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# Environmental impacts of on-board carbon capture on two LNG-fueled ships

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ABSTRACT

Decarbonization targets for the maritime sector until 2050 require greenhouse gas (GHG) mitigation options like alternative fuels and on-board carbon capture (OCC). This study assesses GHG mitigation and side-effects of OCC via Life Cycle Assessment of two LNG-fueled ships, the large crane ship Sleipnir and an LNG carrier, and their distinct operational profiles. A large bandwidth of 32%–55% GHG emissions mitigation is achievable, depending on the ship, operation and design. Non-Climate impacts increase without raising major environmental concerns for the monoethanolamine-solvent OCC systems, based on the measured emissions from pilot operation, despite the limited applicability of current impact pathway modelling on open-sea context. With lower GHG mitigation potential compared to alternative fuels but potentially better availability due to less competition from other sectors, including OCC into the portfolio of intermediate decarbonization options for the marine sector is recommended, emphasizing case-by-case evaluation of life cycle emissions, especially fuel supply and methane slip affected by the operational profile.

## 1. Introduction

Recently, the International Maritime Organization (IMO) tightened its maritime decarbonization targets until 2050 (IMO, 2023) and started developing the greenhouse gas (GHG) emission net-zero framework, underlining the demand for decarbonization options despite the frameworks' recently adjourned discussion to 2026 (IMO, 2025). As the maritime sector encompasses a vast amount and variety of ships (IMO, 2020), both the availability and applicability of mitigation options determine its implementation potential for a specific ship. Strategies include low-emission fuels, electrification or application of on-board carbon capture (OCC) (Luo and Wang, 2017). Using well-proven land-based carbon capture system components (McCulloch et al., 2020), OCC can be applied on ships with enough room for capture system and $CO_2$ tanks (Feenstra et al., 2019). Explorative projections for future fuel use, including electrification, fossil and alternative fuels, show fuels combined with carbon capture and storage to cover more than 20% of the marine fuel consumption by energy in 2050 (DNV, 2024a, 2024b). It is therefore imperative to assess whether OCC represents a viable decarbonization pathway without resulting in unacceptable environmental burden shifting.

In comparison to land-based systems, variable operation conditions of different engines, fuel types, and $CO_2$ handling and offloading affect OCC systems (Subramani et al., 2024). The corresponding environmental performance is determined via Life Cycle Assessment (LCA) (ISO 14040/44, 2006), where production to end-of-life are modelled and evaluated covering a broad range of environmental impacts.

For alternative low-carbon fuels, LCAs estimate 60–90% climate impact reduction compared to heavy fuel oil (HFO) ships, with broad variation (Gray et al., 2024; Lee et al., 2022; Ramsay et al., 2023; Tomos et al., 2024) and overall limited comparability (Roux et al., 2024). The first LCAs of OCC by Negri et al. (2022, 2023) considered HFO-fueled ships integrating a land-based capture system. In the context of the FuelEU Maritime regulation for GHG emission reduction (European Commission, 2023), Oh et al. (2024) compare OCC operation for different fuels and engine types, while Ingwersen et al. (2025) compare alternative fuels and OCC in the future. Similarly to alternative fuels, the fuel type is a decisive factor for how the OCC system is designed and operated. While liquefied natural gas (LNG) as a fuel is recommended in design studies for OCC (Feenstra et al., 2019; Ros et al., 2022; Tavakoli et al., 2024; van den Akker, 2017), environmental assessments of LNG fuel (Roux et al., 2024; Sphera, 2021) and OCC paired with LNG

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(Ingwersen et al., 2025; Oh et al., 2024) find strong effects of methane slip on climate impact. These effects depend on engine types and load profiles (IMO, 2020), only considered in some LCAs of OCC. Those studies including load changes limit their evaluation to $CO_2$ or greenhouse gas (GHG) emissions (GCMD, 2025; Güler and Ergin, 2025). Some LCAs of OCC also consider environmental impacts beyond climate change (Ingwersen et al., 2025; Negri et al., 2022, 2023) and most model the fate of the captured $CO_2$ at lower complexity.

This study examines the suitability of OCC as a GHG mitigation measure for LNG-fueled ships by combining and expanding on key elements from the above-mentioned LCAs of OCC. Two distinct case studies of LNG-fueled ships are evaluated, an LNG carrier and the Sleipnir (large crane ship), capturing effects of fuel supply until $CO_2$ storage. Findings obtained in the EverLoNG project (EverLoNG; Linders et al., 2025) form the basis of the system model, including the first measured data from an OCC prototype on amine and ammonia emissions, methane slip in the LNG engines and measured operational engine load profiles (Reitz and Zapp, 2025). Consequently, this study combines not only a full life cycle perspective on the potential environmental benefits and trade-offs of OCC with fully implemented OCC designs but also measured operation cases and includes pilot system observations. The resulting inventories are openly shared for future analyses. Along with the sensitivity analysis, this broadens the perspective on the sustainability of OCC towards identifying and quantifying potential challenges for explicit future implementation cases.

In the following sections, the LCA is presented, including goal and scope definitions and inventory documentation. The results for environmental impacts are presented and explored via sensitivity study. In summary, OCC is discussed in the context of marine decarbonization.

## 2. Methodology

This study evaluates the potential environmental impact of applying monoethanolamine (MEA)-solvent OCC for marine decarbonization via LCA methodology based on the ISO 14040/44 (2006) standards and the draft Marine Environment Protection Committee (MEPC) LCA guidelines (MEPC, 2023). The methodology is divided into four parts, setting the stage in the Goal and Scope definition, modelling the Life Cycle Inventory (LCI), evaluating the resulting environmental impacts via Life Cycle Impact Assessment (LCIA), and interpreting each part.

### 2.1. Goal and scope

The two ships investigated in this study are an LNG carrier delivering LNG from the United States to the Netherlands and the Sleipnir, a very large crane ship, operating out of the port of Rotterdam, in the Netherlands. From the operation cases shown in Fig. 1, the functional units (FU) for each ship are determined from their main purpose:

- six weeks of ship operation, starting and ending at the Port of Rotterdam for the Sleipnir and
- delivering 1 t of LNG from the United States to the Netherlands for the LNG carrier.

The functional units are fulfilled by supplying the power demand required for the conventional ship operation case, including all sailing, working and idle operation. This can be achieved with and without OCC, leading to the reference flows of the system in Fig. 1. The reference flows for conventional (CON) and capture (OCC) operation are compared for each ship individually, as the functional units are not directly comparable between ships. Comparisons between the two ships are only possible in a more generalized or relative context but not in absolute impacts. One example is the achievable relative reduction of impacts on climate change discussed as one of the key result indicators.

The assessment aims to improve the understanding of environmental impacts of ships when including OCC, covering GHG mitigation performance, potential hotspots or trade-offs. For this comparison, system parts not affected by the OCC system, such as ship construction, maintenance and end-of-life, are excluded from the system boundaries in Fig. 2, following the approach for alternative fuels (MEPC, 2023). The Fig. includes the relevant processes associated with the conventional case (CON) without OCC and the ship operating with OCC, including direct flows of $CO_2$ to and from the OCC operation, emitted to the environment and geologically stored. Depending on the operational

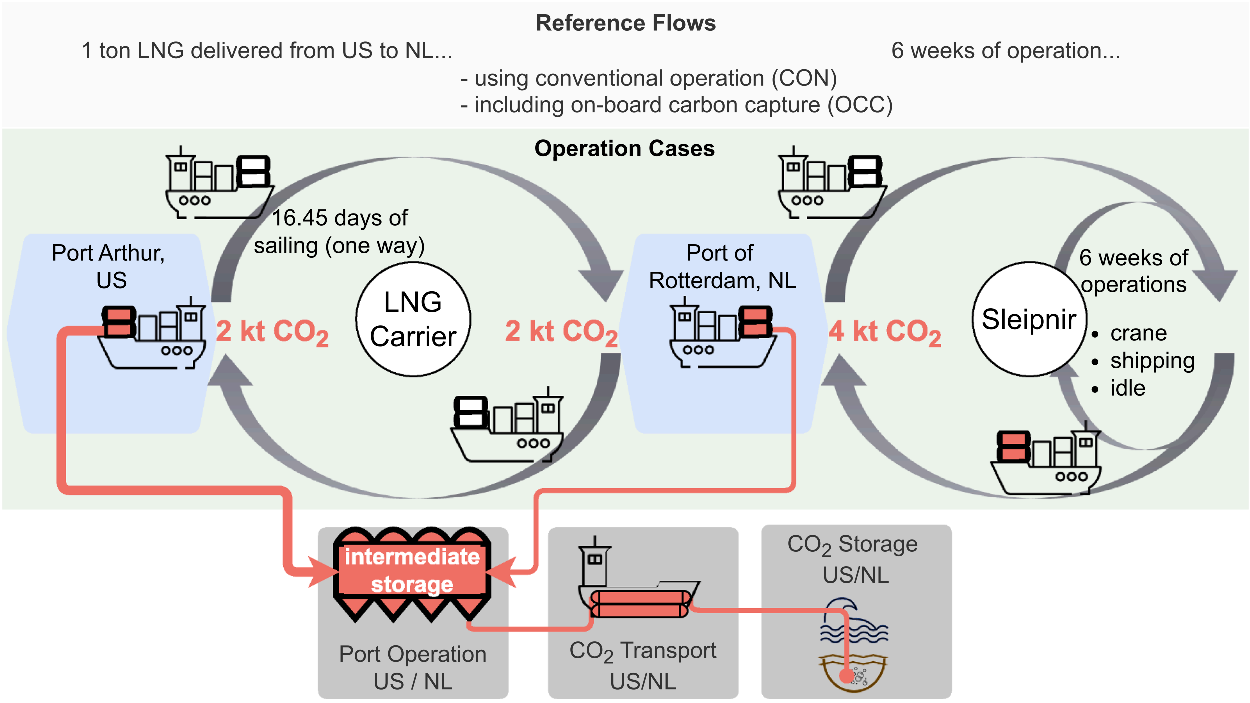

**Fig. 1.** Operation cases for the conventional operation (green) between ports (blue) for the LNG carrier on the left and the Sleipnir on the right. The flow of captured $CO_2$ (red) indicates the $CO_2$ pathway (grey).

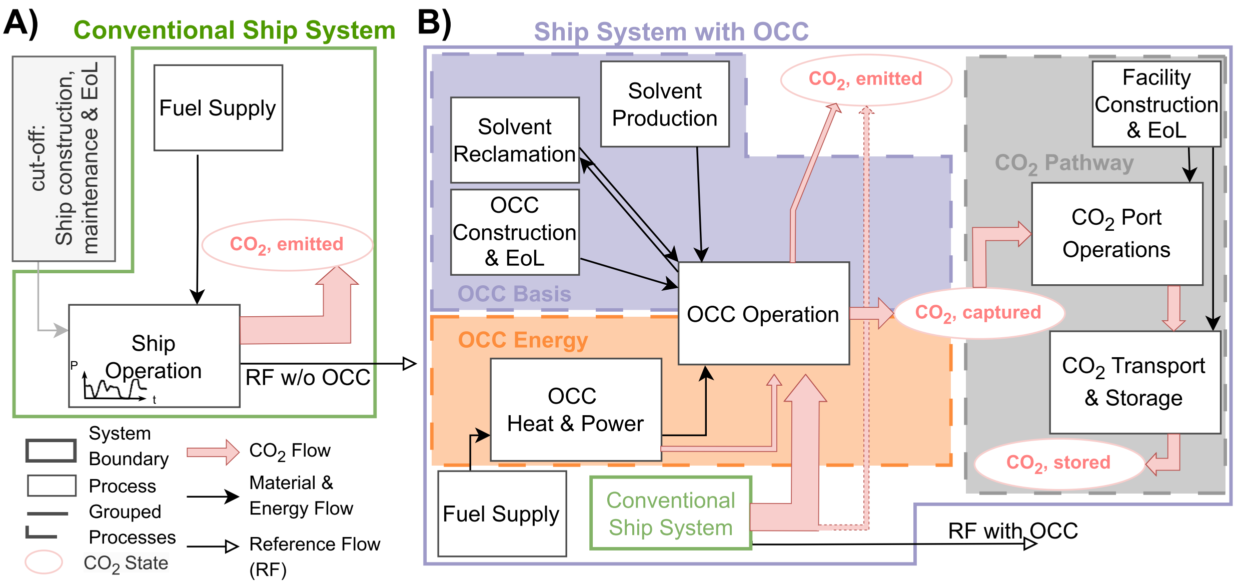

**Fig. 2.** System boundaries for a conventional ship in A) and a ship operating with OCC in B), including the reference flows (RF) fulfilling the functional units. The $CO_2$ flows and states in both systems as well as material and energy flows between processes are indicated. Some OCC-related processes are grouped into subsystems.

profile, emissions above the capacity of the OCC system are not fed into the OCC system. For evaluation, the processes related to the OCC operation are divided into the OCC Basis needed to run the capture, covering construction and solvent, and the OCC Energy required to operate the system. Following the analysis schemes of mitigation policies (MEPC, 2023), the conventional system boundaries can be divided into well-to-tank (WtT), tank-to-wake (TtW) and their combination well-to-wake (WtW). Generally, WtT includes fuel supply, TtW ship operation and WtW the combination of both.

As OCC is expected to be implemented in the coming years, recent data from around 2021, and the background database ecoinvent 3.9.1 cutoff (Wernet et al., 2016) are used to model the inventory. Geographically, operations in Fig. 1 are centered around the Port of Rotterdam in the Netherlands (NL) and $CO_2$ transport to the (Northern Lights, n.d.) storage project, adjusted for the United States (US)-based operation. The inventory model is implemented in the open-source software Brightway2 (Mutel, 2017) and its graphical interface the Activity Browser (Steubing et al., 2020). Its components are based on both process modelling and pilot operation measurements, complemented by literature data.

Given the European context of the study, the recommended life cycle impact assessment method of the European Commission (2022) Environmental Footprint (EF3.1) and the 100-year timeframe global warming potential (GWP100) of the climate change impact category are used in the LCIA. While the main target of OCC is reducing $CO_2$ emissions, evaluating OCC's potential for mitigating climate impacts calls for including all GHG emissions and investigating further environmental impacts. From the LCIA method, relevant impact categories are selected based on the reliability of the individual impact category given in the EF3.1 description (Andreasi Bassi et al., 2023; Fazio et al., 2018) as well as derived from their applicability to the modelled inventory. Land-based effect pathways (Posch et al., 2008) used especially in toxicity related impact categories have reduced applicability for emissions at open sea, while global impact categories such as climate change and ozone depletion remain fully applicable. As an exemplary discussion, the effect pathway for marine eutrophication in relation to open sea emissions can be affected by higher deposition and higher dilution effects. Especially nitrogen oxides and ammonia emitted to air on open sea by the OCC system have a high chance of being fully deposited in the ocean. This would increase their characterization factor for marine eutrophication, measured as fraction of nutrients reaching the marine end compartment in nitrogen equivalents (N-Eq), from 0.38 and 0.092 kg N-Eq to the nitrogen share in the molecules of 0.46 (NO as maximum for NOx) and 0.82 ($NH_3$) kg N-Eq per kg emitted. This would especially increase the impact of ammonia emissions on marine eutrophication. However, marine eutrophication impacts are often related to coastal regions, as the accumulation of nitrogen from terrestrial emission occurs there, leading to an increased algae growth. Deposition anywhere on the open sea leads to a massive dilution of nitrogen compounds compared to considering coastal waters alone, leading to a potentially much lower marine eutrophication effect from open sea emissions compared to terrestrial emissions. Therefore, the marine eutrophication impact category is used as a conservative estimate, with the caveat that the relative contribution of ammonia might be strongly underestimated. Fate and effect models including open sea emissions would be required to have validated impact factors instead of relying on a stand-in impact model and these more qualitative deliberations.

Concluding from the additional description in the supporting information (SI) S3, climate change, marine eutrophication and ozone depletion are deemed most reliable and relevant impact categories for evaluating OCC. The GHG mitigation performance of the system is evaluated by determining the effective reduction of emissions from the conventional to the OCC system.

### 2.2. *Life cycle inventory*

The following sections describe the modelling of the major system components. A more detailed implementation is supplied in SI S1 and the provided excel inventories.

#### 2.2.1. *Conventional operation*

The conventional case is defined as the ship operation without any modifications related to OCC, consisting of fuel production and fuel combustion in Fig. 2A. Real-life operational profiles, indicating power demand over time, have been obtained for each ship engine for a timeframe of around two years between 2020 and 2024 (Heerema Marine Contractors; TotalEnergies). The timeframes have been scaled down to match the respective operation cases of 6 weeks for the Sleipnir and twice 16.45 days for 70.99 kt LNG delivery between US and NL of the LNG carrier, including both sailing and idle times.

Emissions and fuel consumption during ship operation are related to the power demand of its engines. The conversion factors from power to emissions and fuel consumption, as given by the IMO (2020) study, engine specification sheets and direct measurements (Comer et al., 2024; Linders et al., 2025), are strongly affected by the type of engine and engine load used. For the Sleipnir, 12 LNG-Otto medium speed engines operate on either LNG and marine gas oil (MGO) as pilot fuel for ignition or purely on MGO. The LNG carrier is equipped with two main engines (ME), four auxiliary engines (AUX) and a gas combustion unit (GCU), classified as LNG-Diesel, LNG-AUX and Boiler, respectively. Combining the operational profiles with the emission factors leads to emissions and fuel consumptions collected in Table 1. As the resulting GHG emissions are of particular relevance to the OCC assessment, an example calculation showcases their implementation: The total fuel consumption results from integrating over the power demand of the operational profile (kWh) multiplied by the specific fuel consumption (g fuel/kWh) for each given point in time. For instance, this results in 1.5 kt LNG and 47 t pilot MGO burned in the main engine of the LNG carrier for a delivery of 105 t LNG shown in Table 1. The associated $CO_2$ emissions result from the combusted fuel, meaning fuel consumption reduced by slipped fuel, and the combustion factors of 2.75 g $CO_2$/g LNG and 3.206 g $CO_2$/g MGO. Fuel slip is mainly methane emissions when using LNG fuel, estimated to constitute 90% of all slipped fuel. The methane emissions are determined from the operational profile and the methane emission factors (g/kWh), resulting in 3 t of direct methane emissions. Tracing this back to the amount of combusted LNG fuel and including the emissions from MGO combustion leads to the total emissions of 4.26 kt $CO_2$ for the main engines in Table 1. Though the underlying operational profiles and specific fuel consumption values cannot be disclosed, the resulting emissions other than $CO_2$ and methane are listed in the supporting information S1. A detailed description of the calculation approach and emission factors can be found in Appendix 3 of the report by Reitz and Zapp (2025).

Fuel production and transport to the ships are modelled reflecting either US production or NL imports as presented in the EverLoNG report (Reitz and Zapp, 2025), based on the ecoinvent approach for fuel supply modelling and 2021 fuel import statistics (eurostat, 2021a, 2021b).

**Table 1**

Fuel consumption and major operational GHG emissions of conventional (CON) and capture (OCC) operation. The OCC emissions (Occ add.) are determined by what is additional to the normal ship operation (CON).

| Operation<br>Unit: kt<br>LNG carrier | Fuel consumption per $10^5$ t LNG delivered | $CO_2$ emissions | $CO_2$ capture potential | $CH_4$ emissions |
|---|---|---|---|---|
| CON | | 6.66 | 5.77* | 0.021 |
| ME | 1.50 + 0.05 pilot | 4.26 | 3.69* | 0.003 |
| AUX | 0.76 + 0.01 pilot | 2.07 | 1.79* | 0.018 |
| GCU | 0.12 | 0.33 | 0.28* | 0.000 |
| OCC add. | | 0.99 | 0.71 | 0.004 |
| Power | 0.19 + 0.003 pilot | 0.52 | 0.37 | 0.004 |
| Heat | 0.17 | 0.47 | 0.34 | 0.000 |
| Sleipnir | per 6 weeks of operation | | | |
| CON | | 5.15 | 3.93 | 0.047 |
| LNG | 0.76 + 0.03 pilot | 2.04 | 1.77 | 0.047 |
| MGO | 0.97 | 3.10 | 2.16 | 0.000 |
| OCC add. | | 0.30 | 0.10 | 0.001 |
| LNG | 0.04 | 0.10 | 0.10 | 0.001 |
| MGO | 0.06 | 0.20 | 0.00 | 0.000 |

LNG and MGO refer to the Sleipnir operation modes using either Liquefied Natural Gas (LNG) or Marine Gas Oil (MGO) in the engine.

ME, AUX and GCU refer to the LNG carrier main engines, auxiliary engines and gas combustion unit, respectively.

[*] $CO_2$ amounts are given relative to the amount of LNG delivered of the OCC case, as the amount of LNG delivered is slightly lower when running OCC, but only then can the capture potential be realized.

### 2.2.2. *On-board carbon capture operation*

The flue gas from the conventional operation is treated in the capture unit up to its maximum capacity, determining its heat and power demand. The variability of the flue gas flow over the operational profile marks one of the most striking differences to land-based carbon capture systems, in addition to the heat integration potential of the flue gas and cooling from the LNG tanks. Considering the available heat from the operational profiles, the OCC system designs are tailored to each ship, while the Sleipnir is further distinguished into LNG and MGO operation modes, detailed in SI S1. Both occur about half the time in the operational profile, with similar load profiles. The OCC system energy demand for the LNG carrier is divided into 0.17 kWh electricity and 3.5 MJ heat per t $CO_2$ captured while both fuel operation modes of the Sleipnir use approximately 0.15 kWh electricity per t $CO_2$ captured and no additional heat, see SI S1.3 for a more detailed description. For the Sleipnir design, power is supplied via increased demand on all its engines, while for the LNG carrier, an auxiliary engine at 50% load and a boiler supply heat and power to the OCC system. Investment costs for a boiler on the Sleipnir are avoided due to the high heat availability in the flue gas especially when running on LNG, however, effectively lowering the achievable MGO capture rate. For LNG operation, additional emissions for OCC energy are again processed in the OCC system. The design capture rates are 90% for the LNG carrier, 95% and 77.5% for the Sleipnir LNG and MGO operation, respectively. The capture rates only apply at the design capacity of the capture system, between 2-8t $CO_2$ input per hour for the LNG carrier and operating at 4.5 to 15MW cumulative engine load for the Sleipnir. While the OCC does not operate at all below the lower bound, above the upper bound, it operates at full capacity, and any additional flue gas is directly vented to air without passing the capture system. This design capacity was chosen to cost-efficiently capture most $CO_2$ during operation with lowest system size and associated investment. Strong fluctuations in engine loads such as during maneuvering are thus also curtailed before entering the system. Additional effects from the weight of the capture system on either propulsion energy or cargo capacity are excluded in the base case for simpler comparability, but explored in the subsequent sensitivity analysis.

Applying the OCC design to the operational profiles determines the OCC fuel consumption and emissions collected in Table 1, further emissions are listed in SI S1. Fuel consumption during the LNG carrier OCC operation leaves a remaining LNG delivery of 70.73 kt. Overall, the OCC operation requires additional fuel of around 5–6% for the Sleipnir and 15% for the LNG carrier, 7% for heat and 8% for power.

### 2.2.3. *On-board carbon capture basis*

The OCC basis encompasses both on-board and land-based components that are not directly related to energy supply for OCC operation. The on-board OCC basis operation, complementing the heat and power supply for OCC operation discussed in Section 2.2.2, includes $CO_2$ venting during liquefaction, which leads to a 0.5% release of the originally captured $CO_2$ (Table 1) before it is stored on-board as captured $CO_2$. This amount of captured $CO_2$ is reduced from the conventional operation emissions when using OCC. Apart from $CO_2$, the operation of the OCC basis includes the MEA solvent degradation, which in turn leads to emissions of amines and ammonia. Emission amounts are based on prototype measurements within the EverLoNG project (Linders et al., 2025) and are in line with degradation rates (Moser et al., 2020) and emissions from land-based systems (Morken et al., 2017). The emissions depend on the amount of flue gas processed and its composition, leading to an average assumption of around 60 mg amine and 300 mg ammonia emitted per kg $CO_2$ captured. Emissions of formaldehyde and acetaldehyde are not included in the model, as their contribution is both minor and uncertain, expected below 0.3 mg per kg $CO_2$ captured (Morken et al., 2017). Further effects on the emissions to air are related to the operation of the quench system at the flue gas inlet, where a wash column with potassium hydroxide removes most remaining sulfur oxides from the flue gas.

The land-based supply chain for the OCC basis consists of the solvent production and port-based reclamation systems as well as the construction and end-of-life of the capture system itself.

### *2.2.4. Port operations, transport & storage of carbon dioxide*

The fate of the captured $CO_2$ must be considered to comprehensively assess the climate mitigation potential and environmental burdens of OCC. In this study, the $CO_2$ pathway is modelled including a port offloading terminal, transport via barge to a $CO_2$ export terminal of the port, followed by 964 km ship transport from port to storage. The $CO_2$ shipping matches the distance from the port of Rotterdam to Øygarden, the Northern Lights storage project's $CO_2$ receiving terminal (sea-distances.org; TerraMetrics, 2024). The detailed model was derived from previous LCAs (Burger et al., 2024; Lerche Raadal and Saur Modahl, 2021; Nöhl et al., 2025; Richardson et al., 2023) and reports by the Northern Lights project (DNV GL and Carbon Limits, 2019; equinor, 2019, 2020; Gentile et al., 2023) to reflect the emissions of its operation at 5 Mt annual storage capacity, including fugitive emissions for $CO_2$ handling (Lerche Raadal and Saur Modahl, 2021), offloading (Erlandsson and Tannoury, 2020), operation, construction and end-of-life of the facilities. The model was validated against the Northern Lights LCA report (Gentile et al., 2023), showing below 1% discrepancy for the reported total $CO_{2\text{-Eq}}$ emissions for transport and storage. For $CO_2$ offloaded in the US, the storage effort is modelled analogously by adapting the geography for materials and wastes, e.g. using US electricity supply.

## 3. Results

The evaluation of OCC is focused on its climate change mitigation performance contextualized with other environmental impacts. The model is explored via sensitivity analysis, and its limitations and broader context are discussed, result data is provided in the supplementary excel file.

### *3.1. Climate change*

Climate impacts arise from emissions of $CO_2$, methane ($CH_4$), nitrous oxide ($N_2O$) and other GHGs. The climate impacts along the complete life cycle of applying OCC versus the conventional ship operation are shown in Fig. 3A and B for the LNG carrier and Sleipnir, respectively. The contributions reflect the components of the two systems shown in Fig. 2.

For the conventional case, operation dominates the climate impacts at more than 75%. Impacts of the fuel supply play an increasing role for OCC, taking up 36% for the Sleipnir and even the majority share of 53% for the LNG carrier. This reflects the two major effects of using OCC: reduced operational emissions at the cost of burning additional fuel. Especially for the LNG carrier, a larger impact of fuel supply is observed due to the higher share of LNG fuel compared to the Sleipnir. This is related to the larger well-to-tank impact of LNG from processing and methane venting during natural gas and petroleum production. Fuel consumption for the capture system further distinguishes the two cases, using both electricity and heat on the LNG carrier contrasts the waste heat use without an additional boiler in the Sleipnir design. However, this design also leads to a lower capture rate for MGO operation of the Sleipnir, which would otherwise require additional heat from a boiler and thus additional fuel. Therefore, the OCC design choices, based on the engines and operational profiles of the different ships, quite heavily affect the respective system performance as reflected in the GHG emissions in Table 1. For the conventional case, a significant share of methane emissions during operation comes from the Sleipnir LNG operation, both due to large slip rates in the engines and low operational loads. This remains unchanged in the OCC operation in Fig. 3B, where the reduction of the LNG operational $CO_2$ emissions is clearly visible, but the large share of methane emissions persists. Similarly, in Fig. 3A, methane slip in the auxiliary engine of the LNG carrier both during normal ship operation and powering the OCC plays a significant role in the remaining climate impacts.

Apart from operation and upstream fuel, the remaining impacts for the OCC are largely due to the $CO_2$ pathway. It takes up 3% of the total emissions for the Sleipnir, using storage in Norway, and 6% for half Norwegian, half US-based storage of the LNG carrier. In Norway, $CO_2$ pathway emissions are determined to 95% by $CO_2$ transport, especially transport on the $CO_2$-cargo ship already contributing 76%. For the US-based pathway, the transport share goes down to 72% due to the much larger electricity grid impacts related directly to storage operation with 473 g/kWh emissions in the US versus 28 g/kWh emissions in Norway (Wernet et al., 2016). The almost 2% remaining contributions for OCC basis emissions are distributed quite evenly between solvent reclamation, OCC construction efforts and $CO_2$ venting during liquefaction.

In summary, fuel supply, operation, $CO_2$ pathway and OCC basis stages each make up a significant share of the system impacts for both ships, thus being relevant parts when evaluating the effective reduction of emissions. As it is not clearly defined how the $CO_2$ pathway and OCC basis shares are to be included in the commonly used TtW and WtW boundaries, an overview including extended interpretations of TtW and WtW boundaries matching the OCC context is given in Table 2. As discussed before, while the amount of $CO_2$ that can be reduced on TtW scale ranges from 72% for the Sleipnir to 82% for the LNG carrier, when considering all GHGs this is reduced to 55% and 71% $CO_{2\text{-Eq}}$ mainly due to methane slip in the engines. Combining this with fuel supply leaves 43% and 50% climate impact reduction, respectively. Further expanding the boundaries to include $CO_2$ pathway and ultimately OCC basis effects outside of energy supply leaves 40% and 46% reduction for the Sleipnir and LNG carrier, respectively.

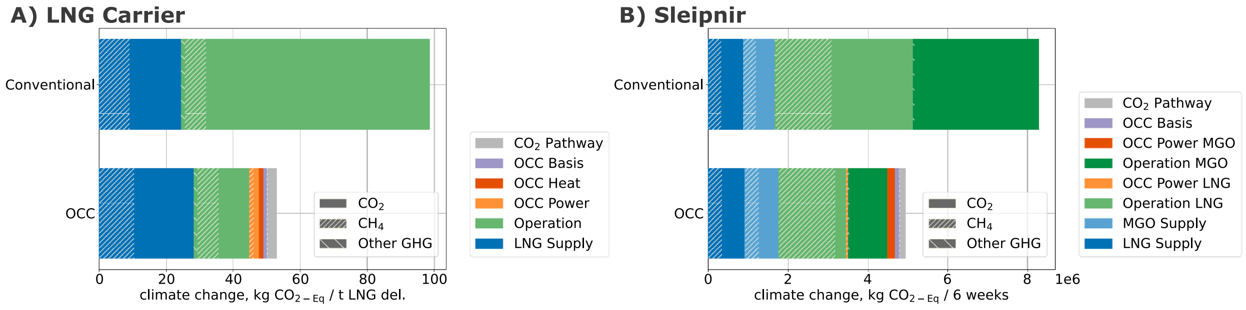

**Fig. 3.** On-board carbon capture (OCC) and conventional climate change impacts using GWP100 in kg $CO_2$ equivalent ($CO_{2\text{-Eq}}$) per FU for the LNG carrier (A) and the Sleipnir (B). $CO_{2\text{-Eq}}$ impacts include methane ($CH_4$) and other greenhouse gases (GHG). Fuel types are distinguished between liquefied natural gas (LNG) and diesel-like marine gas oil (MGO). OCC basis and OCC energy (heat and power) combine processes related to the capture operation as defined in Fig. 2.

**Table 2**
Overview of climate change impact reduction of capture (OCC) compared to the conventional (CON) operation for the well-to-wake (WtW) and intermediate system boundaries. Included contributions from Fig. 3: fuel supply (WtT), operation and OCC energy (TtW), $CO_2$ pathway ($TtW^{path}$) and OCC basis ($WtW^{sys}$). CON and OCC refer to the total system impacts, both including fuel combustion for ship operation. The positive percentages represent the amounts reduced compared to CON. For presentation, the LNG carrier functional unit was scaled by $10^5$.

| System Boundaries | | LNG carrier (/$10^5$t LNG del.) | | | Sleipnir (/6 weeks) | | |
|---|---|---|---|---|---|---|---|
| | Unit: kt $CO_{2\text{-Eq}}$ | CON | OCC | red. | CON | OCC | red. |
| WtT | fuel supply | 2.45 | 2.82 | -15% | 1.67 | 1.76 | -6% |
| TtW | fuel combustion | 7.41 | 2.12 | 71% | 6.61 | 2.94 | 55% |
| $TtW^{path}$ | fuel combustion incl. $CO_2$ pathway | 7.41 | 2.36 | 68% | 6.61 | 3.07 | 54% |
| WtW | WtT + TtW | 9.85 | 4.94 | 50% | 8.28 | 4.70 | 43% |
| $WtW^{path}$ | WtT + $TtW^{path}$ | 9.85 | 5.24 | 47% | 8.28 | 4.86 | 41% |
| $WtW^{sys}$ | full system boundaries incl. OCC basis | 9.85 | 5.30 | 46% | 8.28 | 4.94 | 40% |

### 3.2. Other environmental impacts

The impacts in categories other than climate change in Fig. 4 increase in most cases. The categories can be distinguished by the major contributions coming either from direct CON and OCC operation emissions or the fuel supply chain. This distinction affects the interpretation of resulting impacts in terms of reliability and gravity.

More than 99% of impacts for eutrophication and acidification are determined by nitrogen oxide (NOx) and some ammonia emissions. The increase in these categories is related to operation emissions from combustion and ammonia emissions from capture operation as e.g. for the LNG carrier, NOx emissions are dominated by ship operation (85%) and OCC energy (5%). The varying differences of OCC compared to CON in Fig. 4 for acidification, marine and terrestrial eutrophication are related to the impact pathway modelling of the categories (Posch et al., 2008). Due to the emissions taking place mainly on sea, the underlying land-based emission pathway models have limited applicability but are seen rather as an explorative range of effect strengths that could be expected, where terrestrial eutrophication explores a larger contribution of ammonia to the impacts compared to marine eutrophication. In addition, the cleaner combustion of LNG compared to MGO leads to a larger relative contribution from the OCC ammonia emissions especially for the LNG carrier. This observation is counteracted by the Sleipnir case with an overall reduced amount of NOx emissions for MGO operation including OCC. Instead of additional auxiliary operation, here the main propulsion engines supply the OCC power. Due to the generally low loads of the operational profile with high associated NOx emissions, increased engine load improves towards slightly lower NOx emissions per kWh. Therefore, when using the main engines for OCC energy, the actual operational profile of the ships can significantly change the effect of OCC, with the Sleipnir MGO operation showcasing an extreme case of this. When independent engines are used for OCC, the LNG carrier case estimates a 10–25% increase in NOx and ammonia-related impacts.

Similar to eutrophication, operational emissions determining human toxicity related impact categories are even more strongly limited in their reliability of the effect pathway modelling, including particulate matter formation and photochemical oxidant formation (POF). For POF, both NOx (80–70%) and non-methanic volatile organic compounds (NMVOC) (18–28%) determine the impacts, half of which is related to gas venting during fuel production and also potentially lower human proximity to the resulting smog than in more rural or urban settings.

The higher operational emissions of OCC coincide with larger fuel demand, reflected in the increased resource use of fossil fuels by 5% and 15% for OCC energy of Sleipnir and LNG carrier, respectively. An additional 3% increase arises due to the $CO_2$ pathway with only a minor contribution from the OCC basis.

A larger outlier is observed in Fig. 4 for the use of metals and minerals, rising by 85% and 74% for the Sleipnir and LNG carrier, respectively. For OCC, impacts are dominated by the fuel supply, for CON (54–58%) and OCC energy (3–8%). The remaining impacts are due to construction efforts for the OCC system (23–16%), the storage site (12–14%) and remaining OCC basis (8–4%). Higher construction impacts for retrofitting the Sleipnir stem from designing for stricter integration requirements compared to the LNG carrier. However, the conventional system excludes ship construction, limiting interpretation of construction-related impact categories. To put the increase into perspective, a comparison of the LNG carrier results with ship construction is made using the ecoinvent process “tanker production, for liquefied natural gas”, see SI S2. Including ship construction and maintenance results in the CON system leads to an increase in impacts of 15%, similar in magnitude to categories related to operation. The stronger effect is thus seen as more related to the choice of system boundaries and comparability limitations rather than a major area of concern. A similar observation is made for the peak in carcinogenic human toxicity, where inclusion of construction efforts lowers the effect of including OCC from 66% to 17% and to a smaller extent also for non-carcinogenic human toxicity.

The identified environmental trade-offs of generally around 5-25% impact increase do not raise concerns around the general viability of

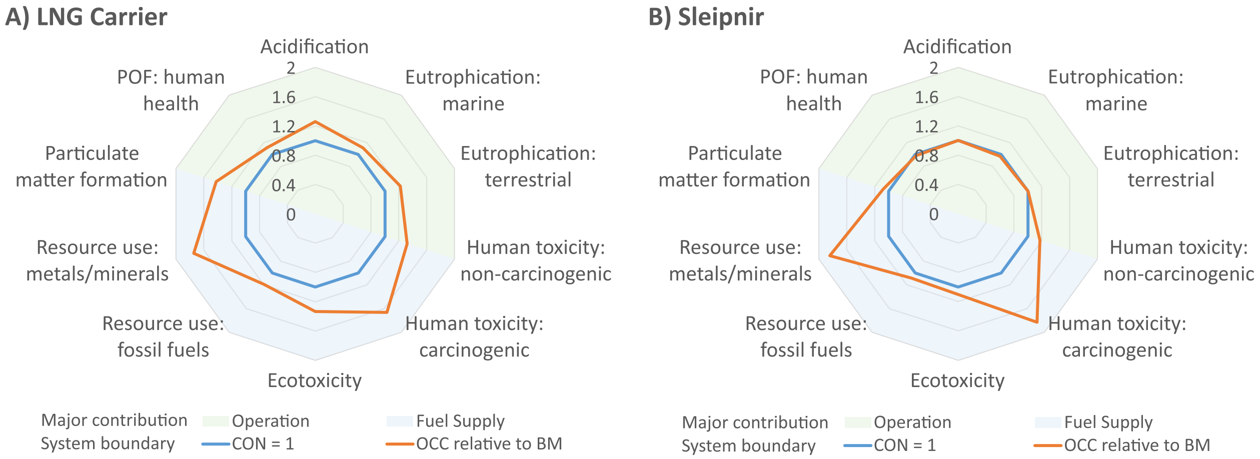

**Fig. 4.** Environmental impacts other than climate change of the conventional (CON) ship and the ship with carbon capture (OCC) normalized to the CON impacts, for the LNG carrier in A) and the Sleipnir in B). Impact categories are grouped (background color) based on their largest contributor, either operation on the ships (green) or fuel supply (blue). The abbreviation POF is used for Photochemical oxidant formation.

OCC as a climate impact reduction method, as some shifting of environmental burdens is to be expected for climate mitigation technologies and larger outliers above 50% increase were related to the choices of system boundaries rather than inherent environmental hotspots of the system. Nevertheless, efforts to reduce these trade-offs are highly encouraged, e.g. by deliberately choosing low-emission fuel supply chains and limiting solvent degradation, as explored in the following sensitivity analysis.

### 3.3. Sensitivity analysis

A sensitivity analysis is performed to explore the effects of plausible variation of major model parameters and assumptions capturing potential uncertainty in the system models in place of statistical methods such as Monte Carlo analysis. As no probabilistic foreground system uncertainty is available, no substantial information gain is expected from sampling the background database uncertainty (Heijungs, 2020; Kim et al., 2025; Marsh et al., 2025). Therefore, singular critical parameters are tested for their influence on the environmental impacts, covering fuel supply with lower environmental impact in the supply chain, variation of OCC energy demand, handling of the captured $CO_2$, higher solvent degradation and lifetime capacity effects as described in SI S2.

The sensitivities show strongest improvements in climate change reduction for low-impact fuel supply, lower fuel slip and nearby storage options. Strongest performance decline is observed for very high venting and high conditioning efforts during $CO_2$ transport to storage. A 10% variation in the energy demand from the model is not seen as major concern if the system can compensate for the increased demand instead of reducing the capture rate. Similarly minor effects are observed for increased draught due to the additional weight of OCC, modeled instead of lowering cargo capacity. The effects of flue gas composition on solvent degradation and potential further treatment of the degradation emissions in an acid wash show prominent effects on environmental impacts, e.g. removing the 18% share of ammonia emissions in particulate matter impacts of the LNG carrier. As a point of concern for ships intending to use OCC, other solvents than MEA could be explored for potentially reduced degradation in some flue gas compositions.

An estimate of the range of reduction effects is based on plausible combinations of factors that lead to impact increases or decreases resulting in upper and lower estimates, described in SI S2. The climate impact reduction is therefore estimated at a range of 37%–55% around the 46% base case results for the LNG carrier and 32%–48% around 40% for the Sleipnir.

## 4. Discussion

This study contributes to the discussion on how well OCC can serve as a GHG emission mitigation measure in the marine decarbonization portfolio, finding mitigation potentials of 32% –55% of GHG emissions based on the explorative sensitivity study and the two ship case studies with vastly different operational and emission profiles. This underlines the general potential for OCC to contribute as a GHG mitigation option for LNG fueled ships, even when considering the complete life cycle of the system, fuel supply and subsequent $CO_2$ pathway. The main drivers of remaining emissions were identified as fuel supply and methane slip, either of the main engines for the Sleipnir or the commonly overlooked methane slip of the auxiliary engines for the LNG carrier. In addition, the limited capture potential on MGO leaves significant remaining emissions for the Sleipnir, partly due to the LNG-focused designs excluding an additional boiler. $CO_2$ pathway and OCC basis show relevant contributions and therefore should not be neglected.

Increased impacts in categories other than climate change do not raise major environmental concerns, their tendencies and drivers could be identified as increased fuel consumption, $CO_2$ pathway and construction effects. Direct emissions from the OCC operation play a minor role in toxicity and eutrophication-related impacts. Potentially higher degradation emissions measured for different flue gas compositions were explored in the sensitivity analysis and should be considered when investigating different engines and solvents. While the chosen MEA solvent serves as a safe and stable baseline in many industrial carbon capture applications, investigating systems relying on more novel capture media, such as thermally more stable amine-based solvent blends, could result in both reduced energy demand and reduced impacts from degradation emissions such as amines and ammonia (Du et al., 2024). While some proprietary blends are already widely used in CCS projects, this work focused on providing the data for a MEA baseline with widely available data. Future commercial OCC systems could be optimized using such blends. However, especially on ships, the solvent selection is also guided by the strict safety requirements for chemicals used on board, hampering the viability of e.g. ammonia-based solvents. For a robust evaluation of solvents and the impacts of their different degradation products, a strong need for extending the current impact models to open sea emission and impact pathways was identified.

Major differences between the ships stem from the different capture rates, additional fuel demands for OCC and engine methane slips. These in turn depend on properties like engine and fuel type, operational profile and resulting heat integration potential, indicating that no direct extrapolation should be made for a different ship. In addition to assessing the additional space required for system and tanks, translating the tailored OCC inventories to other ships requires analyzing their operational profile and available heat in the exhaust gas. This determines the necessary fuel for heat and power of OCC, as reflected in the range of additional fuel required for the Sleipnir and LNG carrier from 5–6% up to 15%. Even extrapolations to different operation cases of the investigated ships are difficult, as the operation is not distinguished into independent and representative components. Therefore, different tasks of the Sleipnir or longer distances travelled for the LNG carrier would ideally be reassessed.

Most OCC LCA studies find climate impact reduction for OCC operation compared to a HFO baseline in the order of 50% and increased burdens in all other impact categories (Negri et al., 2022, 2023; Oh et al., 2024). As an alternative to LNG, Oh et al. (2024) find better performance for oil-fueled ships and OCC, e.g. HFO or MGO, largely because of high methane emissions of LNG, at up to 68% impact reduction without considering $CO_2$ pathway or varying operational profiles. However, direct comparison of such impact reductions is often misleading, due to different system assumptions, such as different baselines, fuel supply, operation and storage pathways. The detailed inventory model presented here can facilitate future studies seeking to consistently incorporate OCC into broader mitigation strategy assessments. Avoiding generic assumptions by using accurate methane slip and fuel supply emissions in future assessments of OCC and ships could incentivize transitioning towards improved practices, as both showed strong potential in the sensitivity study. Fleet-wide assessments of OCC would need to differentiate operation and engine cases but could encompass variations within similar ships via lower and upper bound scenarios.

The resulting case-specific mitigation potentials suggest carefully assessing where to apply OCC and strongly encourage a combination with appropriate measures ensuring low methane emissions during fuel production and ship operation. Considering the long lifetime of ships, retrofitting will play an important role in decarbonization efforts, highlighting that OCC should also be further evaluated for oil-burning engines. Alternative fuels studies (Roux et al., 2024) show a general tendency of higher GHG impact reduction compared to HFO, ranging mostly within 60% up to 90% (Gray et al., 2024; Lee et al., 2022; Ramsay et al., 2023; Tomos et al., 2024), also considering additional space requirements for lower-density alternative fuels. Despite the comparability issues, in this study OCC is not deemed preferable compared to alternative fuels due to its limited overall mitigation potential. Instead of competing, OCC can support mitigation efforts while building up capacity for lower-emission solutions to be available for the range of industrial sectors needing them and then OCC can be used in combination with alternative fuels via circular fuel approaches as proposed by Malmgren et al. (2021) and Charalambous et al. (2025). To support this development, it is essential to explicitly include OCC in assessment frameworks of marine decarbonization currently in development.

## 5. Conclusion

The findings showcase the variability of environmental viability of OCC on two distinct implementation scenarios, on a specialized large crane ship and a more generalizable LNG carrier. It finds general potential for OCC to contribute as a GHG mitigation option for LNG fueled ships, emphasizing case-by-case evaluation of integrability, engine specifications and operational profiles to capture the strong effect observed for methane slip emissions. Current availability for implementation on suitable vessels is deemed potentially higher than for low-carbon fuels, as there is direct competition from other industrial sectors as expected for alternative fuels, e.g. for aviation. However, clear roadmaps and infrastructure availability for $CO_2$ handling could pose an additional hurdle for OCC as discussed by Linders et al. (2025) and proposed by Kan et al. (2026). Therefore, including OCC into the portfolio of intermediate decarbonization options for the marine sector is recommended. Future viability assessments for specific cases would additionally require realistic economic assessment of $CO_2$ abatement costs, including the costs associated with $CO_2$ handling and storage expanding on current assessments (GCMD, 2025). In addition, future assessments and comparisons of different marine decarbonization options require a more reliable assessment of impacts tailored to emissions at open sea, characterized by dedicated fate and effect models.

## Supplementary material

Supporting information on LCA modelling S1 to S3 (PDF); Brightway exported inventories of the modelled systems (XLSX); Collection of result data (XLSX).

## CRediT authorship contribution statement

**Lavinia Reitz:** Writing – original draft, Visualization, Methodology, Formal analysis, Data curation, Conceptualization. **Nils Thonemann:** Writing – review & editing, Conceptualization. **Christina Wulf:** Writing – review & editing, Supervision, Conceptualization. **Bernhard Steubing:** Writing – review & editing, Conceptualization. **Petra Zapp:** Writing – review & editing, Supervision, Project administration, Funding acquisition, Conceptualization.

## Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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## Supplementary materials

Supplementary material associated with this article can be found, in the online version, at doi:10.1016/j.ijggc.2026.104722.

## Data availability

Data is shared in supplementary materials, including inventory excel files (Brightway format). Some underlying assumptions on engines and operational profiles are not shared due to confidentiality.

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