_2 emission reduction targets and the related global warming impacts. However, comprehensive data on resources used and emissions are collected as much as possible, to investigate the multitude of impact categories in the EF3.1[32] impact assessment method. This approach makes it possible to identify potential shifting of burdens from climate to other categories, such as extensive resource use. In addition, potential hotspots and key factors are investigated, aiding in future development of the technology.

The LCA is performed following the ISO 14040/14044[33,34] standards, using the ecoinvent 3.9.1 database. The boundaries of the assessment are shown in Figure 18, indicating that the full life cycle of the capture process and ship operation are investigated, including upstream processes such as fuel production and downstream waste handling and CO_2 pathway. The End-of-Life (EoL) and construction impacts of the ships are not included, as they are the same for both cases. The various processes are grouped largely following the boundaries of the TEA parts.

Here, a difference to the TEA approach is made. CO_2 and other impacts from upstream and downstream processes are included in the overall assessment results such as CO_2 avoidance results.

[32] "European Platform on LCA | EPLCA," accessed March 28, 2025, https://eplca.jrc.ec.europa.eu/LCDN/developerEF.html.
[33] "ISO 14040:2006," ISO, accessed March 28, 2025, https://www.iso.org/standard/37456.html.
[34] "ISO 14044:2006," ISO, accessed March 28, 2025, https://www.iso.org/standard/38498.html.

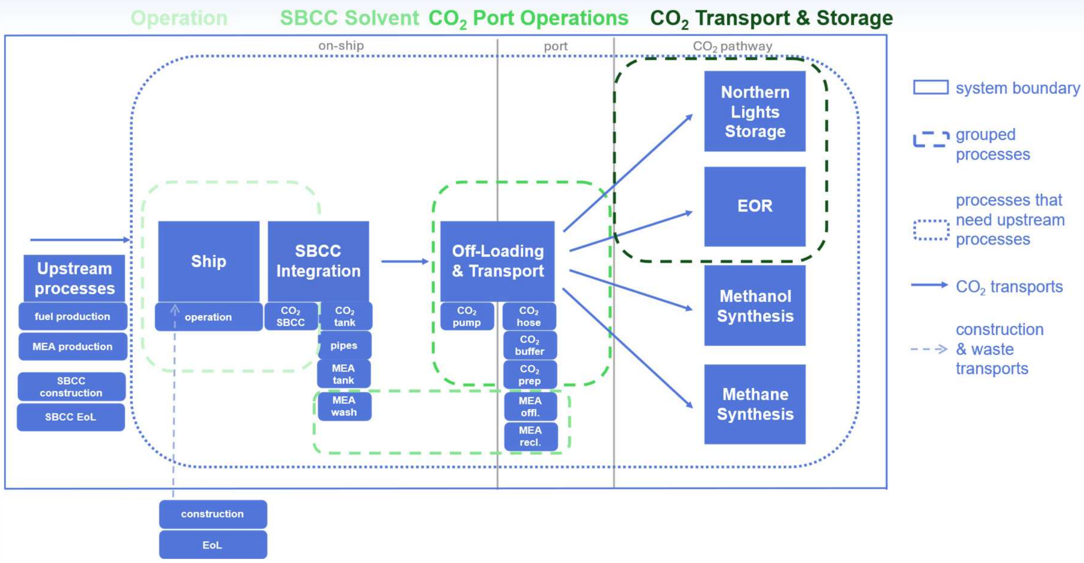


Figure 18: Schematic of the LCA System Boundary

LCI Model

Similarly to the TEA, detailed information on equipment sizing, power consumption, but also general material composition and emissions during operation is required to build the Life Cycle Inventory (LCI) model. Following the system boundary, this also includes potential upstream impacts from manufacture or transport of such components, where available.

For system construction, all associated components and their respective specifications, materials, power consumption, resources used, and emissions generated a required to build the LCI. In addition, associated transport, materials and power used for construction are to be included.

Considering operation of a system, used materials, power and waste disposal will be required. Expected maintenance needs over the lifetime are also included in the life cycle inventory.

The modelling of each component is based on background data from the ecoinvent database[35], or more updated literature data where available. Similarly to the TEA, if components are used only partially, such as pipelines for CO_2 transport, then their associated environmental impact is allocated based on the component lifetime and capacity. If for other components allocation based on such physical quantities is not feasible, economic allocation based on pricing is used as well.

For the SBCC operation, the CO_2 avoided is the main measure for the technology development, but in the LCA the total emissions are included in the LCI. Such that combined with other contributors like methane and N_2O, the total global warming potential can be determined during LCIA. The determined amount of CO_2 captured can slightly differ for the LCA and TEA considerations, as in the LCA the fuel slip, which leads to methane and other emissions, is considered to reduce the amount of fuel which is combusted to result in CO_2. The amount of fuel consumed is thus the sum of combusted and slipped fuel.

[35] "The Ecoinvent Database Version 3 (Part I): Overview and Methodology | The International Journal of Life Cycle Assessment," accessed March 28, 2025, https://link.springer.com/article/10.1007/s11367-016-1087-8.

LCIA

The Life Cycle Impact Assessment (LCIA) is performed on the LCI using the open source Brightway2[36] and ActivityBrowser LCA[37] software and their built in EF3.1 assessment method with the impact categories collected in Table 20.

Table 20: Impact Categories of the EF3.1 assessment method

Impact categories	**Unit**
Acidification	mol H+ eq
Climate change	kg CO_2 eq
Ecotoxicity, freshwater	CTUe
EF-particulate matter	disease incidences
Eutrophication, freshwater	kg P eq.
Eutrophication, marine	kg N eq.
Eutrophication, terrestrial	mol N eq.
Human toxicity, cancer	CTUh
Human toxicity, non-cancer	CTUh
Ionizing radiation	kBq U-235 eq.
Land use	pt
Ozone depletion	kg CFC-11 eq.
Photochemical ozone formation	kg NMVOC eq.
Resource depletion, fossils	MJ
Resource depletion, minerals and metals	kg Sb eq.
Water use	m^3 water eq of deprived water

Choosing a variety of these impact categories ensures that burden shifting from one impact category to another can be quantified and potential points for improvement identified.

[36] Chris Mutel, "Brightway: An Open Source Framework for Life Cycle Assessment," *Journal of Open Source Software* 2, no. 12 (April 19, 2017): 236, https://doi.org/10.21105/joss.00236.
[37] Bernhard Steubing et al., "The Activity Browser — An Open Source LCA Software Building on Top of the Brightway Framework," *Software Impacts* 3 (February 1, 2020): 100012, https://doi.org/10.1016/j.simpa.2019.100012.

Conclusions

This report has showed the scope/boundary evaluated in each part of the chain with their associated input and assumptions needed to perform LCA and TEA in the EverLoNG project for the cases elaborated in this report.

1. **Techno-Economic Analysis (TEA)**:
    a. **Key Metrics**: Includes CAPEX, OPEX, and specific costs per ton of CO_2 captured/$CO_{2,eq}$ avoided.
    b. **Onboard Considerations**: Equipment sizing, energy requirements, and operational costs tailored to ship systems.
    c. **Onshore Considerations**: Costs for CO_2 receiving, processing, and solvent reclaiming facilities.
    d. **Transport and Storage**: Uses existing/planned infrastructure to minimize costs.

2. **Life Cycle Assessment (LCA)**:
    a. Includes upstream and downstream processes, emphasizing $CO_{2,eq}$ avoidance and broader environmental impacts.
    b. Utilizes a comprehensive set of impact categories (e.g., climate change, resource depletion) to evaluate potential burden shifting.

3. **Key Performance Indicators**

   Onboard capture efficiency, energy consumption, and avoidance cost metrics.

   Environmental impacts assessed via the EF3.1 method, covering climate change, resource use, and other categories.

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