Life Cycle Assessment

of Ship-based Carbon Capture

D4.1.1 & D4.2.1

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Executive Summary

This report describes identified environmental impacts of the technically feasible ship-based carbon capture (SBCC) systems evaluated in the EverLoNG project on the two case studies: Heerema Marine Contractors' crane vessel Sleipnir and the liquefied natural gas (LNG) carrier operated by TotalEnergies. Using a Life Cycle Assessment (LCA) approach to evaluate CO_2 mitigation, greenhouse gas reduction as well as further environmental impact potentials have been considered on-board the vessels as well as the entire life cycle from fuel supply up to final geological storage of CO_2. Only if the additional efforts required for capture, transport, and storage are less than the amount of CO_2 captured on-board can this technology truly contribute to maritime decarbonisation.

The two ships provide different functions. The crane operations of the Sleipnir are the relevant function, supplemented by shipping to and from operation site. Thus, an average 6-week operational profile was determined. Delivering U.S. LNG to Rotterdam, The Netherlands, is the function of the LNG carrier. While the Sleipnir is assessed as being retrofitted for CO_2 capture, the design and operation of the LNG carrier was considered newly-built, using a new engine type, more suited for SBCC. For the subsequent CO_2 treatment, offloading of CO_2 and spent solvent at the Port of Rotterdam and sending the CO_2 to the Northern Lights storage project was assumed, as well as offloading CO_2 and spent solvent on the vessel's return trip to the U.S. at Port Arthur, Texas, and subsequent processing and use of the CO_2 for enhanced oil recovery.

The GHG reduction potentials were evaluated for the on-board (tank-to-wake (TtW)) system separately and for the entire life cycle (well-to-wake (WtW) plus handling and storing of CO_2). Benchmarks are the same ships operating without capture. Running the capture unit reduces the TtW CO_2 emissions by 72% over the complete operational profile for the Sleipnir and 82% for the LNG carrier. This surpasses the goal of >70% on-board CO_2 capture, set within the EverLoNG project. The effects of methane slip, which cannot be captured by the CO_2 capture unit, are considered in the climate change impact ($CO_{2\text{-Eq}}$ emissions). Climate change impacts reduce by 55% for the Sleipnir and 71% for the LNG carrier. While the Sleipnir shows some increase in the methane emissions from the main engines, the LNG carrier methane emission increase is driven by the auxiliary engine used for the capture system power.

The full system includes fuel supply, capture system production, operation (ship and capture unit) and CO_2 handling. The overall reduction of climate change impacts for the full systems equals 39% and 44% $CO_{2\text{-Eq}}$ for the Sleipnir and LNG carrier, respectively. The main drivers against further reduction of climate impacts are found in the fuel production stages, which are increased by additional fuel demand due to capturing CO_2 and the on-board methane slip. Higher reduction could be obtained by reducing fuel consumption of the capture operation with further improved heat integration or by choosing fuel explicitly from suppliers guaranteeing lower upstream fuel emissions. A general handling of the methane slip provides additional improvement potential which is, however, independent from CO_2 capture.

The higher fuel demand due to CO_2 capture also causes an increase in all other environmental impacts for the LNG carrier. For the Sleipnir, this increase is compensated by lower NOx emissions, due to an optimized combustion regime, especially for low engine loads. Therefore, effects strongly impacted by NOx emissions, such as acidification, eutrophication or photochemical ozone depletion potentials stay in the same range as operation without capture for the Sleipnir. For acidification, terrestrial eutrophication and particulate matter, the impact of ammonia emissions as a degradation

product from the capture process becomes visible for both ships, though to a much lesser extent than NOx emissions. Main construction impacts lie with the CO_2 tanks. For the port facility, this can be reduced when using more of the available capacity, as the on-shore facility has the capacity to handle more ships with the base case equipment.

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I Nomenclature

AUX	Auxiliary engine
BM	Benchmark
BOG	Boil-off Gas
$CO_{2\text{-Eq}}$	CO_2 equivalent
CC	Climate Change
Ef	Emission factor
EoL	End-of-Life
EOR	Enhanced Oil Recovery
FU	Functional Unit
GCU	Gas Combustion Unit
GHG	Greenhouse Gas
GWP	Global Warming Potential
HFO	Heavy Fuel Oil
IMO	International Maritime Organization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
LHV	Lower Heating Value
LNG	Liquefied Natural Gas
LPSCR	Low-pressure Selective Catalytic Reduction
MCR	Maximum Continuous Rating
ME	Main Engine
MEA	Monoethanolamine
MeOH	Methanol
MGO	Marine Gas Oil
MEPC	Marine Environment Protection Committee
Nf	Normalisation Factor
OCC	On-board Carbon Capture
PE	Person Equivalent
SBCC	Ship-based Carbon Capture
TEA	Techno-economic Assessment

TtW	Tank-to-Wake
WtT	Well-to-Tank
WtW	Well-to-Wake

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1 Introduction

The objective of this joint Deliverable 4.1.1 and 4.2.1 is the assessment of environmental impacts associated with the implementation of ship-based carbon capture (SBCC), also on-board carbon capture (OCC), to mitigate emissions from existing vessels while alternative fuels and propulsion systems are still under development. First results for this study have already been presented at the GHGT-17 conference in 2024 [1].

1.1 Background

In 2022, the international shipping sector contributed nearly 3% to the global greenhouse gas (GHG) emissions [1-3]. Three-quarters of global freight transport measured in tonne-kilometres worldwide is transported by ships, both large and small scale [6]. With increasing importance of the shipping industry, this calls for a portfolio of complementing decarbonization measures to bring the large amount of emissions down. Against this background, the International Maritime Organization (IMO) has again strengthened its GHG emission reduction ambition for the shipping sector to reach net zero around 2050 compared to 2008, aiming for a 20% GHG emission reduction by 2030, 70% by 2040 targets in between [4]. Additionally, the EU has proactively established the FuelEU Maritime initiative and included maritime emissions into its emissions trading system [5]. Starting in 2025, the GHG intensity should be reduced by 2%, based on the 2020 values, and gradually increase to an 80% reduction by 2050. Both initiatives widen their scope beyond on-board, Tank-to-Wake (TtW) carbon dioxide (CO_2) emissions to methane and nitrous oxide (N_2O) gases as well as upstream fuel supply in a so called Well-to-Wake (WtW) approach. The effectiveness of such measures needs to be thoroughly evaluated and validated, especially concerning their overall environmental performance.

In the EverLoNG project [7], ship-based carbon capture (SBCC) is evaluated as a transitional measure to reduce carbon emissions of both retrofit and new-built liquefied natural gas (LNG)-fueled vessels, benefitting from the technological maturity of its land-based counterpart [8]. On two differently operating LNG-fueled test vessels, the crane vessel Sleipnir owned by Heerema Marine Contractors [9] and an LNG carrier operated by TotalEnergies, the SBCC technology was tested, providing deep insight into the performance of on-board CO_2 capture. With these first-hand test results, CO_2 reduction was verified and reduction potentials for full-scale applications as well as solvent performance on ship flue gas were estimated. The two vessel types with different purposes follow their own operation profiles, resulting in two distinct systems to analyse. Tailored full-scale SBCC systems are designed for both vessels, including heat integration, placement on-board and their respective measured operational profiles, provided by Heerema Marine Contractors and TotalEnergies. To reflect the whole picture, the pathways of the captured CO_2 are evaluated as well, including port operations and transport to permanent storage or utilization.

The full-scale designs serve as basis for an environmental evaluation of SBCC via the Life Cycle Assessment (LCA) methodology according to the ISO14040/44 standards [13] and Marine Environment Protection Committee (MEPC) LCA guidelines [14]. This approach identifies potential burden shifting between different parts of the environment, such as climate impacts and resource depletion, as well as burden shifting within the life cycle itself. As the concept of SBCC is still young, not many LCA studies have been carried out. Negri et al. [15, 16] performed an LCA for a standardized land-based carbon capture system on-board using LNG fuel from an additional tank. The system is placed on heavy fuel oil (HFO) fueled vessels equipped with scrubber technology to remove contaminants in the flue gas. With a net capture efficiency on the ship and capture unit emissions of 94%, they found that the full pathway to storage via pipeline yields a reduction of 50-52% in global warming related impact categories when compared to the HFO operation without capture. Oh et al. [17] conducted a study on on-board carbon capture, comparing its efficiency for different fuel types and engine modes based on the well-to-wake GHG intensity defined in the FuelEU Maritime regulation [18]. They found 54-68% reduction compared to their baseline scenarios, not including the CO_2 pathway. Due to high upstream emissions, methane slip, and lower heat availability for LNG fuels, oil-based fuels are found to outperform in terms of reduction potential.

SBCC is proposed as one of the transitional measures, using an already mature technology, and its expected environmental performance considering realistic operational conditions is evaluated in this LCA.

2 Methodology

This report contains a Life Cycle Assessment (LCA) of the SBCC concept developed in the EverLoNG [2] project. The methodology for the LCA is based on the ISO14040/44 standards [3], also considering the guidelines on life cycle GHG intensity of marine fuels by IMO's Marine Environment Protection Committee (MEPC) [12]. The LCA stages are depicted in Figure 1.1-1, showing their iterative feedback relation. While Goal and Scope definition set the overall frame for the analysis, the technology is modelled in detail in the Life Cycle Inventory stage. The resulting impacts on the environment are assessed during Life Cycle Impact Assessment. Taking into consideration all assumptions, limitations and results, the Interpretation stage summarizes the findings to either require more refined inventory data or for the conclusion.

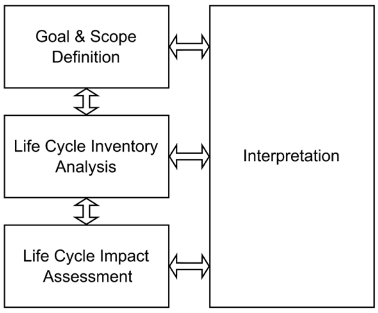

Figure 1.1-1 Framework of LCA according to the ISO 14040 standard [2]

In the following sections, the detailed goal and scope definitions as well as methods and approaches used in the LCI and LCIA stages are discussed. They are in line with the general arrangements defined in a framework documented (deliverable D4.3.1) defining the basic case studies for harmonized techno-economic and environmental assessments.

2.1 Goal Definition

The goal definition sets the basis for the study, collecting the reasons for carrying out the study, the intended applications, the target audience, and the commissioner of the study.

2.1.1 Reasons for Carrying Out the LCA Study

Within the EverLoNG project, ship-based carbon capture (SBCC) by absorption, using a well-established and well-understood 30% monoethanolamine (MEA) solvent, is developed as a measure to reduce CO_2 emissions from shipping. Targets are defined for on-board CO_2 emission reduction of >70%. The purpose of this study is to verify the target and to validate the effectiveness of SBCC from an LCA perspective, including upstream and downstream impacts.

The results give insight to what degree SBCC can mitigate CO_2 emissions in the considered application cases and what other environmental impacts are associated with SBCC. Findings can be used for comparison with alternative options for decarbonization of the maritime sector (e.g. green fuels, new propulsion systems).

2.1.2 Intended Applications

In the study, the potential environmental impacts of carbon capture on two LNG-fuelled ships compared to operation without capture are assessed, evaluating the potential environmental benefits and trade-offs surrounding SBCC, both on-board and considering further CO_2 pathways. Two vessels with very different functions, a large crane ship and an LNG carrier, are evaluated. The main goal is the verification of benefits concerning the climate change impacts of these ships and at the same time validating the environmental target of the EverLoNG project to reach a CO_2 reduction of >70% on-board. Potential hotspots and key factors are to be identified to aid in further development of the technology. Additionally, potential burden shifting to other environmental effects due to the application of SBCC shall be visualized.

2.1.3 Target Audience

The results are to be communicated within the project. Potential impacts of the study are informing project partners, potential first-movers, in their design and decision process to implement SBCC as well as to prepare for dialogue with external stakeholders, such as policy makers considering regulation, guidelines, and support of the technology in general.

2.1.4 Commissioner of the LCA Study

The study was conducted as part of the ACT programme (Accelerating CCS Technologies, Horizon2020 Project No 691712) [4] funded EverLoNG project [2]. Financial contributions have been made by the Ministry of Economic Affairs and Climate Policy, the Netherlands; The Federal Ministry for Economic Affairs and Climate Action, Germany; the Research Council of Norway; the Department for Business, Energy & Industrial Strategy, UK; and the U.S. Department of Energy. All funders are gratefully acknowledged.

2.1.5 Limitations

The LCA is based on research findings of the demonstration of pilot plants during the EverLoNG project and additionally modelled scale-up to full size systems, representing the status-quo of SBCC research and knowledge. Hence, the results are specific for the two cases and their operational profiles. Environmental impacts specified for each case can be identified and hot-spots depicted. It is not meaningful to compare the two ships to each other, due to their very different functions. Only generic findings related to retrofitting or new-built systems can be reflected between each other.

2.2 Scope Definition

The scope definition frames the study to match the goal definition, including e.g., description of the case studies, functional units, system boundaries, but also LCI and LCIA frameworks. The definitions of the investigated systems are closely linked to the framework document established in the WP 4 of the EverLoNG project (see deliverable D4.3.1), forming the basis for harmonized LCA and techno-economic assessments (TEA) of the two case studies within the project.

2.2.1 Case Studies

2.2.1.1 On-Board Capture

Two ships, a large crane ship and an LNG carrier, having very different functions are assessed. The crane operations provided define the relevant function of this ship. Surrounding the crane operations, shipping to and from operation site and idle time are necessary. Delivering LNG is the determining function of the LNG carrier. Though vessels often are operated on a chartering basis, meaning that they do not have a regular route and ports they visit, a representative case is chosen. The specific delivery route from Port Arthur (U.S. Gulf Coast) to the Port of Rotterdam (NL), including a ballast trip back, serves as an example.

To develop representative and realistic full-scale systems, it is important to know the CO_2 volumes captured between each offloading. Therefore, operation of two specific ships form the basis for the SBCC design and are also used for the demonstration of the pilot plants developed within EverLoNG:

a) Heerema Marine Contractors' semi-submersible crane vessel Sleipnir [5]
b) TotalEnergies-chartered LNG carrier Seapeak Arwa

These vessels represent different operational profiles and fuel use scenarios, which will be described in the following. To evaluate the CO_2 reduction on-board, the results are compared to benchmark systems, being the same ships without capture.

The captured CO_2 is stored on-board and offloaded at the port. After the CO_2 has been received and intermediately stored at the port, it needs to be transported to its final destination, either for permanent storage or utilization.

2.2.1.1.1 Ships

Sleipnir

Figure 2.2-1 Sleipnir crane ship

Heerema's Sleipnir is a very large semi-submersible crane vessel. Its main purpose is the installation or dismantling of offshore platforms, wind farms, bridges and more. For this, the Sleipnir operates its 12 dual fuel engines, using both marine gas oil (MGO) and liquefied natural gas (LNG). Frequently fuelled close to the port of Rotterdam, return trips to the port are estimated around 8-10 times a year for refuelling. Its function is thus represented by the ship operation itself, given by the engine power used over time. In this project, operational data for two years, 2021 and 2022, was provided by Heerema, which were used to define a representative operational profile of the Sleipnir.

LNG carrier

Figure 2.2-2 LNG carrier

The LNG carrier assessment is based on an LNG carrier operated by TotalEnergies with a total tank capacity of 170000 m^3 transporting LNG around the globe. A two-year operational profile was provided, including engine power and fuel consumption for two main engines (ME) and four auxiliary engines (AUX), as well as the gas combustion unit (GCU) to avoid overpressure in the LNG tank. While the original vessel operates on LNG and heavy fuel oil (HFO), a new-built ship case operating on LNG and MGO is considered.

For the Sleipnir, retrofitting of a full-scale SBCC system is considered, including detailed integration designs on the ship, piping, CO_2 and chemicals storage tanks as well as on-board installation. The LNG carrier is designed with more freedom for placing storage tanks, cooling systems and specific engine types optimal for use with carbon capture systems, in a new-built type of case.

2.2.1.2 Benchmark Operation

The benchmark operation of the ships is determined via their respective operational profile, meaning the power consumption over time, and the resulting fuel consumption and emissions corresponding to the ships' engines specifications. For both the Sleipnir and the new-built LNG carrier, the original ship operation is considered as power demand on the engines, leading to fuel combustion and ultimately flue gas emissions.

2.2.1.3 CO_2 Pathways

2.2.1.3.1 Storage pathway

The considered CO_2 pathways (red) for geological storage relating to the operation characteristics (blue) for the Sleipnir and LNG carrier cases are shown in Figure 2.2-3 and Figure 2.2-4, respectively. The Sleipnir is considered to operate around the Port of Rotterdam [6], offloading its CO_2 and spent solvent at port and sending the CO_2 to the Northern Lights storage project [7]. Similarly, the CO_2 that is captured at the LNG carrier while travelling to Rotterdam is sent to the same pathway. The ballast trip back to the US leads to additional CO_2 captured, which can be sent to an enhanced oil recovery (EOR) site via pipeline.

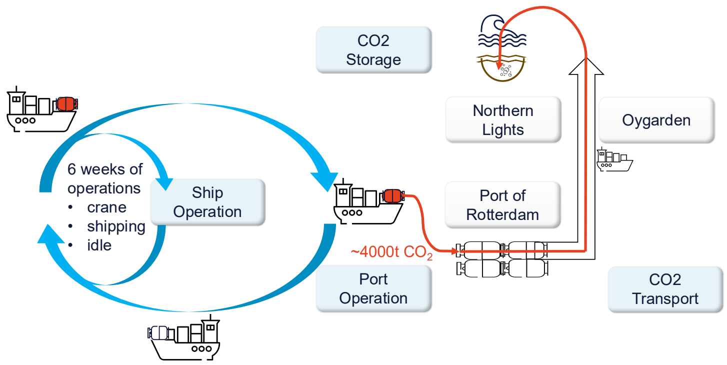

Figure 2.2-3 Sleipnir CO_2 storage pathway to Northern Lights

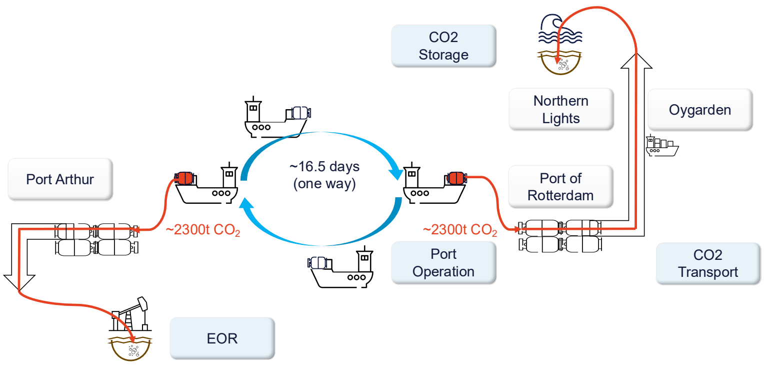

Figure 2.2-4 LNG carrier CO_2 storage pathway to Northern Lights and EOR

2.2.1.3.2 CO_2 Utilization

Utilization of the captured CO_2 is another option beside storage. The list of possible utilization options with their various products is long, reaching from direct use of CO_2 in greenhouses, to conversion into synthetic fuels, or the production of chemicals, each with its own specifications for CO_2 quality. To stay in the maritime context, two possible utilization approaches were considered: the production of methanol and of methane transformed into LNG via liquefaction. As the utilization is not a core element of the EverLoNG project, data from literature were taken to model the entire

CO_2 utilization pathway. For using and providing shipping fuel, the utilization is modelled fully based on the Port of Rotterdam location, with no additional transport of CO_2 or synthesised fuels. The consideration of methane production even allows the closing of the fuel cycle in the project by substituting fossil-based LNG supply for the two ships. For methanol, substitution of conventional methanol production processes is considered to compare the climate change impacts. The utilization modelling is largely taken from Charalambous et al. [8] who recently focused on an analysis of on-board carbon capture with utilization with circular fuel combustion and synthesis, and published a detailed inventory of their system [9].

2.2.2 Functional Unit

Considering the different functions of the two ships, individual functional units, to which all environmental impacts are assigned, are defined.

When refuelling 8-10 times a year, the Sleipnir on average returns to port every 6 weeks, thus an average '6-week operational profile' including sailing, idle times and crane operation, starting and ending at the Port of Rotterdam, The Netherlands, is determined to be the functional unit for the Sleipnir case. While not considered in this study, more flexibility on the frequency and location of offloading could be achieved when offloading the CO_2 offshore.

In this study, the LNG carrier is assessed for a specific delivery route, from Port Arthur, in the U.S. Gulf Coast, to the Port of Rotterdam, including the ballast trip back with 5% heel still in the tank as well as idle waiting and port times. Overall, 16.45 days are assumed for one trip. The functional unit of this case is set to 'one metric ton of LNG delivered' to Rotterdam, with a total tank capacity of 170000 m^3 LNG and 5% heel.

2.2.3 System Boundaries

For the LCA, the system is modelled to quantify the potential impacts on the environment, caused by interactions between the Technosphere and the Ecosphere, such as resource use for construction or emissions to air from fuel combustion. The Technosphere system is framed in the system boundary, including, or excluding, specific parts of the system in accordance with the goal of the study.

2.2.3.1 Process Chains

The whole life cycle of a SBCC system from so-called cradle-to-grave considers the operation of the ship, the capture and handling of CO_2, either by final geological storage or by utilization of the CO_2. The on-board impacts are related to the commonly called Tank-to-Wake (TtW) impacts, while the full life cycle impacts can be similarly interpreted as Well-to-Wake (WtW) impacts, with the notion that also waste treatment and CO_2 pathways are included here.

Figure 2.2-5 shows the processes considered in this study. The upstream systems take into account the fuel and solvent (MEA) supply as well as construction of the SBCC system. Besides regular operation of the ships, additional power and solvent consumption due to the capture unit operation and its End-of-Life (EoL) are considered. Unchanged equipment, related to the original ship, such as construction and EoL of the vessel, are excluded from the system boundaries as these have the same impact with and without SBCC. Offloading of liquefied CO_2 at port as well as subsequent transport and treatment, storage or utilization, complete the process chains. As no primary data for utilization was available the focus of the LCA in this report lies on the geological storage, while utilization (grey boxes) options will only be discussed briefly, using literature data.

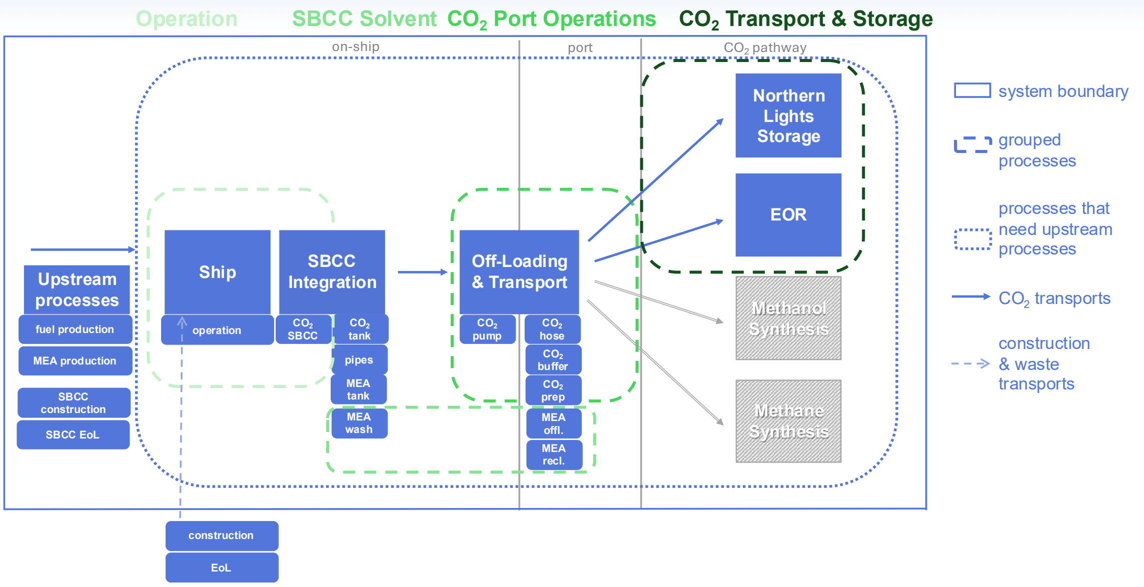

Figure 2.2-5 System boundaries for the entire process chains

2.2.3.2 Upstream Processes

2.2.3.2.1 Fuel Production

The upstream impacts of fuel production in the various countries exporting LNG or petroleum to The Netherlands according to Eurostat [10, 11] are modelled. LNG is liquified at the country of origin and transported via carrier to Rotterdam. For MGO, petroleum imports to Rotterdam and refinery operation at port are considered. The upstream fuel stage ends with bunkering the respective fuels to the ship tanks. Additionally, for the case study of the LNG carrier, LNG and MGO is sourced in the U.S. for the delivery route.

2.2.3.2.2 MEA Production and Handling

The production of a 30% monoethanolamine (MEA) solvent is considered. During capture operation, some of the solvent degrades. Spent solvent is offloaded and reclaimed at port after each trip and the ship is supplied with reclaimed solvent for the next trip, filling up losses by new, fresh MEA solvent.

2.2.3.2.3 SBCC Construction

All SBCC equipment parts, such as pipes, CO_2, and MEA tanks are included. The detailed designs of the capture systems are provided by the project partners in WP3 (see Deliverables there). Upstream process chains for the materials used for the equipment are included in the construction stage as well.

2.2.3.2.4 SBCC EoL

The effort for disposal of the SBCC system are modelled assuming that the same amount of material being used for construction must be discarded or can be recycled (e.g., in case of steel).

2.2.3.3 Ship Operation and Capture

In this section, the regular operation to fulfil the ship's functions defined are considered. Emissions due to burning the fuels are assessed. Additional emissions caused by running the SBCC unit result from increased heat and power demands during SBCC operation. The increased power demand represents the fully integrated design and is considered to linearly decrease with the ship's load.

Operability concerns like e.g. efforts for training a dedicated person or crew training to operate the system are not considered here but generally need to be taken into consideration.

2.2.3.4 CO_2 Port Operations

From intermediate storage on-board, the captured and liquefied CO_2 is pumped though a flexible hose connection to intermediate storage at shore. Minor processing steps are required to ready the CO_2 for further transport in a CO_2 export system.

2.2.3.5 CO_2 Transport & Storage

From the intermediate storage at the Port of Rotterdam, the CO_2 is transported to the site for geological storage at Northern Lights via ship and pipeline. For Port Arthur, only enhanced oil recovery (EOR) is considered as the CO_2 storage option based on its strong prevalence in the region, with the CO_2 being transported via pipeline. Emissions for both construction of the storage facilities as well as for transporting the CO_2 are quantified for this stage.

2.2.3.6 Utilization

Two utilization options are considered. Using hydrogen from a wind-powered electrolyzer, the offloaded CO_2 is synthesized into either methanol (MeOH) or methane, adapting the system model described by Charalambous et al. [8, 9]. The synthesized methane is further liquefied to LNG, such that it can replace some of the LNG which could be burned as fuel. All utilization related activities are modelled based on the Port of Rotterdam as the operation site of the electrolyzer, synthesis and fuel use, meaning no additional transport to operation sites is considered. The boundaries of utilization considerations include an additional function, namely the produced fuels. This is handled using the substitution approach, where equivalent products from conventional sources are deemed replaced by the produced fuels, counted as a negative impact for the SBCC system.

The burning of the produced fuels is not accounted for in the system, which would re-release the bound carbon back to the atmosphere. This happens at a very short time scale, especially compared to underground storage. A circular approach, using the e-fuels again in systems with carbon capture, could to some extent attenuate this effect.

2.2.4 LCI Modelling Framework

The LCI is the result of modelling the foreground systems investigated in detail by translating design parameters provided by the project partners, such as power demand and construction components, into fuel combustion or system construction processes. Each process is a collection of interactions with the environment, either resources used, or emissions released. Additionally, inputs from the database for so-called background processes, e.g., steel for constructing the capture unit, are integrated into the LCA system modelling. As a combination of all involved processes, the resulting LCI builds the foundation for the following impact assessment. The foreground LCI is based on the full-scale modelling of the SBCC system construction and operation today as performed within the EverLoNG project. Prototype operation measurement data from the project forms the basis for modelling solvent and capture performance of the full-scale system.

The modelling follows the attributional approach, where the system construction and operation are modelled from existing supply chains and market average data. Data which are not directly provided by project partners are taken from the ecoinvent 3.9.1 [12] cutoff database as implemented in the Brightway2 software [13] and its graphical interface, the Activity Browser [14].

2.2.4.1 Representativeness of LCI Data

2.2.4.1.1 Technological Representativeness

The implemented SBCC designs, and CO_2 pathways are closely matched to the investigated ships and their regular operation. Changing the investigated pathways, for e.g. CO_2 transport distances, could significantly impact the results. The technologies assessed in this report are designed based on currently available components, such as pumps, compressors, and storage tanks. Manufacturing of such components is therefore based on available inventories in ecoinvent, current market averages for the required material components, and manufacturing processes. Material requirements are estimated from design parameters whenever possible, otherwise from scaling analogous components available in background databases.

2.2.4.1.2 Geographical Representativeness

The production, use, and EoL of the analysed systems is centred around the Port of Rotterdam, The Netherlands, and in a broader context Europe. Supply of manufactured components, fuel, and solvent are matched to these geographies where available. This implies using the fuel supply mix of LNG and petroleum to the Netherlands for the Sleipnir and using the refineries located at the Port of Rotterdam for MGO production. The geographical scope is expanded to include the Port Arthur area in the LNG carrier case for LNG cargo and the CO_2 pathway.

Technologies for, e.g., solvent and fuel production are chosen from background databases for the established countries of origin or closely matched proxies.

2.2.4.1.3 Temporal Representativeness

The study is set in the current timeframe, with full-scale systems starting to be built in the coming years. Thus, background data is used for the recent years, referring where possible explicitly to the year 2021, e.g., for the Dutch LNG and petroleum supply mixes. This recent supply data is likely to change over the estimated lifetime of the system of 25 years, however, prospective effects are not included in the assessment.

2.2.5 Impact Assessment Approach

The impact assessment builds on two pillars: The carbon capture system's direct effect on CO_2 emissions is quantified and complemented by the Life Cycle Impact Assessment Methods, quantifying the potential impacts on the environment.

2.2.5.1 CO_2 reduction

The capture system has multiple effects on the CO_2 emissions associated with the ship operation and the capture unit operation. While the CO_2 emissions of the benchmark ship operation (CO_2^{BM}) are in part captured and stored on-board ($CO_2^{capt:BM}$), some additional emissions (CO_2^{add}) from additional fuel consumption are produced. Of these additional emissions some CO_2 can be captured again ($CO_2^{capt:add}$). Therefore, the total amount of CO_2 produced is more than what was initially emitted by the ship, and the total amount of CO_2 captured is more than the CO_2 captured from the benchmark ship operation.

For quantifying the reduction effect on the CO_2 emissions, these relations are considered in the CO_2 reduction, where the reduced, also called avoided, CO_2 in relation to the original benchmark emissions is quantified:

$$\mathrm{CO_2\ reduction} = \frac{\mathrm{CO_2^{capt:BM}} - \mathrm{CO_2^{add}} + \mathrm{CO_2^{capt:add}}}{\mathrm{CO_2^{BM}}}$$

For systems including not only the direct on-board emissions but also, e.g., upstream fuel production emissions, both the benchmark and additional CO_2 emissions include associated CO_2 emissions of the fuel production processes, while the captured amounts stay unchanged. Therefore, the CO_2 reduction that can be reached is strongly reduced with expanded system boundaries beyond direct on-board emissions.

2.2.5.2 Life Cyle Impact Assessment Approach

Focusing on the project's European context and impacts, the European Commission's recommended method Environmental Footprint EF3.1 [15] for products and organisations is used to evaluate potential environmental impacts. The impact assessment is performed using the implementation of the EF3.1 method in the Brightway2 software [13]. First of all, the focus of the assessment lies on climate change impacts, in line with the targets set in the EverLoNG project. EF3.1 is based on the most recent IPCC AR6 [16]. The climate impacts are obtained using the 100-year timeframe global warming potential of the various GHG emissions to air, mainly determined by CO_2 and methane in this study, with an impact factor of 30 kg $CO_{2\text{-}Eq}$ /kg methane, as defined by the IPCC [16]. Additionally, a comprehensive approach to avoid burden shifting to other environmental impacts is taken, hence including multiple impact categories alongside climate impacts, depicted in Table 2.2-1.

Table 2.2-1. EF3.1 impact categories considered [4]

Impact categories considered	Indicator	Unit
Climate change	Radiative forcing as global warming potential – GWP100	kg CO_2 eq.
Acidification	Accumulated Exceedance – AE	mol H+ eq
Particulate matter	Impact on human health	disease incidence
Eutrophication, marine	Fraction of nutrients reaching marine end compartment	kg N eq.
Eutrophication, terrestrial	Accumulated Exceedance – AE	mol N eq.
Photochemical ozone formation	Tropospheric ozone concentration increase	kg NMVOC eq.
Human toxicity, non-cancer	Comparative Toxic Unit for humans	CTUh
Ecotoxicity, freshwater	Comparative Toxic Unit for ecosystems	CTUe
Resource use, fossils	Abiotic resource depletion, fossil fuels – ADP-fossil	MJ
Resource use, minerals and metals	Abiotic resource depletion – ADP ultimate reserves	kg Sb eq.

As absolute values for the different impact categories are often difficult to interpret and additionally to allow the comparison of different environmental impacts having different units, the ISO standards support the optional step of normalization. During normalization, values of each impact category are set in relation to the same impact induced by an average person per year, thus providing information on the magnitude of impacts. The results of the normalization step are expressed in person equivalents PE. Within the EF3.1 methodology, normalising factors (NF) for each impact category are presented [4] (see also Table A.1-1). They are used in this study to show the relative environmental impacts compared to the reference case and at the same time allowing a comparison to the climate change impact.

3 Life Cycle Inventory Assessment

This section describes data collection for the specific segments of the life cycle and the modelling of its components in detail. In summary, selected LCI results are presented, in the form of environmental flows between the Technosphere and the Ecosphere, and sources of uncertainty are collected for the modelled inventory.

3.1 Data Collection

The data for the different life cycle stages were collected from project partners, literature, and ecoinvent as an LCA background database. Modelling of the ship operation was based on design and operational profile data from project partners TotalEnergies and Heerema. The design of the capture system and operation was performed within WP3 of the EverLoNG project, providing detailed construction and operation data to the LCA model. In addition, WP1 provided valuable verification information on the assumptions around operation performance. The cases for CO_2 handling and pathway design were chosen in close collaboration with WP2, which also provided detailed models of the port operations for CO_2 and solvent handling.

The technical design models from the project partners were adopted to the LCA logic and completed with additional data for upstream processes like, e.g., fuel or steel supply, using the ecoinvent 3.9.1 background database in combination with literature data for storage and utilization to represent the full life cycle.

3.2 System Modelling Per Life Cycle Stage

3.2.1 Fuel Supply

The shipping fuels used for the analysed vessels are LNG and MGO. The emissions for the fuels supply depend on various variables, including the fuel origin or origin mix and transportation distance, processing facilities, and technologies used in the different steps. This leads to a range of resulting emissions for both LNG and MGO, a collection of which can be found in the guidelines by MEPC [17], concerning the respective upstream GHG emissions. One quite recent report is Sphera's GHG study 2021, where the WtT GHG emissions of the LNG supply range from 17.1 – 19.1 g $CO_{2\text{-}Eq}$/MJ (LHV) [18].

Fuel origins for fueling in Rotterdam have been modelled to reflect the Dutch imports of 2021, including proxy descriptions of countries of origin not included in the ecoinvent 3.9.1 database. The MGO production chain is modelled as light fuel oil produced in refineries at port (process: petroleum refinery operation) and the LNG is liquefied in the countries of origin following the LNG import modelling in ecoinvent (process: natural gas, liquefied, import from …). For the LNG carrier, U.S.-based production and no transport is considered for both fuel types. A more detailed description of the assumptions and modelling can be found in Appendix A.2.

3.2.2 Fuel Combustion and Operational Emissions

The operational emissions are highly dependent on engine power and fuel consumption during combustion. Most emission factors (Ef) are sourced from the 2020 IMO study [19] and in part from the ship owner emission measurements, specifically for the Sleipnir. The emissions are either defined based on direct fuel consumption (g emission per g fuel combusted) or based on energy given via the engine load (g emission per kWh of the engine). A third option arises where fuel-based emissions vary depending on the engine load. To estimate the emissions during operation, the fuel consumption as well as engine type and load factors are determined from engine specifications and the operational profile, as shown in Appendix A.3.1.

Some LNG fuel consumptions are given with respect to the ISO standard MGO LHV, and the specific fuel oil consumption is therefore calculated back to LNG as a basis using the LHVs given in Table A.3-1. Fuel oil consumption also includes MGO pilot fuel. This contribution is therefore calculated separately.

The Sleipnir runs a 4-stroke engine falling under the LNG-Otto MS category in the IMO 2020 report [19] engine classification. For this engine no pilot fuel is included in the IMO considerations, the pilot fuel consumption of the Sleipnir is however considered according to the provided engine test data from Heerema. The minor contribution of MGO emissions of this engine from burning pilot fuel is approximated via the medium-speed diesel engine emissions, applicable to manly oil-fueled engines.

The emissions of the LNG carrier are quantified for all three engine types: main engines (ME), auxiliary engines (AUX) and the gas combustion unit (GCU). Classified in the IMO report as LNG-Diesel, LNG-AUX and Boiler.

3.2.3 Benchmark Operation

For both vessels, the emissions are determined based on the measured operational profile, giving the engine load over time for each of the considered engines. The fuel consumption is determined according to the engines' respective specific fuel consumptions combined with the power demand described in the operational profiles. The energy-based emissions are determined, while the fuel-based emissions are determined from the resulting fuel consumptions of MGO, LNG and Pilot MGO fuels. The measured operational profiles reflect the different operation modes very well, over a timeframe of roughly two years of operation: shipping, idle time and crane operation in case of the Sleipnir as well as laden and ballast trips for the LNG carrier.

3.2.3.1 Sleipnir

The Sleipnir operates 12 medium speed dual-fuel engines, each of them either running in gas mode (LNG + pilot MGO) or in diesel mode (MGO). The operational profile gives the power for each engine and operation mode every 10 minutes for the two-year timespan. All engines operate at relatively low loads most of the time, as they are often used for maintaining stability. The resulting emissions of the operation are divided by main fuel, LNG and MGO. The maximum continuous rating (MCR) of the engines is given as 8020 kW and 8009 kW, when operating on LNG and MGO, respectively.

The total fuel consumptions and the determined emissions for 6 weeks of all engines operating according to the two-year operational profile are collected in Table 3.2-1 and Table 3.2-2.

Table 3.2-1. Sleipnir benchmark emissions for 6-weeks operation

	Amount [t]		
Emission	**LNG operation**	**MGO operation**	**total**
CO_2	2043	3105	5148
CH_4	46.98	0.05	47.02
NOx	10.88	85.46	96.34
SOx	0.05	1.33	1.38
NMVOC	5.22	4.86	10.08
N_2O	0.08	0.14	0.23
PM10	0.10	0.82	0.92
PM2.5	0.10	0.75	0.85
CO	5.26	0.22	5.47

Table 3.2-2. Sleipnir benchmark fuel consumption for 6-weeks operation

Fuel consumption	Amount [t]
LNG	761.6
Pilot	28.3
MGO	973.2

3.2.3.2 LNG carrier

The LNG carrier is considered as a new-built design to accommodate SBCC in a more optimal way. This includes more freedom in placing the CO_2 tanks as well as choosing an optimal engine configuration. The measured power demand of the operational profile is supplied via the chosen configuration of two slow-speed ME-GI Low-Pressure Selective Catalytic Reduction (LPSCR) main engines and 4 auxiliary engines, two 6- and two 8-cylinder engines. The main engines have a MCR of 12.6 MW while the auxiliary engines supply a maximum of 2.9 MW and 3.8 MW, respectively. The LNG carrier is fuelled by burning its LNG cargo and MGO as pilot fuel, the emissions are therefore not divided by fuel type, but by engine type: main engine (ME) and auxiliary engine (AUX). The resulting emissions and fuel consumption for a one-way trip Port Arthur-Rotterdam, totalling to 16.45 days sailing and idle time, are collected in Table 3.2-3 and Table 3.2-4.

Table 3.2-3. LNG carrier benchmark emissions per round trip

	Amount [t]			
Emission	**ME operation**	**AUX operation**	**GCU operation**	**total**
CO_2	3026	1470	232	4728
CH_4	1.98	12.92	0.01	14.91
NO_x	27.40	5.56	0.39	33.34
SO_x	0.06	0.02	0.00	0.09
NMVOC	3.30	1.57	0.03	4.90
N_2O	0.24	0.06	0.01	0.31
PM_{10}	0.12	0.07	0.01	0.20
$PM_{2.5}$	0.11	0.07	0.01	0.18
CO	8.26	5.35	0.06	13.67

Table 3.2-4. LNG carrier benchmark fuel consumption

	Amount [t]			
Fuel consumption	**ME operation**	**AUX operation**	**GCU operation**	**total**
LNG	1064	537	84	1685
Pilot	33	10	-	43

3.2.4 SBCC Operation

The operation of the capture system is determined by the amount of CO_2 in the flue gas flowing to the capture unit and the amount of it that is captured. This determines the heat and electricity demand of the capture system and with the variability of the flue gas flow comes one of the most striking differences to land-based systems. On-board a ship, excess heat in the exhaust gas can be used for the capture system. The design and required additional heat are determined in WP3 (see deliverables there) and applied on the complete operational profiles. The application differs for the Sleipnir and the LNG carrier due to their differing engine setups and operational profiles. Solvent performance, degradation and emissions are estimated based on the prototype measurements on the vessels during the EverLoNG project. During liquefaction of captured CO_2 some is vented to the atmosphere. A recirculation design brings this value down to 0.5% of the CO_2 that is being processed.

3.2.4.1 SBCC System Overview

The SBCC System consists of CO_2 capture and liquefaction parts. In a first step, before entering the capture process, the flue gas is cooled in a quench. There, an addition of about 10g NaOH for LNG (20g LNG carrier) and 73g NaOH for MGO per ton CO_2 captured also removes SOx (99%) from the flue gas. The drainage is collected and sent to hazardous waste treatment. In the following absorber column, flue gas and MEA solvent are brought into contact, and CO_2 is captured in the solvent. The CO_2-rich solvent is heated in a stripper, separating it again from the CO_2 and the resulting CO_2-lean solvent is circulated back into the absorber. The CO_2 is then dried and cooled in the liquefaction unit, to be stored in liquefied form in the storage tanks on-board the ships. The electricity use of the capture system is split up by about 21% capture, 71% liquefaction and 8% other pumping activities.

The gaseous outflow from the absorber also carries out amine and ammonia from MEA solvent degradation. Such elements could potentially be removed in an acid wash, with a small additional electricity and sulfuric acid consumption. Effective removal of 99% for both emissions would be expected.

3.2.4.1.1 Sleipnir

The power demand for the capture operation on the Sleipnir is assumed to be shared equally between all engines, by increasing the power by 6.6% for LNG operation 7.9% for MGO operation, while the ship operates between 4.5 MW and 15MW cumulative load of all engines combined. At higher cumulative loads, a share of the emissions corresponding to maximum operation of the capture system are captured, while at lower cumulative loads, the capture system is not operating. The additional emissions from the SBCC operation are determined by the difference to the benchmark operation emissions. All available heat is used for the capture operation, thus only additional power consumption in the engines and no additional boiler is considered. When running on LNG, capturing on the additional emissions caused by the SBCC operation is modelled as several loops and included in the initial power demand by WP3 (see deliverables there). The capture rate for LNG is designed to be 95%, for MGO 77.45%, but with no heat available for capture loops. The resulting emissions and fuel consumptions for the complete system of ship operation and SBCC unit are collected in Table 3.2-5 and Table 3.2-6, respectively. These emissions do not consider effects of the capture system itself, such as reduced CO_2 emissions via capture or reduced SOx emissions after the quench.

Table 3.2-5. Sleipnir SBCC emissions for 6-weeks operation

	Amount [t]		
Emission	**LNG operation**	**MGO operation**	**total**
CO_2	2144	3300	5444
CH_4	48.19	0.05	48.24
NOx	11.26	80.42	91.68
SOx	0.05	1.42	1.47
NMVOC	5.35	4.99	10.34
N_2O	0.09	0.15	0.24
PM10	0.11	0.88	0.99
PM2.5	0.10	0.81	0.91
CO	5.56	0.23	5.79

Table 3.2-6. Sleipnir SBCC fuel consumption for 6-weeks operation

Fuel consumption	Amount [t]
LNG	800.1
Pilot	28.3
MGO	1034.3

The additional emissions and fuel consumption because of the capture system result as the difference of the SBCC and the benchmark systems, shown in Table 3.2-7 and Table 3.2-8, respectively. The emissions of, e.g., NOx decrease for MGO operation, as the additional power needed for the capture operation sets the engines to operate at a more favourable load point leading to a slight reduction in NOx emissions. This effect is solely related to the low-load operation of the Sleipnir, where predominantly MGO operation mode is running.

Table 3.2-7. Additional Sleipnir SBCC emissions for 6-weeks operation

	Amount [t]		
Emission	**LNG operation**	**MGO operation**	**total**
CO_2	101	195	296
CH_4	1.21	0.00	1.22
NOx	0.37	-5.04	-4.66
SOx	0.00	0.08	0.08
NMVOC	0.13	0.13	0.26
N_2O	0.00	0.01	0.01
PM10	0.01	0.06	0.06
PM2.5	0.00	0.05	0.06
CO	0.30	0.01	0.32

Table 3.2-8. Additional Sleipnir SBCC fuel consumption for 6-weeks operation

Fuel consumption	Amount [t]
LNG	38.5
Pilot	0.0
MGO	61.1

3.2.4.1.2 LNG carrier

On the LNG carrier, electricity is provided by the auxiliary engines, while the main engines only propel the ship. During operation, the 4 available auxiliary engines share the required power in such a way, that they run in most optimal load points. Therefore, the electricity for the capture operation is assumed to be provided by an auxiliary engine, denoted as SBCC Power. A conservative assumption reflecting an optimized procedure is assuming constant operation at 50% load. In addition to the electricity, the capture unit requires heat, supplied by an auxiliary LNG boiler with an assumed efficiency of 90%, denoted by SBCC Heat. One capture loop on the additional emissions produced from the capture operation is considered, further additional emissions are considered to be vented to the atmosphere.

The design capacity of the capture unit is set to 8000kg CO_2 per hour, while the minimum operation reached down to a CO_2 flow per hours of 2000kg, with a nominal capture rate of 90%. Operating the SBCC unit for the LNG delivery round trip results in the additional emissions from auxiliary engine (power) and boiler (heat) given in Table 3.2-9 and the related additional fuel consumption in Table 3.2-10.

Table 3.2-9. Additional LNG carrier SBCC emissions per round trip

	Amount [t]		
Emission	**SBCC Power**	**SBCC Heat**	**total**
CO_2	367	335	701
CH_4	3.03	0.02	3.04
NOx	1.39	0.56	1.95
SOx	0.01	0.00	0.01
NMVOC	0.38	0.04	0.43
N_2O	0.02	0.01	0.02
PM10	0.02	0.01	0.03
PM2.5	0.02	0.01	0.03
CO	1.23	0.09	1.32

Table 3.2-10. Additional LNG carrier fuel consumption per round trip

Fuel consumption	SBCC Power [t]	SBCC Heat [t]
LNG	133.9	121.7
Pilot	2.5	0.00

3.2.4.1.3 Fuel consumption to LNG delivery (LNG carrier)

The LNG carrier uses its cargo as fuel as well, such that using more fuel for the same trip impacts the amount of LNG that can be delivered. All round-trip fuel consumption is used to determine what fuel is left to be delivered, considering a 5% heel share of the cargo volume and a density of 450kg/m³ LNG in the 170,000m³ cargo tank. The resulting cargo capacity, LNG delivered for the benchmark operation and LNG delivered for the SBCC operation are collected in Table 3.2-11.

The functional unit for the LNG carrier case is determined by the amount of 1 metric ton LNG delivered, thus all round-trip emissions, materials and CO_2 amounts are scaled by dividing with 70990 for the benchmark case and 70734 for the SBCC case, as indicated in bold in Table 3.2-11.

Table 3.2-11. LNG carrier cargo capacity and LNG delivery

LNG cargo capacity	Benchmark LNG delivered	SBCC LNG delivered
170,000 m³	157,755 m³	157,187 m³
72.68 net kt	**70.990 kt**	**70.734 kt**

3.2.4.2 *CO_2 captured*

The amount of CO_2 captured during operation is determined from the amount of CO_2 that is processed by the benchmark systems, based on their operational profiles, combined with the capture rate to apply. In addition, for LNG operation the additional emissions from the capture unit can be treated in the capture unit. For the Sleipnir LNG case, additional heat is available, and the electricity demand is included in the power increase for the capture operation. For the LNG carrier case, extra operation of the heat and power generation is considered, associated emissions of which are vented to the atmosphere as normal flue gas. The captured CO_2 is liquefied, where 0.5% of the captured CO_2 are released back into the atmosphere and the rest is stored on-board. Any CO_2 that is produced but not stored on the vessel is emitted to the atmosphere.

3.2.4.2.1 Sleipnir

The Sleipnir SBCC system captures CO_2 at a capture rate of 95% in LNG mode and 77.5% in MGO mode. Also, for the additional emissions in LNG mode, 95% are captured while none are captured in the MGO mode, as no additional heat is available. Table 3.2-12 summarizes the CO_2 capture operation, resulting in 4.01kt CO_2 to be offloaded and sent to storage or utilization.

Table 3.2-12. Sleipnir SBCC CO_2 capture for 6-weeks operation

System	CO_2 produced [kt]	CO_2 captured [kt]	CO_2 stored [kt]
From Benchmark	5.15	3.93	3.91
LNG	*2.04*	*1.77*	*1.78*
MGO	*3.10*	*2.16*	*2.15*
SBCC add. emissions	0.30	0.10	0.10
LNG	*0.10*	*0.10*	*0.10*
MGO	*0.20*	*0.00*	*0.00*
Total SBCC	**5.44**	**4.03**	**4.01**

3.2.4.2.2 LNG carrier

The LNG carrier SBCC system operates with a capture rate of 90% on any flue gas it is supposed to treat. The operation of the ship with SBCC system, scaled to the functional unit of 1 ton LNG delivered, is summarized in Table 3.2-13. Per functional unit, 64.46kg CO_2 need to be stored, amounting to an offloading volume of 4.6kt per round trip and 2.3kt at each port.

Table 3.2-13. LNG carrier SBCC CO_2 capture per ton LNG delivered

System	CO_2 produced [kg]	CO_2 captured [kg]	CO_2 stored [kg]
From Benchmark	66.84	57.72	57.44
ME	*42.78*	*36.95*	*36.76*
AUX	*20.77*	*17.94*	*17.85*
GCU	*3.28*	*2.84*	*2.82*
SBCC add. emissions	9.92	7.06	7.02
SBCC Power	*5.18*	*3.69*	*3.67*
SBCC Heat	*4.73*	*3.37*	*3.35*
Total SBCC	**76.76**	**64.78**	**64.46**

3.2.5 SBCC Construction

The construction of the capture system is based on the detailed designs provided by the project partners in WP3 (see deliverables there), including construction of the capture unit, piping, storage tanks and overall equipment integration on-board the ships. Major contributors are the CO_2 storage tanks of the liquefaction section for carbon steel and the columns and vessels of the capture section for stainless steel, summarized in Table 3.2-14. The dimensioning of the tanks depends on the operation case, such that for the Sleipnir the tanks are sized much larger than for the LNG carrier. The tanks are insulated with polyurethan insulation and aluminium cladding.

Integrating the system on-board needs additional steel construction, which for the Sleipnir retrofit includes extending the deck. With more flexibility of a new-built consideration for the LNG carrier less steel is needed for integration.

Table 3.2-14. Summary of capture unit construction and integration demands for stainless and carbon steel

Section	Stainless Steel [t]		Carbon Steel [t]		Compressors and Pumps [t]		total weight* [t]	
Ship	Sleipnir	LNG Carrier	Sleipnir	LNG Carrier	Sleipnir	LNG Carrier	Sleipnir	LNG Carrier
Capture section	161	149	2		5		168	156
Liquefaction section	5		1330	860	50	49	1455	974
Integration	56		1749	175			1805	231
System and integration	222	210	3081	1037	55	54	3428	1361

*incl. 70t insulation and cladding of the CO_2 tanks

No energy consumption for construction or dismantling of the capture system itself is included in the modelling.

3.2.6 SBCC EoL

The EoL modelling includes waste treatment or sending steel to recycling. The effects of disassembly and transport are negligible when looking at the functional unit of ship and capture unit operation. The same amounts of materials are treated for EoL as are used for construction. The main processes used are "iron scrap, unsorted, Recycled Content cut-off" for steel, "market for waste polyurethane foam" for insulation. Due to the cut-off approach, sending off steel waste to recycling does not introduce new impacts.

3.2.7 SBCC Solvent and Reclamation

The MEA in the solvent inventory degrades during the capture operation, such that at a certain share of degraded solvent, the full inventory is sent to reclamation at port. Per ton CO_2 captured, an amount of 1.5kg MEA is deactivated, to be sent to reclamation. Of this, 95% can be reclaimed and used again in the inventory, while 5% is sent to hazardous waste incineration. For reclamation, the spent solvent must be heated, using an electric boiler to evaporate both the MEA and water. The addition of caustic sodium hydroxide neutralizes heat stable salts, for removal as sodium salts in the reclaimer, using 0.1t per 30m³ spent solvent.

The main inputs to the solvent reclamation plant are electricity and heat from electric reboilers, amounting to 19MWh of electricity. In addition, fresh MEA is restocked by the process "ethanolamine production" at 2.6t to arrive back at a full inventory of 30 wt.% MEA solvent. Expected emissions of 0.9t of CO_2 to air from residual CO_2 in the solvent are included as well.

In addition, losses due to emissions of MEA and ammonia to air during the capture operation are considered and restocked with fresh solvent at the reclamation facility. Thus, the amount of fresh solvent is given as the sum of the lost MEA and the MEA-equivalent of lost ammonia based on their respective molar masses. The emission rates per ton CO_2 processed are collected in Table 3.2-15 for the Sleipnir LNG and MGO operation and the LNG carrier. The differences between LNG and MGO stem from the varying concentrations of CO_2 in the flue gas for the fuels. Variations between the LNG case on the ships are below the rounding accuracy chosen here. This results in emissions for a full trip of 0.6t ammonia and 0.1t MEA to air during LNG and MGO operation, respectively. In addition, activated silica production of 2 (1) kg is needed for the dryer for MGO (LNG) operation. The carrier trip lies in the same order of magnitude, with 0.7t ammonia, 0.1t MEA to air and activated silica production of 1kg.

Table 3.2-15. Summary of on-board SBCC solvent emissions per ton CO_2 processed

Emission [kg/ton CO_2 processed]	**Solvent Operation**		
Ship	Sleipnir MGO	Sleipnir LNG	LNG Carrier
MEA emissions	0.04	0.06	
Ammonia emissions	0.2	0.3	

3.2.8 CO_2 Port Operations

The port operations concerning CO_2 handling are split into the CO_2 receiving facility, where intermediate storage, conditioning, and exporting is carried out. A boil-off-gas (BOG) handling facility is included to reliquefy boiled-off CO_2 and keep the CO_2 handling equipment cool in between shipments. This system may not be necessary if there is a higher frequency of ships coming in and offloading CO_2 and the onshore facility can be operated continuously. In our cases however, the frequency of ships coming in is every 4 to 6 weeks. The port side designs are all based on the models from WP2 and NexantECA, starting with the offloading of CO_2 and spent solvent and ending with transport of CO_2 to either enhanced oil recovery or sequestration, with reconstituted solvent returned to the vessel. Construction of the port facilities is dominated by the intermediate storage tanks, using 4 kt of carbon steel, 16 t of aluminium and 40 t of polyurethane foam insulation.

Operation of the port facilities is summarised to use 0.02 kWh per kg CO_2 handled, 0.2 g of cooling water and 0.2 g of liquid nitrogen is vented from the cooling circle.

3.2.9 CO_2 Transport and Storage

For the base analysis with focus on the effects of the capture system, the CO_2 is assumed to go to storage in the Northern Lights project in the European North Sea (see deliverables of WP2). For Northern Lights storage, a recently published LCA report [20] estimates a $CO_{2\text{-}Eq}$ penalty of 2.6% per tonne CO_2 stored assuming 5Mt per year stored from various sources. Fugitive emissions are given as 0.076% of stored CO_2 during transport and handling. The transport strongly dominates the emissions at a share of 91%. The transport stage is split up into 91% operation (87%-pts ship fuel consumption, 4%-pts methane slip and purging) and the remaining 9% construction and EoL of the ships. For this study, a larger transport distance by CO_2-ship of 964 km [21] instead of 700km from Rotterdam to the receiving terminal in Øygarden, Norway is adapted. Accounting for the fugitive emissions during handling of the CO_2 leads to an adjusted total $CO_{2\text{-}Eq}$ penalty of 3.4% per tonne CO_2 sent on the storage pathway, with a transport share of 93.14%. Only $CO_{2\text{-}Eq}$ emissions are implemented for this base case, keeping consistency with the detailed GHG report available [20] and ensuring comparability between the performance of Sleipnir and LNG carrier application of on-board carbon capture.

The storage scenario for the LNG carrier on the US side is enhanced oil recovery (EOR) as potential storage option. Using EOR to store CO_2 has been modelled following [22, 23], assuming the oil produced in the EOR process substitutes the conventional production of crude oil. Large variations in the GHG emissions associated with operating the EOR site as well as varying net CO_2 use per barrel of oil produced lead to potential emissions of 0.03 to 0.2t CO_2-Eq/t CO_2 sent to EOR. This excludes sites with very low use and storage of CO_2 per barrel of oil produced. Due to the large uncertainty in the EOR GHG emissions, the results in this study consider storage-focused EOR operation, with a 3.4% GHG emissions for the EOR pathway. This is the same assumption as for the Northern Lights storage case, improving comparability between the Sleipnir and LNG carrier cases.

3.2.10 Utilization

The demonstration of captured CO_2 utilization was originally planned within EverLoNG, to assess what impact possible ship specific impurities in the exhaust gas can have on utilization processes. Thus, during the test campaigns in WP1 these impurities of the liquefied CO_2 were monitored. However, due to a potentially mistakenly open valve, all the liquified CO_2 on ship was vented, so that no CO_2 was available for utilization and no data for CO_2 quality could be provided.

Therefore, literature data for the two utilization options was considered, adapting the recent work on circular marine fuels from on-board carbon capture presented by Charalambous et al. [8, 9]. While Charalambous et al. included a prospective assessment for fuel production in 2030 and 2050, the adapted model is based on the current state of industry and grid electricity reflected in ecoinvent 3.9.1. The location is set to reflect conditions at the Port of Rotterdam, such that process locations are adapted accordingly where possible. Both e-fuels require hydrogen input, which is supplied via proton exchange membrane electrolysis powered by the electricity process for onshore wind turbines larger than 3 MW. In the prospective setup by Charalambous et al., the remaining production steps are powered from low voltage grid electricity. With the combined setting at port, complete powering from renewable sources is deemed feasible. Thus, two scenarios are defined, one following the original approach with 'Grid & Wind' and the alternative using 'Wind' only.

In the model, the utilization pathways are included after offloading the captured CO_2 and transporting it from the receiving site until the utilization site, assumed at same distance as the export terminal in the storage case. Per kg of CO2 to handle for utilization, 0.72 kg of Methanol or 0.37 kg LNG are synthesized using the major inputs and outputs collected in Table 3.2-16. A full inventory has been made available by Charalambous et al. [8, 9].

Table 3.2-16. Summary of utilization inputs and outputs of LNG production, combined from methanation and liquefaction of the resulting methane, and methanol production

Type	Electrolysis	Methanation	Liquefaction	Methanol production
Product (kg)	Hydrogen	Methane	LNG	Methanol
CO2 (kg)	-	2.72	-	1.38
Hydrogen (kg)	-	0.50	-	0.19
Methane (kg)	-	-	1.00	-
Electricity (kWh)*	52.61	0.39	1.81	0.24

*Electricity production via wind turbine or grid electricity.

As no liquefied CO_2 could be provided CO_2 quality is not known. Monitoring of the test campaigns in WP1, however, have shown that the higher NOx emissions must be expected (see deliverable 2.4.1), which most likely exceed specifications for transport, storage, or utilization. Thus, an additional purification process on-board or at the port would become necessary, which is not considered in the assessments here.

3.3 Sensitivity Analyses

The base case of on-board capture operation is investigated with respect to varying assumptions. Though none of the assumptions are directly related to the capture process itself, it shows the impact of sensible assumptions, like fuel supply or methane slip, which strongly determine the results for the full chain systems.

3.3.1 Fuel Supply

Upstream fuel production is subject to large variability, especially due to venting in the natural gas and petroleum production, leading to a range for potential upstream impacts. As the base case is modelled using the ecoinvent database, the upstream impacts algin with the various import activities for the specific supplying countries considered. Comparing these data to the assumptions given in the FuelEU Maritime regulation (0.6kg $CO_{2\text{-}Eq}$ emissions for MGO WtT and 0.9kg $CO_{2\text{-}Eq}$ emissions for LNG WtT for 1kg of fuel at tank), these assumptions are rather conservative. Thus, the

FuelEU Maritime upstream climate impacts for MGO and LNG are used as more optimistic substitutes.

3.3.2 Methane Slip

As the Sleipnir's 4-stroke engines are prone to high methane slip, especially at its low loads, a discussion on reduction measures has been started. While the base case assumes a quite conservative methane slip, two generic improvement scenarios have been investigated: Choosing around 3% of the fuel to slip, which could be potentially achieved for 4-stroke engines with some additional measures. And as a second scenario, 0.1% of the fuel slipping has been investigated, which is in line with the 2-stroke LNG carrier engine. Even though changing the ship engines is not deemed likely at all, this scenario shows the potential for on-board capture and showcases the significance of methane slip. No additional measured that are needed to achieve such a methane slip are modelled, which could have an effect, e.g., on fuel consumption and heat availability.

3.3.3 100 LNG

The retrofit Sleipnir case includes both LNG and MGO fuel use, based on the real operational profile of the ship. However, with changing fuel prices, the fuel use when sailing is up to flexible change. In addition, the system has been designed to perform better on LNG, as an additional boiler would need to be installed for a higher capture rate on MGO. Thus, a 100 LNG scenario has been investigated, interpreting the power demand given in the operational profile as though it was all provided by the engines running on LNG and Pilot fuel.

3.3.4 CO_2 Venting

During the operation of the liquefaction part of the capture unit, CO_2 needs to be vented. During the design phase, the liquefaction part in the capture system was improved upon by heat integration, such that only a low amount of 0.5% of the captured CO_2 had to be vented to the atmosphere based on recirculation. However, other discussed approaches included venting rates of up to 10%. The effects of these rates on the overall system performance are investigated.

3.3.5 Shore power

For the Sleipnir, there is a possibility to connect the ship to shore power instead of running the engines to supply power when in the Caland Canal and operating below 8MW cumulative load. This could be beneficial considering the absolute emissions, especially when using renewable electricity. If low load operation was replaced specifically, a positive effect on methane slip could be expected. However, it would also alter the operational profile for the on-board carbon capture. Thus, the effect of replacing some of the power in the operational profile with shore power is investigated.

4 Life Cycle Impact Assessment

The impact assessment aligns the material and energy inputs and outputs to environmental impacts via the EF3.1 method and their characterisation factors for the various impact categories. For each case study the SBCC system is compared to the related benchmark operation.

First, strong focus is set on CO_2 and GHG emissions and their impact category climate change (CC), relating to both on-board (TtW) and full life cycle (WtW plus CO_2 treatment at port, transport and geological storage/utilization) impacts. Additional impact categories investigated are fine particulate matter formation (PM), acidification (AP), marine and terrestrial eutrophication (EP_m, EP_t), photochemical ozone formation, human toxicity non-cancer ($HTP_{non\text{-}can}$) and freshwater ecotoxicity (ETP_f). The impacts on resource use are described in the categories abiotic depletion potential for fossils or for minerals and metals ($ADP_{fossils}$, ADP_{elem}).

4.1 Climate change, CO_2 and Methane

The Global Warming Potential (GWP) calculates the radiative forcing over a 100-year time horizon. It assesses the potential impact of different GHGs on climate change. The list of emissions contributing to this impact is long, though the most frequent emissions related to the maritime sector are CO_2 and methane. This impact category is directly related to the targets set in the EverLoNG project, as one main goal is to reduce CO_2 emissions on-board by >70%, in an effort to reduce climate impacts of the maritime sector. Besides CO_2, the impacts of other climate related emissions, especially methane, are also quantified to show the overall effect on climate impact reduction, rather than focusing only on CO_2.

4.1.1 On-board Analysis (TtW)

The on-board analysis includes the operational aspects, such as emissions generated by burning fuel for the regular function as well as additional burning during the capture operation and degradation emissions from the latter. Thus, this scope covers the maritime sector's TtW analysis scope. The ship benchmark operations show distinct features of the Sleipnir and LNG carrier operational profiles and engine properties, which are directly reflected in the emissions.

First, the CO_2 emissions are shown in Figure 4.1-1 for the Sleipnir and Figure 4.1-2 for the LNG carrier.

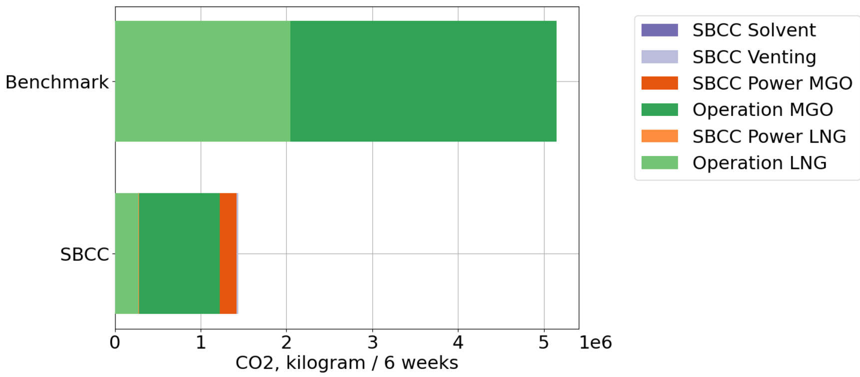

Figure 4.1-1 Sleipnir - On-Board - CO_2 emissions per FU

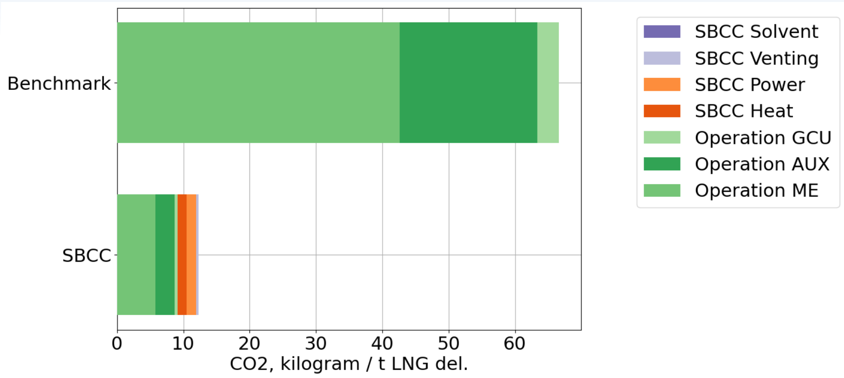

Figure 4.1-2 LNG carrier - On-Board - CO_2 emissions per FU

Running the capture unit reduces the TtW CO_2 emissions by 72% over the complete operational profile for the Sleipnir and 82% for the LNG carrier. This surpasses the goal of >70% on-board CO_2 capture and even reduction set within the project.

Second, the emission and impact results obtained for climate change impacts are assessed and presented in Figure 4.1-3 for the Sleipnir and Figure 4.1-4 for the LNG carrier, respectively. Besides CO_2 emissions specifically methane emissions play a crucial role in LNG fuelled ships.

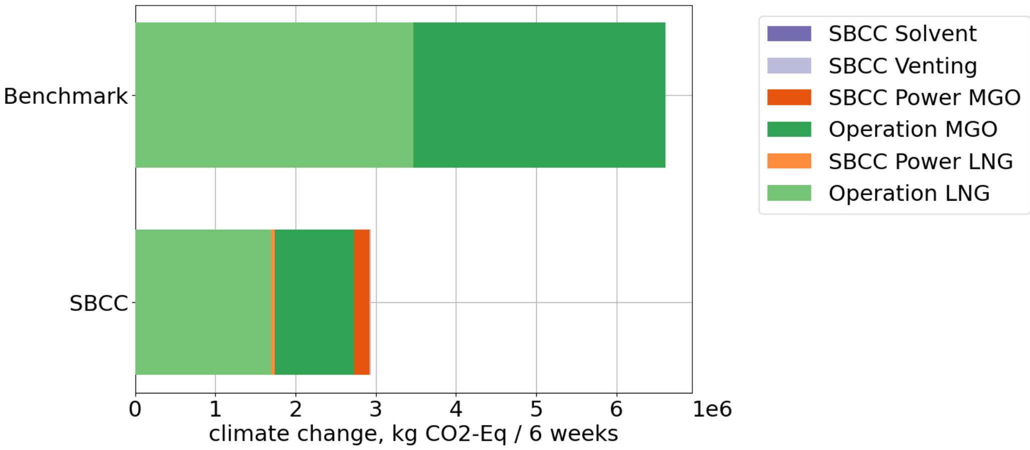

Figure 4.1-3 Sleipnir - On-Board - Climate change impacts (GWP100) per FU

Additional emissions contributing to the climate change impact due to the operation of the SBCC system are only 3.64% of the benchmark impacts for the Sleipnir, which are mainly caused by the electricity production using MGO. This is related to the SBCC system with no additional boiler not being able to capture any additional emissions in MGO mode, while capturing 95% in LNG mode. Additional increase is outside of the on-board scope, within upstream fuel production and downstream CO_2 and solvent handling.

The effects of methane slip, which cannot be reduced by the capture unit but even slightly increases due to the additional fuel burned, are clearly demonstrated when converting it to the $CO_{2\text{-}Eq}$ emissions. The climate change impacts due to on-board (TtW) emissions reduces by 55% for the Sleipnir, as shown in Figure 4.1-3. The low load operation paired with a high methane slip of the 4-stroke engines results in a large, more than 20%, contribution of methane to the overall climate change impacts (see Figure 4.1-5).

For the LNG carrier the climate change impacts TtW reduces by 71% (see Figure 4.1-4). Even though the LNG carrier uses a main engine with very low Methane slip, the overall Methane contribution is still more than 8% for the benchmark and more than 35% for the SBCC case (see Figure 4.1-5), in large parts attributed to the 4-stroke auxiliary engines operating with higher methane slip.

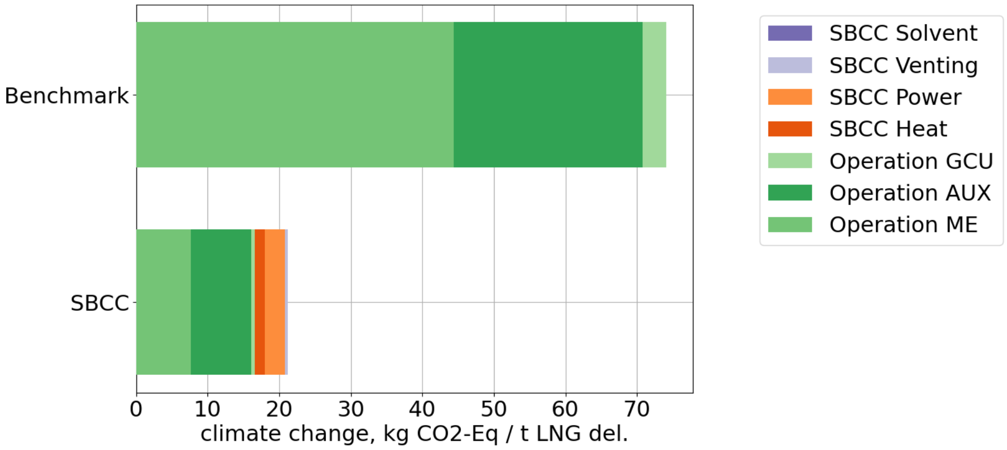

Figure 4.1-4 LNG Carrier - On-Board - Climate change impacts (GWP100) per FU

Additional climate change impacts caused by the capture unit operation contributes with 22% to the overall on-board capture case, amounting to 6% of the original benchmark impacts of the LNG carrier.

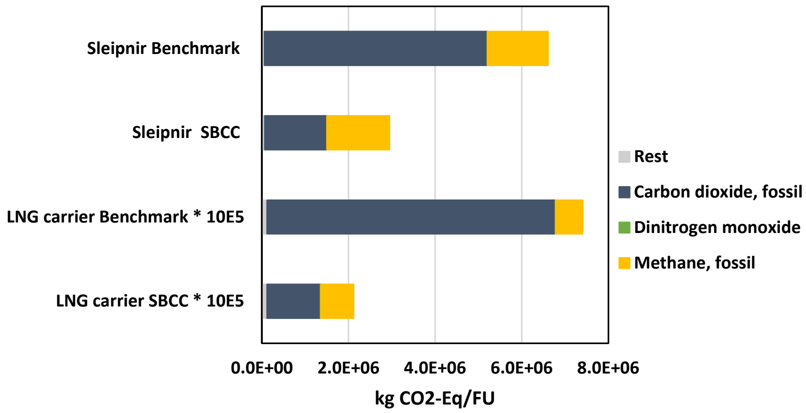

Figure 4.1-5 Overview of elementary flow contributions to climate change for both ships in kg CO_2 equivalent per FU (LNG carrier expressed in 10E5 for better readability)

4.1.2 CO_2 Pathway Analysis

Port operations and CO_2 handling afterwards lead to GHG emissions due to operation using electricity and fuel for CO_2 shipping as well as fugitive CO_2 emissions. The CO_2 pathway of the base case considers permanent storage of the CO_2, utilization discussions are included in a dedicated section 6 below. Table 4.1-1 summarizes the climate change impacts for the separate pathway stages distinguished by operation and construction contribution. The total $CO_{2\text{-Eq}}$ emissions for the CO_2 storage pathway amount to 220.3t and 3.76kg per functional units for the Sleipnir and LNG carrier, respectively.

Table 4.1-1. Total CO_2 equivalents per FU for the CO_2 pathway stages

Stage		Sleipnir t $CO_{2\text{-}Eq}$/FU	LNG carrier kg $CO_{2\text{-}Eq}$/FU
Port facility	**total**	**83.7**	**1.56**
	operation	42.7	0.62
	construction	41.0	0.94
Transport	**total**	**127.1**	**2.05**
	operation	118.2	1.90
	construction	8.9	0.14
Storage	**total**	**9.6**	**0.15**
	operation	3.3	0.05
	construction	6.3	0.10

For the port facilities, the operation impacts are determined by the electricity use. The relative shares of construction and operation are determined by the offloading amounts and frequency of use of the port facilities for the respective functional unit. As two port facilities are assumed with less CO_2 per side for the LNG carrier case, the construction share covers 60% of the port emissions, with 40% electricity share. For the Sleipnir with only one power facility, the construction share amounts to 49%, and 51% operational electricity. The construction impacts are largely attributed to the CO_2 storage tanks, causing 82%. The remaining 18% are related to building the CO_2 transport pipeline to the export terminal.

The large contribution of port operations compared to the storage operation stem from the relatively low use, also needing the BOG system running at high capacity, with a share of almost 20% of the total receiving port operation electricity. Higher frequency of CO_2 handling could reduce the runtime of the BOG system or even make it obsolete as well as drastically reduce the construction impacts per ton CO_2 handled.

Additionally, well-integrated systems at port of CO_2 receiving and export to storage could further reduce the need for pressurisation and vaporisation steps, thus reducing the energy consumption overall. The assumptions for the port of Rotterdam conservatively use Dutch electricity grid mixes with current emissions of about 505g $CO_{2\text{-}Eq}$/kWh, which could also be replaced by renewable sources at about 13g $CO_{2\text{-}Eq}$ for better climate performance [12]. However, either additional batteries would be needed to bridge the intermittency of renewable resources, or only a fraction of the full electricity use can be considered replaceable.

The shipping distance and transport mode to storage plays a considerable role in the overall CO_2 pathway emissions. It was adapted from the Northern Lights report to the transport distance from Rotterdam to Northern Lights, as described in the inventory modelling (section 3.2.9). The transport share of the storage pathways after adapting the new distance is 93% with 7% remaining for storage. Operational emissions dominate the adapted transport stage with 93% share and 7% construction and decommissioning. The storage stage itself is dominated by 66% construction and decommissioning, and 34% operational emissions. These assumptions hold for the Sleipnir case shown in Table 4.1-1. However, for the LNG carrier case, the EOR considerations are expected to have a higher contribution of storage versus transport emissions. Leakages and additional electricity use during EOR operation increase the storage emissions while the existence of the green pipeline for transport in contrast to long-distance ship transport decrease the transport emissions. In principle, this overview shows that though they do not dominate the results, transport and storage emissions are not negligible and simpler modes of transport such as pipelines and overall lower transport distances could be beneficial.

4.1.3 Full System Analysis

The full system includes upstream fuel, system equipment production (SBCC and CO_2 pathway), operation as well as waste and CO_2 handling. It therefore widens IMO's WtW system approach by the subsequent handling of CO_2 at the port and the transportation to a storage or utilization facility, thus keeping the entire CO_2 life cycle in mind.

As with the on-board analysis, first CO_2 emissions are assessed. Figure 4.1-6 and Figure 4.1-7 show CO_2 emissions for the full systems for the Sleipnir and the LNG carrier cases. The reduction shared for the system stages from well to tank and CO_2 pathway are collected in Table 4.1-2. The overall CO_2 reduction achieved by the capture system lie at 54% and 57%, compared to 72% and 82% on-board reduction, for the Sleipnir and the LNG carrier, respectively. The strong contribution of the upstream fuel supply (WtT) in all systems becomes obvious. An increase of 6% up to 15% is observed for the Sleipnir and LNG carrier in the WtT absolute values of the SBCC systems relative to the respective benchmark. This leads to a fuel supply share on CO_2 emissions of 37% for the Sleipnir full system and even 51% for the LNG carrier, underpinning the importance of this section of the life cycle. However, this section of the full chain cannot be directly influenced by the ship operator, only the additional demand due to the SBCC unit can be optimized. SBCC integration and operation, port receiving facilities, solvent reclaiming, and transport and storage contribute to a smaller extend. However, for the Sleipnir they add 13% (8%) to full system CO_2 ($CO_{2\text{-}Eq}$) emissions and 15% (10%) for the LNG carrier.

Table 4.1-2. Overview of the impact reduction from benchmark to SBCC system for the well-to-tank (WtT), tank-to-wake (TtW) and well-to-wake (WtW) stages as well as the full analysed system until storage. The percentages give the amount reduced compared to the benchmark case.

Section		$CO_{2\text{-}Eq}$		CO_2		CH_4	
Ship		Sleipnir	LNG Carrier	Sleipnir	LNG Carrier	Sleipnir	LNG Carrier
WtT	Upstream Fuel	-5.57	-15.41	-5.55	-15.39	-5.60	**-15.45**
TtW	On-board	55.50	71.42	72.05	81.53	-2.59	**-20.85**
WtW	WtT & TtW	50.43	49.86	67.11	63.35	-2.11	-17.66
Full System	Incl. port and CO_2 pathway	38.80	44.37	53.86	57.21	-2.59	-19.88

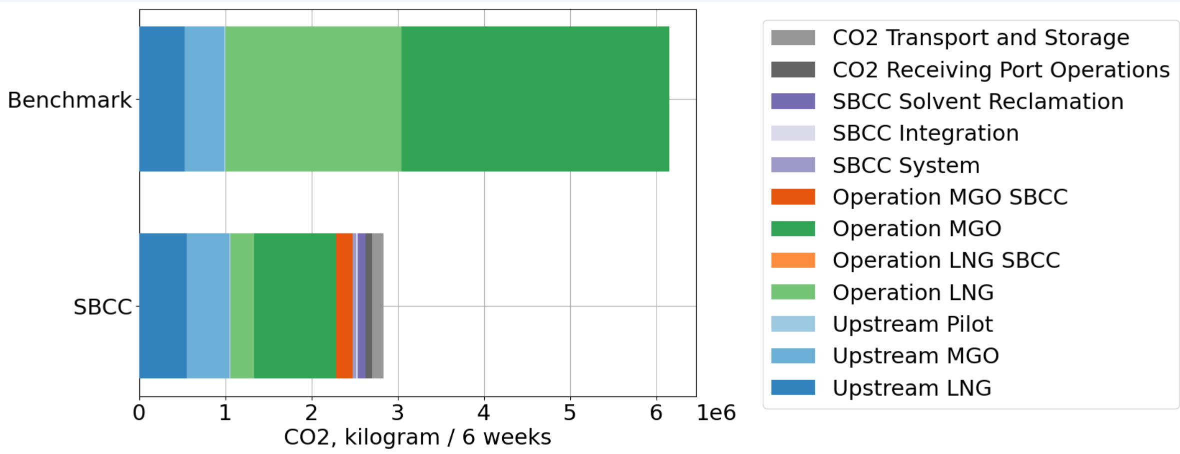

Figure 4.1-6 Sleipnir - Full Life Cycle - CO_2 emissions per FU

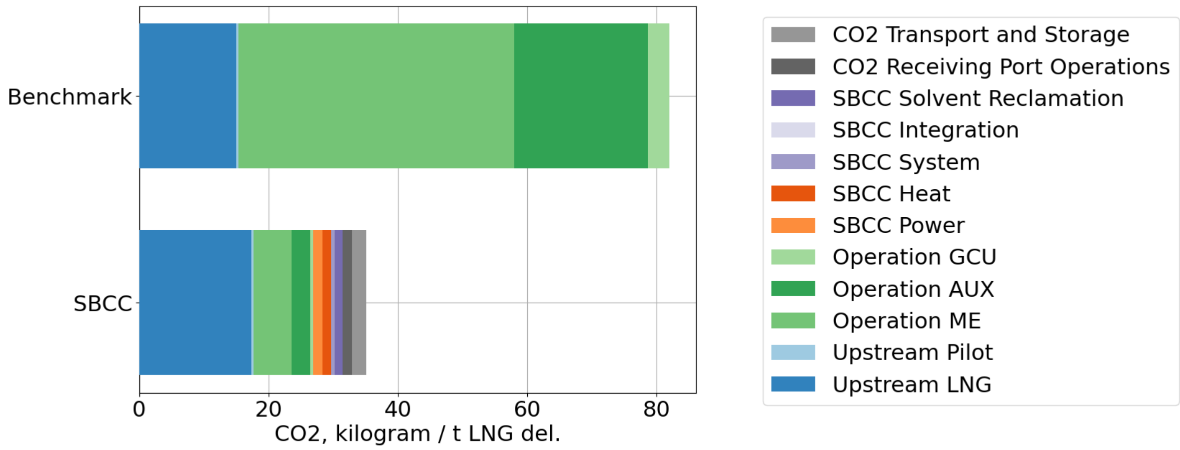

Figure 4.1-7 LNG carrier - Full Life Cycle - CO_2 emissions per FU

A different picture emerges when exclusively looking at methane emissions (Figure 4.1-8 and Figure 4.1-9). Due to the additional power demand for capture, methane emissions for the SBCC systems increase, by 3% for the Sleipnir and even 20% for the LNG carrier heat and power. While for the Sleipnir case methane emissions occur to a greater extend during operation, fuel supply contributes more than half to the overall emissions for the LNG carrier. The same reasons as for the on-board section also apply here, namely that the Sleipnir's engines are operated at a more efficient load point, and the LNG carrier operates 4-stroke auxiliary engines with high methane slip for the additional energy demand for the SBCC. CO_2 handling processes are negligible.

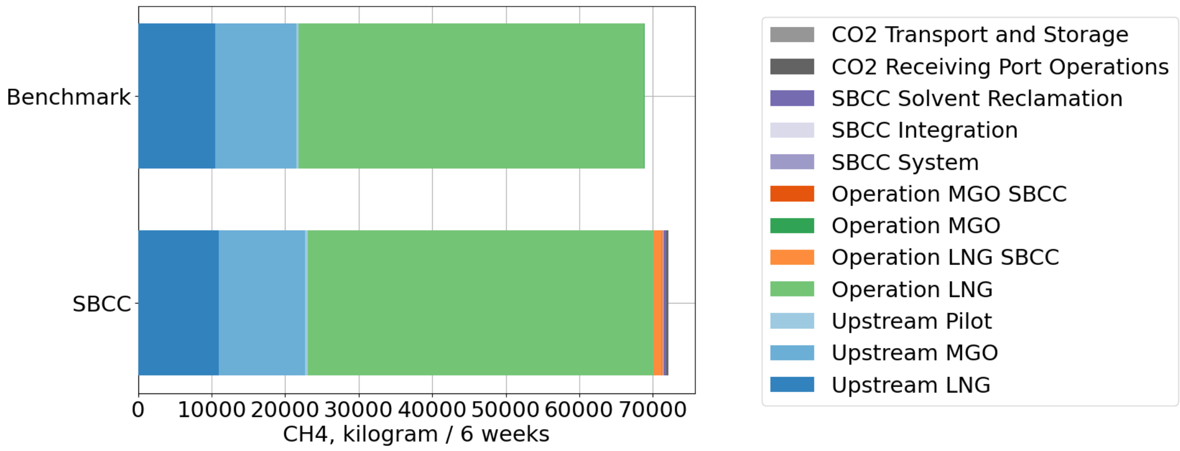

Figure 4.1-8 Sleipnir - Full Life Cycle - methane emissions

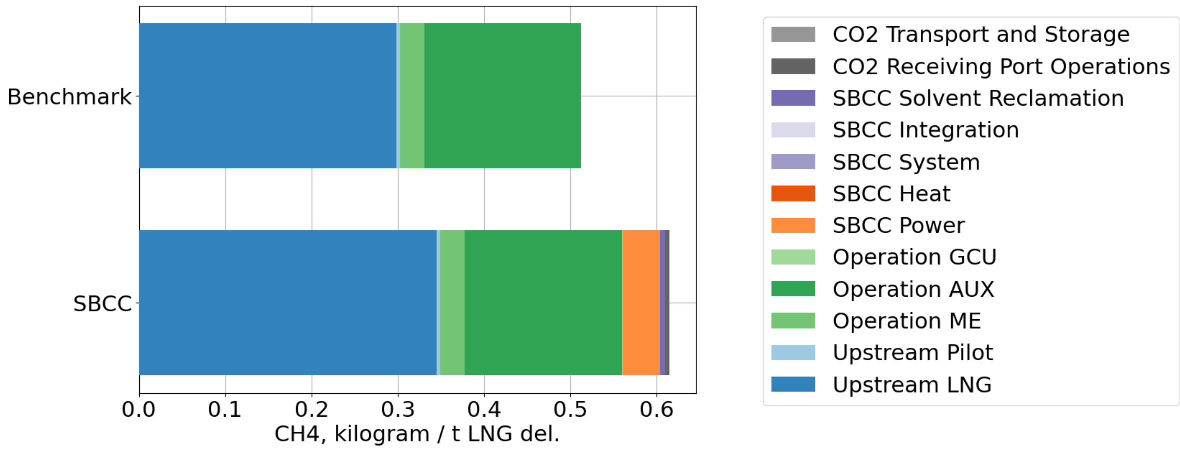

Figure 4.1-9 LNG carrier - Full Life Cycle - methane emissions

Taking all GHGs into account the overall reduction in climate change impacts adds up to 39% for the Sleipnir (Figure 4.1-10) and 44% $CO_{2\text{-}Eq}$ for the LNG carrier (Figure 4.1-11).

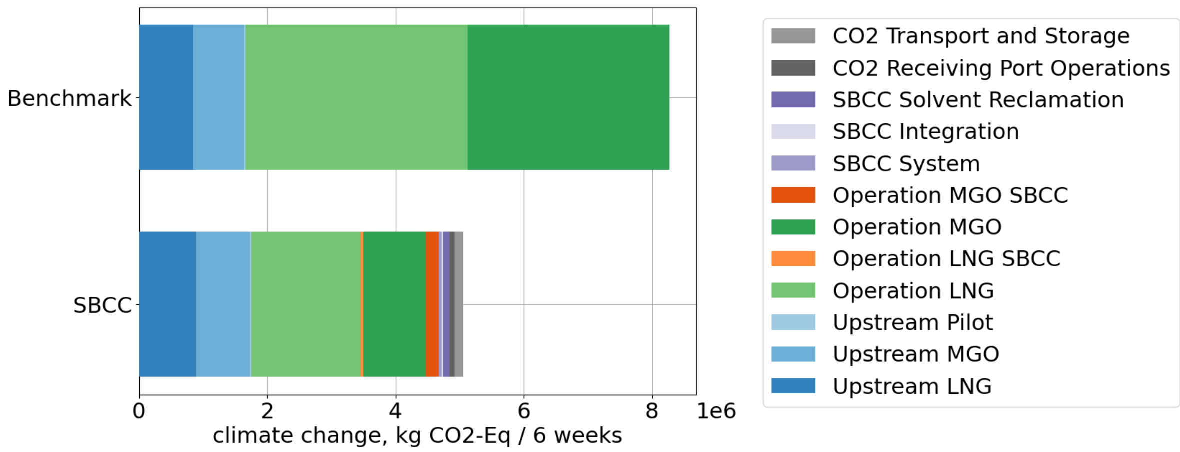

Figure 4.1-10 Sleipnir - Full Life Cycle - climate change impacts using GWP100 in kg CO_2 equivalent per FU

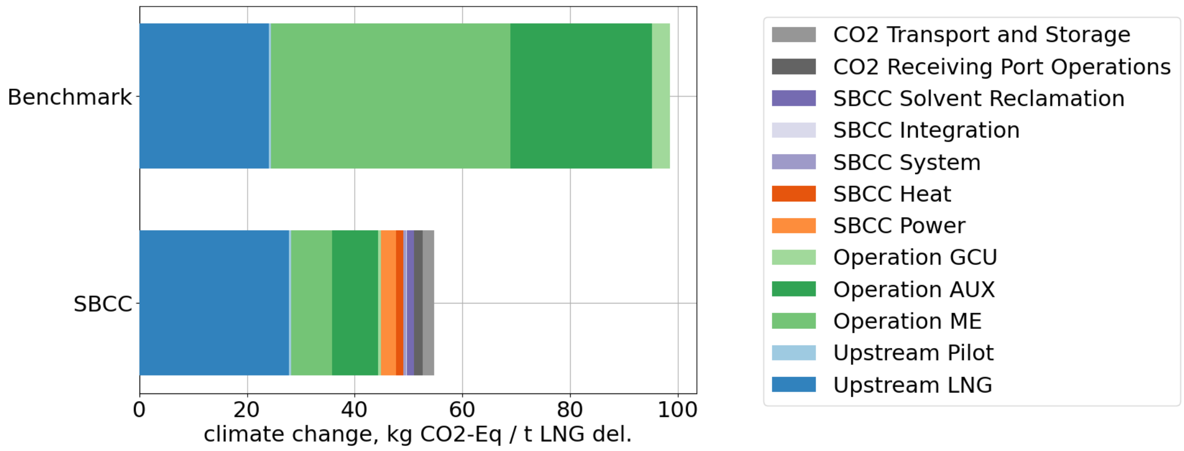

Figure 4.1-11 LNG carrier - Full Life Cycle - climate change impacts using GWP100 in kg CO_2 equivalent per FU

The WtT upstream impacts of the fuel play a non-negligible role, with a contribution to SBCC climate change impacts of 35% and 52%, respectively. It increases notably compared to the benchmark systems (20% Sleipnir, 25% LNG carrier). Especially the LNG carrier, running almost purely on LNG is affected by its larger upstream impacts. The additional emissions during on-board operation, linked to TtW, play a minor role compared to upstream fuel, with a contribution of 5% and 8%, respectively. For IMO's WtW system approach this leads to a reduction on climate change impact of 50% for both the Sleipnir and the LNG carrier. System construction and integration, solvent operation and reclamation amount to 3% and 4%, respectively. Handling CO_2 at port and its storage contributes 4% and 7%.

On-board the higher methane emissions are compensated by the CO_2 reduction, leading to the low share of additional TtW impacts. The shares of GHG emissions for the full system are shown in Figure 4.1-12.

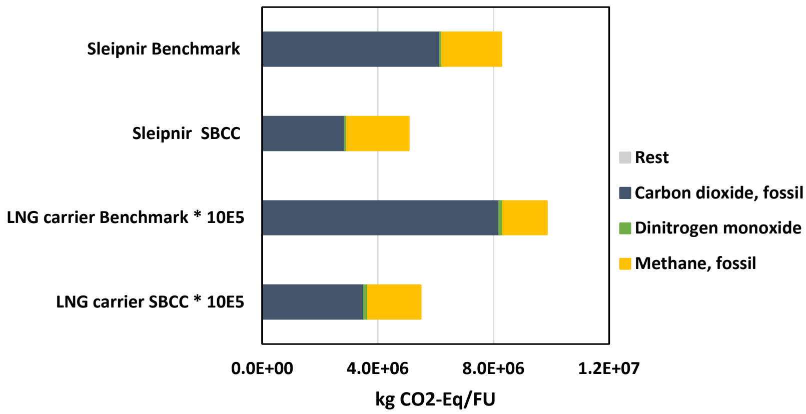

Figure 4.1-12 Overview of elementary flow contributions to climate change for both ships in kg CO_2 equivalent per FU (LNG carrier expressed in 10E5 for better readability)

Thus, the main drivers against further reduction of climate impacts are found in the fuel production stages and the on-board methane slip during operation. Higher overall reduction shares for SBCC systems could be obtained by reducing fuel consumption of the capture operation, e.g., with further improved heat integration or explicitly by choosing fuel from suppliers guaranteeing lower upstream fuel emissions. Addressing benchmark LNG-operation methane slip follows as strong handle for overall climate impact reduction, which is however out of the scope of a CO_2 capture system.

The emission calculation for the benchmark LNG carrier can be compared against shipping contributions assumed for the LNG production from literature sources in order to verify the order of magnitude of the results. The total delivery of 1 kg LNG from the US to Europe amounts to almost 0.099kg $CO_{2\text{-Eq}}$. Literature values of 0.11 for LNG from the US in ecoinvent 3.9.1[12] and 0.13 for LNG imports to Europe from Sphera [18] align very well with the results from our model, though e.g. ecoinvent assumes an HFO carrier.

4.2 Other impact categories

The impact on other environmental categories when introducing the capture system on-board are investigated also. The results are shown in Table 4.2-1, differentiating again between on-board and full life cycle. Reduction values which are negative point to an increase in the respective impact category. For comparability of the importance of the different impacts, the impacts are normalised to the average impacts of a person per year (see section 2.2.5.2). Thus, all impacts are expressed in person equivalence (PE) and values in the same order of magnitude can be interpreted as equally important. Normalization factors for each impact category were taken from the EF3.1 methodology [4] (see also Table A.1-1).

The on-board boundaries focus on the direct emissions of the ship operation (gate-to-gate), thus explicitly excluding the upstream and downstream impacts of fuel production and CO_2 pathway. Therefore, e.g. abiotic depletion of fossil fuels is not applied for this boundary, avoiding inconsistent statements of no fossil depletion while fossil fuel is being burnt on the ship. Similarly, abiotic depletion of metals and minerals is not applied, however the contributions of upstream fuel, on-board and downstream CO_2 handling are collected in section 4.2.5.1, Figure 4.2-22 to Figure 4.2-26.

Table 4.2-1. Normalized environmental impacts in person equivalents per functional unit (PE/FU) for on-board and full life cycle for both case studies (BM = benchmark; SBCC =system with on-board carbon capture).

		Sleipnir			Carrier		
Impact Category	**System level**	**BM**	**SBCC**	**red [%]**	**BM**	**SBCC**	**red [%]**
Climate Change	on-board	875.55	389.65	55.5	9.81E-03	2.80E-03	71.4
	full pathway	1095.52	670.35	38.7	1.31E-02	7.26E-03	44.4
Acidification	on-board	1314.84	1290.60	1.8	6.28E-03	7.71E-03	-22.8
	full pathway	1440.68	1438.37	0.2	7.00E-03	8.75E-03	-25.1
Particulate matter	on-board	618.04	655.45	-6.1	2.32E-03	3.24E-03	-39.6
	full pathway	684.79	752.55	-9.9	2.71E-03	4.06E-03	-49.8
Eutrophication, marine	on-board	1921.91	1834.51	4.5	9.37E-03	1.00E-02	-7.2
	full pathway	2009.65	1939.10	3.5	1.01E-02	1.11E-02	-9.5
Eutrophication, terrestrial	on-board	2318.75	2297.39	0.9	1.13E-02	1.35E-02	-19.5
	full pathway	2414.62	2410.27	0.2	1.22E-02	1.47E-02	-20.5
Photochemical ozone formation	on-board	2622.49	2513.23	4.2	1.34E-02	1.43E-02	-6.7
	full pathway	2986.89	2918.13	2.3	1.76E-02	1.94E-02	-10.3
Human toxicity non-carcer	on-board	22.58	23.26	-3.0	1.13E-04	1.34E-04	-18.6
	full pathway	91.05	115.37	-26.7	9.02E-04	1.33E-03	-47.4
Ecotoxicity, freshwater	on-board	1.80	4.36	-142.3	1.17E-05	5.44E-05	-363.2
	full pathway	401.71	445.91	-11.0	9.44E-04	1.35E-03	-42.9
Resource use, fossils	on-board	------- Not applied -------					
	full pathway	1494.30	1621.37	-8.5	2.22E-02	2.62E-02	-18.1
Resource use, minerals and metals	on-board	------- Not applied -------					
	full pathway	16.41	36.77	-124.1	2.57E-04	5.81E-04	-125.8

The different operation profiles and engine properties affect the changes of the other environmental impacts also. For the LNG carrier the reduction in climate change induces an increase of all other impact categories, mainly due to the additional fuel and power demand of the capture unit. In case of the Sleipnir, there are several impacts which hardly change, some improve a bit, but there are also impacts which worsen. One reason for the different effects compared to the LNG carrier is the high amount of MGO fuel being used by the Sleipnir, another cause is the higher share of low load operation.

Differences between on-board and full chain impacts are not always the same for the different impact categories. They depend on the emissions contributing to the environmental effect and where they occur in the life cycle. If, for example ammonia emissions are contributing to an effect, they occur mainly on-board, while NOx is emitted also in upstream and downstream processes. A detailed description of the responsible emissions and the contribution of the different stages along the life cycle are discussed in the following sections.

The comparability of all impact categories in Table 4.2-1, obtained via normalization, highlights the categories photochemical ozone formation, eutrophication and acidification as most relevant compared to the standard impacts of a person, followed by climate change, particulate matter and toxicity. In addition to the relevance, the relative increase of an impact category from Benchmark to SBCC, also points towards relevant impact categories most directly impacted by the SBCC system. In this case, especially toxicity and abiotic depletion related impact categories are highlighted. When visualising the Sleipnir and LNG carrier in a single graph, a scaling for the LNG carrier functional unit of 1e5 i.e. 100 000 has been chosen to improve its visibility on the scale.

4.2.1 Acidification & Eutrophication

Acidification potential based on accumulated exceedance of what the environment can safely take up is mainly caused by ammonia, ammonium compounds, nitrate, NOx, SOx and sulphuric acid. Many of the components are part of the foreground system, meaning the combustion and capture unit operation emissions, such that this impact category is evaluated in detail.

Terrestrial eutrophication impacts are related to accumulation of nutrients exceeding what the systems can safely take up. Marine eutrophication is based on fractions of nutrients reaching the maritime compartment. This varies between regions and ecosystems, such that a coarse distinction is made between marine, terrestrial and freshwater eutrophication potentials. Most direct emission components such as ammonia and NOx are strongly related to the marine and terrestrial impact compartments. For freshwater, the most influential emissions would include phosphates, phosphoric acid, detergents and phosphorus which play no role in direct operation of the capture unit. Therefore, only marine and terrestrial eutrophication is investigated.

Both acidification and eutrophication are strongly impacted by NOx emissions of fuel combustion and see some contribution from ammonia emissions, related to solvent degradation. The on-board impact reductions for the Sleipnir are an effect of the combination of its operational profile and the way the capture operation is implemented. Due to the rather low engine loads especially for MGO operation and a distribution of the additional load of the capture system over all running engines, the system operates at a more optimal combustion regime thus reducing the overall NOx emissions. Therefore, the overall operation impacts are lower and no additional 'SBCC Power' contribution is necessary in the graphics below. This effect is not observed in the LNG carrier operation case, as the operation is at a much higher average load, and the overall effect of NOx is much smaller.

4.2.1.1 Acidification

In Figure 4.2-1 the lower acidification potential during operation becomes visible for the Sleipnir, caused by the low-load operation and the slightly higher loads due to the power demand of the SBCC unit improving the operation load point. However, additional fuel demand as well as ammonia emissions from the SBCC system mainly cancel out these gains made. Emissions during the pathway of CO_2 are contributing only very limited. Overall, the acidification accumulated exceedance is not changed when introducing SBCC on the Sleipnir.

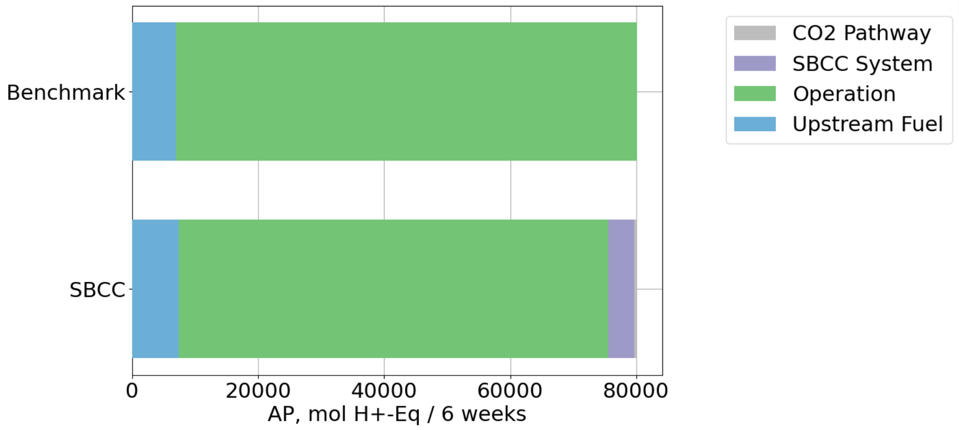

Figure 4.2-1 Sleipnir - Full Life Cycle – acidification accumulated exceedance in mol H⁺ equivalent per FU

This looks different for the LNG carrier case in Figure 4.2-2. As mentioned earlier, the engines already operate quite efficiently, the additional fuel demand as well as emissions due to the operation of the SBCC system increase the acidification accumulated exceedance by 25% for the full chain.

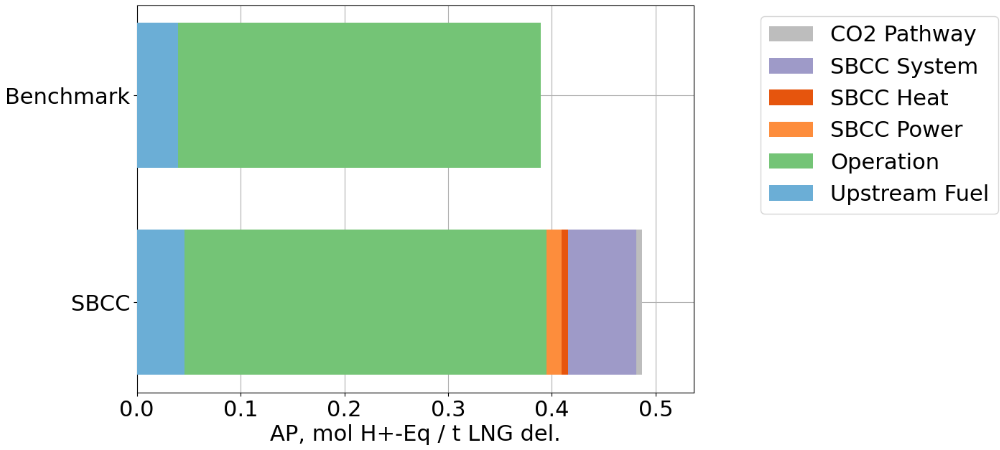

Figure 4.2-2 LNG carrier - Full Life Cycle – acidification accumulated exceedance in mol H⁺ equivalent per FU

As Figure 4.2-3 shows, NOx emissions from fuel combustion are the main contributors to acidification exceedance in all four cases. For the capture cases on both ships ammonia emissions become visible. Also, SO_2 from fuel production and SOx emissions due to the burning of mainly MGO are higher for the Sleipnir cases. The quench wash of the capture reduces the SOx drastically, such that mostly SOx from flue gases not passing the capture system remain.

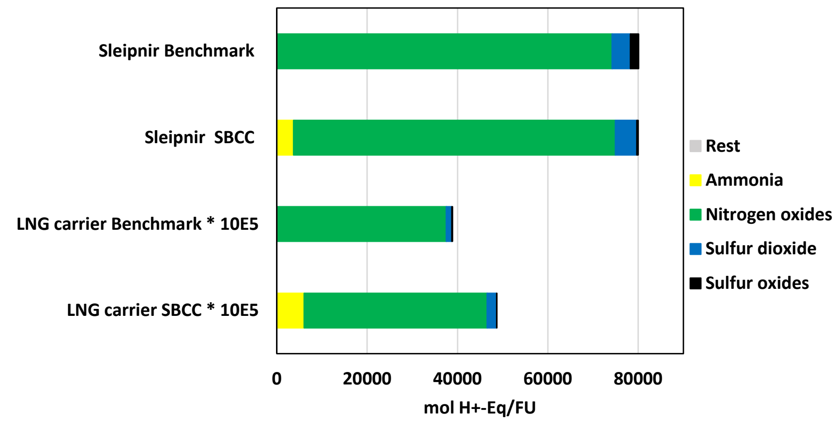

Figure 4.2-3 Overview of elementary flow contributions to acidification accumulated exceedance for both ships in mol H+ equivalent per FU (LNG carrier expressed in 10E5 for better readability)

Comparing the Sleipnir and LNG carrier shows that especially for otherwise low-emission operation of the LNG carrier, the contribution from ammonia emissions of the capture system plays a larger role in the remaining impacts. When targeting the lowest possible emissions, an acid-wash could remove the ammonia and amine from the gas stream leaving the capture system. The operation of such a system can become inevitable if strict regulations for marine environments come into place.

4.2.1.2 Eutrophication

The same effects as for acidification also apply to the impacts on terrestrial and marine eutrophication, which are also vastly dominated by NOx and some ammonia emissions (Figure 4.2-6 and Figure 4.2-9Figure 4.2-9). For the Sleipnir improvements in terrestrial as well as marine eutrophication, due to improved engine load points, are offset by downstream emissions during CO_2 handling (Figure 4.2-4 and Figure 4.2-7). The increased NOx and ammonia emissions for the LNG carrier SBCC operation are visible in Figure 4.2-5 and Figure 4.2-8 for both terrestrial and marine eutrophication, respectively.

Eutrophication terrestrial

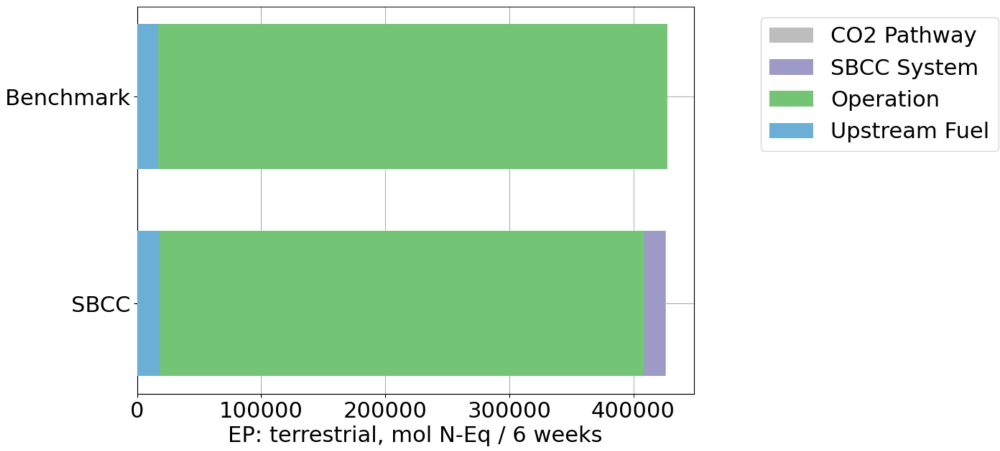

Figure 4.2-4 Sleipnir - Full Life Cycle – eutrophication terrestrial accumulated exceedance in mol nitrogen equivalent per FU

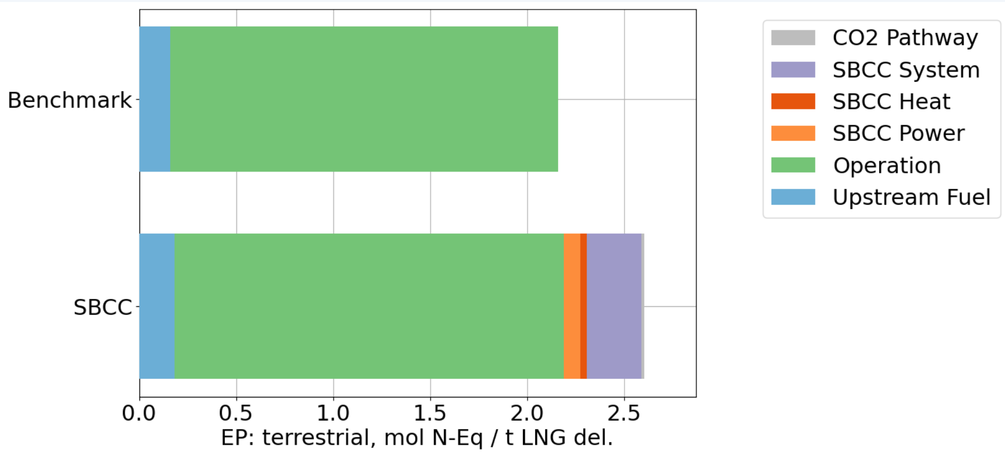

Figure 4.2-5 LNG carrier - Full Life Cycle – eutrophication terrestrial accumulated exceedance in mol nitrogen equivalent per FU

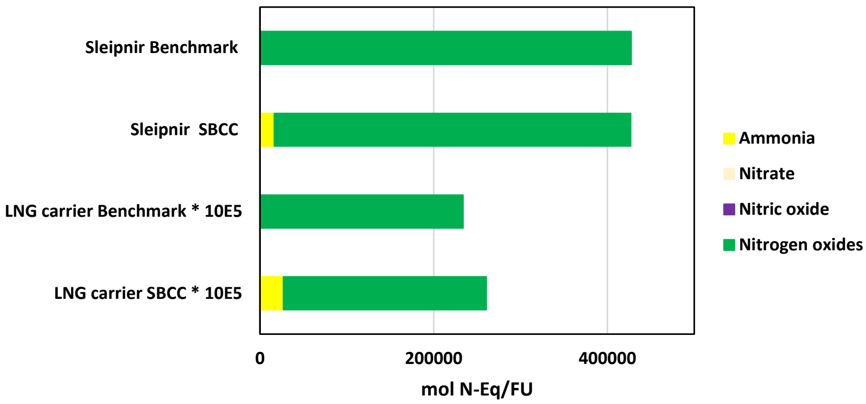

Figure 4.2-6 Overview of elementary flow contributions to eutrophication terrestrial accumulated exceedance for both ships in mol nitrogen equivalent per FU (LNG carrier expressed in 10E5 for better readability)

Eutrophication marine

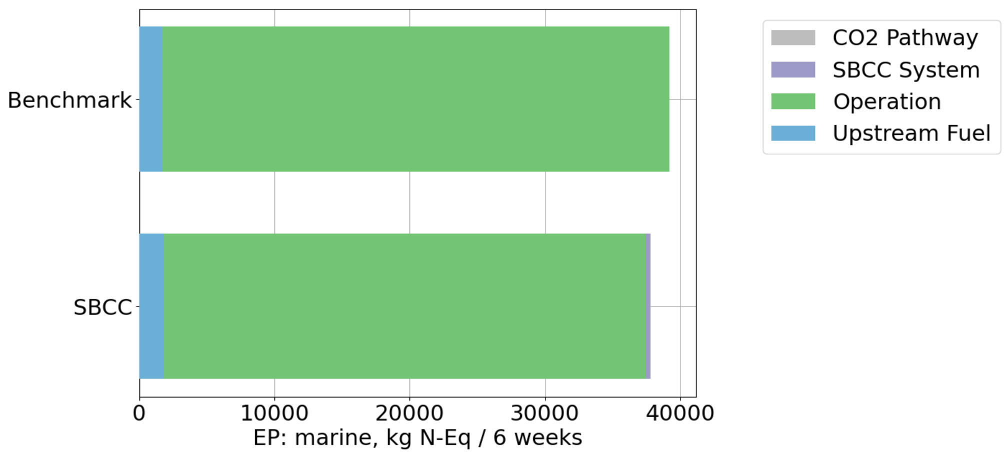

Figure 4.2-7 Sleipnir - Full Life Cycle – eutrophication marine fraction of nutrients reaching marine end compartment in kg nitrogen equivalent per FU

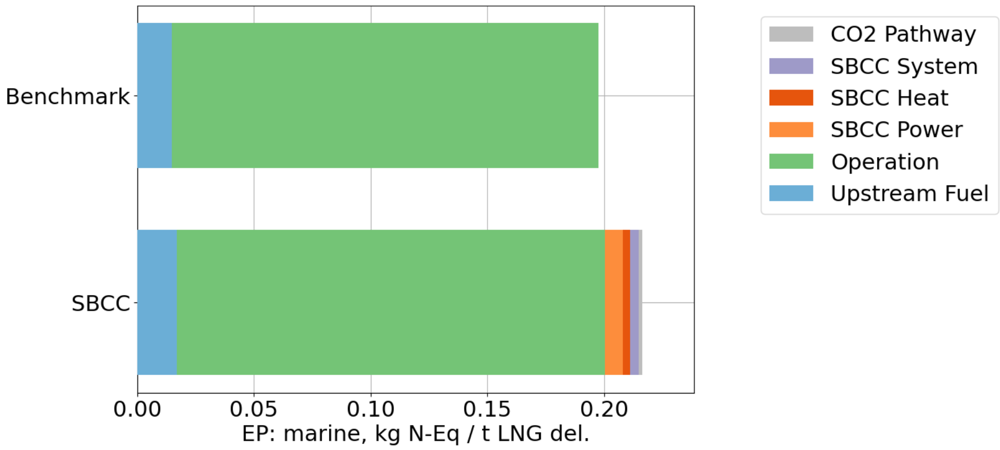

Figure 4.2-8 LNG carrier - Full Life Cycle – eutrophication marine fraction of nutrients reaching marine end compartment in kg nitrogen equivalent per FU

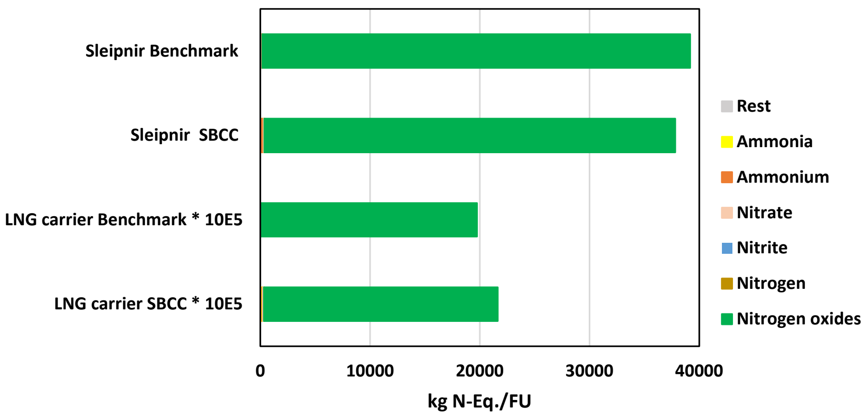

Figure 4.2-9 Overview of elementary flow contributions to eutrophication marine fraction of nutrients reaching marine end compartment for both ships in kg nitrogen equivalent per FU (LNG carrier expressed in 10E5 for better readability)

4.2.2 Photochemical oxidant formation

Ozone near to the ground is formed by the oxidation of the primary contaminants VOC or CO in the presence of NOx under the influence of light, which can in turn lead to a tropospheric ozone concentration increase. The effects of the system are similar to acidification and eutrophication, as all are heavily influenced by NOx emissions (Figure 4.2-12). In addition, non-methanic volatile organic compounds (NMVOC) play a role for photochemical oxidant formation, about half of which stem directly from fuel combustion while the other half results from the venting of natural gas during fuel production.

The on-board emission of NOx and NMVOC largely determine the impacts on photochemical ozone formation, with similar small reduction effects of less NOx emissions visible for the Sleipnir in Figure 4.2-10. As already mentioned before, for the LNG carrier the auxiliary engine use for additional power with a higher NOx emission factor than the main engines, leads to the overall stronger increase visible in Figure 4.2-11. The CO_2 pathway is negligible for both ships.

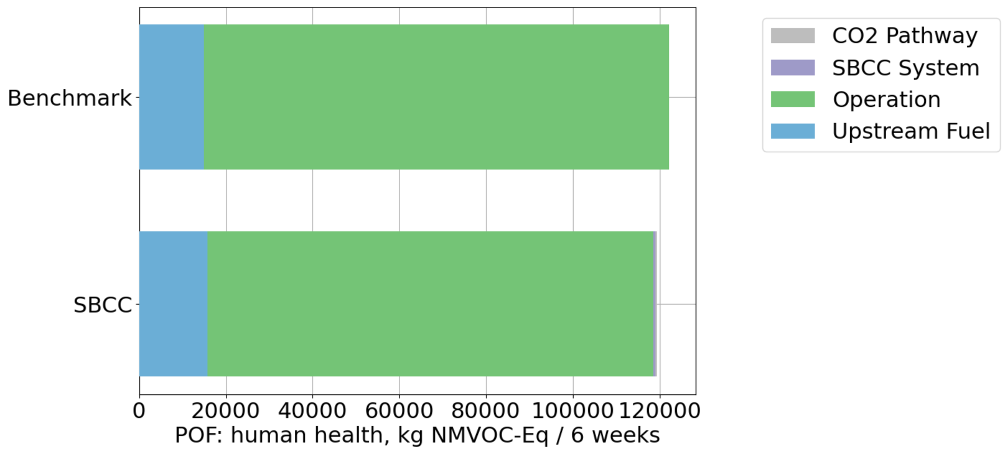

Figure 4.2-10 Sleipnir - Full Life Cycle – photochemical ozone formation - impact on human health in kg non-methane volatile organic compounds equivalent per FU

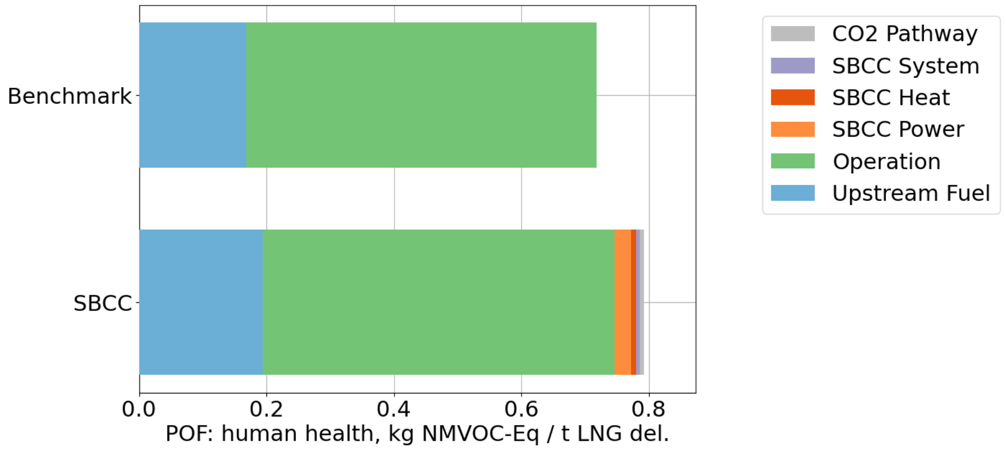

Figure 4.2-11 LNG carrier - Full Life Cycle – photochemical ozone formation - impact on human health in kg non-methane volatile organic compounds equivalent per FU

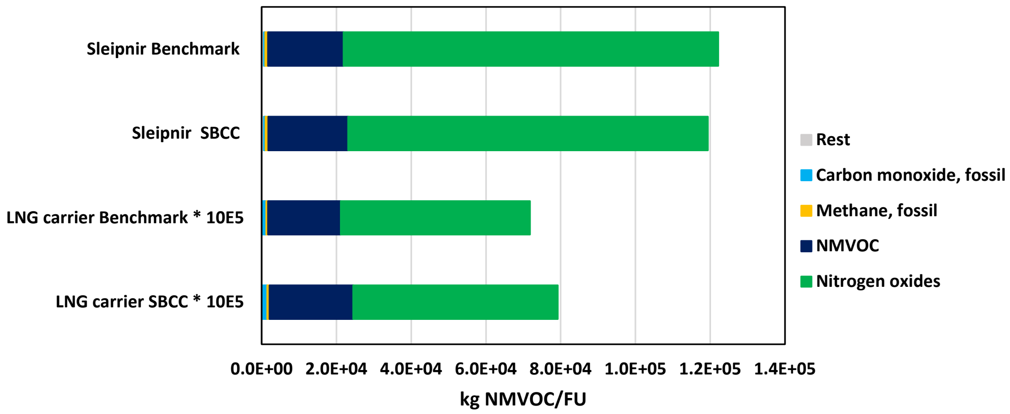

Figure 4.2-12 Overview of elementary flow contributions to photochemical ozone formation for both ships in kg non-methane volatile organic compounds equivalent per FU (LNG carrier expressed in 10E5 for better readability)

Results for the photochemical ozone formation in Table 4.2-1 show the highest values, thus indicating the importance of LNG-fuelled ships on this environmental effect. While the stress on the environment slightly decreases for the Sleipnir, due to its more optimized load-operation, for the LNG carrier this effect increases by 10%.

4.2.3 Particulate Matter Formation

For the impact category fine particulate matter formation the most influential emissions are particulates, ammonia, nitrate, NOx and SOx. The impact of these emissions on human health is measured counting disease incidence.

Toxicity related impacts stem mostly from particulates and NOx during combustion, while especially for the LNG carrier, with low particulate and NOx emissions during combustion, the ammonia emissions from the capture system play a more significant role, see Figure 4.2-13 to Figure 4.2-15.

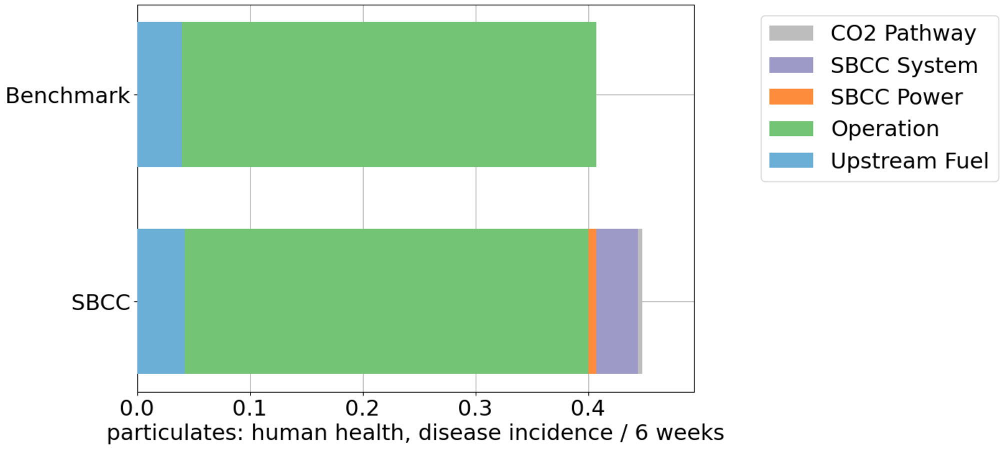

Figure 4.2-13 Sleipnir - Full Life Cycle – particulate matter formation in disease incidence per FU

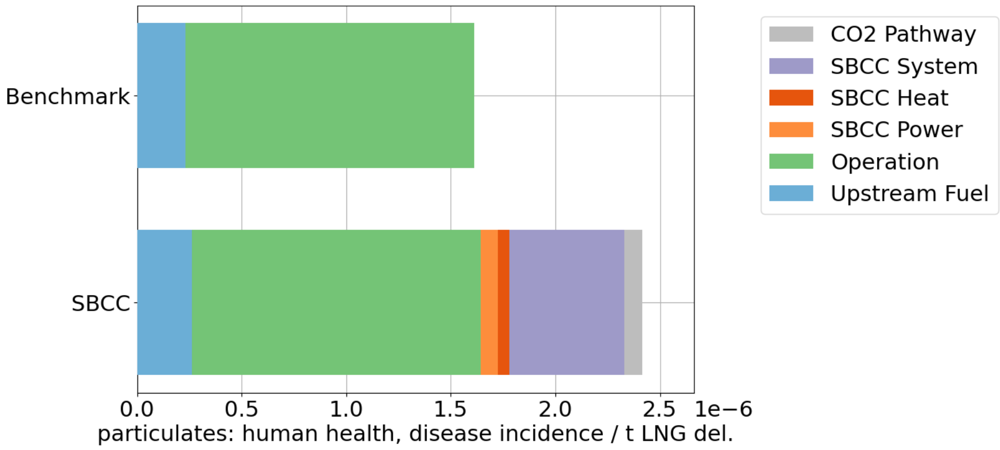

Figure 4.2-14 LNG carrier - Full Life Cycle – particulate matter formation in disease incidence per FU

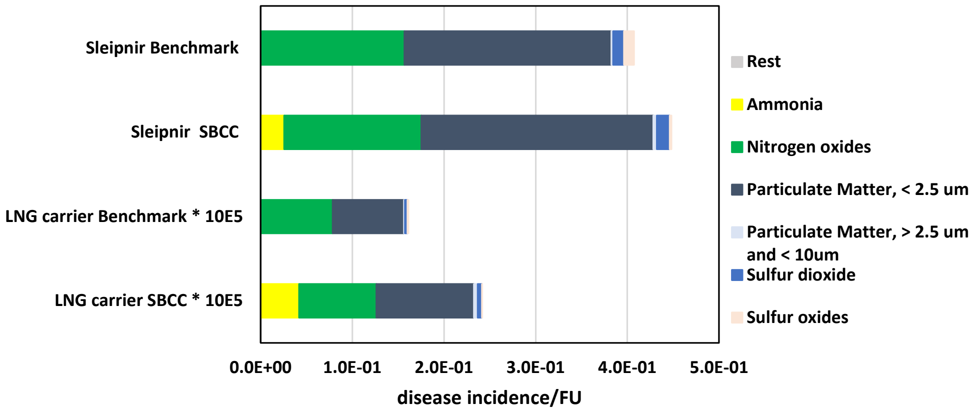

Figure 4.2-15 Overview of elementary flow contributions to particulate matter formation for both ships in disease incidence per FU (LNG carrier expressed in 10E5 for better readability)

4.2.4 Human Toxicity and Ecotoxicity

Toxicity-related impact categories always have a vast catalogue of potentially contributing emissions. They are distinguished between impacts on humans, differentiating between cancer and non-cancer effects as well as on the ecosystem. Due to its high complexity of these impact categories the European Commission-Joint Research Centre - Institute for Environment and Sustainability recommends to use them, however with caution. In comparison to the other normalized impacts (Table 4.2-1) they show lower values, indicating a lower importance.

4.2.4.1 Human Toxicity, non-cancer

Human toxicity is related to emissions of toxic substances into contact with humans. The capture system emits some non-cancer related toxic emissions, such as ammonia and MEA. Thus, non-cancer human toxicity is evaluated. Most of the impacts are related to the upstream fuel production emitting, e.g., mercury, see Figure 4.2-16 to Figure 4.2-18. Some impacts are attributed to fossil methane emissions as well. The capture unit is not seen to introduce concerning emissions compared to the normal combustion emissions, apart from ammonia at otherwise very clean combustion. Emissions from the CO_2 pathway are also visible.

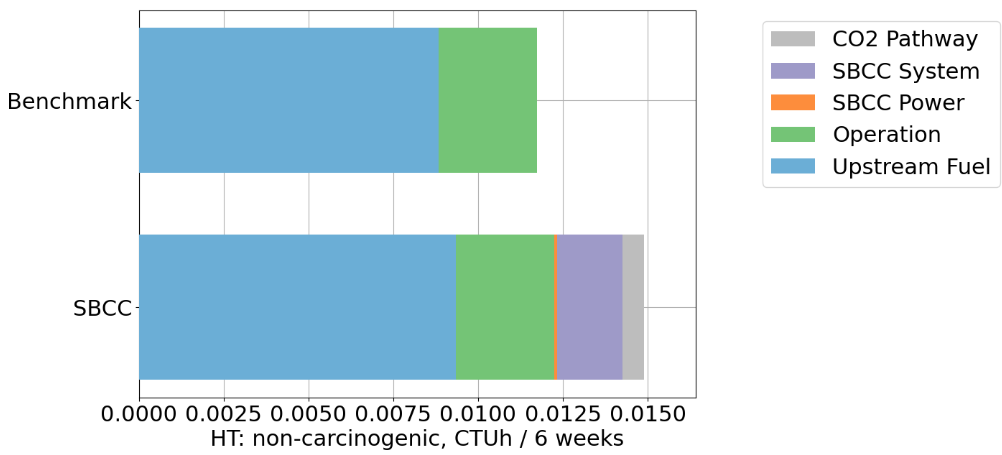

Figure 4.2-16 Sleipnir - Full Life Cycle – human toxicity (non-cancer) in comparable toxic unit per FU

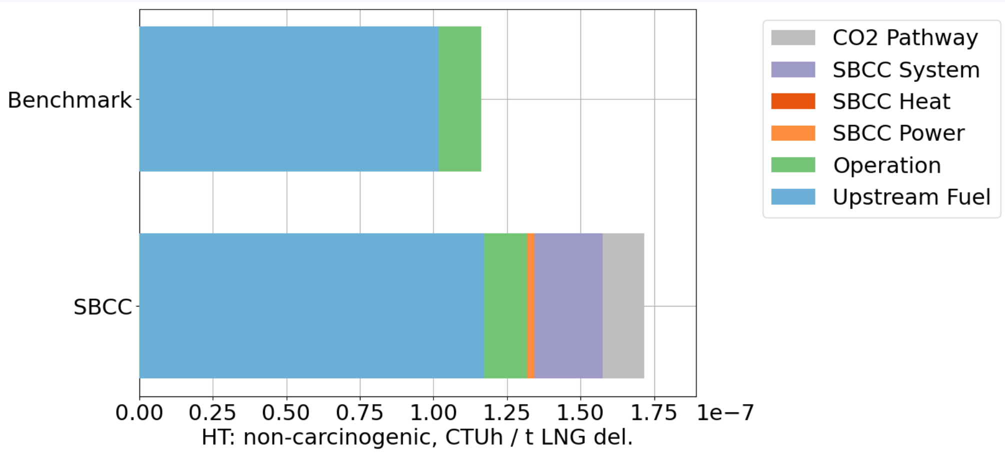

Figure 4.2-17 LNG Carrier - Full Life Cycle – human toxicity (non-cancer) in comparable toxic unit per FU

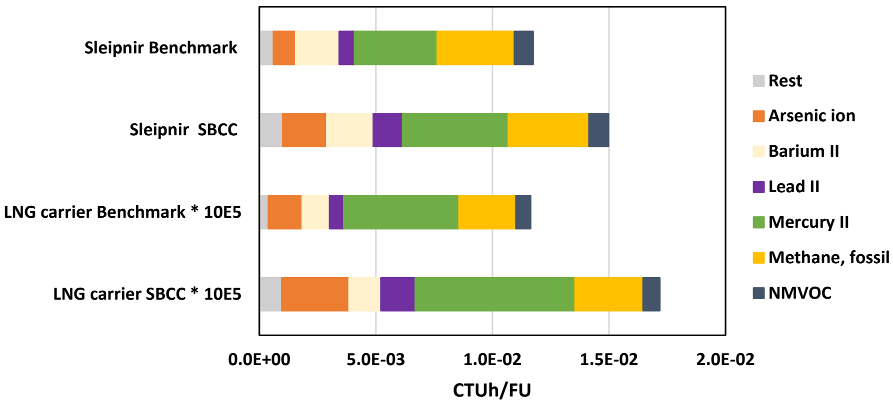

Figure 4.2-18 Overview of elementary flow contributions to human toxicity (non-cancer) for both ships in comparable toxic unit per FU (LNG carrier expressed in 10E5 for better readability)

Though the increase is quite pronounced, especially for the LNG carrier, it must be taken into account that the initial values are not very high and even after the introduction of SBCC the values reached remain comparatively low.

4.2.4.2 Ecotoxicity

Ecotoxicity impacts are mostly related to upstream fuel production impacts, due to emissions of chloride. Impacts related to the capture system construction and operation are also observed, caused mostly by direct ammonia emissions, construction of the CO_2 tanks, and solvent reclamation wastewater treatment. A strong dominance of upstream emissions over operation and CO_2 pathway can be observed for ecotoxicity (Figure 4.2-19 and Figure 4.2-20).

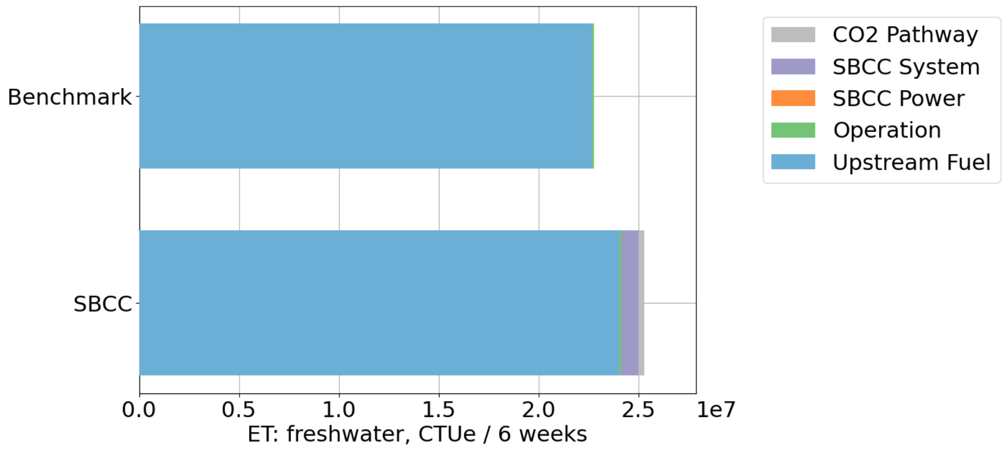

Figure 4.2-19 Sleipnir - Full Life Cycle – ecotoxicity (freshwater) in comparable toxic unit per FU

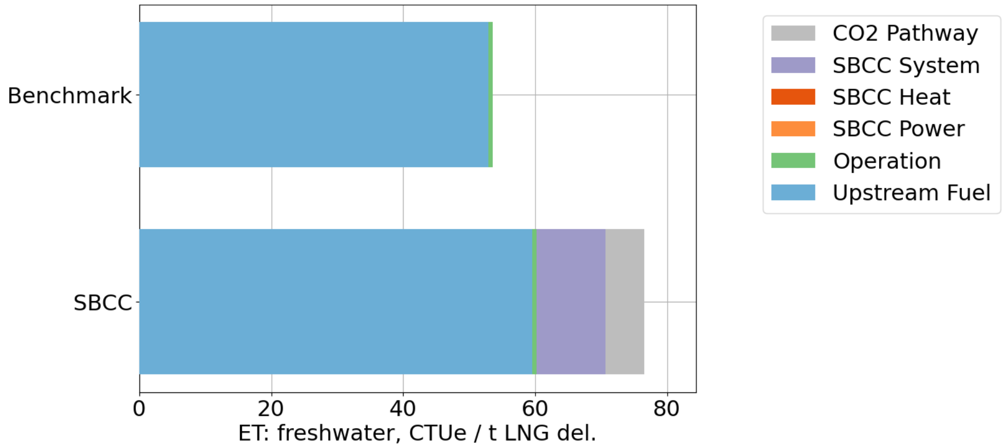

Figure 4.2-20 LNG Carrier - Full Life Cycle – ecotoxicity (freshwater) in comparable toxic unit per FU

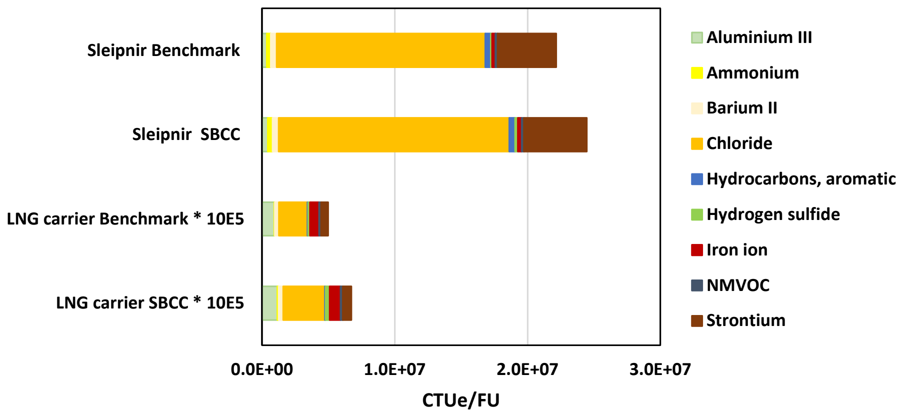

Figure 4.2-21 Overview of elementary flow contributions to ecotoxicity (freshwater) for both ships in comparable toxic unit per FU (LNG carrier expressed in 10E5 for better readability)

4.2.5 Resource use

The resource depletion impacts account for the reserves available versus the newly mined materials for the inventory. This is applied to fossil fuel resources and metals and minerals in the two respective categories, thus not necessarily the most amounts of e.g. metals determine the highest impacts but the most amounts weighted by their abundance and mining availability.

4.2.5.1 Abiotic Depletion Potential, fossils

Fossil abiotic depletion impacts are expectedly dominated by upstream fuel production as can be seen in Figure 4.2-22 and Figure 4.2-23. They show the increase in additional fuel demand due to the capture process and to a very small extent for the CO_2 pathway.

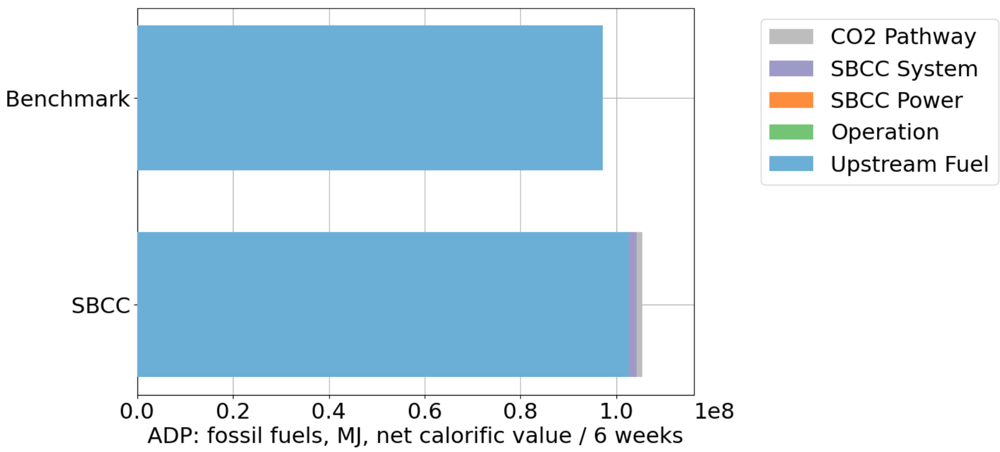

Figure 4.2-22 Sleipnir - Full Life Cycle – abiotic depletion potential (fossils) in MJ, net calorific value per FU

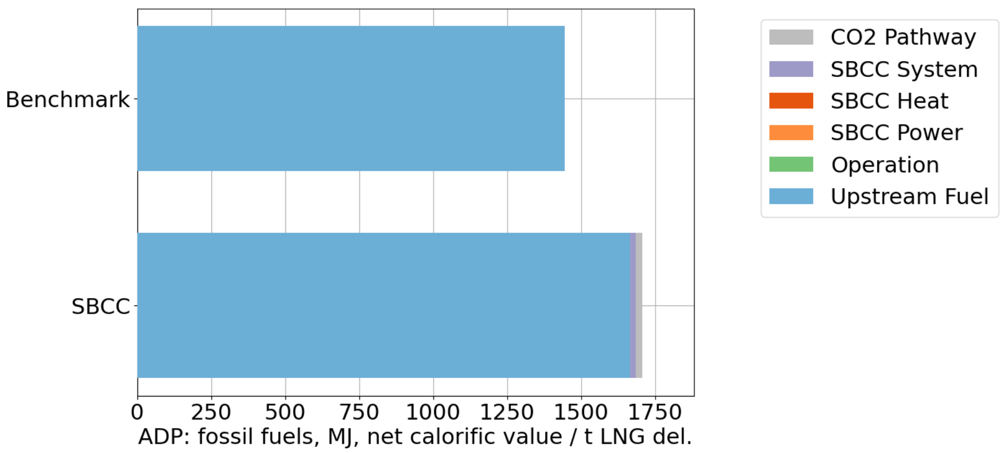

Figure 4.2-23 LNG Carrier - Full Life Cycle – abiotic depletion potential (fossils) in MJ, net calorific value per FU

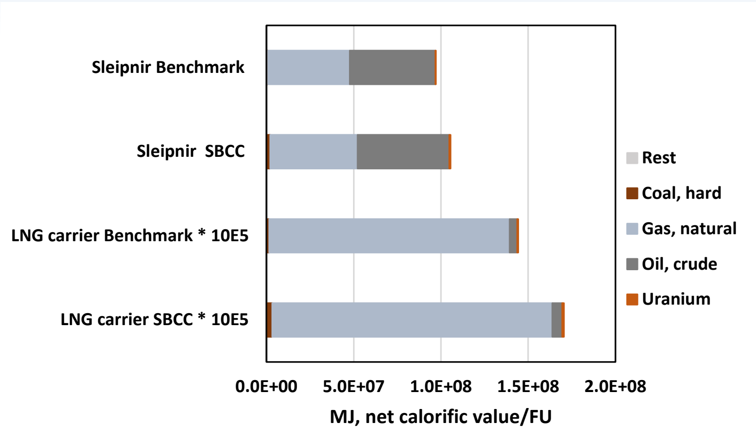

Figure 4.2-24 Overview of elementary flow contributions to abiotic depletion potential (fossils) for both ships in MJ, net calorific value per FU (LNG carrier expressed in 10E5 for better readability)

4.2.5.1 Abiotic Depletion Potential, minerals and metals

Construction of system components for capture, port handling and reclamation plays a role for material depletion as shown in Figure 4.2-25 and Figure 4.2-26. The normalized absolute impacts, however, are small compared to the other impact categories investigated as shown in Table 4.2-1. However, it has to be kept in mind that the construction of the ships are not included in the systems boundaries, which otherwise would increase the absolute values.

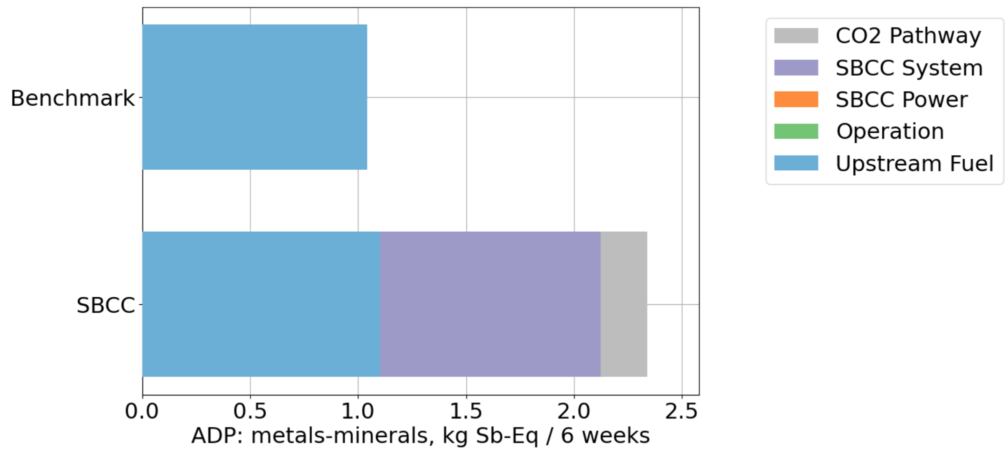

Figure 4.2-25 Sleipnir - Full Life Cycle – abiotic depletion potential (metals and minerals) in kg antimony equivalents per FU

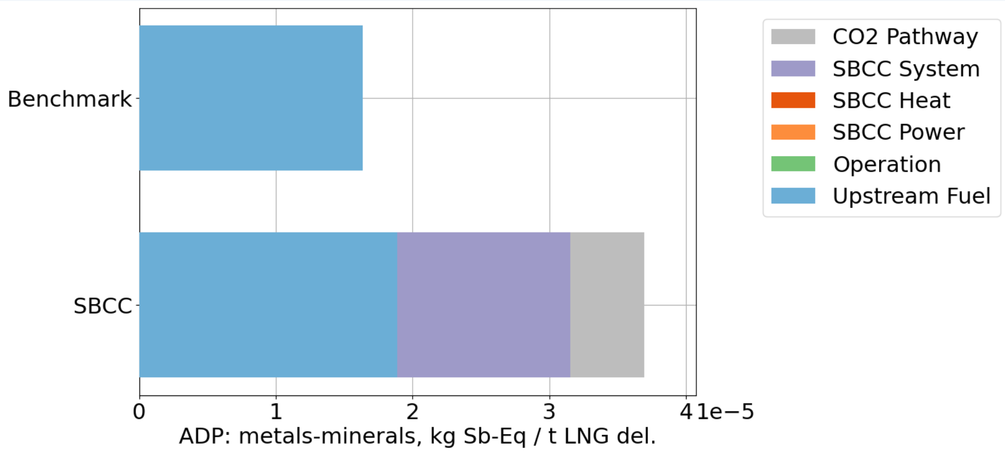

Figure 4.2-26 LNG Carrier - Full Life Cycle – abiotic depletion potential (metals and minerals) in kg antimony equivalents per FU

Figure 4.2-27 shows the various materials used for the systems. Tellurium is dominating the abiotic depletion for all systems. It is mainly an effect of copper mining activities, related to several background processes such as wastewater treatment, fuel supply and port construction. It has a high impact share because of its relative scarcity. As mentioned earlier, iron, though being used to a large extend for the high amount of steel needed for the system construction, is not visible due to its high availability and thus low depletion potential.

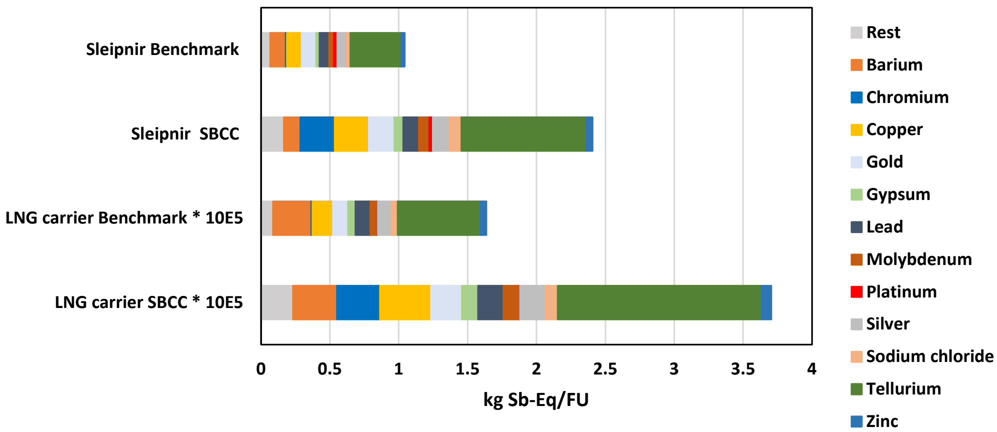

Figure 4.2-27 Overview of elementary flow contributions to abiotic depletion potential (minerals - metals) for both ships in kg antimony equivalents per FU (LNG carrier expressed in 10E5 for better readability)

5 Sensitivity Analysis Results

This section presents results for sensitivity considerations testing the effect of major assumptions with a focus on the climate change impact reduction, which were introduced in Section 3.3.

5.1 Fuel Supply

Upstream fuel production is subject to large variability; however, it has a very high impact on many environmental effects. The cases so far were modelled conservatively using data for fuel supply from the ecoinvent database. In this sensitivity assessment, impacts are compared to more optimistic assumptions for fuel supply, e.g., given in the FuelEU Maritime regulation [24], similar to assumptions by Sphera. Thus, the FuelEU Maritime upstream climate change impacts for MGO and LNG are used as more optimistic substitutes, see Table 5.1-1. The results are collected in Table 5.1-2. For the full life cycle reduction increases by 2%-pts for the Sleipnir and 2.8%-pts for the LNG carrier. Hence, using low-emission upstream fuels can improve the emissions in general and benefits the operation of the SBCC system.

Table 5.1-1. Scenario upstream fuel supply: Assumptions CO_2 equivalent emissions per kg fuel supply (WtT)

Assumption	Source	WtT LNG kg $CO_{2\text{-}Eq}$/kg	WtT MGO kg $CO_{2\text{-}Eq}$/kg
Conservative	Ecoinvent 3.9.1	1.1	0.8
More optimistic	FuelEU Maritime	0.9	0.6

Table 5.1-2. Scenario upstream fuel supply: Climate change impacts per FU for Sleipnir and LNG carrier for the full life cycle

Assumption		Sleipnir kt $CO_{2\text{-}Eq}$/FU	LNG carrier kg $CO_{2\text{-}Eq}$/FU
Conservative	BM	8.27	98.54
	SBCC	5.06	54.81
	red (%)	**38.8**	**44.4**
More optimistic	BM	7.91	94.17
	SBCC	4.68	49.76
	red (%)	**40.8**	**47.2**

5.2 Methane Slip

As the Sleipnir’s 4-stroke engines are prone to high methane slip, especially at its low loads, the discussion among the project partners concerning possible methane slip reduction measures has been addresses in two scenarios. While the base case assumes conservative methane slip as it is right now two improvement scenarios have been investigated: Choosing a approx. 3% fuel slip, achievable via direct engine measures, and an optimistic 0.1% fuel slip which would be in line with switching the engine to a 2-stroke like the LNG carrier engine.

The results for the climate change impacts of the base case and the two scenarios for on-board and full life cycle stages are collected in Table 5.2-1. For comparison, the LNG carrier base case in included as well, which methane slip assumptions align with the 0.1% scenario. A reduction in methane slip already strongly affects the benchmark operation, which combined with the good heat availability of the Sleipnir leads to a strongly improved performance of the capture unit even outperforming the LNG carrier results. However, as the capture system only reduce CO_2 emissions, any remaining methane emissions on-board and upstream emissions for the full life cycle reduce the overall climate change improvement. In addition, the heat availability considerations are not adapted to the different engine measures and types and could potentially increase the required additional heat for the capture system. Such effects are, however, not taken into account in this scenario.

Table 5.2-1. Scenario methane slip: Climate change impacts per FU for Sleipnir and LNG carrier on-board and full system cases, and the resulting reduction shares.

Assumption		**Sleipnir kt $CO_{2\text{-}Eq}$/FU**		**LNG carrier kg $CO_{2\text{-}Eq}$/FU**	
		On-board	Full system	On-board	Full system
Conservative	BM	6.61	8.27		
	SBCC	2.94	5.06		
	red (%)	**55.5**	**38.8**		
4-Stroke 3%	BM	5.83	7.49		
	SBCC	2.16	4.28		
	red (%)	**62.9**	**42.9**		
2-Stroke 0.1%	BM	5.24	6.90	74.06	98.54
	SBCC	1.54	3.66	18.33	54.81
	red (%)	**70.6**	**47.0**	**75.2**	**44.4**

5.3 100 LNG

A 100 LNG scenario has been investigated for the Sleipnir, where the power demand given in the operational profile if fully supplied by the engines running on LNG.

When designing the case, a significant improvement in performance was expected for more LNG based operation. However, translating all MGO operation strictly to LNG operation also includes very low load operation, which is better handled using MGO as fuel with lower methane slip. Therefore, a 100 LNG scenario is even more strongly affected by methane slip already in the benchmark operation, lowering the reduction shares compared to the 50 MGO -50 LNG case. This is already visible in the absolute benchmark emissions, which are increased in the conservative base case from 8.27kt $CO_{2\text{-}Eq}$/FU to 9.18 kt $CO_{2\text{-}Eq}$/FU.

The results and reduction shares including the methane slip scenario considerations are collected in Table 5.3-1. With an improved methane slip, this flips for the on-board operation, as the LNG case also performs better with higher capture rate and slightly lower additional energy demand for capture. The full life cycle results however are still lower, as with higher LNG demand also the higher upstream fuel emissions like for the LNG carrier case play a role. For the engine swap case to two-stroke engine emissions the 100 LNG scenario Sleipnir would also outperform the LNG carrier, due to the higher heat availability on the Sleipnir with a lower base heat demand. Though with a different engine, this heat availability would potentially also reduce, such effects are, however, not taken into account in this scenario.

For the 50-50 operation case, the NOx-related impact categories show a decrease leading to an overall slight reduction in the impacts because of operating the engines at a slightly higher, thus less inefficient load for MGO operation. This effect is not observed for the 100 LNG scenario, with much lower NOx contribution overall, including low loads. Therefore, all non-climate change impact categories show an increase in burdens using LNG only. The burden shifting observed for the Sleipnir is very similar to the LNG carrier case, see Table A.4-1 in the Appendix A.4.

Table 5.3-1. Scenario 100 LNG Sleipnir incl. methane slip changes: Climate change impacts for 100% LNG operation of the Sleipnir and LNG carrier on-board and full system cases, and the resulting reduction shares.

Assumption		**Sleipnir 100 LNG kt $CO_{2\text{-}Eq}$/FU**		**LNG carrier kg $CO_{2\text{-}Eq}$/FU**	
		On-board	Full system	On-board	Full system
Conservative	BM	7.35	9.18		
	SBCC	3.72	6.01		
	red (%)	**49.3**	**34.5**		
4-Stroke 3%	BM	5.72	7.56		
	SBCC	2.09	4.38		
	red (%)	**63.4**	**42.0**		
2-Stroke 0.1%	BM	4.45	6.29	74.06	98.54
	SBCC	0.76	3.05	18.33	54.81
	red (%)	**83.0**	**51.6**	**75.2**	**44.4**

5.4 CO_2 Venting

The effectiveness of CO_2 capture was optimised by improving heat integration and fuel consumption as well as targeting low venting rates of 0.5% during liquefaction. The effects of these venting rates on the overall system performance are investigated in this scenario and shown in Table 5.4-1. An increase of venting to at times 10%, for achieving very high purity without recirculation systems, strongly impacts the reduction shares. The shares are decreased by 6%-pts for the Sleipnir and even 6-8%-pts for the LNG carrier. This leads to the conclusion that the better the on-board carbon capture system performs, the worse it is to have high liquefaction venting and makes a strong argument to use recirculation systems aiming for low venting rates.

Table 5.4-1. Scenario CO_2 Venting: Climate change impacts for Sleipnir and LNG carrier on-board and full system cases, and the resulting reduction shares.

Assumption		Sleipnir kt $CO_{2\text{-}Eq}$/FU		LNG carrier kg $CO_{2\text{-}Eq}$/FU	
		On-board	Full system	On-board	Full system
Optimized 0.5% venting	BM	6.61	8.27	74.06	98.54
	SBCC	2.94	5.06	18.33	54.81
	red (%)	**55.5**	**38.8**	**75.2**	**44.4**
High venting 10%	BM	6.61	8.27	74.06	98.54
	SBCC	3.32	5.42	24.49	60.61
	red (%)	**49.7**	**34.4**	**66.9**	**38.5**

5.5 Shore Power

For the Sleipnir, the option to connect to shore power instead of running the engines at specific times when in the Caland Canal and operating below 8MW cumulative load is investigated. While the base case considers fully fuel-based power production, the shore power scenarios use either Dutch grid mix electricity or surplus renewable energy, quantified as zero-emission electricity. With these cases, the boundaries of potential effects of using shore power are explored. Using normal renewable electricity comes with environmental impacts depending on the energy system and technology mix, but at much lower impacts than normal grid electricity.

The results are compiled in Table 5.5-1 for the on-board and full system cases. Replacing low-load operation has the potential to lower the methane emissions of the operation, which is visible in the reduced absolute emissions in the CH_4 column. Significant reduction in absolute GHG emissions as well as methane emissions for the benchmark operation are observed when switching to shore power. However, on-board carbon capture performance using grid electricity from shore power shows much lower reduction potential. Even when using zero-emission shore power reduction potentials are slightly lower. This is attributed to the design and operation of the system, as using shore power removes many opportunities for the capture system to run on the complete amount of flue gas. In addition, times with higher cumulative powers are retained where capture operation can only be performed on a fraction of the resulting flue gas. Using grid electricity as shore power replacement also introduces a GHG emission base level that cannot be influenced at all using the capture system, which in turn leads to a strongly lowered reduction potential.

In summary, using renewable shore power reduces the absolute emissions and is therefore a good choice for ship operation where possible, but it would also need to be taken into account when designing and sizing the capture unit to ensure complementing design operation ranges for both.

Table 5.5-1. Scenario Shore Power: Climate change impacts and methane emissions for Sleipnir operating on fuel only, with grid shore power and with surplus renewable energy for on-board and full system cases, and the resulting reduction shares.

Assumption		Climate Change kt $CO_{2\text{-}Eq}$/FU		CH_4 t CH_4/FU	
		On-board	Full system	On-board	Full system
Fuel-based	BM	6.61	8.27	47.02	68.86
	SBCC	2.94	5.06	48.24	72.11
	red (%)	**55.5**	**38.8**	**-2.6**	**-4.7**
Shore Power	BM	6.32	7.74	41.7	60.27
Grid	SBCC	3.25	5.07	42.7	63.12
	red (%)	**48.6**	**34.4**	**-2.5**	**-4.7**
Shore Power	BM	5.64	7.06	40.33	58.93
Surplus	SBCC	2.57	4.40	41.38	61.78
	red (%)	**54.4**	**37.7**	**-2.6**	**-4.8**

6 Utilization

The CO2 pathway climate change impacts for utilization are compared to the base case of storage and the benchmark ship operation. First, the impacts for the utilization processes are discussed as an addition to the SBCC operation and upstream impacts similarly to the storage case. In a second step, the produced fuels are credited to the system as negative conventional production impacts, allowing for a comparison between reduction shares for LNG and Methanol pathways compared to the benchmark and storage operation.

6.1 Absolute Impacts for Utilization

Utilization of the CO_2 in LNG or MeOH production leads in first instance to 3 different systems, one including only the ship operation, and two including the ship operation and the products, either LNG or MeOH. These systems are not directly comparable as their functions are not the same anymore, a comparison via substitution approach is discussed in Section 6.2. The amounts of produced fuels and treated CO_2 are collected in Table 6.1-1. The climate impacts of the isolated production processes are collected in Table 6.1-2, showing rather high impacts especially for LNG production using current grid electricity. Even though most electricity is supplied from wind energy with about 26kWh, the liquefaction share of almost 2kWh grid electricity takes up about half of the LNG impacts. Therefore, the scenario with only wind energy has been investigated, showing much lower impacts. The observation is in line with the results of the original literature source, which included a more renewable based future electricity mix of 2030.

Figure 6.1-1 shows the associated climate impacts for the full system including these different utilization routes and the alternative electricity scenarios. The systems including the utilization products all show much higher impacts than the storage pathway but need the substitution approach in Section 6.2 to be comparable systems.

Table 6.1-1. Consumption of CO_2 and production amounts for CO_2 utilization pathways into LNG and methanol

Type (kt)	Sleipnir / FU	LNG carrier / 10E5
CO_2	4.01	6.45
LNG	1.47	2.37
MeOH	2.90	4.67

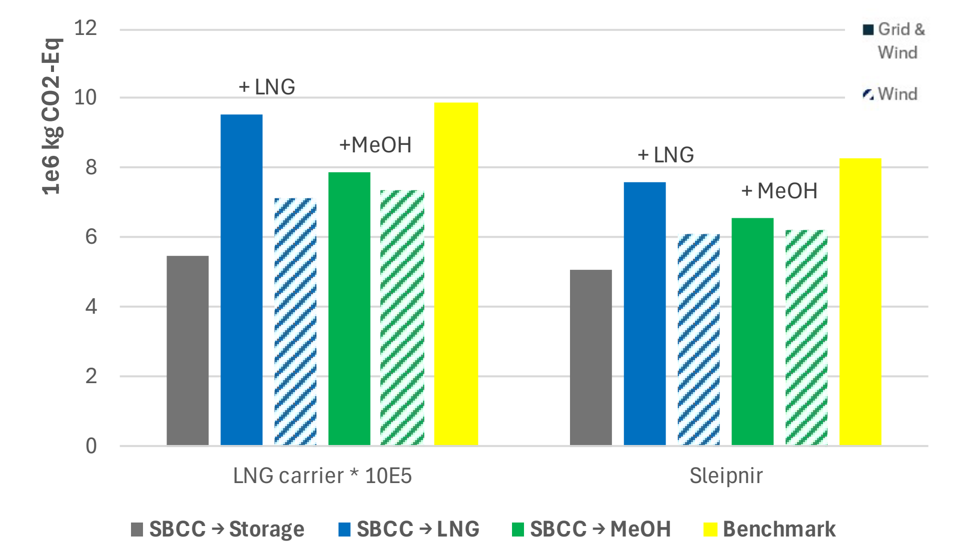

Figure 6.1-1 Absolute impacts of CO_2 Pathways with storage and utilization and the benchmark ship operation for the LNG carrier and Sleipnir. The pathways include the impacts for the additional fuels, LNG and Methanol (MeOH), which are synthesized from the captured CO_2. Electricity supply for the used Hydrogen is assumed to be from wind turbines. Electricity supply for the synthesis and liquefaction are provided either from grid or also from wind energy. Above the respective utilization bars, the difference in system functions is highlighted, as the utilization impacts include the produced fuels. The amounts are collected in Table 6.1-1.

Table 6.1-2. Substitution processes for produced LNG and methanol and their associated climate change impacts. For comparison the modelled utilization process using grid & wind and only wind electricity as well as the results for 2030 from Charalambous et al. [8, 9] are included for each product.

Climate Impact ($CO_{2\text{-}Eq}$ / kg product)	LNG	MeOH
Substitution	1.07	0.76
	LNG in Rotterdam, this study	Market for methanol, ecoinvent 3.9.1
Utilization process		
Grid & Wind	1.81	0.56
Wind	0.78	0.45
Charalambous et al.	0.83	0.43

6.2 Impact substitution approach for Utilization

The substituted processes in Table 6.1-2 times the production amounts of MeOH and LNG as given in Table 6.1-1 result in the negative impacts credited to the utilization pathways shown in Figure 6.2-1. The reached reduction shares compared to the ship benchmark are indicated above the impact bars, showing a larger reduction potential for MeOH than LNG. The pronounced impacts for the LNG production pathway based on grid electricity case are again related to the high liquefaction energy and the high grid electricity emissions. The results for fully renewable wind electricity of 45 LNG to 62% MeOH reduction are similar to the findings for the circularity approach of Charalambous et al. who find 65% reduction for their LNG ship and 55% reduction for their methanol ship. However, the performance order on the products is switched. This could be an effect of the choice of substitution process, as the results are highly dependent on this choice. In addition, the different system boundaries are likely to play a large role, as Charalambous et al. model different ships a fuel cycle sustained by carbon capture and direct air capture CO_2.

When comparing the various CO_2 pathways, apart from the grid-based electricity LNG production, all utilization routes seemingly outperform storage. However, the permanence of CO_2 storage is not considered, as the combustion of the products is not included in the system boundaries. The effect of ultimate combustion and re-release of the captured carbon from the utilization products does need to be taken into consideration, while the permanent storage does not face similar difficulties. This underlines the importance of potentially re-capturing CO_2 from utilization products and thus leads to circular approaches as discussed by Charalambous et al.

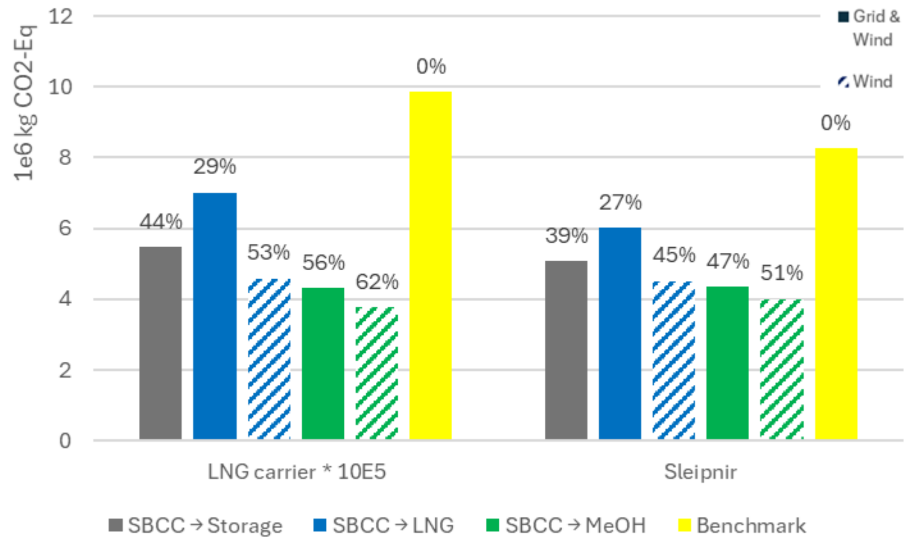

Figure 6.2-1 CO2 pathway impacts reduced by the substituted fuels compared to the benchmark ship operation for LNG carrier and Sleipnir. The pathways include the production impacts for the additional fuels, LNG and Methanol (MeOH), which are synthesized from the captured CO2, and are reduced by the avoided impacts of substituted fuel production collected in Table 6.1-2. Electricity supply for the used Hydrogen is assumed to be from wind turbines. Electricity supply for the synthesis and liquefaction are provided either from grid or also from wind energy. The reduction shares for the respective pathways are displayed above the bars.

7 Limitations

The largest contributions to all impacts of the full chain systems lie either in the on-board fuel combustion or the upstream fuel production, which is modelled conservatively in the base case. For the impact category climate change, which this study is centred around, a sensitivity analysis has been conducted using alternative upstream fuel impacts to determine the overall variation in reduction shares, leading to around 2%-pts improvement for more favourable fuel production scenarios. However, the real-life supply systems most likely look different to the more generic supply systems.

Similarly, a screening of the effect of future methane slip reductions has been implemented, showing their strong effects in the Sleipnir case. Variation of the assumptions for all other emissions or fuel consumptions have not been considered even though they are all subject to uncertainty and variability.

Additionally, the functional unit is based on a specific real-life operational profile for each ship and thus can be subject to change due to changing circumstances or operational emissions. Even though NOx emissions dominate quite many impact categories, the expanded use of an SCR system has not been investigated, as it is in reality used only frequently when near to the shore to comply with Tier III emission regulation.

The reduction shares are determined when compared to the benchmark system, however the chosen system boundaries exclude e.g. ship construction which would lead to lower overall reductions if included because the unaffected baseline increases. However, in most cases system construction plays a minor role especially in the climate impacts if the long system lifetime is allocated to the functional unit.

The two cases considered present two different approaches how capture units can be installed. For the Sleipnir a retrofit approach was assumed. The results represent an optimized integrated system, relying heavily on the equipment situation as it is right now. The assumption of a newly-built capture system on an LNG carrier provides much more freedom in setting the unit and additional equipment. Especially results concerning SBCC construction need to be interpreted against this background.

All results shown in this report describe the impacts of SBCC installation compared to the related benchmark operation. Thus, climate change reduction values calculated here cannot be compared to IMO's future reduction targets for the maritime sector, because the system boundaries are diverging. While the targets are set WtW for the entire shipping fleet, EverLoNG specifies only on LNG fuelled ships fulfilling specific functions, considering also CO_2 pathways.

8 Conclusions

The study assesses the CO_2 and GHG emission mitigation potential for deploying full-scale carbon capture systems on-board of the crane ship Sleipnir and an LNG carrier, its main drivers and hindrances as well as potential impacts on other environmental effects. In both cases, on-board CO_2 reduction rates above 70% have been verified, considering detailed emissions modelling on real-world operational profiles spanning two years of operations for each ship provided by project partners. Including upstream emissions for the used fuel, the complete SBCC system construction, solvent operation as well as port operations and CO_2 pathways leads to an overall reduction of climate change impact of 39% to 44%. The contributions highlight that next to the upstream emissions of the fuel supply as main contributor, each part of the subsequent chain adds impacts to an overall visible amount for many environmental impacts. Methane slip for LNG engines and upstream fuel emissions for LNG supply have been determined key factors limiting the achievable climate change impact reduction. This aligns with the recent findings of Oh et al.[25], comparing different engines and fuels with SBCC. It underlines the necessity to include more GHGs than CO_2 as well as the complete upstream and downstream impacts when assessing mitigation technologies. This is also increasingly reflected in guidelines such as the LCA guideline of the MEPC [17] and partly in the FuelEU Maritime [24] regulation. This study finds lower impact reductions compared to previous studies on SBCC, such as Oh et al. [25] and Negri et al.[26], which is attributed to higher upstream emission assumption, inclusion of port operations and CO_2 pathways and determining performance, based on the real-life operational profiles of the two ships, instead of a fixed, high engine load. In addition, the fully integrated SBCC systems on board include construction and power consumption for piping and sea water cooling systems. Overall, the comparability of the reduction shares is limited, as this assessment considers two specific cases of ship operation compared to their benchmarks, instead of an often-applied heavy fuel oil ship as benchmark or as is the case for the IMO reduction targets, the whole shipping fleet in 2008. Similarly, the reduction shares are estimated to be lower than for most alternative fuels currently under development, if their requirements for sustainable production and use are fulfilled. Such comparisons need to be made with the uncertainty of the results in mind. Investigation of utilization pathways of CO_2 as an alternative to permanent storage showed similar potential to the storage case. However, it also highlighted the need to consider permanence of CO_2 reduction and its re-release during combustion of utilization products in such a comparison, which was not part of the system boundaries of this study.

Burden shifting to other environmental impacts, due to higher fuel demand causing higher NOx emissions or ammonia as a degradation product of the capture process, can be observed for all environmental effects considered, though no unexpected or unreasonable shifts were noted. Especially for the NOx driven impacts, such as acidification and eutrophication, the ship operation emissions outweigh additional emissions of ammonia from the capture system. However, reduction potentials in other impact categories than climate change rely heavily on measures out of the scope of the capture system operation itself: cleaner combustion, e.g. via SCR NOx scrubbing, and lower burdens in fuel production.

The main drivers of impacts were investigated via scenarios on upstream fuel emissions, methane slip, fuel type and CO_2 venting. Most scenarios were chosen more optimistic, as the base case was already chosen conservatively, resulting in more reduction efficiency of the capture system. Only venting during liquefaction was investigated as potential driver of efficiency loss if not optimised to lowest venting. For future scenarios, increasing reduction potentials are projected with improving methane slip of ship engines and lowered upstream fuel emissions [18].

It was shown here that applying SBCC, at full-scale and integrated on-board, can have a tangible climate mitigation effect, underlining the usefulness of SBCC as a short-term transition measure for fossil-based ships already in operation and those still making up the largest part of newly ordered ships. As two detailed integration designs, operation cases and operational profiles were analysed, it became evident that the results for SBCC are not generalizable for application on every ship. Whether retrofitting a SBCC system can be reasonable depends highly on the type of vessel, operation and heat availability as well as space availability for the capture system and CO_2 tanks and ultimately access to necessary CO_2 and solvent port infrastructure. However, where possible and economically viable, SBCC can play a role in bridging the transition to a fleet based on more readily available and sustainably produced alternative fuels.

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A Appendix (Public)

A.1 Normalization Factors for Impact Assessment

Table A.1-1 EF3.1 Normalization factors [4]

Impact categories considered	Unit	NF
Climate change	kg CO_2 eq./PE	7.55E+03
Acidification	mol H+ eq./PE	5.56E+01
Particulate matter	disease incidences/PE	5.67E+04
Eutrophication, marine	kg N eq./PE	1.95E+01
Eutrophication, terrestrial	mol N eq./PE	1.77E+02
Photochemical ozone formation	kg NMVOC eq./PE	4.09E+01
Human toxicity, non-cancer	CTUh/PE	1.29E-04
Ecotoxicity, freshwater	CTUe/PE	5.67E+04
Resource use, fossils	MJ/PE	6.50E+04
Resource use, minerals and metals	kg Sb eq./PE	6.36E-02
Water use	m^3 water eq of deprived water/PE	1.15E+04

A.2 Upstream Fuel

A.2.1 LNG

A.2.1.1 Natural Gas Production and Sweetening

The ecoinvent processes of onshore and offshore natural gas production include the production of natural gas and oil as well as the transportation to onshore and sweetening. Transport to liquefaction is included as onshore pipeline transport where necessary, which includes gas leakage in Europe and North America of 0.019%, and 0.204% in other regions of the world [12]. Additionally, pipeline transport uses compressors, which in turn require additional energy from burning natural gas. This is also adapted to the country of origin, where not already available in the ecoinvent database, country proxies are defined according to their respective production shares onshore and offshore as well as their geographical proximity.

Combined production of oil and gas are allocated via energy content and annual production. The final product is high pressure dry natural gas ready to be further transported, e.g., via pipeline [12].

A.2.1.2 Liquefaction

The liquefaction of natural gas to LNG in ecoinvent is assumed to use up 8.6% of the natural gas. The common procedure is to release the separated CO_2 into the air. The leakage during the process is assumed to be 0.05% [12].

A.2.1.3 LNG Ocean Transport

In ecoinvent the LNG delivery to Europe's regasification plants is already included for the origin countries United States, Russia, Nigeria, Qatar and Algeria. Other relevant origin routes are modeled following these examples, considering the onshore and offshore production ratio and distances of sea transport port-to-Rotterdam.

For consistency, the sea transport distances of the available countries of origin are reassessed.

The ocean transport is modelled using a HFO fueled tanker for LNG, as described in ecoinvent [12].

LNG import shares in the Netherlands

To represent the LNG mix at the Port of Rotterdam, the eurostat LNG import mix of 2021 for the Netherlands is used [10], see Figure A.2-1.
Countries that are not included in ecoinvent as LNG import to Europe processes are modelled accordingly, using their own estimated onshore-offshore gas production shares and sea shipping transport distances to Rotterdam. The onshore-offshore production ratios are estimated based on gas production and reserve maps, gas field production values and pipeline connection to LNG terminals. Where no country specific gas production dataset is included, proxies for gas production are chosen based on geographical proximity and similar onshore/offshore shares. The estimates are collected in Table A.2-1.

LNG export ports are chosen, mainly based on the presence of LNG terminals. The transport distances to Rotterdam are estimated from sea-distances.org [27]. Ecoinvent implemented transport distances are determined according to [28], see Table A.2-2.

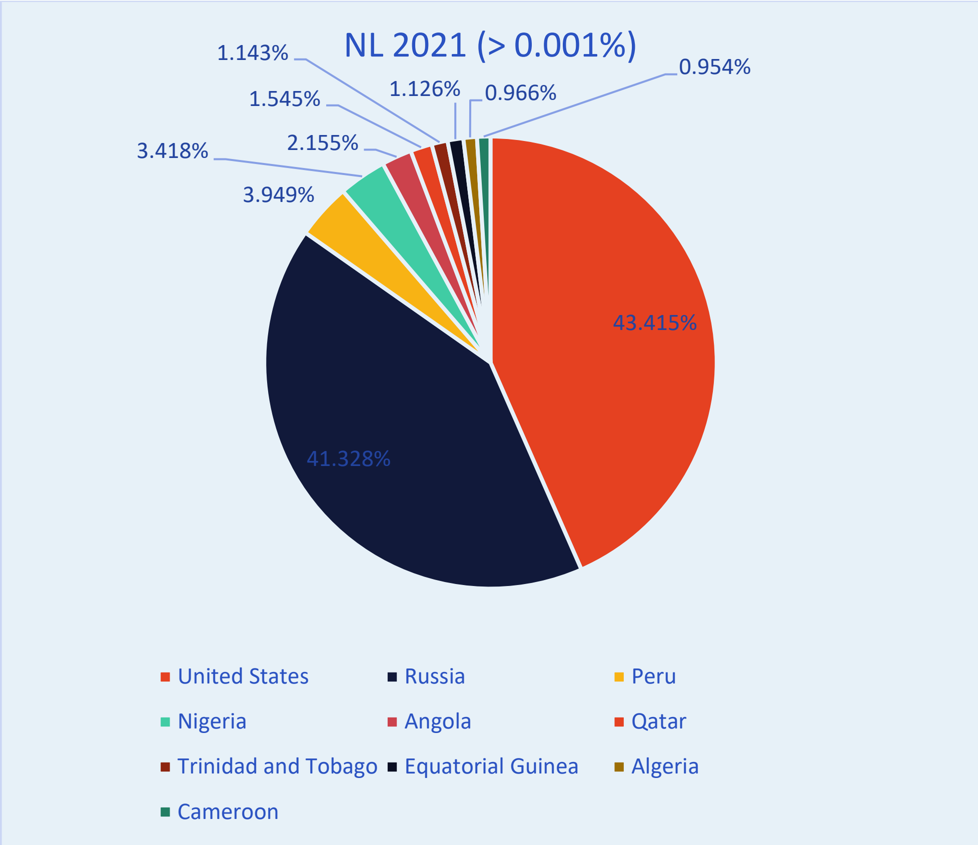

Figure A.2-1 Dutch LNG import countries of origin with a contribution above 0.001% [10]

Table A.2-1 Natural gas production types and country proxies selected for Dutch LNG supplying countries

Country	2021 import %	Onshore	Offshore	Proxy	ecoinvent database
United States	43.415%	97%	3%		US
Russia	41.328%	82%	18%		RU
Peru	3.949%	100%	0%	EC onshore gas	
Nigeria	3.418%	10%	90%		NG
Angola	2.155%	25%	75%	NG	
Qatar	1.545%	31%	69%		QA
Trinidad and Tobago	1.143%	0%	100%	VE offshore gas	
Equatorial Guinea	1.126%	0%	100%	NG offshore gas	
Algeria	0.966%	100%	0%		DZ
Cameroon	0.954%	25%	75%	NG	

Table A.2-2 Transport distances to Rotterdam for Dutch LNG supplying countries. [27]

Country	offshore pipeline [km]	onshore pipeline [km]	port	sea transport [km]
United States	20	1120	Port Arthur	9700
Russia	20	3500	St. Petersburg	2406
Peru	0	540	Pisco	11653
Nigeria	200	140	Lagos	7800
Angola	200	100	Cabinda	8934
Qatar	200	100	Doha	11747
Trinidad and Tobago	200	0	Port Fortin	7502
Equatorial Guinea	200	0	Malabo	8299
Algeria	0	100	Algiers	3300
Cameroon	200	100	Limboh Terminal	8340

A.2.1.4 LNG Terminal and Bunkering

The description in the Sphera study on GHG emissions of marine fuels [18] provides both Electricity consumption and methane emissions of LNG terminals and bunkering. Terminals use power to transfer the delivered LNG from incoming vessel to bunker storage, which also results in small amounts of gas emissions. Storage of LNG during bunkering always requires the BOG to be processed, either delivered to regasification, used for gas power production directly or reliquefied and sent back to the tank as in this case. All such operations lead to gas losses, collected in Table A.2-3 from multiple sources.

Table A.2-3 LNG terminal operation and bunkering gas losses estimated from multiple sources: Sphera 2021 [18], ICCT 2013 [29], Balcombe et al 2021 [30], Bengtsson et al 2011 [31].

LNG Terminal	Boil off rate (%/day)	release rate [%]	release [%]	Electricity [kJ/kg LNG and day]	Duration [days]	comment
LNG Receiving at Import Terminal						
Sphera 2021	-	-	1.50E-03	-	total	
ICCT 2013	0.13	5	0.0065	-	total	
LNG Bunkering			**release [%/day]**			
Storage at Import Terminal and Vessel Fueling						
Sphera 2021	-	-	0.0361	4.456	3	Assumed duration
ICCT 2013						
Storage	0.05	5	0.0025	-	5	
Fueling	0.22	5	0.011	-	total	
Balcombe et al 2021						
Storage	0.13	10	0.013	-	1	0-2
Fueling	0.22	50	0.11	-	total	
Bengtsson et al 2011						
	0.2	-	-	4.157	10	

The energy consumption found in the Sphera 2021 report is consistent with the assumptions from Bengtsson et al 2011 [31] where a 10-day terminal operation and storage is accounted for with $0.85 kJ/MJ_{[LHV]}$ = 41.565kJ/kg LNG which translates to 4.2 kJ/kg daily.

During typical 21-day LNG cargo transport, a boil-off rate of 0.1-0.15% of the full cargo content per day is assumed in Bengtsson et al 2011 [31]. Similarly, an assumption of 0.05% boil-off rate during bunker storage is found in the ICCT white paper [29]. The stated 0.13% are assumed to represent the boil-off rate in Balcombe et al 2021 [30]. They conservatively assume that during storage, 10% of the BOG is released, which leads to 0.013% gas emission per day. No flaring is assumed to take place at the terminal but rather the BOG is recaptured and reliquefied. In addition, they assume that 0.22% are either boiled off or released as fueling vapor, with a capture rate of 50%. This can be summed up to 0.11% gas emissions during bunkering. In this case, the ICCT white paper assumes a capture rate of 95%.

For a 3-day LNG terminal and bunkering operation shown in Table A.2-4, a range between 0.025% and 0.149% of gas losses are extracted from the report. This range is used for scenario analysis, using the Sphera study as a standard reference case.
Electricity consumption by the LNG terminal for the 3 days is taken from Sphera 2021 as 13.368kJ/kg LNG using the energy mix of the Netherlands included in ecoinvent.

Table A.2-4 Total gas release and power consumption for terminal operation and bunkering estimated from multiple sources: Sphera 2021 [18], ICCT 2013 [29], Balcombe et al 2021 [30]

Total	release [%]	Electricity [kJ/kg LNG]	Duration [days]
Sphera 2021	**0.110**	**13.368**	**3**
ICCT 2013	0.025		3
Balcombe et al 2021	0.149		3
Sphera 2021	**0.038**	**4.456**	**1**
ICCT 2013	0.020		1
Balcombe et al 2021	0.123		1

For transporting the fuel to the ship, a standard tanker barge burning diesel fuel is assumed. No LNG-fuelled bunker barge was available in the ecoinvent database, and the effect of the barge on the overall upstream emissions is estimated to be negligible when compared to the long-distance sea transport or fuel production.

A.2.1.5 LNG Carrier LNG supply

The LNG carrier is assumed to run on its LNG cargo, such that the sole supply of LNG is from the US, represented by the ecoinvent process ‘production of natural gas, liquefied’. Consequently, no ship transport for the LNG is considered. The bunkering is assumed to follow the same pattern per kilogram LNG as for the fueling in Rotterdam.

A.2.2 MGO

The ship operating with MGO, the Sleipnir, is based in Rotterdam. Therefore, the fueling of MGO in Rotterdam is considered primarily in this study. The pilot fuel MGO used in the LNG Carrier is then adapted according to the conditions at Port Arthur.
MGO is produced from refining crude oil imported to Rotterdam. The crude oil import is represented by Dutch import shares. At port, the crude oil is received at the oil terminals, transported to the refineries at-port via pipeline and refined in one of the refineries. The finished MGO product is bunkered to ship tank completing the upstream description of MGO.

A.2.2.1 Crude oil production and transport to refinery

The ecoinvent 3.9.1 process represents the trade statistics of 2019 for both origin countries and transporting distance allocated to 1kg of crude “petroleum” oil delivered to European refineries. International trade of crude oil has changed drastically in the last years, in large parts due to the war in Ukraine. The BP/EI trade statistics of crude oil for 2021 and 2022 show a sharp decrease in Russian oil imports to Europe. However, these statistics do not include intra-European trade.

For representing the crude oil import to Rotterdam, Dutch import shares from eurostat [11] of the year 2021 are used, see Figure A.2-2. All countries of origin contributing at least 0.001% of the total imports are included, which leaves only 6E-6% of Eurostat data unaccounted for. The resulting import distribution is shown in Figure A.2-3, including local crude oil production of the Netherlands.

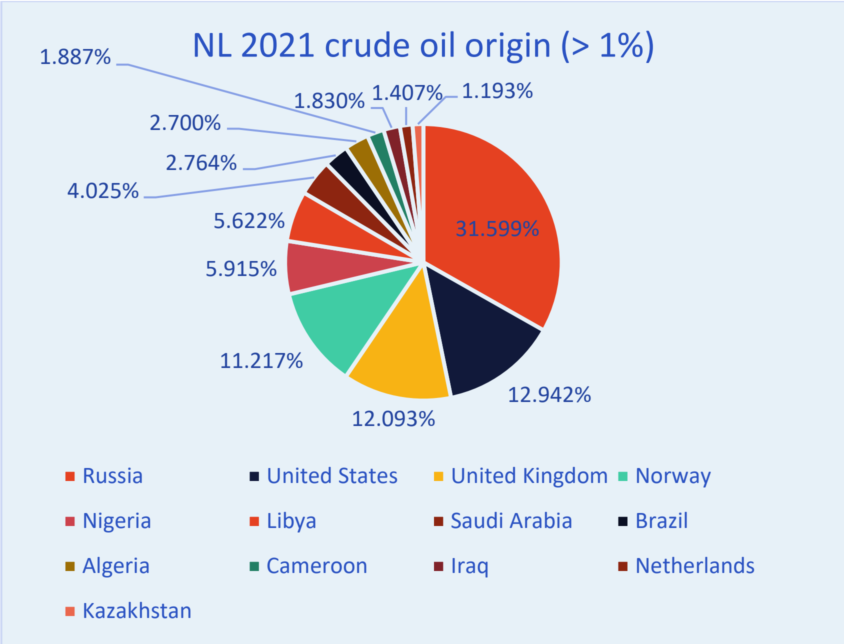

Figure A.2-2 Dutch crude oil import countries of origin with a contribution above 1% [11]

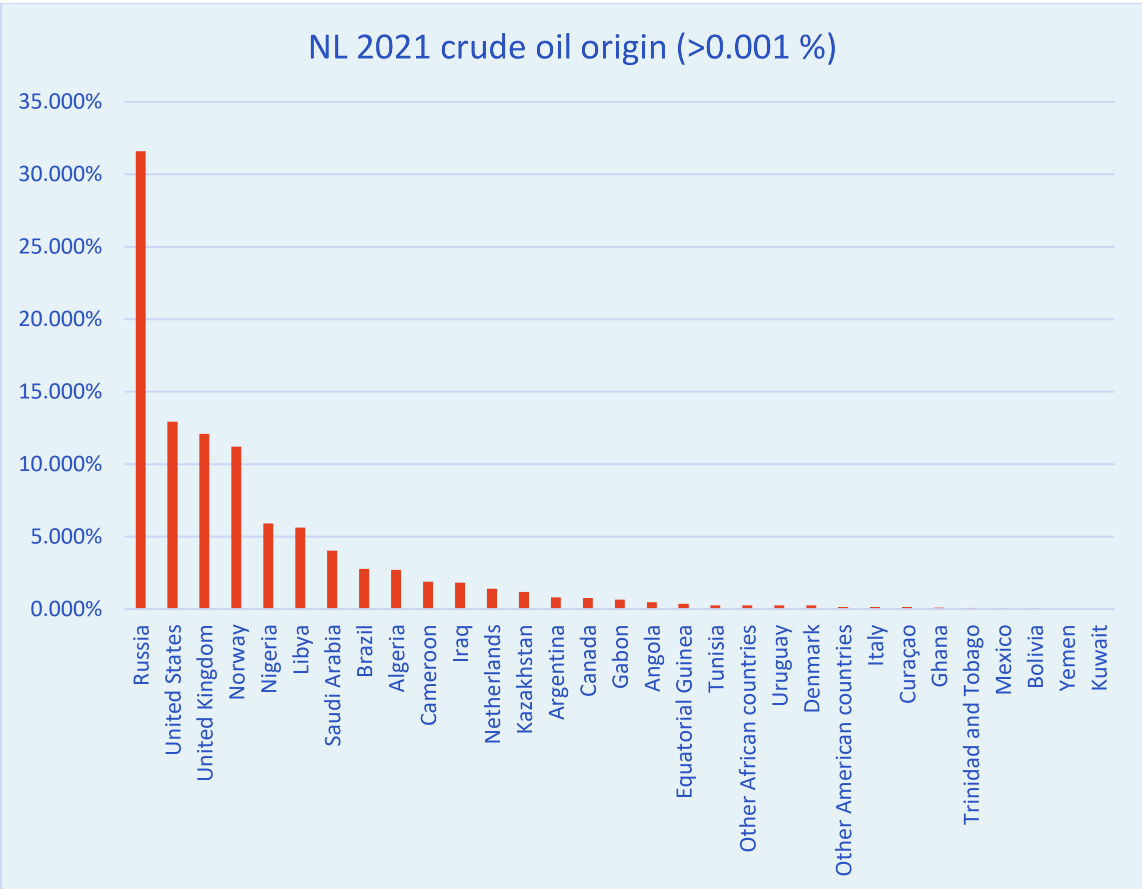

Figure A.2-3 Dutch crude oil import countries of origin with a contribution above 0.001% [25]

Not all countries of origin are included with specific petroleum production data in the ecoinvent database. In these cases, proxy production data is chosen based on geographic and political closeness and onshore/offshore focus. As there is no general database on the shares of onshore and offshore petroleum production, the production ratios of the recent years (2019-2021) are roughly estimated from government data, resource maps, oil field data and other, where available. The collected production shares are shown in Table A.2-5.

Table A.2-5 Crude oil production types and country proxies selected for Dutch crude oil supplying countries.

Country	2021 import %	Onshore	Offshore	Proxy	ecoinvent database
Denmark	0.259%	0%	100%	GB offshore	
Italy	0.145%	100%	0%	DE onshore	
Norway	11.377%	0%	100%		NO
United Kingdom	12.265%	2%	98%		GB
Russia	32.050%	82%	18%		RU
Angola	0.481%	25%	75%	NG	
Cameroon	1.914%	25%	75%	NG	
Equatorial Guinea	0.362%	0%	100%	NG offshore	
Gabon	0.654%	50%	50%	NG	
Algeria	2.738%	100%	0%		DZ
Libya	5.703%	80%	20%		LY
Tunisia	0.270%	60%	40%	LY	
Ghana	0.109%	0%	100%	NG offshore	
Nigeria	5.999%	10%	90%		NG
Other African countries	0.266%	39%	61%	NG	
Canada	0.768%	93%	7%		CA
United States	13.126%	85%	15%		US
Curaçao	0.143%	0%	100%	VE offshore	
Trinidad and Tobago	0.072%	0%	100%	VE offshore	
Mexico	0.059%	3%	97%		Mx
Argentina	0.815%	68%	32%	BR	
Bolivia	0.054%	100%	0%	BR onshore	
Brazil	2.803%	3%	97%		BR
Uruguay	0.259%	3%	97%	BR	
Other American countries	0.146%	43%	57%	VE offshore and BR onshore	
Kazakhstan	1.210%	87%	13%		KZ
Iraq	1.856%	100%	0%		IQ
Kuwait	0.002%	99%	1%		KW
Saudi Arabia	4.082%	67%	33%		SA
Yemen	0.011%	100%	0%	SA onshore	

Following the approach in Meili et al 2021 [28], as used in ecoinvent, the transport distances offshore and onshore to a selected port are determined. Sea transport distances that are not directly available from this source are estimated using sea-distances.org [27] from port of origin to Rotterdam, NL, see Table A.2-6.

Table A.2-6 Transport distances to Rotterdam for Dutch crude oil supplying countries. [20]

Country	offshore pipeline [km]	onshore pipeline [km]	port	sea transport [km]
Denmark	200	0	Esbjerg	532
Italy	0	350	Santa Panagia	4421
Netherlands	200	100	Rotterdam	0
Norway	200	200	Bergen	1100
United Kingdom	200	100	Southampton	500
Russia	20	3500	St. Petersburg	2406
Angola	200	100	Luanda	9217
Cameroon	200	100	Limboh Terminal	8340
Equatorial Guinea	200	0	Malabo	8299
Gabon	20	200	Port-Gentil	8395
Algeria	0	100	Algiers	3300
Libya	20	100	Sirtica Terminal	5100
Tunisia	20	250	La Skhirra	4428
Ghana	200	0	Takoradi	7151
Nigeria	200	140	Lagos	7800
Other African countries	200	110	Lagos	7800
Canada	0	4000	Saint John	5625
United States	20	1120	Port Arthur	9700
Curaçao	200	0	Puerto La Cruz, VE	7760
Trinidad and Tobago	200	0	Port of Spain	7502
Mexico	200	240	Veracruz	10000
Argentina	20	800	Puerto Rosales	12260
Bolivia	0	1368	Arica, Chile	12508
Brazil	200	100	Rio de Janeiro	9710
Uruguay	200	0	Montevideo	11564
Other American countries	200	412	Balao - Ecuador	9853
Kazakhstan	20	3400	Novorossiysk	6699
Iraq	0	970	Basrah	2900
Kuwait	0	100	Shuaiba	12149
Saudi Arabia	20	1300	Ju' aimah	12000
Yemen	0	100	Mukalla	9149

The Port of Rotterdam Port has 5 refineries, and pipeline connection from oil terminals to the refineries [32]. At port, an additional 10km pipeline transport from crude oil terminal to refinery is assumed, considering 1/4th of the full length of the Port of Rotterdam of roughly 42km.

A.2.2.2 Crude oil refinery to MGO

The refinery operation from crude oil to MGO is represented by the ecoinvent dataset light fuel oil production, petroleum refinery operation in Europe without Switzerland. This equivalency is derived from light fuel oil referring to the German ‘Heizöl EL’, a gasoil used for heating and as motor fuel in shipping, with a sulfur content of less than 0.1% [33]. This agrees well with the description of MGO, which itself meets EU port sulphur requirements of less than 0.1% sulphur content.

The crude oil/petroleum input of the refinery are modeled according to the Dutch crude oil origin shares described above.

The refinery model implemented in the ecoinvent database represents the consecutive steps during refinery operation and allocates resulting emissions and power consumption accordingly. The main driver for allocation at each step is the energy content of the respective products [34]. This is in accordance with the LCA guidelines for shipping fuels [17].

The natural gas, high pressure input for refinery is adapted to the Dutch market situation.

A.2.2.3 MGO Bunkering

For bunkering the MGO at refinery is loaded onto a bunker vessel, which then travels to the ship and fuels it via hose connection. Storage and loading are modelled following [31], where for the oil harbor Gothenburg emissions to air of 0.1709 kg NMVOC/tonne MGO loaded are assumed due to evaporation.

Barge transport via canal is described in ecoinvent in the activity ‘transport, freight, inland waterways, barge tanker’. For the port of Rotterdam 10km for bunkering is assumed, and 10km for the empty trip back. The choices are consistent with previous literature assumptions for MGO fueling [31] and following studies [35, 36] as well as the Sphera GHG study 2021 [18].

A.2.2.4 Pilot Fuel MGO for the LNG Carrier

The considerations for the LNG carrier pilot fuel MGO follow the same assumptions as for the Dutch MGO supply. As the US and Texas are large suppliers of crude oils and have numerous refineries, only US crude oil supply is considered as input the ecoinvent global refinery model. No further ship transport is considered for petroleum before bunkering.

A.3 Fuel Combustion to Operational Emissions

A.3.1 Operational Parameters and emission calculation

Total *energy-based emissions* (Em_e) are calculated from the load factor (Lf) in the operational profile and the Maximum Continuous Rating of the engine (MCR) multiplied by the energy-based emission factor ($Ef_e(Lf)$), which can vary with load and therefore with time t. All energy-based emission factors except Black carbon are either dependent on the load directly or corrected for low loads using their respective low load factors (LLf(Lf)) which also depend on the load factors.

$$Em_e = \int_{t_0}^{T} Ef_e(Lf) \cdot LLf(Lf) \cdot Lf(t) \cdot MCR\ dt$$

The load factor is often given in % with respect to the MCR of the engine.

Fuel-based emission factors need the respective fuel consumption of LNG and MGO. As the fuel consumption is dependent on the engine load and therefore the operation time $Fc(Lf)$, the total fuel consumption Fc^{total} results from the sum over all fuel consumptions at each point in time.

$$Fc^{total} = \int_{t_0}^{T} Fc(Lf) \cdot Lf(t) \cdot MCR\ dt$$

From the total fuel consumption, the fuel-based emissions Em_f are calculated by simple multiplication with the fuel-based emission factors Ef_f for the respective fuel.

$$Em_f = Ef_f \cdot Fc^{total}$$

The fuel-based emission factors for Black Carbon vary with load and therefore with time t, which means no simplification is possible. Due to its high uncertainty in impact modelling, Black Carbon is not included in the inventory.

$$Em_f = \int_{t_0}^{T} Ef_f(Lf) \cdot Fc(Lf) \cdot Lf(t) \cdot MCR\ dt$$

The fuel consumption is calculated from the given SFOC [g/kWh] and the operational profile. It is standardized to MGO equivalents following ISO standards. Therefore, the SFOC must be converted back to actual g fuel combusted. This is done by multiplying the actual LHV of the fuel divided by the ISO standard LHV. Additionally, in gas mode pilot contribution and LNG contribution need to be separated. Therefore, the pilot fuel contribution to fuel flow is subtracted after the ISO correction[1].

A.3.2 Fuel-based emissions

From the total amount of fuel used, the CO_2 emissions can be calculated by multiplication with the fuel-based CO_2 emission factors for MGO and LNG. All fuel-based emission factors are given in Table A.3-2.
Some emissions depend on the fuel sulfur content (S). S is taken from [19] for both MGO, fulfilling

[1] This is less intuitive than first removing pilot contribution and then correcting to LNG. But it is checked with MAN (source TNO) and the effect is in the range of XY% more/less LNG

the requirement of having less than 0.1% sulfur content using the MDO average 2018, and LNG. The assumed sulfur contents are also included in Table A.3-1.
Using the formula translating Sulphur content to emission factors [19], the SO_x fuel-based emission factors are determined. Here the LNG and MGO contributions are strictly separated, as the pilot fuel contribution when running on LNG is explicitly included in the calculation.

Fuel that is not combusted in the engine, taken from measured hydrocarbon slip (HC)[2] in the exhaust gas, is also subtracted before calculating the fuel-based CO_2 emissions. This is meant to keep a more consistent mass balance, as no Hydrocarbon that slipped through the engine can be combusted. In gas mode, only the HC is applied fully to LNG, as the heavier pilot fuel is assumed to be fully combusted. Following the same argument as for HC, the determined CO emissions in principle cannot contribute to the CO_2 emissions either. However, large uncertainties on the determination of the CO amounts resulted in excluding this step. This is consistent with the standard procedure of the IMO, which also explicitly considers fuel combustion and slip as the CO_2 determining factors [17].

The SO_x emissions are based on the full fuel consumption.

Table A.3-1 Fuel lower heating value (LHV) and Sulphur content (S)

Fuel	LHV [kJ/kg]	S [%]
LNG	48000	8.29E-04
MGO	42700	0.07

Table A.3-2 Fuel-based emission factors independent of engine type

Ef g/g fuel	CO_2	SO_x
MGO	3.206	1.37E-03
LNG	2.75	1.62E-05

A.3.3 Energy-based Emissions

Energy-based emission factors [g/kWh] give emissions due to fuel combustion per engine power [kW] and operational time [h].
Most energy-based emission factors are based on the IMO 2020 study [19], but for NOx and hydrocarbons Heerema has provided engine exhaust gas measurements of the Sleipnir that are used instead. The measured emission factors for NOx at higher loads agree well with the IMO 2020 study but are expected to represent the emission behavior with changing load. NOx emissions depend on a lot of conditions, such as humidity. Therefore, these emission factors are only an estimate to what happens during the actual ship operation.

In the case of gas mode operation these measurements however include both pilot fuel and LNG as emission sources. For the other cases, IMO emission factors for MGO as pilot fuel and LNG are used,

[2] HC means Hydrocarbons in general. This can include both CH_4 and NMVOC

weighted by their respective contribution to the energy provided and resulting in a modified total gas mode emission factor.

The emission factors depend on the engine type and are therefore given once for MGO burned in the Sleipnir in Diesel mode, once for LNG burned in the Sleipnir in Gas mode, see Table A.3-3 and Table A.3-4. The contributions of pilot fuel in LNG mode are included in Table A.3-5. For the LNG carrier, emission factors are collected for all engine types in Table A.3-6 to Table A.3-9.

Table A.3-3 Sleipnir LNG operation - Energy-based emission factors for LNG fuel

Emission factors [g/kWh]			Sleipnir LNG Mode*	IMO Engine: MDO MS / LNG Otto-MS		Maximum Load: 8,020kW	
Engine Load [%]	**NOx**	**CH4****	**NMVOC****	**PM10**	**PM2.5**	**CO**	**N2O**
100%				0.02	0.02	1.28	0.02
75%				0.02	0.02	1.29	0.02
50%				0.02	0.02	1.27	0.02
25%				0.03	0.02	1.24	0.02
20%***				0.03	0.03	1.24	0.02
10%***				0.04	0.04	2.42	0.03
2%***				0.22	0.20	11.81	0.10
* LNG including pilot fuel from exhaust gas measurement, emission factors weighted by energy share contributions							
** Hydrocarbon (HC) measurements are split up into 90% methane and 10% NMVOC							
*** Low load regime determined via low load factors given in the 4th IMO GHG Study [19]							
Source			Heerema	[19]			

Emission factors that differ for various engine loads are linearly interpolated to match the engine load of the respective operational profile. For very low loads, below 20%, the IMO [19] gives low load adjustment factors, which greatly increase the emissions, especially towards 2% engine load. The low load factors are already included in the presented emission factors, also for emission factors derived from measurements of the Sleipnir. The measurements of the Sleipnir only include 100%, 75%, 50% and lowest 25% loads. The low load factors are applied to the 25% load emission factor values.

Table A.3-4 Sleipnir MGO operation - Energy-based emission factors

Emission factors [g/kWh]			IMO Engine: MDO MS	Sleipnir MGO Mode		Maximum Load: 8,009kW	
Engine Load [%]	**NO_x**	**CH_4**	**NMVOC**	**PM_{10}****	**$PM_{2.5}$****	**CO**	**N_2O**
100%		0.01		0.18	0.16	0.05	0.03
75%		0.01		0.18	0.16	0.05	0.03
50%		0.01		0.18	0.16	0.05	0.03
25%		0.01		0.17	0.16	0.05	0.03
20%***		0.01		0.17	0.16	0.05	0.03
10%***		0.02		0.24	0.22	0.09	0.04
2%***		0.21		1.24	1.14	0.45	0.14
** PM depends on the SFOC, the calculation is based on the Sleipnir running exclusively on MGO as this is seen as representative of the engine operation							
*** Low load regime determined via low load factors given in the 4th IMO GHG Study [19]							
Source	Heerema	[19]	Heerema, [19]	[19]	[19]	[19]	[19]

Table A.3-5 Sleipnir LNG operation - Energy-based emission factors, weighted contributions from Pilot and LNG

Emission factors [g/kWh]			Sleipnir LNG Mode* IMO Engine: MDO MS / LNG Otto-MS			Maximum Load: 8,020kW	
Engine Load [%]	**NO_x**	**CH_4****	**NMVOC****	**PM_{10}**	**$PM_{2.5}$**	**CO**	**N_2O**
100%				0.02	0.02	1.28	0.02
75%				0.02	0.02	1.29	0.02
50%				0.02	0.02	1.27	0.02
25%				0.03	0.02	1.24	0.02
20%***				0.03	0.03	1.24	0.02
10%***				0.04	0.04	2.42	0.03
2%***				0.22	0.20	11.81	0.10
* LNG including pilot fuel from exhaust gas measurement, emission factors weighted by energy share contributions							
** Hydrocarbon (HC) measurements are split up into 90% methane and 10% NMVOC							
*** Low load regime determined via low load factors given in the 4th IMO GHG Study [19]							
Source	Heerema			[19]	[19]	[19]	[19]

Table A.3-6 LNG Carrier GCU - Fuel-based emission factors

Emission factors [mg/g fuel]	Carrier GCU Analogue: Boiler IMO, 285g/kWh fuel					
	NO_x	CH_4	NMVOC	PM_{10}	$PM_{2.5}$	CO	N_2O
	4.56	0.14	0.37	0.11	0.10	0.70	0.07
Source	[19]						

Table A.3-7 LNG carrier Main Engines - Energy-based emission factors

Carrier Main Engines* Emission factors [g/kWh]			IMO Engine: LNG-Diesel			Maximum Load: 12,590kW	
Engine Load [%]	**NO_x °**	**CH_4****	**NMVOC****	**PM_{10}**	**$PM_{2.5}$**	**CO**	**N_2O**
100%	3.40		0.40	0.01	0.01	1.02	0.03
75%	3.40		0.40	0.01	0.01	1.02	0.03
50%	3.40		0.40	0.01	0.01	1.01	0.03
25%	3.40		0.40	0.02	0.02	1.00	0.03
20%***	3.40		0.40	0.02	0.02	1.00	0.03
10%***	3.40		0.87	0.02	0.02	1.97	0.04
2%***	3.40		8.47	0.13	0.12	9.68	0.14
* LNG including pilot fuel, emission factors weighted by energy share contributions							
** Hydrocarbon (HC) measurements are split up into 90% methane and 10% NMVOC							
*** Low load regime determined via low load factors given in the 4th IMO GHG Study [19]							
° NOx emissions set to Tier III emissions due to engine SCR, not explicitly modelled							
Source	[19]	MAN CEAS file	[19]				

Table A.3-8 LNG carrier Auxiliary engines - Energy-based emission factors

Carrier Auxiliary Engines* Emission factors [g/kWh]				Maximum Load: 2,880kW			
				IMO Engine: LNG-AUX			Maximum Load: 3,840kW
Engine Load [%]	**NO_x**	**CH_4****	**NMVOC****	**PM_{10}**	**$PM_{2.5}$**	**CO**	**N_2O**
100%		5.32	0.50	0.02	0.02		0.02
75%		3.07	0.50	0.02	0.02		0.02
50%		3.93	0.50	0.02	0.02		0.02
25%		7.33	0.50	0.03	0.02		0.02
20%***		9.54	0.50	0.03	0.03		0.02
10%***		13.14	1.09	0.04	0.04		0.03
2%***		15.57	10.59	0.22	0.21		0.10
* LNG including pilot fuel, emission factors weighted by energy share contributions, Pilot modelled as MS engine emissions							
** Hydrocarbon (HC) measurements are split up into 90% methane and 10% NMVOC							
*** Low load regime determined via low load factors given in the 4th IMO GHG Study [19]							
Source	CONO Engine Sheet	[37]	[19]			CONO Engine Sheet	[19]

Table A.3-9 LNG carrier - Energy-based fuel slip

Fuel factors [g/kWh]	LNG carrier fuel slip* Main Engine	Auxiliary Engines
Engine Load [%]	**HC slip**	**HC slip**
100%		5.91
75%		3.41
50%		4.37
25%		8.15
Source	TNO_Carrier_calc based on MAN CEAS file	[37]
*no SFOC description was needed, as both LNG and Pilot consumption were reported in the operational profile, HC = CH4/0.9		

A.4 Burden Shifting to other impact categories: Overview including 100% LNG operation

Burden shifting is quantified via investigating the increase of other impact categories when introducing the capture system on-board. This is showcased in Table A.4-1, where both on-board and full life cycle benchmark (BM) and on-board carbon capture (OCC) impacts for the investigated impact categories are collected. This includes the reduction calculation, which in most cases is negative – pointing to an increase in the respective impact category. For comparability, the impacts are normalised to the average impacts of a person per year and the LNG carrier absolute reductions are quantified not only per ton LNG delivered but also for the full two-way trip. For comparability reasons, the table includes all major casa: bases 50-50 Sleipnir case, the 100% LNG operation case, the LNG Carrier functional unit and the two-way travel case.

Burden Shifting - Normalized to the global average person per year		Sleipnir 50-50				Sleipnir 100LNG				Carrier	FU: 1 ton LNG delivered		
Impact Category	Process	BM	OCC	red [abs]	red [%]	BM	OCC	red [abs]	red [%]	BM	OCC	**red [abs]**	red [%]
EF v3.1 acidification accumulated exceedance (AE)	on-board	1314.84	1290.60	**24.2**	1.8	308.16	381.33	**-73.2**	-23.7	6.28E-03	7.71E-03	**-0.00143**	-22.8
	full	1440.68	1438.37	**2.3**	0.2	443.52	538.11	**-94.6**	-21.3	7.00E-03	8.75E-03	**-0.00175**	-25.1
EF v3.1 ecotoxicity: freshwater comparative toxic unit for ecosystems (CTUe)	on-board	1.80	4.36	**-2.6**	-142.3	2.24	4.81	**-2.6**	-114.6	1.17E-05	5.44E-05	**-0.00004**	-363.2
	full	401.71	445.91	**-44.2**	-11.0	79.36	102.10	**-22.7**	-28.7	9.44E-04	1.35E-03	**-0.00040**	-42.9
EF v3.1 energy resources: non-renewable abiotic depletion potential (ADP): fossil fuels	on-board					------- Not applied -------							
	full	1494.30	1621.37	**-127.1**	-8.5	1494.30	1621.37	**-127.1**	-8.5	2.22E-02	2.62E-02	**-0.00403**	-18.1
EF v3.1 eutrophication: marine fraction of nutrients reaching marine end compartment (N)	on-board	1921.91	1834.51	**87.4**	4.5	458.12	479.57	**-21.4**	-4.7	9.37E-03	1.00E-02	**-0.00068**	-7.2
	full	2009.65	1939.10	**70.6**	3.5	566.48	605.20	**-38.7**	-6.8	1.01E-02	1.11E-02	**-0.00096**	-9.5
EF v3.1 eutrophication:	on-board	2318.75	2297.39	**21.4**	0.9	552.72	662.68	**-110.0**	-19.9	1.13E-02	1.35E-02	**-0.00220**	-19.5

terrestrial accumulated exceedance (AE)	full	2414.62	2410.27	**4.3**	0.2	682.54	810.63	**-128.1**	-18.8	1.22E-02	1.47E-02	**-0.00251**	-20.5
EF v3.1 human toxicity: non-carcinogenic comparative toxic unit for human (CTUh)	on-board	22.58	23.26	**-0.7**	-3.0	42.75	43.91	**-1.2**	-2.7	1.13E-04	1.34E-04	**-0.00002**	-18.6
	full	91.05	115.37	**-24.3**	-26.7	99.91	123.46	**-23.5**	-23.6	9.02E-04	1.33E-03	**-0.00043**	-47.4
EF v3.1 material resources: metals/minerals abiotic depletion potential (ADP): elements (ultimate reserves)	on-board						------- Not applied -------						
	full	16.41	36.77	**-20.4**	-124.1	18.41	38.69	**-20.3**	-110.1	2.57E-04	5.81E-04	**-0.00032**	-125.8
EF v3.1 particulate matter formation impact on human health	on-board	618.04	655.45	**-37.4**	-6.1	144.27	191.17	**-46.9**	-32.5	2.32E-03	3.24E-03	**-0.00092**	-39.6
	full	684.79	752.55	**-67.8**	-9.9	186.35	261.56	**-75.2**	-40.4	2.71E-03	4.06E-03	**-0.00135**	-49.8
EF v3.1 photochemical oxidant formation: human health tropospheric ozone concentration increase	on-board	2622.49	2513.23	**109.3**	4.2	868.78	896.12	**-27.3**	-3.1	1.34E-02	1.43E-02	**-0.00090**	-6.7
	full	2986.89	2918.13	**68.8**	2.3	1252.20	1318.23	**-66.0**	-5.3	1.76E-02	1.94E-02	**-0.00181**	-10.3

Table A.4-1 Appendix: Burden Shifting Quantification for on-board and full life cycle on-board carbon capture.

EverLoNG