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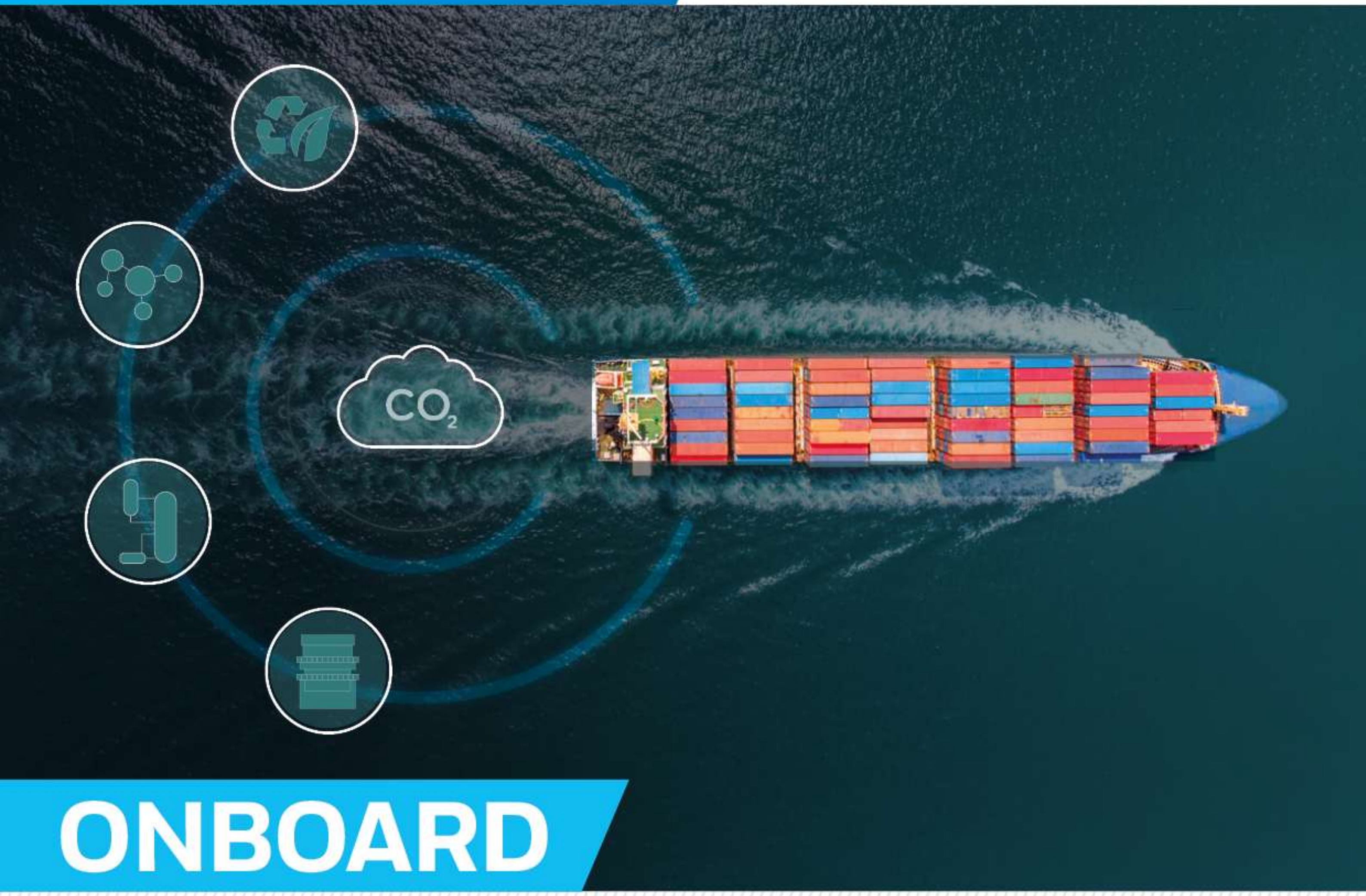

ONBOARD CARBON CAPTURE TECHNOLOGIES

STUDIES ON TECHNOLOGIES & ALTERNATIVE FUELS FOR SUSTAINABLE SHIPPING

EMSA

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Executive Summary

Maritime transportation is growing, but there's increasing pressure to decarbonize to reduce its contribution to the global warming effect. The International Maritime Organization (IMO) has set ambitious targets for reducing Greenhouse Gas (GHG) emissions from international shipping, including a 40% reduction in carbon intensity by 2030 and achieving net-zero emissions by around 2050. To address these challenges, shipping companies are exploring various solutions, such us alternative fuels, energy efficiency measures, aftertreatment systems, operational measures, and renewable energy integration. Among these technologies, Onboard Carbon Capture and Storage (OCCS) may be a key technology for decarbonizing shipping, with potential for newbuilds (NBs) and retrofits. However, its applicability depends on technology development, commercial viability, fuel prices, and regulatory requirements.

The European Green Deal further underscores the urgency of these efforts, aiming to make Europe the first climate-neutral continent by 2050. This ambitious plan includes the Fit for 55 package[2], which sets a target of reducing net GHG emissions by at least 55% by 2030 compared to 1990 levels. Relevant legislation includes Regulation (EU) 2023/1805[3] on the use of renewable and low-carbon fuels in maritime transport, and the inclusion of maritime emissions in the European Union (EU) Emissions Trading System (ETS)[4] starting January 2024. These measures incentivize energy efficiency, low-carbon solutions, and the adoption of technologies to ensure that the maritime sector contributes to the EU's climate objectives.

Technology Overview

OCCS technologies capture carbon from the fuel before carbon dioxide (CO_2) is produced by the ship's energy system, or capture CO_2 in the exhaust gases. While OCCS can significantly reduce emissions, it comes with an energy penalty and requires a downstream value chain for permanent CO_2 storage and utilization. OCCS allows ships to continue using fossil fuels while reducing CO_2 emissions, serving as a transitional technology and an alternative solution to switching to carbon-free fuels.

As part of the study, a comprehensive overview of OCCS technologies revealed that from all categories of carbon capture technologies there exist concepts or pilots in shipping, including pre-, post-combustion and oxyfuel paradigms. Furthermore, the work identified numerous feasibility studies and pilots on chemical absorption (above 15 pilots and installations), as well as variant concepts for membrane separation technologies, mineralization, and pre-combustion technologies. However, the Technology Readiness Level (TRL) varies, with chemical absorption and mineralization being the OCCS technologies with current higher number of pilots and installations. A non-exhaustive overview of the market is also included, encompassing more than 25 makers for all OCCS technologies.

Despite the importance of innovation, knowledge sharing in this field is often fragmented. Challenges for OCCS include lower maturity levels compared to land-based counterparts, energy penalties, carbon price influences, safety concerns, regulatory gaps, and dependence on the Carbon Capture Utilization and Storage (CCUS) value chain development. Future regulatory frameworks and financial incentives will be crucial for OCCS adoption and integration into the broader CCUS value chain. Alignment between international and regional regulations should contribute to a smoother transition while reducing risks for shipping companies. The decarbonization of shipping will involve a diverse range of technological solutions, OCCS being one of them. Successful collaborative pilots will increase OCCS readiness, and shipping companies will need to plan their decarbonization pathways through feasibility studies, comparing OCCS with other options like biofuels and energy efficiency measures.

Sustainability

The analysis of the sustainability of OCCS includes its GHG reduction potential, resource use, lifecycle impacts, and integration challenges. OCCS technologies demonstrate significant potential for reducing emissions, with chemical absorption systems achieving capture rates between 30% and 90%. Alternative technologies such as membrane separation, cryogenic capture, and pre-combustion methods offer promising performance but face integration and energy efficiency challenges. While OCCS can deliver substantial emissions reductions, its operation introduces an

[2] Reducing emissions from the shipping sector - European Commission
[3] Transport and the Green Deal - European Commission
[4] EU Emissions Trading System (EU ETS) - European Commission

energy penalty, typically 9% to 30% for chemical absorption, due to heat and power demands for solvent regeneration and CO_2 compression.

Sustainability also depends on resource use, particularly the handling of amine-based solvents such as mono-ethanolamine (MEA), diethanolamine (DEA), and methyl diethanolamine (MDEA). These solvents degrade over time, requiring replacement and generating byproducts that pose environmental and safety concerns. Lifecycle assessments showcase that OCCS can reduce well-to-wake emissions by 29–44% on its own and up to 120% when combined with biofuels. Post-capture pathways, including concrete fixation and permanent storage, further enhance emissions reduction potential. However, operational challenges remain, such as the need for specialized infrastructure for Liquefied CO_2 (LCO_2) offloading and integration with the broader CCUS value chain.

Suitability

The suitability of OCCS depends on three main categories of factors: technology-related, ship-related, and value chain-related parameters.

Technology-related considerations include health and safety risks, technology maturity, compactness, corrosion resistance, operating conditions, and energy demands. Marine environments impose stricter requirements than land-based systems, especially for hazardous materials and high-pressure operations. Chemical absorption is the most mature technology but requires significant space and energy for solvent regeneration and CO_2 liquefaction. Other technologies, such as membranes, cryogenic systems, and mineralization, offer varying trade-offs in space, energy, and operational complexity.

Ship-related factors focus on space availability, structural strength, stability, and integration with existing systems. Large vessels are generally more suitable due to their size and operational profiles, which allow better accommodation of LCO_2 tanks and capture units. Smaller vessels face tighter constraints due to limited deck space and passenger safety requirements, in case of passenger vessels.

Value chain considerations include port infrastructure for CO_2 offloading, compatibility with CCUS networks, and solvent management systems. Successful OCCS deployment requires alignment with compression, liquefaction, and sequestration facilities to ensure efficient CO_2 handling.

Vessel-Specific Analysis

The analysis conducted includes six representative vessel types calling into European ports, selected on the basis of their emissions profiles and operational diversity. These include a:

- Suezmax oil tanker, a large deep-sea vessel with long voyages and ample deck space offering favourable conditions for OCCS retrofits and newbuild designs,
- 15,000 TEU Liquefied Natural Gas (LNG)-fuelled container ship, a high-capacity vessel with predictable schedules that enable optimized OCCS integration and port offloading, and
- LNG carrier, a technologically advanced platform with cryogenic systems providing synergies for OCCS integration.

Short-sea vessels were also examined, including:

- RoPax ferry, which presents spatial and safety challenges due to frequent port calls,
- 1,700 TEU feeder container ship, operating in regional trades and requiring compact OCCS solutions with minimal cargo impact, and
- MR tanker, a medium-range vessel with consistent coastal routes suitable for moderate capture rates and retrofit scenarios.

The results showcase that chemical absorption technology, selected as the reference solution for its maturity and adaptability, can achieve capture rates of up to 15–60% over the examined operational profile depending on the vessel. Fuel penalization ranges from 9–30%, also depending on vessel type, capture rate, and integration strategy. Cargo capacity impact varies as well across vessel types: container ships may lose up to 175 TEU slots (1–3% capacity), while RoPax ferries could sacrifice up to 100 vehicle spaces. Conversely, tankers and LNG carriers experience minimal cargo interference but would require structural reinforcements. Still other integration challenges remain, including those related to space constraints, respecting compliance with hazardous areas requirements, management of solvents, as well as needed port infrastructure to support LCO_2 offloading.

Cost Economic Analysis

The economic viability of onboard carbon capture systems (OCCS) was assessed across multiple vessel types under varying cost scenarios and regulatory frameworks. The analysis considered Capital Expenditure (CAPEX), operational expenditure (OPEX), CO_2 abatement costs, and potential savings under the EU ETS, as well as implications for compliance with the International Maritime Organization (IMO) Net-Zero Framework's GHG Fuel Intensity (GFI) metric.

OCCS-ready newbuild configurations show the lowest abatement costs, while retrofits incur higher costs due to integration complexity and fuel penalties. Across all cases, costs range widely depending on capture rate and technology configuration. Fuel prices and CO_2 disposal costs exert the greatest influence on total abatement cost, followed by CAPEX and maintenance. Solvent costs contribute minimally.

EU ETS allowance savings improve OCCS competitiveness, especially for vessels with high EU exposure. OCCS becomes increasingly cost-effective under mid- to long-term fuel price projections compared to biofuels, which remain viable only under minimum price scenarios.

Under IMO GFI compliance scenarios, OCCS shows potential as a scalable solution, though methodological clarity on lifecycle emissions accounting remains critical.

Top-down approach

In addition, the study extended its scope through a top-down approach, aiming to generalize findings from the six case vessels to a broader pool of ship segments within the EU fleet. This extrapolation considered operational similarity, machinery scale, voyage duration, and emissions contribution to estimate OCCS performance indicators for vessel types such as Very Large Crude Oil Carrier (VLCC), bulk carriers, chemical tankers, cruise ships, and general cargo vessels. The top-down analysis revealed that deep-sea vessels like VLCCs, Ultra Large Container Vessels (ULCV), LNG carriers, and Suezmax tankers offer the highest feasibility for OCCS deployment due to their high emissions intensity, and available deck space. Medium-feasibility segments, including MR tankers and feeder containers, show promise with tailored engineering and modular solutions, while low-feasibility segments such as cruise ships may require alternative decarbonization pathways.

Regulatory and Safety Framework

The study also explores the regulatory landscape, standards, initiatives, and guidelines related to OCCS as developed internationally in the IMO, the EU or by Classification Societies. By analysing these efforts, the study offers valuable insights into the current state of OCCS regulations and the challenges that lie ahead.

In particular, the existing safety regulatory framework covering the OCCS technology, storage and procedures is more robust in terms of the carbon capture technology where Classification Societies and International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC) code have applicable standards, while the safety standards for procedures and storage are relevant to OCCS but not yet at a readily available stage. More challenging, however, is the environmental regulation landscape, where at the moment the OCCS is included only in the EU ETS regulatory framework, showing the need for more steps to be taken in establishing environmental regulations around OCCS technology.

However, steps are already being taken at the International Maritime Organization (IMO) to address identified gaps. At the 83rd session of the Marine Environment Protection Committee (MEPC), held in April 2025, the IMO approved a dedicated work plan to develop a regulatory framework for OCCS. This includes the establishment of guidelines for testing, measurement, and verification, as well as a structured review of existing IMO instruments to accommodate OCCS within the broader decarbonization strategy.

Risk Assessment and Infrastructure Needs

Beyond technical and economic feasibility, the study also addressed risk assessment, recognizing that safety considerations are critical for OCCS adoption. A structured Hazard Identification Analysis/ Hazard and Operability

Study (HAZID/HAZOP) analysis was performed for selected vessel types and OCCS configurations, identifying hazards across design, operation, and offloading phases. Key risks include CO_2 leakage and asphyxiation hazards, high-pressure system failures, chemical solvent handling, corrosion, and operational errors. While no high-risk hazards were identified, most events were ranked as medium risk, requiring mitigation measures such as corrosion-resistant materials, leak detection systems, ventilation standards, and crew training. The findings confirm that OCCS can be integrated within acceptable risk thresholds when supported by robust engineering safeguards and operational protocols aligned with the International Organization for Standardization (ISO) risk management standards.

Finally, the study emphasizes that OCCS effectiveness depends on the availability of a fully integrated CCUS value chain. Captured CO_2 must be safely offloaded, transported, and permanently stored or utilized to deliver real climate benefits. Current developments in CO_2 storage near major EU shipping hubs, such as Antwerp, Rotterdam, Dunkirk, and Piraeus, show promising alignment with maritime decarbonization goals. However, challenges remain in harmonizing technical standards between ship-based systems and land-based infrastructure, particularly regarding pressure and temperature regimes for liquefied CO_2. Investments in port infrastructure, conditioning facilities, and multimodal transport networks are essential to ensure interoperability. Moreover, cost considerations across the CCUS chain, capture, transport, and storage, will influence commercial viability, requiring tariff structures, regulatory alignment, and collaborative business models.

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List of Abbreviations

AA-IL	Amino-Acid Ionic Liquid
ACT	Accelerating CCS Technologies
AEECO	Auxiliary Engine Economizer
ASEF	Asia-Europe Foundation
ASU	Air Separation Unit
CAPEX	Capital expenditure
CCS	Carbon Capture & Storage
CCGT	Combined-Cycle Gas Turbine
CCUS	Carbon Capture Utilization & Storage
CII	Carbon Intensity Indicator
COSSMOS	Complex Ship Systems Modelling and Simulation
DWT	Deadweight
EEA	European Economic Area
EEDI	Energy Efficiency Design Index
EEXI	Energy Efficiency Existing Ship Index
EGCS	Exhaust Gas Cleaning Systems
EMSA	European Maritime Safety Agency
ESSF	European Sustainable Shipping Forum
ETS	Emissions Trading System
EU	European Union
GCMD	Global Centre for Maritime Decarbonization
GFI	GHG Fuel Intensity
GHG	Green House Gas
HAZID	Hazard Identification Analysis
HAZOP	Hazard and Operability Study
IACS	International Association of Classification Societies
ICS	International Chamber of Shipping
IGC	International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk
IGF	International Code of Safety for Ships Using Gases or Other Low-flashpoint Fuels
IL	ionic liquids
IMO	International Maritime Organization
ISO	International Organization for Standardization
ISWG-GHG	Intersessional Working Group on Reduction of GHG Emissions from Ships
JDP	Joint Development Project
KPI	Key Performance Indicator
LCA	Life Cycle Analysis

LCO_2	Liquefied CO_2
LNG	Liquefied Natural Gas
LP	Low Pressure
LPG	Liquefied Petroleum Gas
MDO	Marine Diesel Oil
ME	Main Engine
MEPC	Marine Environmental Protection Committee
MP	Medium Pressure
MSC	Maritime Safety Committee
NA	Not available (used for indicating that information is not available)
NB	Newbuilding
NG	Natural Gas
OCCS	Onboard carbon capture and storage
OPEX	Operational expenditure
PM	Particulate matter
PPE	Personal Protective Equipment
PSA	Pressure Swing Adsorption
PTO	Power Take Off
ROI	Return of Investment
RED	Renewable Energy Directive
SEEMP	Ship Energy Efficiency Management Plan
SMR	Steam Methane Reforming
TRL	Technology readiness levels
TPH	Ton per hour
TSA	Temperature Swing Adsorption
TtW	Tank-to-Wake
ULCV	Ultra Large Container Vessel
VPSA	Vacuum Pressure Swing Absorption
VCG	Vertical Center of Gravity
VLCC	Very Large Crude Oil Carrier
VLSFO	Very Low Sulphur Fuel Oil
VOC	Volatile Organic Compounds
WtT	Well-to-Tank
WtW	Well-to-Wake
ZNZ	Zero- and Near-Zero

List of Abbreviations for Chemical substances

C	Carbon
Ca	Calcium
$CaCO_3$	Limestone or Calcite
CaO	Calcium Oxide or Lime
CH_4	Methane
CO	Carbon Monoxide
CO_2	Carbon dioxide
DEA	Diethanolamine
DMEA	N,N-Dimethylethanolamine
H_2	Hydrogen
H_2O	Water
K_2CO_3	potassium carbonate
MDEA	methyl diethanolamine
MEA	mono-ethanolamine
Mg	Magnesium
N_2	Nitrogen
N_2O	Nitrous Oxides
NO_x	Nitrogen Oxides
O_2	Oxygen
OH-	hydroxides
PZ	Piperazine
SO_x	Sulphur oxide

1. Introduction

1.1 Background

Maritime transportation is undergoing significant growth at a time when the need to rapidly decarbonize the sector has become critical due to the escalating climate emergency, rising global temperatures, and the associated environmental societal impacts and regulatory demands (IMO, 2023). From a European perspective, the European Union (EU) is taking a leading role in driving maritime decarbonization through its ambitious climate policies. As part of the European Commission's Fit for 55 legislative package, the FuelEU Maritime Regulation 2023/1805 aims to reduce GHG emissions from ships, targeting a 55% reduction by 2030 and full climate neutrality by 2050. This regulation is a cornerstone of the EU's broader strategy to align maritime transport with the European Green Deal and global climate goals.

To meet the demands of decarbonization and energy efficiency improvements, the maritime industry is rapidly advancing in innovative technologies, with continued momentum expected, (DNV, 2023c), (DNV, 2024a). Decarbonization strategies include the adoption of alternative fuels, energy efficiency measures, and aftertreatment systems, such as OCCS. Several studies have highlighted OCCS' relevance. For example, in (Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2022), the emissions reduction potential and energy footprint of OCCS is assessed through several vessel case studies. The report presents challenges related to the OCCS applicability in newbuilds (NB) and various ship types, depending on factors such as technology development, commercial viability, fuel prices, and regulatory requirements. In (OGCI, GCMD, Stena Bulk, 2024), the role of OCCS technologies in shipping decarbonization is elaborated, along with the technical feasibility and potential of OCCS to reduce GHG emissions. The 2024 DNV Maritime Forecast to 2050 report illustrates how OCCS can be combined with alternative fuels to support the achievement of the IMO strategy by 2050 (DNV, 2024a). Additionally, DNV's OCCS whitepaper discusses the feasibility, challenges, and potential benefits of implementing OCCS systems on ships, emphasizing the importance of integrating these technologies into the broader Carbon CCUS value chain (DNV, 2024d).

While innovation is crucial for the shipping industry's evolution and success, knowledge sharing in this field often remains fragmented, with studies focusing on individual technology paradigms and limited scopes (Koukaki & Tei, 2020). Many studies assess various aspects such as feasibility analysis, performance evaluation, risk assessment, contingency planning, response strategies, gap analysis, and regulatory impact. However, there is a pressing need to collect and consolidate these fragmented efforts to fill the existing knowledge gaps. Comprehensive studies that integrate these diverse aspects are essential to ensure a thorough understanding and effective adoption of these technologies. Mapping industry efforts in this field is also useful to provide a holistic view of the technology's potential and to guide the maritime industry toward decisions for sustainable growth.

This work aims to provide an overview of OCCS technologies, including their status, projects, value chains, and market positions within the maritime industry, by examining the technological, regulatory, safety, sustainability, suitability and market landscapes.

1.1.1 Sailing in challenging waters

As maritime environmental regulations become more stringent, demanding drastic reductions in carbon emissions, the costs to achieve compliance increase, pushing the maritime industry to investigate changes in its energy mix. Additionally, pressures from cargo owners and stakeholders to meet decarbonization goals, from charterers to reduce fuel consumption, and geopolitical factors influencing energy independence further complicate the landscape. The International Maritime Organization (IMO) has set ambitious targets for reducing GHG emissions from international shipping. Key targets of the 2023 IMO Strategy on Reduction of GHG Emissions from Ships include (IMO, 2023):

- **Reduction in carbon intensity:** The strategy aims to reduce the carbon intensity of international shipping (carbon dioxide, CO_2, emissions per transport work) by at least 40% by 2030, compared to 2008 levels.
- **Uptake of zero or near-zero GHG emission technologies:** By 2030, at least 5%, striving for 10%, of the energy used by international shipping should come from zero or near-zero GHG emission technologies, fuels, and/or energy sources.
- **Net-Zero GHG emissions:** The strategy sets an enhanced common ambition to reach net-zero GHG emissions from international shipping by or around 2050.

As highlighted in (UNCTAD, 2023), the need for a "just and equitable transition" to a decarbonized shipping industry requires system-wide collaboration, regulatory intervention, and investments in green technologies to address the challenges faced by the maritime sector. The maritime transition, however, comes with many challenges:

- **Competition of carbon neutral fuels:** There is expected to be fierce competition against other industries in allocating fuel resources for the shipping sector. In (DNV, 2024a), projections indicate that future shipping demands for carbon-neutral fuels will correspond to a significant portion of the expected production capacity, while shipping contributes only 3% to the overall transport industry GHG footprint.
- **Lack of bunkering network and infrastructure:** This depends heavily on the location of fuel production projects worldwide, further complicating the transition. Another potential issue may be that some fuel types specialized bunker vessels that may further complicate the transition.
- **Potential high prices of alternative fuels:** The anticipated high prices of alternative fuels, particularly in the early stages of adoption, are largely due to limited production scale and technological maturity. However, as demand increases, economies of scale and improved production efficiency are likely to drive prices down over time. The key economic challenge lies not just in the absolute price of alternative fuels, but in the wide price spread between different fuel types, which affects competitiveness and adoption strategies.
- **Adoption of new and expensive energy converters:** For fuels like ammonia, there is a lack of large-scale demonstration. While fuel cells have been installed on ships and the first ships have been contracted with ammonia engines, this is still considered novel technology where more experience and development are needed.
- **Safety issues with novel fuels:** While established risk assessment methodologies can identify hazards and propose safeguards, operational experience with certain novel fuels remains limited. This is particularly true for ammonia (NH_3) and hydrogen (H_2), fuels that pose unique safety and operational challenges. Although ammonia has been transported as cargo for decades, its use as a marine fuel introduces new risks and handling requirements. Hydrogen, on the other hand, represents uncertainty, as it has neither been widely carried nor used as fuel onboard ships. In contrast, LNG, Liquefied Petroleum Gas (LPG), and methanol (MeOH) have seen increasing adoption, with operational experience now accumulated. However, for fuels like NH_3 and H_2, the lack of mature marine standards, proven procedures, and dedicated crew training complicates daily operations and hinders broader uptake. Long-term maintainability of systems using these fuels also remains uncertain, adding further complexity for crew and operating departments.

The commitment to this transition is also evident in the European Green Deal[5] , which is the EU's ambitious plan to achieve climate neutrality by 2050, transforming Europe into a modern, resource-efficient, and competitive economy. It aims for zero net emissions of greenhouse gases by 2050, with an intermediate target of reducing net greenhouse gas emissions by at least 55% by 2030 compared to 1990 levels. The Fit for 55 package further supports this transition by revising and updating EU legislation to align with the 2030 climate target. This comprehensive approach spans various sectors, including energy, transport, agriculture, and industry, driving the shift towards a sustainable future.

However, as stated above there are challenges for this transition. These challenges are further elaborated in The Draghi Report, authored by former European Central Bank President Mario Draghi and published in September 2024, providing a comprehensive analysis of Europe's economic competitiveness, with specific insights into the shipping sector (Mario Draghi, 2024). The report recognizes European shipping as a global leader and a strategic asset vital for the continent's energy, food, and supply chain security. It highlights that a well-structured regulatory and taxation framework has been instrumental in maintaining the sector's competitiveness.

Addressing the challenges of decarbonization, the report identifies shipping as one of the most difficult sectors to decarbonize, projecting investment needs of approximately €40 billion annually from 2031 to 2050. It emphasizes the necessity of scaling up the production of clean fuels and innovative technologies within Europe to meet climate objectives and enhance competitiveness. To support this transition, the report advocates for adequate access to finance, including dedicated calls for shipping under the EU Emissions Trading System (ETS) Innovation Fund.

In view of the above, changing the energy mix in shipping is not a straightforward process. It requires significant alterations in energy converters, heavy operating costs, and drastic changes in crew training requirements. The International Chamber of Shipping (ICS) report on "Shipping’s Role in the Global Energy Transition" discusses these complexities, highlighting the above. To resolve the decarbonization puzzle, shipping companies are exploring all possible solutions to identify viable options that fit the philosophy and trade of each company. At the time this report

[5] The European Green Deal - European Commission

is written, the orderbook is mostly populated with conventionally fuelled ships in most ship segments. LNG has been the preferred alternative fuel, while methanol is being considered as a potential future retrofit, despite the challenges associated with grey methanol in the compliance costs according to the FuelEU and the EU ETS regulations (Jones, et al., 2022).

In summary, within this complex and evolving landscape, a set of solutions is being considered to support shipping decarbonization, including as follows (International Renewable Energy Agency (IRENA), 2021):

- Alternative fuels
- Energy efficiency measures
- Aftertreatment systems
- Operational measures
- Renewable energy integration

Currently, the prevailing solutions are related to energy efficiency improvements, including both technical and operational measures, such as speed optimization and hydrodynamic improvements. Exhaust gas abatement technologies are often considered as part of the decarbonization puzzle, and OCCS also fits in this category. While the capacity for minimal intervention in existing ship machinery and fuel can be a driving force for the uptake of OCCS in shipping, the extensive experience in installing and using exhaust gas after-treatment systems also provides a foundation for implementing OCCS technologies, (DNV, 2024).

1.1.2 OCCS technologies as means to navigate challenges

OCCS represents a category of abatement technologies aimed at capturing carbon from either the fuel or the exhaust gas of the ship, before CO_2 is emitted into the atmosphere, (DNV, 2024b). In principle, OCCS can achieve emissions reduction onboard, albeit at the expense of an energy penalty and onboard carbon storage capacity. Additionally, it necessitates a value chain that can receive and store the captured carbon permanently away from the atmosphere.

At the forefront of the decarbonization wave, technology providers are actively developing concepts and pilots to demonstrate the technical feasibility of OCCS alternatives. The maritime environment presents a wide range of challenges, including limited resources and space onboard, high safety standards, interoperability requirements, the impact of ship motions, vibrations, humidity and corrosive conditions. Therefore, technology maturity is crucial in addressing these maritime technical challenges by leveraging established experience.

Some of the carbon capture technologies have a long history in land-based applications, achieving the highest TRL, such as amine-based absorption (IEA, 2023). Other concepts introduce innovative features that will be implemented at sea for the first time. Beyond technical maturity, supply chain readiness is equally important. It is expected that OCCS technologies will reach high readiness level for onboard implementation as mature retrofit and NB options with supply chain integration within the decade of 2030 to 2040, (DNV, 2023c). As the integral CO_2 transport network gradually emerges, it will support the OCCS element of the value chain, (DNV, 2024b). By summarizing the above, OCCS is associated with the following challenges:

- **Maturity level:** The OCCS maturity level is lower compared to land-based counterparts. Maritime technology providers are looking towards the upscale of cost-effective solutions that reduce emissions at rational costs.
- **Energy penalty:** OCCS operations bear an energy penalty, which depends on the technology type.
- **Carbon price** is a key driver to justify OCCS investments. Depending on the OCCS business case and technology, the break-even investment cost, compared to other decarbonization options, differs.
- **Safety concerns** exist for various OCCS concepts. As with alternative fuels, class guidelines and rules identify the necessity of dedicated risk assessments to analyse risks and describe safeguards.
- **Regulatory gaps** exist in OCCS implementation in environmental performance measures, like in example the Carbon Intensity Index (CII), Energy Efficiency Existing Ship Index (EEXI), GHG fuel intensity (GFI) standard or other factors. In the lack of clear emission derogation benefits, the uptake of the technology is hindered.
- **Carbon disposal network** development is dependent on the progress of the CCUS value chain both on land and maritime sectors.

The comparative weight of carbon-neutral fuel price, availability, and safety can be evaluated against retrofit options like OCCS. Although current regulations have gaps in recognizing OCCS as emissions abatement technology, bodies such as the IMO and regional authorities are actively working on the issue. Alignment between international and regional regulations is essential for smooth adoption; fragmentation would increase complexity, costs, and risks. Future rules will likely be shaped by factors such as energy mix requirements, carbon pricing mechanisms (taxes, penalties and levies), and financial incentives – key drivers for investments and innovation in technologies like OCCS. The development of carbon markets and the broader CCUS value chain will also be pivotal. Without coordinated regulatory action, implementation and compliance challenges are expected to persist.

1.2 Objective and Scope

The primary objective of this work is to provide a review of OCCS technologies, examining their potential to reduce ship emissions, and while considering sustainability, suitability and adaptability perspectives. The study identifies existing challenges and opportunities associated with OCCS and offers guidance to ship owners, technology providers, and the broader shipping industry.

The study covers the following thematics, structured in separate Chapters, as follows:

- **Chapter 1** covers the background, objective and scope of the study.
- **Chapter 2** presents an overview of state-of-the-art OCCS technologies, with relevant performance indicators analysed to evaluate different solutions. A desktop review results in an inventory of feasibility studies, pilot projects, and OCCS performance analyses.
- **Chapter 3** provides a technical and cost analysis for integrating OCCS technology on various ship types across different trade patterns, at NB and retrofit stages. The impact on onboard integration, net emissions, and lifecycle costs is assessed.
- **Chapter 4** examines the CCUS value chain beyond onboard capture, including global storage project status, transportation options, CO_2 specifications, offloading methods, permanent storage and utilization pathways, cost considerations, and key challenges. This chapter connects onboard capture to the broader infrastructure required for effective carbon management.
- **Chapter 5** reviews current regulations, standards, initiatives, and guidelines implicitly or explicitly related to OCCS, as developed by various international bodies, including the IMO, the EU, Classification Societies, and other relevant organizations.
- **Chapter 6** presents a safety assessment through dedicated HAZID/HAZOP workshops of selected OCCS concepts for cargo and passenger ships, engaged either in short-sea (coastal) or deep-sea trade, at both NB or retrofit stage.
- **Chapter 7** consolidates findings from all chapters and provides conclusive recommendations.

2. State of Play on the Use of OCCS Technologies

This chapter presents the current state of OCCS, covering:

- **OCCS categories:** A classification of OCCS technologies is provided, drawing on advancements inherited from both land-based and offshore sectors, (DNV, 2024b), (Yaseen A. A., 2025).
- **Description of OCCS technologies and terminology**: A description is made of the principles behind each OCCS category, detailing operational concepts and terminology, to ensure clarity for stakeholders evaluating technology options.
- **Current state / Project inventory:** The status of OCCS technologies in the shipping sector is presented through a review on past, present, and future projects. Past, ongoing, and planned initiatives are analysed to illustrate technology maturity and adoption trends.
- **Assessment of technology maturity and commercial readiness:** The readiness level of different OCCS technologies is evaluated, supported by research findings and case studies, and including insights into their applicability across ship types and trade patterns.

2.1 Overview of OCCS Systems and Technology Categories

Three main categories of carbon capture technologies can be recognized based on the stage at which CO_2 is separated from the fuel stream or combustion products (post-combustion, pre-combustion and oxy-fuel combustion), (IEA, 2020), (Pancione, Erto, Di Natale, Lancia, & Balsamo, 2024), (Energy & Environmental Science, 2018), (Yaseen A. A., 2025), (DNV, 2024d). Each category is presented in the following sections.

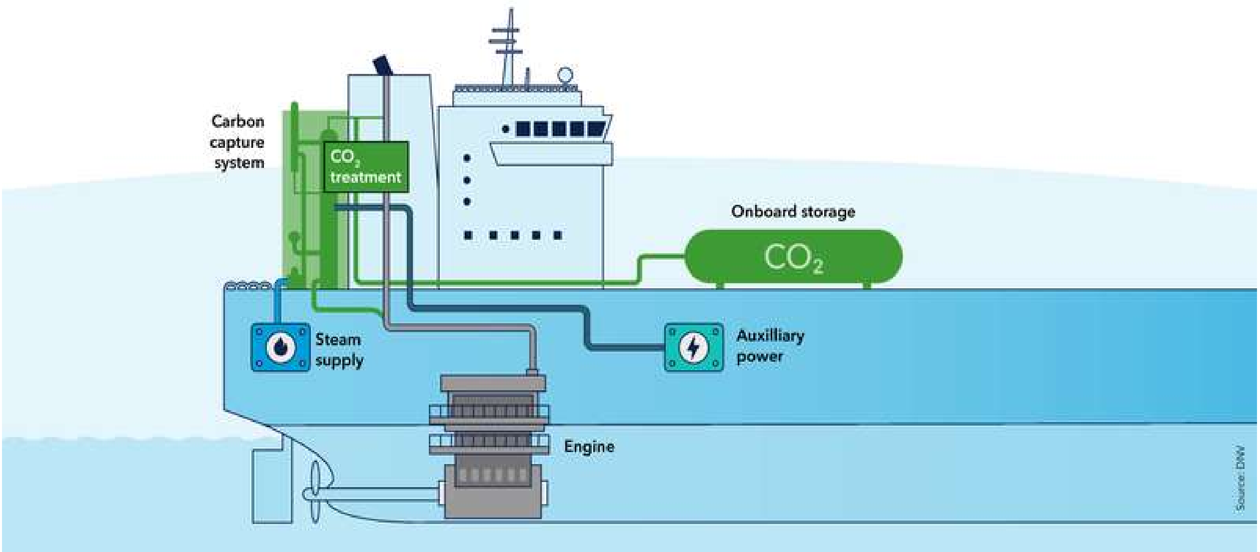

Figure 2-1. General overview of OCCS technologies. Source: (DNV, 2024d).

2.1.1 Post-combustion technologies

In post-combustion technologies, carbon capture occurs after the fuel has been burned. The exhaust gas stream, containing approximately 4 to 8% CO_2 by volume under normal operating conditions (depending on engine type), is directed through specialized equipment designed to capture a portion of the CO_2 for further handling and processing. The carbon emissions are partly or fully separated from the exhaust gas stream. The captured carbon is further processed before temporarily stored onboard, and the treated exhaust gas is discharged into the atmosphere. Depending on the technology, the captured CO_2 can be temporarily stored on board in various forms (gas, liquid, mineral) until it is transferred for offloading. The current leading commercial option for post-combustion capture is to separate carbon emissions from the rest of combustion gases using chemical solvents. Other technologies are also being considered, but these are less mature and require further development.

As an overview, post combustion OCCS represents an integrated system comprised of sub-systems, each accomplishing different objectives depending on the technology type and OCCS concept. These sub-systems include:

- **Pre-treatment system:** Prepares the input stream for carbon capture. OCCS systems may include pre-treatment technologies to condition the exhaust gas stream for efficient carbon capture.
- **Carbon capture plant:** The core system responsible for capturing CO_2. The capture plant is the prevailing component of the technology, significantly influencing the design and operation of the other sub-systems.
- **After-treatment system:** Processes the captured CO_2 for storage or further use. Aftertreatment systems in OCCS are essential for preparing the captured CO_2 product for temporary storage or further use, until it can be disposed of at a port, (DNV, 2024d).
- **Temporary storage system:** Temporarily stores the captured CO_2 before it is transferred to a permanent storage site or further use. The form of the CO_2 product can vary depending on the capture process and may be: (a) liquid saturated with CO_2, (b) compressed gas CO_2, (c) liquid CO_2 in cryogenic conditions, (d) solid in mineral form, (e) solid in carbon form.

The main post-combustion technology variants include, (Pancione, Erto, Di Natale, Lancia, & Balsamo, 2024):

- **Chemical absorption** involves the use of liquid solvents, such as amines, to selectively absorb CO_2 from exhaust gas stream, with applications in both land-based and maritime industries. The CO2 gas gets absorbed into the liquid solvent and bonded with the liquid chemical. The effluent is fed to specialized equipment to release the captured CO_2, by breaking it from the solvent through a regeneration process, allowing the solvent to be reused. This method is widely used in industrial applications due to their high removal efficiency, low vapour pressure, and low cost, (IEA, 2020), (Du, et al., 2024).
- **Physical adsorption** involves the use of materials that adsorb CO_2 through the creation of bonds, such as Van der Waals bonds. The process is particularly effective at high pressures. By altering pressure or temperature, the bonds are activated or deactivated, allowing CO_2 to be captured and then released as high-purity gas. Variants of the process include Pressure Swing Adsorption (PSA) and Temperature Swing Adsorption (TSA). PSA achieves this by reducing pressure to release the captured CO_2, while TSA uses heat to desorb CO_2 from the adsorbent, (Karimi, Shirzad, & Silva, 2023).
- **Mineralization** converts CO_2 into stable carbonates through reactions with minerals, offering permanent storage solutions. The process involves the reaction of CO_2 with minerals rich in calcium or magnesium, such as silicates, to form stable carbonate compounds. One of the technologies utilizes lime, generating limestone, the so-called calcium looping process. (Pancione, Erto, Di Natale, Lancia, & Balsamo, 2024).
- **Membrane separation** is a post-combustion carbon capture method where exhaust gases pass through membrane modules that selectively filter CO_2 via defined pore structures. The treated gas exits the system, while the CO_2-rich stream undergoes further treatment, such as compression into gas or liquid form, (DNV, 2024b).
- **Cryogenic separation** involves CO_2 separation into solid forms by cooling down the exhaust gas stream to low temperatures (-100°C to – 135°C). The separation is possible as the other gas components (oxygen and nitrogen; O_2 and N_2, respectively) need lower temperatures to solidify, (Pancione, Erto, Di Natale, Lancia, & Balsamo, 2024).
- **Electrochemical separation** for carbon capture is an innovative technology that uses electrical energy to facilitate the capture and release of CO_2. This process involves electrochemically active sorbents that change their affinity for CO_2 molecules during an electrochemical cycle, (Muroyama, Pătru, & Gubler, 2020).

2.1.2 Pre-combustion technologies

In pre-combustion technologies, carbon capture takes place before the fuel is burned. Pre-combustion capture systems can be separated into two main streams based on the form of the capture product: (a) those that generate CO_2 gas and (b) those that produce carbon solids. In this case, the ship's fuel (usually LNG) is converted into a H_2 gas before combustion.

- The first option involves the reaction of a fuel with O_2 or air and/or steam to produce a "synthesis gas" (syngas) composed of carbon monoxide (CO) and H_2, (Rubin, et al., 2016). The CO reacts with steam in a catalytic reactor (shift converter) to produce CO_2 and additional H_2. CO_2 is then removed from the fuel using a physical or chemical absorption process, resulting in a H_2-rich fuel. This fuel is then burned to the respective energy converter.

- The second pre-combustion option involves the pyrolysis of the fuel, which separates it into carbon solids and H_2 fuel (U.S. Department of Energy, 2021). The H_2 fuel can then be burned in an energy converter or used to enrich other fuels.

Similar to post-combustion systems, pre-combustion concepts require supporting sub-systems to enable efficient operation. These typically include (A.G. Olabi, 2022) (Wai Lip Theo, 2016):

- **Fuel conversion unit**: Converts LNG or other fuels into syngas or hydrogen through reforming, water-gas shift, or pyrolysis. These processes operate at high temperature and pressure and often integrate heat recovery to improve efficiency.
- **CO_2 separation and compression system**: Captures CO_2 during reforming or pyrolysis and conditions it for handling. This involves physical or chemical absorption, followed by compression and sometimes cooling and drying before storage.
- **Temporary storage system**: Onboard captured CO_2, is temporary stored either as compressed gas, cryogenic liquid, or solid carbon. Storage design must consider space constraints, safety requirements, and integration with port discharge infrastructure.

2.1.3 Oxy-fuel combustion technologies

In oxy-fuel combustion, the fuel is burnt in pure or enriched O_2 environment, resulting in a stream of CO_2 and water (H_2O) vapor, which can be easily separated. H_2O can be removed by condensation and dehydration. O_2 is usually produced by low-temperature (cryogenic) air separation, (Metz, Davidson, de Coninck, Loos, & Meyer, 2005).

Oxy-fuel systems also require dedicated sub-systems for effective operation, including:

- **Air separation unit (ASU)**: Produces pure or enriched oxygen for combustion. Cryogenic ASUs can achieve high purity (~99.5%) but are energy-intensive, while vacuum pressure swing absorption (VPSA) systems offer lower purity (~90%) with reduced footprint but higher CO_2 contamination risk (Michael Wohlthan, 2024).
- **CO_2 conditioning system**: Beyond water removal, conditioning involves pressurization, deoxygenation (to eliminate residual O_2), drying to prevent hydrate formation, and potential liquefaction for onboard storage.
- **Temporary storage system**: Stores captured CO_2 onboard in liquid or compressed form.

2.1.4 Technology combinations, pre- and after-treatment

Onboard a vessel, all above technologies can be combined with pre- and after-treatment technologies, to fulfil the full scope of OCCS, which starts with the cleaning of the exhaust gases from CO_2 and ends with the onboard temporary storage.

In the sections that follow, these technologies are presented in detail, including the process mechanisms, the key components for onboard implementation, the performance characteristics, and the technology maturity. The system-level interdependency of OCCS technologies is illustratively given in Figure 2-2, in association with the type of energy converter and fuel. For each technology, some indicative performance-related characteristics are addressed, indicating key demands with regards to power, consumables and capacity to operate at marine conditions.

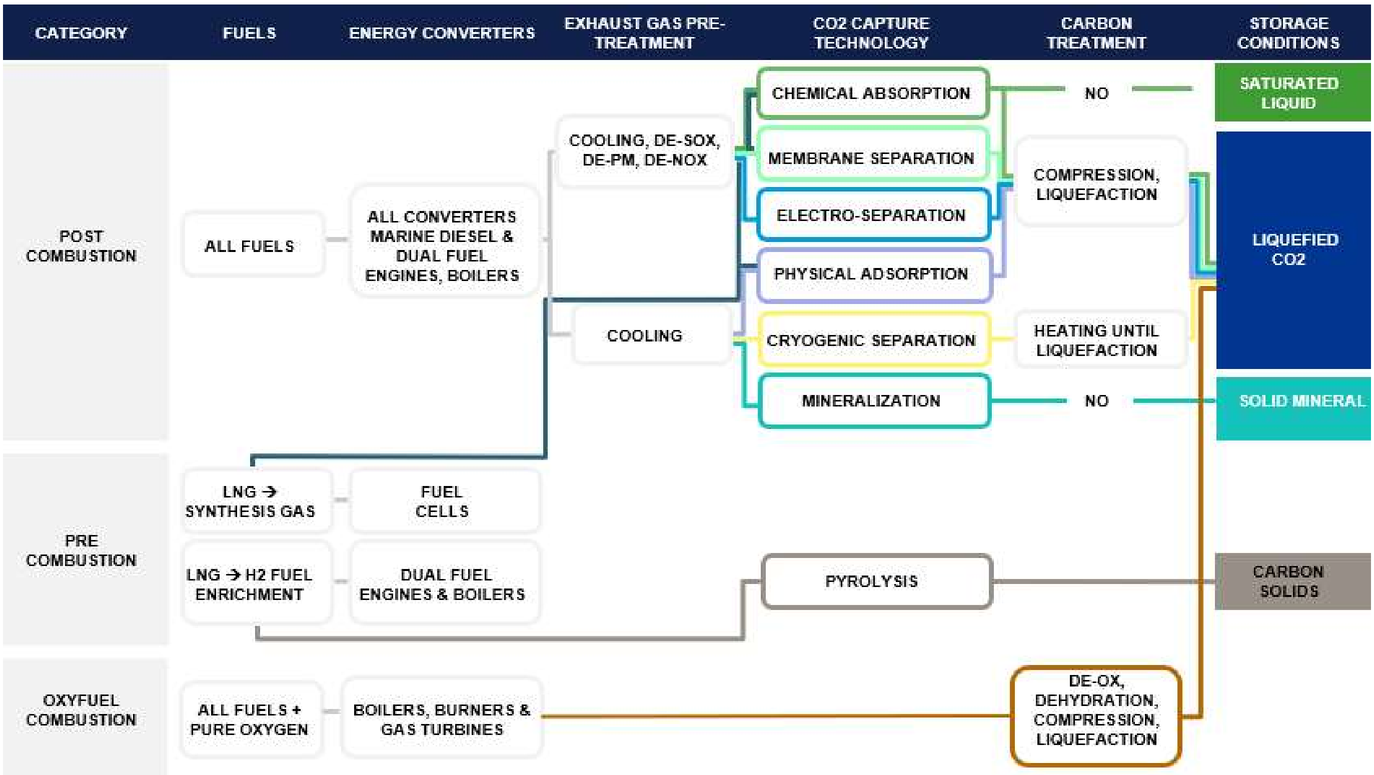

Figure 2-2. General overview of OCCS per technology category. Source: DNV.

2.2 Description of OCCS technologies

In this section, a description of the main OCCS technology variants is given`. Process mechanisms, key components, and operational considerations are presented.

2.2.1 Post combustion OCCS technologies

2.2.1.1 Chemical absorption

Chemical absorption is a mature land-based CO_2 capture technology that has been successfully transferred to the shipping industry. A marine system with chemical absorption for OCCS comprises of the following sub-systems, as described in (DNV, 2024d) and (Yaseen A. A., 2025):

- **Exhaust gas pre-treatment**: Chemical absorption is applicable to exhaust gases from any type of fuel combustion. However, impurities such as CO, methane (CH_4), SO_x, NO_x, particulate matter (PM) and formation of aerosol can degrade solvent performance, making pre-treatment essential (Damartzis et al., 2022). Acidic gases like NO_x and SO_x chemically react with solvents to form heat-stable salts, reducing absorption capacity and necessitating solvent replenishment and proper disposal. To address this, particulate removal and desulphurization are commonly carried out before carbon capture. Additionally, as the process operates at approximately 50°C with conventional solvents, the exhaust gas stream must be cooled, often using a direct air cooler. Effective monitoring and mitigation of PM and aerosol formation are also critical to ensure optimal performance and efficiency.
- **Absorption:** An absorption column (absorber) where the exhaust gas is exposed to an alkaline liquid stream, where CO_2 is chemically absorbed in a chemical solvent, or absorbent. The CO_2 is selectively bonded by the solvent and separated from the exhaust gas through tray-by-tray or packed stages, which increase the gas-liquid contact area. The cleaned gas escapes from the top of the column, while the CO_2 is removed with the liquid stream at the bottom of the column. Liquid absorbents include amine-based options like MEA (mono-ethanolamine), MDEA (methyl diethanolamine), potassium carbonate (K_2CO_3) and ionic liquids (ILs), each with different capture properties, advantages, and drawbacks. The process usually takes place at 50°C.
- **Regeneration:** A regeneration column (stripper), where the CO_2-rich liquid is processed, releasing CO_2 through desorption at around 120°C. Triggered by the reboiler' s heat, the bonds between CO_2 and the solvent break,

releasing high-purity CO_2 gas at the top of the stripper column and regenerating the liquid solvent. The hot solvent returns to the absorber, while the CO_2 gas is transferred to the next stages for treatment.

- **Heating:** Heat for regeneration is supplied via a reboiler, and a cross-stream heat exchanger is used to recover energy from the stripper outlet to the absorber outlet. The reboiler operates with steam, supplied by the ship network. The amount of steam depends on the capacity of the carbon capture unit and the requirements of the solvent. A detailed description of heat demands per solvent is provided in Table 3-2. The process occurs at atmospheric conditions, while the temperature after the cross-stream heat exchanger is at the order of 90°C to 100°C, whereas the reboiler increases the temperature to the required 120°C.
- **CO_2 gas after-treatment**: The high-purity CO_2 gas is led to an after-treatment stage, to remove moisture until the necessary limits for onboard cryogenic storage. The captured CO_2 gas can either be compressed and pressurized at high pressure or liquefied under medium (MP) or low-pressure (LP) cryogenic conditions. The system requires gas-tight safety conditions.
- **Onboard storage:** Depending on form of the CO_2 product, the necessary containment system is used. The options are:
  - Compressed CO_2 gas stored in pressurized gas cylinders at 50 to 70bar pressure and atmospheric temperature,
  - Cryogenic CO_2, compressed and liquefied at low (LP: 6 to 12bar, -55 to -35°C) or medium pressure levels (MP: 12 to 20bar, -35 to -19.5°C) stored in cryogenic C-Type tanks.
  - In one of the technology variants, the step of solvent regeneration is skipped, and the process effluent is a liquid bulk that can be gradually saturated with CO_2. This bulk can be stored onboard at atmospheric conditions until disposal at port.

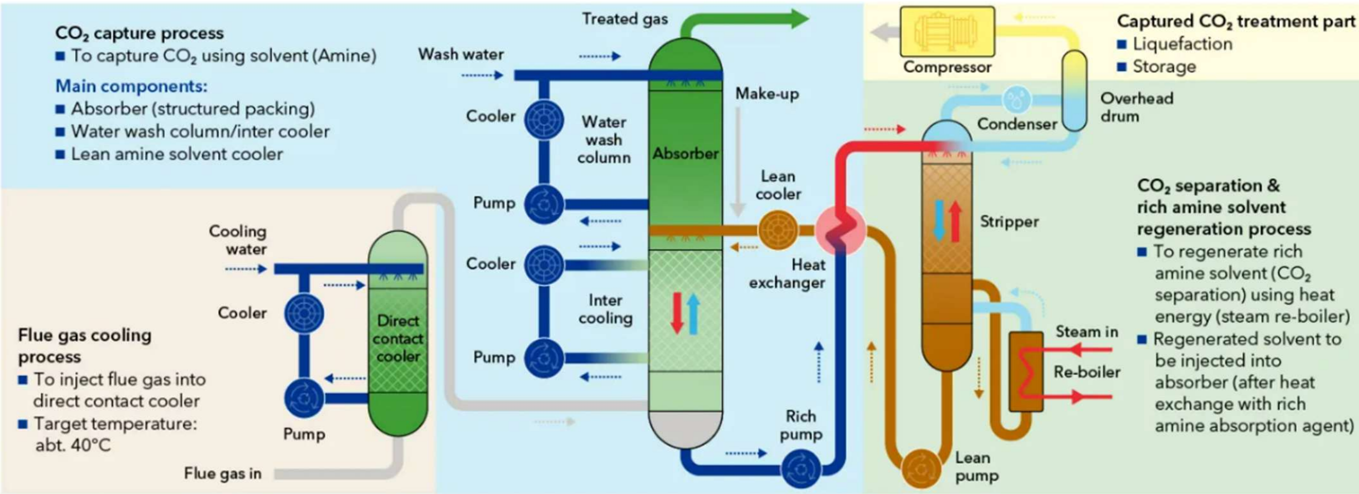

Figure 2-3. Concept of a liquid absorption carbon capture system. Source: (DNV Total JDP, 2021).

2.2.1.2 Physical adsorption

In physical adsorption, the exhaust gas is exposed to a solid that adsorbs CO_2 through the creation of physical bonds between the adsorbent and CO_2 molecules. Generally, the exhaust gas is passed through a reactor, where minerals bond CO_2 into their structures, removing it from the exhaust gas. The saturated mineral can then be gathered as deposited sludge, which is offloaded at the port. Storage areas are required for both the mineral and the saturated product. In application where one would like to regenerate the adsorbent, two alternative processes are commonly used:

- **Pressure Swing Adsorption (PSA):** In the equivalent concept for carbon capture, the exhaust stream enters the reactor following a pressurization stage, during which CO_2 is physically attached to the reactor bed and separated from the exhaust stream. A depressurization stage follows, breaking the bonds and generating a pure CO_2 stream, which is purged out of the column.
- **Temperature Swing Adsorption (TSA)** is a process used to clean the exhaust gases from specific elements, in example Volatile Organic Compounds (VOC), by utilizing temperature cycles. In TSA, the adsorbent is regenerated by applying heat, which desorbs the adsorbed gases.

2.2.1.3 Mineralization

A marinized mineralization process may comprise of the following stages:

- **Capture:** Scrubbing of the exhaust gas stream with a liquid solution, which contains minerals rich in calcium (Ca) and magnesium (Mg), e.g. calcium oxide or lime (CaO). In contact with lime, CO_2 is absorbed and bonded with the mineral, to form stable carbonate minerals such as limestone or calcite (CaCO3), and/or others. The conversion of lime to limestone is called calcium looping.
- **Liquid medium treatment:** The effluent is treated inside a dedicated unit, where the liquid is separated from the mineral containing CO_2. Frequent dosing with the unreacted minerals is required, to maintain the performance in terms of carbon capture. Chemical agents that contain hydroxides (OH-) can be used to trigger the reactions and support the capture process efficiency.
- **Storage** of the reacted mineral onboard until disposal**.**
- **Regeneration of the mineral:** After port disposal, the mineral (e.g. limestone) can be regenerated via heat and reused for the onboard process.

2.2.1.4 Membrane separation

Membrane separation is widely used in the general industry sector for gas separation and purification. Membrane separation technology acts as molecular sieves, where CO_2 is separated through defined pore structures. This technology is well-known for CO_2 separation from natural gas and can operate under a wide range of conditions. Membranes can be arranged into spiral-wound or hollow-fibre modules, with hollow-fibres offering higher packing density and smaller plant sizes.

In post-combustion applications, exhaust gas passes through membrane modules that selectively allow CO_2 to transport through their structure, separating it from the exhaust gas. The clean gas leaves the system, while the CO_2 stream is treated and either compressed into gas or liquid.

Combining membrane separation with chemical absorption can increase efficiency and reduce space and energy demands onboard. In this combination, the gas flows from the one side of the membrane, whereas a liquid solution that includes a chemical agent selective to CO_2 passes through the other side. CO_2 selectively transports through the membrane and gets absorbed in the liquid. CO_2 is then released from the liquid with heating, as in chemical absorption, while the chemical solution recirculates in the membrane modules. The process magnifies the performance of chemical absorption at lower space, (Damartzis, et al., 2022).

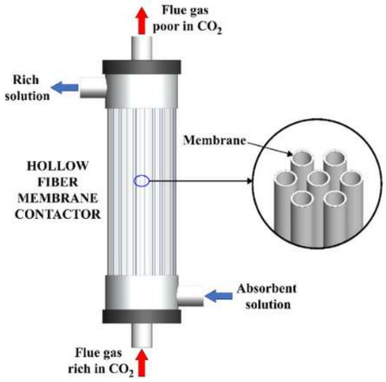

Figure 2-4: Membrane separation systems for OCCS. Source: (Alexandru-Constantin Bozonc, 2022).

2.2.1.5 Cryogenic separation

Cryogenic carbon capture technologies are mature for land-based applications and are commercially available for various industries, including natural gas cleaning, pipeline applications, and exhaust gas treatment. The governing mechanism is to separate CO_2 gas from exhaust gas using their different condensation and de-sublimation properties. The exhaust gas flows through a thermodynamic heat exchanger system or cooled distillation column, avoiding the use of chemical solvents and associated secondary pollution. For energy efficiency purposes, the CO_2

content of the exhaust gas should be around 12% or higher. Tight heat integration with onboard LNG fuel treatment systems can lead to energy-efficient solutions.

Cryogenic OCCS includes the following steps:

- **Exhaust gas drying:** In this stage, H_2O is removed from the exhaust gas by cooling.
- **Cooling of remaining gases**: The remaining exhaust gas is further cooled.
- **Liquefaction of CO_2:** The dry exhaust gas is cooled and pressurized, causing the CO_2 to liquefy.
- **Capture of CO_2:** The liquefied CO_2 is stored onboard until disposal to port.

2.2.1.6 Electro-separation

The governing mechanism of any electrochemical CO_2 separation process is the selective extraction of CO_2 from the exhaust gas stream through electrochemical reactions, (Muroyama, Pătru, & Gubler, 2020):

- **Electrodialysis**: A liquid electrolyte is used to perform the separation process. CO_2 is then released from the liquid via regeneration through an ion-conducting membrane.
- **Electrochemical cells**: CO_2 is directly separated from the exhaust gas using electrochemical reactions in a polymer electrolyte membrane electrochemical cell, operating in a mode of electricity consumption.
- **Alternative liquid electrolytes**: This includes seawater electrolysis, ionic liquids, and amine-based systems, which employ electrogenerated nucleophiles for CO_2 capture and release.

Trace contaminants like SO_x and NO_x could impact the electrolyte within the cell. During discharging, the device can provide part of the power needed for the whole system. The system operates at room temperature and normal air pressure. These technologies have been validated in laboratory environment.

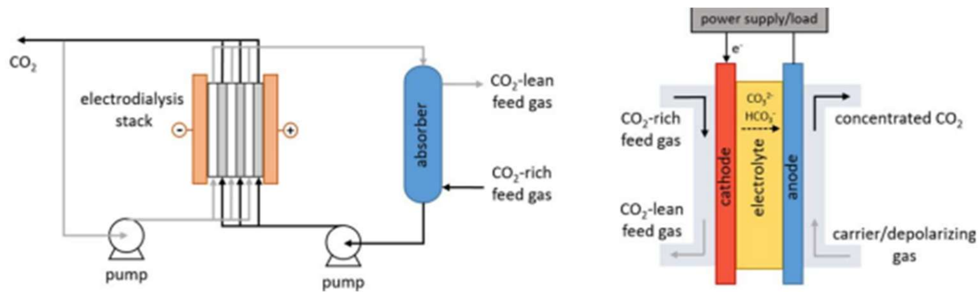

Figure 2-5. Illustration of the pre-combustion with pyrolysis OCCS technology. Source: (Muroyama, Pătru, & Gubler, 2020).

2.2.2 Pre combustion OCCS technologies and key terminology

2.2.2.1 Pre combustion marine fuel reforming

Pre-combustion carbon capture involves converting the ship's fuel into a H_2 gas before combustion. This process typically uses steam-methane reforming (SMR) to convert fuel LNG into syngas, a mixture of H_2 and CO. Further, CO is converted into CO_2 and then separated from H_2. The CO_2 is captured using conventional capture methods. The H_2-rich fuel can be burned in various applications, such as H_2 reciprocating engines, boilers, gas turbines, and fuel cells. A project that looks into this mechanism for shipping is the HyMethShip[6] EC-funded project (Appendix A).

2.2.2.2 LNG pyrolysis

Pyrolysis of LNG involves heating natural gas to high temperatures (typically between 650°C -750°C) in the absence of O_2 and in the presence of a catalyst, preventing combustion and breaking down the gas into simpler components. The primary products of this process are H_2 gas and solid carbon C. The reaction can be represented as: $CH_4 \rightarrow C +$

[6] HyMethShip – Grüne Wende auf hoher See

$2H_2$. This process uses a catalyst to facilitate the breakdown of CH_4 into H_2 and solid carbon (C). The produced H_2 fuel can be burnt in fuel cells or used as a blend-in fuel for combustion engines or gas-fired boilers.

2.2.3 Oxy-fuel combustion OCCS technology and key terminology

2.2.3.1 Oxy-fuel combustion

In oxyfuel combustion capture systems nearly pure O_2 is used for combustion instead of air, resulting in an exhaust gas stream that is mainly CO_2 and H_2O, in which the latter component can be removed by condensation and dehydration. This method is not well-developed in shipping. There are various concepts in literature, that describe process steps with conventional marine Diesel engines and fuel cells, (Wohlthan, et al., 2024):

- O_2 is produced by air separation, e.g. low temperature (cryogenic) air separation, membranes, or other.
- The produced oxygen is fed directly to the engines. This setup ensures a controlled O_2 supply for combustion, enhancing efficiency and reducing emissions.
- O_2 excess from the combustion process is removed using a De-Ox unit, and the produced heat is fed into the onboard heat grid. Moisture is also removed, delivering a stream of CO_2.
- The CO_2 stream is further processed for temporary onboard storage, including compression and liquefaction.

2.2.4 CO_2 conversion

There is a technology category that focuses on CO_2 conversion into other molecules (e.g. oceanic bicarbonate[7]), without involving disposal of the captured CO_2 at port site.

2.3 Assessment of technology maturity level

An integrated assessment of OCCS technologies maturity level is attempted, combining a comprehensive TRL methodology, insights from pilot projects, feasibility research, and market concepts, to conclude with an overview of the current OCCS technology maturity.

2.3.1 TRL categories

The EURAXESS TRL scale[8], as shown in Figure 2-6, evaluates the maturity of a technology through a series of indicators, ranging from TRL 1 (basic principles observed and reported) to TRL 9 (technology proven and ready for full-scale deployment). The TRL scale was introduced into EU-funded projects in 2012 and has since become the standard reference for determining the development stage or maturity of research, as well as its readiness for market uptake and potential investments.

TRL1	Define basic properties
TRL2	Analytical study
TRL3	Proof of concept
TRL4	Pre-prototype
TRL5	Pre-prototype tested in lab
TRL6	Prototype tested in relevant environment
TRL7	Approved Prototype
TRL8	Pre-Serial manufacturing
TRL9	Product on market

Figure 2-6 TRL assessment levels. Source: (EURAXESS).

To map the developing OCCS technology landscape, the following TRL groups are considered in this study:

- TRL1–4: Assessment or demonstration of basic technological components and systems in low fidelity environment, development activities and prototyping. Technology performance for various ship types and proof of concept and pre-prototype of compartments of the OCCS technology.

[7] https://calcarea.com/
[8] TRL | EURAXESS

- TRL5–7: Development activities and prototyping of the technologies in realistic environments that resemble the marine environment.
- TRL8–9: Market products of the technology have been demonstrated onboard in configurations with desired fully- or partially functional characteristics, receiving the necessary approvals for ship installation and tested in the marine environment. This category also includes market products repeatedly installed onboard ships.

2.3.2 Non-exhaustive list of pilot projects[9]

The following paragraph provides an indicative overview of selected shipping pilot projects and feasibility studies related to OCCS, categorized by technology type. This review is based on publicly available information and a comprehensive literature survey; however, it is not intended to be exhaustive. Additional technologies, providers, and test beds may exist but are not included due to limited published data and size of this report. The examples presented were chosen because key results have been disclosed through conferences, industry events, media releases, and technical publications, offering evidence-based insights. They are provided for illustrative purposes only and should not be interpreted as a ranking or endorsement of any specific technology.

2.3.2.1 Chemical absorption

Chemical absorption is a mature technology for land-based applications, for CO2 emissions abatement, natural gas cleaning, chemical product processing, and in the food and pharmaceutical industries. In the shipping industry, there is a growing number of pilot projects:

- **K-Line and Mitsubishi CC-Ocean:** In 2021, the "CC-Ocean" project, a collaboration between K-Line and Mitsubishi Shipbuilding, is a chemical absorption OCCS pilot. Installed on the coal carrier CORONA UTILITY, the project demonstrated CO_2 capture, achieving a purity of over 99.9% during a six-month trial.

Table 2-1 K-Line and Mitsubishi CC-Ocean pilot project.

Year	2021
Stage	Completed
Technology	Chemical absorption; Compressed gas CO_2 (lab test)
Ship type	88,000 ton bulk carrier
Scope	Capture piloting
Performance	CO_2 0.1 Tons per hour (TPH); Weight 5tons

- **SMDERI and Evergreen Marine:** Evergreen Marine, in partnership with the Shanghai Marine Diesel Engine Research Institute (SMDERI), conducted a chemical absorption OCCS system demonstration on the 13,800 TEU containership Ever Top. The system, developed by SMDERI, captured CO_2 from exhaust gases, liquefied it, and stored it onboard for later offloading. During the pilot, over 25 tonnes of CO_2 were captured with a purity exceeding 99.9% and transferred ship-to-ship and then to shore for industrial utilization.

[9] Disclaimer: The information presented in this paragraph is based on publicly available sources and is intended for general informational purposes only. It does not claim to be exhaustive, nor does it constitute endorsement or ranking of any technology, provider, or project. While care has been taken to ensure accuracy, the authors and their organization accept no liability for omissions, errors, or reliance on this content for decision-making.

Table 2-2 SMDERI and Evergreen Marine pilot project.

Year	2024
Stage	Completed
Technology	Chemical absorption; Liquefied CO_2
Ship type	14,000 TEU containership
Scope	Capture and liquefied gas discharge piloting
Performance	System specifications: Max. 40% capture rate, or 6.6 TPH[10]

Figure 2-7 SMDERI pilot discharge in the Shanghai port. Source: (Courtesy of SMDERI).

- **Solvang ASA and Wärtsilä:** Solvang's ethylene carrier Clipper Eris is a DNV-Classed vessel that operates a OCCS system, developed in collaboration with Wärtsilä, MAN Energy Solutions, and SINTEF. The retrofit, completed at Seatrium Admiralty Yard in Singapore, integrates Wärtsilä's OCCS technology to capture CO_2 from exhaust gases before discharge, liquefy it, and store it in deck tanks for later offloading. Early results show up to 70% CO_2 reduction, demonstrating technology viability.

Table 2-3 Solvang ASA and Wärtsilä pilot project

Year	2025
Stage	Conversion
Technology	Chemical absorption; Liquefied CO_2
Ship type	LPG carrier
Scope	Capture and liquefied gas discharge pilot
Performance	System specifications: 75% capture rate or potentially ~2-2.1 tCO2/hr [11]

Figure 2-8 Illustration of the OCCS pilot in Clipper Eris. Source (Courtesy of Solvang / Wärtsilä)

[10] (GCMD, 2025b)
[11] Technical Seminar on Onboard Carbon Capture and Storage (OCCS) Systems

- **Scorpio and Carbon Ridge[12]:** Scorpio Tankers Inc. has implemented a centrifugal OCCS on one of its LR2 product tankers, the STI SPIGA. This project was certified by DNV, and the equipment was manufactured by Spitzer Industries. Endress and Hauser Group contributed essential measurement systems, while Besiktas Shipyard supported the technical installation.

Table 2-4 Scorpio and Carbon Ridge pilot project.

Year	2025
Stage	Completed
Technology	Chemical absorption; Centrifugal Liquefied CO_2
Ship type	LR2 product tanker
Scope	Capture and liquefied gas discharge pilot
Performance	Not available

EverLoNG: A three-year EU research initiative, co-funded by the ERA-NET ACT3 programme, involves the maritime, R&D, and engineering sectors. The project aimed at demonstrating OCCS use on LNG-fuelled ships and advancing its market readiness. Key tasks include installing test installations on two LNG-fuelled vessels, evaluating the cost of land-based logistics, and developing a roadmap for a European CO_2 offloading network. The project achieved capture rates at capture unit boundaries of up to 85%. However, elevated NO_x levels in the exhaust gases increased the degradation rate of the capture solvent. The technology of Carbotreat was demonstrated on two vessels: (a) Heerema Marine Contractors' SSCV Sleipnir and (b) a TotalEnergies-chartered LNG carrier, the Seapeak Arwa. On the LNG carrier Seapeak Arwa, MEA solvent concentrations ranging from 5–30% were tested over 1,500+ operational hours, achieving capture rates from ~23% at low concentration to ~79% at high concentration. In parallel, the Sleipnir campaign demonstrated near-complete capture efficiency (~98%) under low exhaust flow conditions, removing approximately 4,200 kg of CO_2 during 400+ hours of operation.

Table 2-5 EverLoNG pilot project.

Year	2024
Stage	Completed
Technology	Chemical absorption; Liquefied CO_2
Ship type	1 x LNG carrier, 1 x Crane vessel
Scope	Capture and LCO_2 discharge pilot
Performance	250kg per day

- **Ermafirst – Neptune Lines**: Initiated in 2023 with an AiP by DNV, this work continues with a dedicated conversion pilot focused on the onboard capture plant. Ermafirst's OCCS system uses amine absorption technology to capture CO_2 from a vessel's exhaust gas.

[12] Carbon Ridge and Scorpio Tankers deploy centrifugal carbon capture

Table 2-6 Ermafirst – Neptune Lines pilot project.

Year	2024
Stage	Ongoing
Technology	Chemical absorption
Ship type	RoRo vessel
Scope	Capture piloting
Performance	Not available

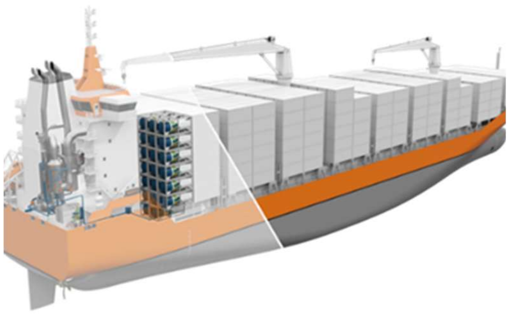

Figure 2-9 ErmaFirst Carbon Fit. (Image © ERMA FIRST. Used with permission).

- **Value Maritime installations:** Eastaway Ship Management[13], JR Ship Management[14], and Samskip[15] have been considering OCCS technology for several containerships, including X-Press Elbe, X-Press Agility, Emotion, Empire, Endurance, Endeavor, Ensemble, Rauma, Endeavour, and Innovator. These systems depend on chemical absorption and solvent saturation with CO_2, provided by Value Maritime. The by-product is disposed at port for further treatment, while regenerated solvent is filled back onboard for reuse.

Table 2-7 Value Maritime installations pilot project.

Year	2021
Stage	Completed
Technology	Chemical absorption with liquid saturation
Ship type	Container feeders
Scope	Installation of system; capture of SO_x and CO_2
Performance	Not available

2.3.2.2 Mineralization

- **Seabound pilot – Sounion trader:** Seabound successfully piloted its carbon capture technology on a commercial container ship, demonstrating a capture efficiency of 78%. The pilot involved fitting the technology on the deck of the 3,237 TEU ship, Sounion Trader, and testing it during a two-month voyage. The system captures CO_2 emissions and converts them into solid calcium carbonate solids, which can be offloaded at port.

[13] https://eastaway.com/news/eastaway-to-install-carbon-capture-on-two-of-their-vessels
[14] https://www.jrshipping.com/news/mv-energy-to-receive-filter-and-carbon-capture-system/
[15] https://www.samskip.com/samskip-expands-sustainability-innovations-with-carbon-capture-utilization-ccu-system

Table 2-8 Seabound pilot project.

Year	2024
Stage	Completed
Technology	Mineralization
Ship type	3200TEU containership
Scope	Pilot installation and functionality testing
Performance	1ton of CO_2 per day; Size: Five 20-feet containers on deck

Figure 2-10 Seabound pilot in Sounion Trades. Source: (Courtesy of Seabound Carbon Ltd).

2.3.2.3 Membranes

In 2022, Ionada[16] has completed a membrane-based carbon capture technology pilot system at Halliburton, in Houston Texas, with funding support from Natural Gas Innovation Fund (NGIF) Industry Grants. The compact and modular design of the technology could make it suitable for onboard integration.

Aqualung presents another maker in the category of membrane-based OCCS. The company is building an R&D test rig on a 250 kW Diesel engine[17], targeting capture from exhaust streams with 11% CO_2 concentration, and designed to handle approximately 130 tonnes of CO_2 annually.

2.3.2.4 Physical adsorption

There have not been identified any shipping pilots of this technology, at the time this work is developed. However, the status is presented with regards to land-based plants. Projects of interest from **land-based** applications include:

- **Carbon8[18]**: Accelerated Carbonation Technology (ACT) is a patented commercial solution used to recover CO_2 from thermal residues of industries like waste-to-energy, biomass for power production, cement, pulp and paper, and steel. The captured CO_2 is then used as an ingredient for valuable products.

- **Carbon Capture Machine (CCM)**: A system at TRL4 used to capture and convert CO_2 into precipitated calcium carbonate (PCC) and precipitated magnesium carbonate (PMC), which can be used as industrial ingredients for concrete.

- **Carbon Upcycling[19]**: Developed by UCLA in 2014, this novel technology captures CO_2, exploits low-grade heat, and produces an equivalent to traditional concrete, CO_2CRETE. A pilot plant of 10 Mtons per day has been developed, bringing this concept to TRL4.

[16] https://ionada.com/2022/12/08/ionada-completes-revolutionary-carbon-capture-pilot-project/
[17] Case Studies - Aqualung Carbon Capture
[18] Our Solution — Carbon8
[19] Home - Carbon Upcycling

2.3.3 OCCS feasibility and research studies

While pilot projects provide valuable operational data, feasibility and research studies offer broader techno-economic perspectives. The current section reviews key studies that assess the viability of OCCS technologies across different vessel types and operational scenarios.

2.3.3.1 Chemical absorption

A review of OCCS studies revealed various analyses with different case specifications, assumptions, and cost calculation bases. Table 2-9 summarises the main findings on feasibility and techno-economic analyses for chemical absorption CO_2 capture onboard ships.

Table 2-9 Summary of references on the OCCS technology with chemical absorption.[20]

Source	Ship type	Emissions reduction	Fuel penalty	CAPEX €	CAPEX in € per ton CO_2 captured	OPEX €	Footprint (Diameter D, Height H)
Remarcabble	MR Tanker	30% (1 tonne CO_2 per hour)	9-10%	13.5 million €	13.5 million €	0.015 - 1.14 million €	Absorber (H=6-12.5m, D=1.5-4.2m)
EverLoNG[21]	LNG Carrier, Crane vessel	70%	1-14%[22]	102 €/ ton of CO_2	NA	NA	NA
McKinsey Moller study[23]	Container ship, Bulk Carrier, Tanker	43-79%	20-45%	2.9 - 4.0 million €	0.8 – 09 million €/ ton CO_2/hr	0.45-1.8 million € /year	NA
DNV Total Joint Development Project (JDP) study	174,000m^3 LNG Carrier	Capture rate 25-70%	9-20%	9-27 million €	1.8 - 9 million €/ ton CO_2/hr	0.15-0.2 million € annually	NA
DNV Suezmax study	Suezmax Tanker	11-38%	5-24%	135-225 €/ton CO_2/year	1.2 – 2.3 million €/ ton CO_2/hr	NA	NA
DNV GL Maritime CCS Study, 2010 – 2013	VLCC	66.5%	30%	18 million €	1.9 million €/ ton CO_2/hr	0.45 million €	Absorber (6m / 12m) Regenerator 6.5m / 8m
[Luo and Wang, 2017]	Cargo ship	73% - 90%	21.4%	35 million €	3.7 – 4.7 million €/ ton CO_2/hr	1.14 million €/year	Absorber 4.2 m / 12.5 m Stripper 1.6 m / 6.5 m
[Feenstra et al., 2019]	Inland ship	60% - 90%	NA	1 - 2.5 million €	1 million €/ ton CO_2/hr	NA	Absorber 2.29 m

[20] Whenever applicable the present study uses an exchange rate USD/EUR of 0.9.
[21] IMO Future Fuels Technical Seminar 2025, Everlong project presentation: PowerPoint Presentation
[22] Depending on heat recovery potential – Estimated.
[23] Range of numbers depends on ship case study and fuel

	8000 MT general cargo ship						/13.9 m Compressor x2 { 7.01 m x 1.14 m x 0.76m} Absorber 1.5 m /10 m
[Awoyomi et al., 2019]	4 Stroke Dual Fuel engines 10MW	60 - 80 %	NA	NA	NA		Absorber H = 10 m D = 5m Stripper H = 6 m, D=2 m
[Van den Akker, 2017]	8000 MT General cargo vessel	87%	1 to 1.2 MW thermal	4.79 million €	4.2 million €/ ton CO_2/hr	0.1 million € per year	Absorber: 1.5m / 10m Stripper: 0.2m / 6m

- **DNV Maritime CCS Eurostars Research Project:** From 2009 to 2013, DNV GL and Process Systems Enterprise PSE Ltd collaborated on the Maritime Carbon Capture and Storage MCCS Eurostars programme[24]. This project assessed the techno-economic feasibility of post-combustion carbon capture for marine applications, focusing on amine absorption, pressure swing adsorption, and membrane separation technologies. Regarding chemical absorption, the study involved a VLCC designed to achieve 90% CO_2 removal from the main engine exhaust and a 65% overall emissions reduction. Advanced modelling and simulation techniques (DNV Complex Ship Systems Modelling and Simulation COSSMOS) evaluated the technologies under actual marine conditions. Health and safety aspects were assessed through HAZID/HAZOP analysis, and a comprehensive techno-economic appraisal was conducted. Economically, the capital cost of a liquid absorption system for the VLCC was estimated at approximately 5.4 million euro. The total system cost, including capture, liquefaction, and storage, was estimated at 9 million euro. Depending on installation and foundation calculations, costs could potentially double. To achieve a successful investment in a hypothetical CO_2 market, where carbon costs would balance the investment, the breakeven CO_2 price was estimated at about 126 euro per tonne of CO_2 recovered.

- **BV Feasibility Study:** The feasibility study of OCCS from Bureau Veritas BV (BV, 2023) assesses a post-combustion system for 2 bulk carrier vessels of Wah Kwong of 53,000 and 176,000 Deadweight (DWT) respectively, targeting a C-rating scenario for CII within 2023-2030, assuming a potential deduction of the captured emissions. The study concluded that for the 53,000 DWT bulk carrier, the carbon capture rate would be at the range of 10.2-29.5% by 2030 with potential savings of about €274,000 for the period of 2023-2030. Similarly, for the case of the 176,000 DWT bulk carrier the carbon capture rate could reach up to 26.3% with total savings within 2023-2030 at about €499,500.

- **McKinney Moller Maersk Zero carbon centre**: The feasibility study conducted by the Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping examined the role of OCCS in decarbonizing the maritime industry. The study analysed the impacts of full or partial application of OCCS on container, bulk, and tanker vessels using carbon-based fuels, considering both NBs and retrofits. The study found that OCCS can be applied to various carbon-containing fossil, electro, and biofuels, with post-combustion liquid amine absorption being a key technology. Emissions reductions varied depending on the vessel type and setup, with significant potential for reducing CO_2 emissions

- **Remarccable:** The Remarccable project focuses on the feasibility of OCCS systems for maritime vessels. It aims to reduce CO_2 emissions by integrating advanced chemical solvent-based capture technologies. The project demonstrated emissions reduction potential ranging from 60% to 90%, with CAPEX between €1.8 million and €35 million, and OPEX from €0.015 million to €1.14 million per year. The system's space footprint includes absorber columns with diameters from 1.5 to 4.2 meters and heights from 6 to 12.5 meters.

[24] DNV and PSE report on ship carbon capture & storage - SAFETY4SEA

In the scientific literature, there is also a wide range of references on the OCCS technology with chemical absorption.

- **DNV, Total, SK Shipping, HD, Marubeni JDP:** The DNV, Total, SK Shipping, HD, Marubeni Joint Development Project (JDP) involved several key players in the maritime and energy sectors, aiming to explore the feasibility of OCCS on LNG carriers. The participants include DNV, which provides technical expertise and certification; TotalEnergies, representing the charterer; SK Shipping, acting as the ship operator; Hyundai Heavy Industries HD-HHI, serving as the shipbuilder and Carbon Capture & Storage (CCS) equipment manufacturer; and Marubeni, functioning as the ship financier. The objective of the project is to investigate the feasibility of installing OCCS on LNG carriers to meet decarbonization targets towards 2050. The scope of the study includes evaluating the cost implications, compliance with regulations, and fuel flexibility of integrating the technology.

- **DNV, TMS Suezmax OCCS feasibility study:** The DNV, TMS Suezmax OCCS feasibility study, conducted by DNV and TMS Tankers Ltd, explored retrofitting a liquid-absorption-based OCCS on a Suezmax tanker. The study assessed three scenarios, revealing complex system interdependencies and valuable insights. Emissions reductions ranged from 11% to 38%, depending on the setup, with advanced chemical solvents and optimized machinery yielding the highest reductions. The study concluded that OCCS is more cost-effective for reducing CO_2 emissions compared to burning biofuels.

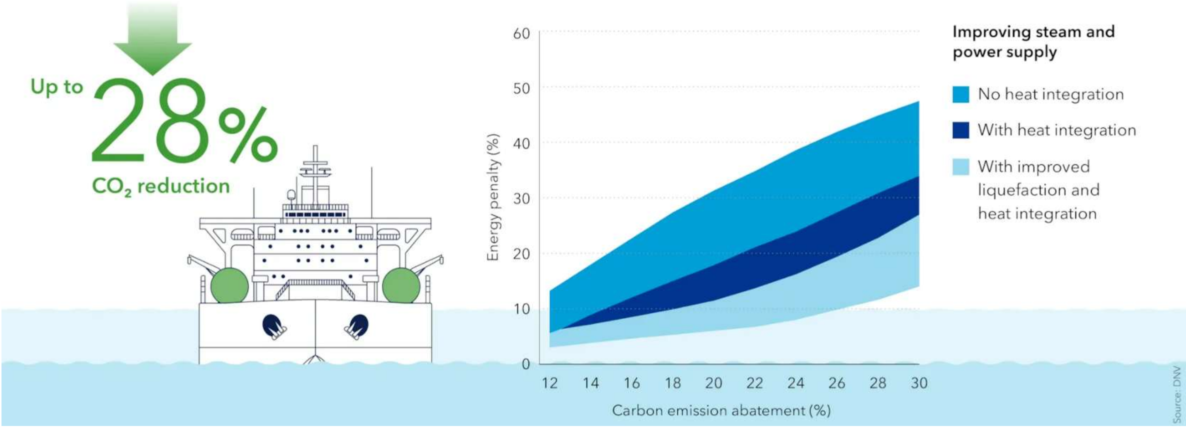

Figure 2-11 Emissions reduction potential versus energy penalty for the DNV TMS Suezmax study[25].

2.3.3.2 Physical adsorption

There are no shipping pilots of this technology, at the time this work is developed. However, the status is presented with regards to land-based plants. Projects of interest from **land-based** applications include:

- **Carbon8**: Accelerated Carbonation Technology (ACT) is a patented commercial solution used to recover CO2 from thermal residues of industries like waste-to-energy, biomass for power production, cement, pulp and paper, and steel. The captured CO2 is then used as an ingredient for valuable products.

- **Carbon Capture Machine (CCM)**: A system at TRL4 used to capture and convert CO2 into precipitated calcium carbonate (PCC) and precipitated magnesium carbonate (PMC), which can be used as industrial ingredients for concrete.

- **Carbon Upcycling**: Developed by UCLA in 2014, this novel technology captures CO2, exploits low-grade heat, and produces an equivalent to traditional concrete, CO2CRETE. A pilot plant of 10 Mtons per day has been developed, bringing this concept to TRL4.

A study that assessed the potential of this technology onboard ships is DNV's MCCS Eurostars programme. The rapid PSA process was assessed via modelling and simulation for marine environment conditions, finding the product purity to be rather low for liquefaction needs. More efficient sorbents could improve efficiencies. Due to the low CO2 purity in the product, the process was found to be inefficient for specific vessel cases.

[25] On-board carbon capture and storage for Suezmax tankers

2.3.3.3 Membrane

- **MemCCSea:** The MemCCSea research project, conducted from 2020 to 2024, aimed to develop hyper-compact membrane systems for flexible, operational, and cost-effective post-combustion CO_2 capture in maritime applications. The project was funded through the ACT programme (Accelerating CCS Technologies, Horizon2020) and included a partnership of EU and US stakeholders, coordinated by CPERI – CERTH Centre for Research and Technology Hellas (Greece) and including DNV. Two types of innovative membrane types were investigated:
    - Ceramic gas-liquid membrane contactors.
    - Polymeric mixed matrix membrane permeators.

The developed systems were evaluated and optimized in laboratory- and pilot-scale experimental facilities, supported by extensive modelling and simulation at both component and system levels. By the end of the project, both membrane technologies had achieved the goal of TRL 5-6. Process simulation was conducted for a tanker vessel with DNV's simulation platform COSSMOS. The system with and without the membrane OCCS technology was modelled, considering the extra electricity and heat demands required for the operation of the OCCS system. For an emissions reduction of 80%, the simulated fuel penalty was 14%, at the expense of a 6.7-million-euro CAPEX and requirement for frequent reinvestments to the membrane replacements.

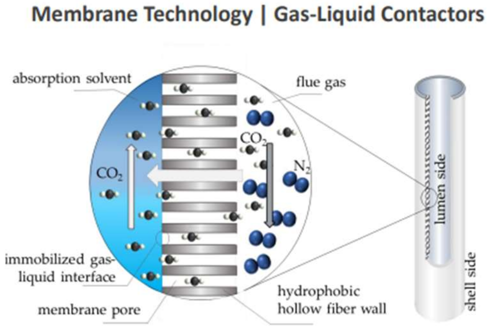

Figure 2-12 Cross section of a porous hollow fiber wall. Source: (Damartzis, et al., 2022).

- **Ionada OCCS feasibility study:** In 2024, Ionada[26] completed a membrane-based OCCS feasibility study for LNG carriers, resulting that the system could reduce more than 20% of ships emissions, while requiring 50% of the space and 30% of the power of convectional marine OCCS technologies.

- **AMbCS project:** The AMbCS[27] (Advanced Membrane-based solutions for CCUS in Shipping) project (2023-2026), is working on the development and demonstration of advanced membrane-based CCUS solution for shipping, using novel membranes and innovative processes at TRL6. The project receives funding from the Research Council of Norway and the Clean Energy Transition Partnership.

2.3.3.4 Cryo-separation

Feasibility studies highlight the potential for cryogenic carbon capture systems in maritime applications, emphasizing the need for optimization to handle lower CO_2 concentrations and maintain efficient thermal insulation. Research is ongoing to develop advanced materials and novel design configurations to achieve high removal efficiencies at lower operating costs.

- **DecarbonIce:** DecarbonICE is a concept project to capture CO_2 from ship exhaust using cryogenic separation, converting CO_2 to dry ice. The concept considers overboard discharge of the dry ice. The project emphasizes the need for a bridging solution that utilizes existing assets and has a low energy penalty.

[26] Ionada Completes Feasibility Study Project for Onboard Carbon Capture of Major Oil Company - ionada
[27] AMbCS | CETPartnership

2.3.3.5 Pre-combustion OCC

In Law et al. (2024), the concept of pre-combustion carbon capture integrated with a combined cycle gas turbine (CCGT) propulsion system is analysed to achieve energy-efficient carbon capture onboard an LNG-fuelled vessel. The study utilizes modelling and simulation to assess the performance of the integrated system. A basic CCGT model with an energy efficiency of 51.6% using LNG as fuel is considered. LNG is converted to syngas through SMR, while the capture process involves traditional capture method, e.g. PSA. The gaseous CO_2 produced in this process is liquefied and stored onboard in cryogenic conditions. The system achieves an overall energy efficiency of 41.5% and 43.2%, with emission reductions of 51.2% and 52.3%, respectively.

The HyMethShip concept integrates pre-combustion carbon capture with a dual-fuel internal combustion engine to create an almost closed CO_2 loop for ship propulsion. Electro-methanol is reformed onboard into hydrogen for propulsion and CO_2, which is liquefied and stored for reuse in methanol synthesis at port. Life cycle assessment indicated environmental benefits compared to conventional systems, with potential reductions of up to 98% in climate impact and over 90% in acidification, eutrophication, and particulate matter formation.

In the study by Nikulainen et al. (2023), the use of Rotoboost's pre-combustion OCCS solution in a new LNG carrier design was assessed at the concept level. The key challenges identified were the storage and use of H_2 as fuel on LNG carriers, and the integration with the LNG carrier's fuel gas supply system, which handles boil-off gas and vaporized natural gas (NG). The concept involved the pyrolysis of a portion of the NG, which, after decomposition, is used to enrich the fuel of onboard GenSets. The selected engine was the W34DF, upgraded to consume H_2 or its blends. The solid carbon produced is in powder form and can be stored onboard in dedicated tanks. In a standard LNG setup without modifications, the engine fuel can be enriched with H_2 by less than 3% vol. For up to 25% vol. blending, proper modifications are needed. The study further assessed the techno-economic and safety impacts of the technology under normal operating conditions of the vessel. Safety aspects were addressed through Class ABS' AiP of the system. The CAPEX was estimated to be between 6.3-13.5 million euro for an LNG carrier, while the produced high-grade carbon could offset part of the operational expenses. In terms of energy performance, the study showed that blending H_2 has a positive impact on combustion and reduces CH_4 slip. However, NO_x emissions need to be further controlled when H_2 is introduced to the engines. For the engine system as proposed, the DF engine reduces its power output to 35% when the fuel is switched from Natural Gas (NG) to 100% H_2. With an 80/20 blend, as investigated in this paper, the output is reduced to 50%.

2.3.4 Non-exhaustive list of OCCS commercial variants

This section presents an overview of OCCS technology concepts that have progressed beyond research and demonstration stages. It describes the main technology variants currently available in the market, their operational principles, and the degree of maturity.

2.3.4.1 Chemical absorption

As of the writing of this work, there are three main process variants in the operational philosophy of chemical absorption systems, available through various market concepts and products. These variants differ primarily in the form of the CO_2 product, while market systems may vary in terms of the absorbent used, these differences have a minimal impact on the core operational philosophy discussed in paragraph 2.1.1. Among the variants, only the capture with liquefaction and the capture in saturated liquid are represented by market solutions. The solutions are graphically presented in Figure 2-13.

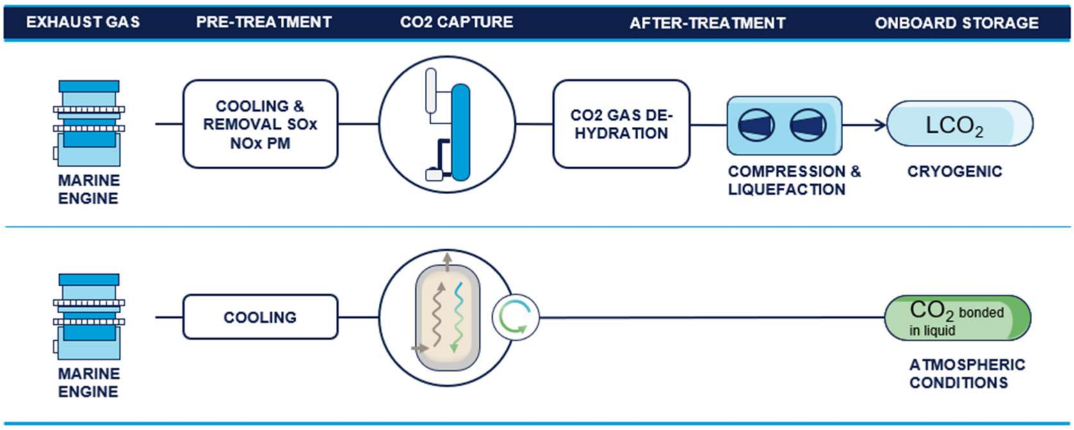

Figure 2-13. Applications of the chemical absorption OCCS technology. Source: DNV

Table 2-10 Key variants of chemical absorption for onboard use and indicative list of market paradigms (non-exhaustive).

Variant	Carbon capture and onboard liquefaction	Carbon capture and onboard compression	Carbon capture until liquid solvent saturation
Description	As for standard chemical absorption. CO_2 gas is compressed and liquefied.	CO_2 gas is compressed	The alkaline liquid stream recirculates in the absorber, until it becomes saturated with CO_2. No regeneration.
CO_2 product form	Cryogenic – Liquefied at low (6 to 12 bar) or medium (12 to 20 bar) pressure	Compressed CO_2 gas (e.g. at 55–70 bar)	Liquid solution at atmospheric conditions, saturated with CO_2
Onboard containment	C-Type tanks	Compressed gas cylinders	Liquid in process tank
Non-exhaustive paradigms	Wärtsilä[28], Erma First[29], SMDERI[30], Baker Hughes[31], Carbon Clean[32], Panaisia[33], Headway[34], Mitsubishi[35], Carbotreat and VDL Carbon Capture[36], Carbon Circle Holding AS, etc.	Mitsubishi K-Line pilot	Value Maritime[37], LanghTech[38]

[28] https://www.wartsila.com/media/news/08-03-2023-wartsila-to-deliver-its-first-ccs-ready-scrubber-systems-3236385
[29] https://www.ermafirst.com/erma-first-carbon-fit/
[30] https://www.csic-711.com/en/main.asp
[31] https://www.bakerhughes.com/process-solutions/compact-carbon-capture
[32] https://www.carbonclean.com/
[33] https://www.worldpanasia.com/eng/solution/ccus.php
[34] http://en.headwaytech.com/product.html
[35] https://www.nafsgreen.gr/sea-world/awards/9955-%E2%80%9Ccc-ocean%E2%80%9D-marine-based-co2-capture-system-demonstration-project-receives-%E2%80%9Cmarine-engineering-of-the-year-2021%E2%80%9D.html
[36] Development of Ship Based Carbon Capture (SBCC) - VDL Carbon Capture
[37] https://valuemaritime.com/
[38] https://www.langhtech.com/single-post/langh-tech-researches-ways-to-reduce-co2-emissions-using-SO_x -scrubbers

2.3.4.2 Physical adsorption

Gas separation with physical adsorption is already applied in the marine environment for N_2-air separation. However, the installation and testing of CO_2 adsorption systems on board vessels have not yet been demonstrated.

2.3.4.3 Mineralization

When this study is being developed, there is a development of market-ready solutions for OCCS using mineralization. Figure 2-14 and Table 2-11 present the key characteristics of these solutions.

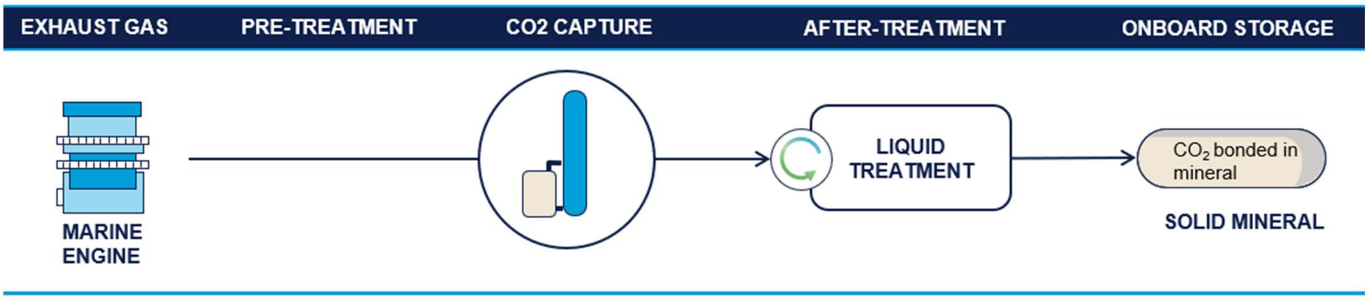

Figure 2-14. Illustration of the mineralization OCCS technology. Source: DNV.

Table 2-11 Mineralization OCCS technology for onboard use and indicative list of market paradigms (non-exhaustive).

Description	Exhaust gas scrubbing with wash-water that contains minerals reacting with CO_2 to form stable solids.
CO_2 product form	Mineral containing captured CO_2 / Solid
Onboard containment	Containers for sludge / solids
Non-exhaustive paradigms	Seabound[39], Hi-Air[40]

2.3.4.4 Membrane Separation

For land-based industries, membrane systems for CO_2 separation are commercially available, targeting applications like natural gas cleaning, pipeline applications, exhaust gas treatment, and more. In marine applications, the pilots are limited in number. Two variants are recognized:

- The system that combines chemical absorption and membranes.
- The system that separates CO_2 from exhaust only via membrane modules.

[39] https://www.seabound.co/
[40] http://www.hiairkorea.co.kr/en/main/index.php

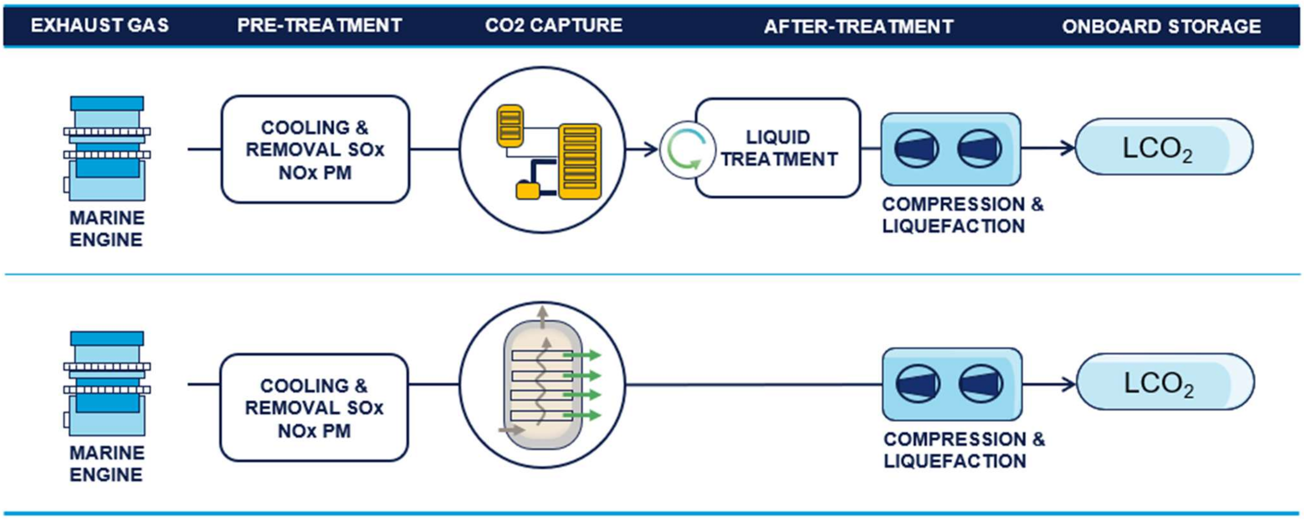

Figure 2-15. Variants of the membranes OCCS technology. Source: DNV.

Table 2-12 Membrane separation variants for onboard use and indicative list of market paradigms (non-exhaustive).

Variant	Combination of chemical absorption and membranes	Membranes only
Description	Exhaust gas passes through a membrane module; CO_2 selectively passes through the membranes and bonds into a liquid. Regeneration is used to release CO_2 gas. The CO_2 gas is liquefied onboard.	Exhaust gas passes through a membrane module; CO_2 selectively passes through the membranes. The CO_2 gas is liquefied onboard.
CO_2 product form	Liquefied CO_2	Liquefied CO_2
Onboard containment	C-type tanks	C-type tanks
Non-exhaustive paradigms	Ionada[41]	Aqualung[42]

2.3.4.5 Cryogenic Separation

Cryogenic carbon capture systems have been developed and tested at pilot scale, but marinization is in early stages.

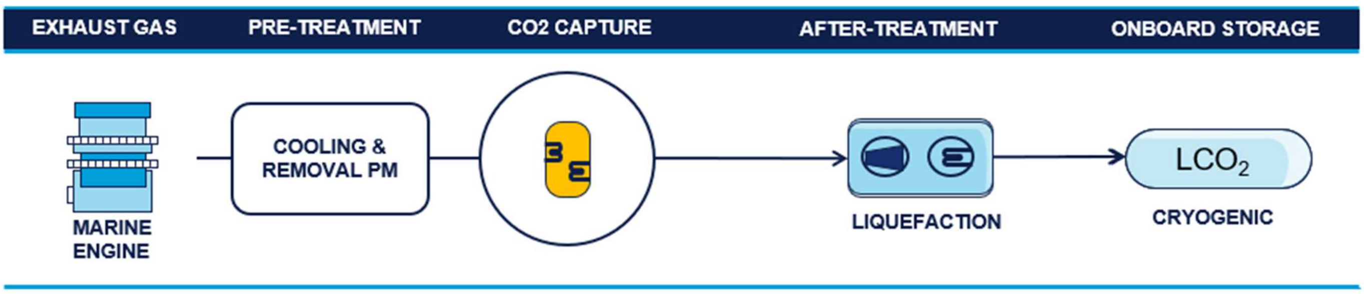

Figure 2-16. Illustration of the cryogenic separation OCCS technology. Source: DNV.

41 https://ionada.com/idecarbon/
42 Case Studies - Aqualung Carbon Capture

2.3.4.6 Electro-separation

Market examples of electrochemical separation are, among others:

- Development of an Electro Swing Adsorption OCCS solution and actively investigating the potential of OCCS technology[43].
- Development of on an electrochemical OCCS solution, with the prototype still in the development phase[44].

2.3.4.7 Pre combustion marine fuel reforming

A pre-combustion market concept is available, where CO_2-rich exhaust gas from a power generation system is fed to the cathode of Molten Carbonate Fuel Cells (MCFC). This process cleans the incoming stream and produces up to a 90% CO_2-rich stream. (Seyedvahid Vakili, 2025) (Plc, 2024). The CO_2 transferred at the anode outlet can be easily separated and liquefied for onboard temporary storage.

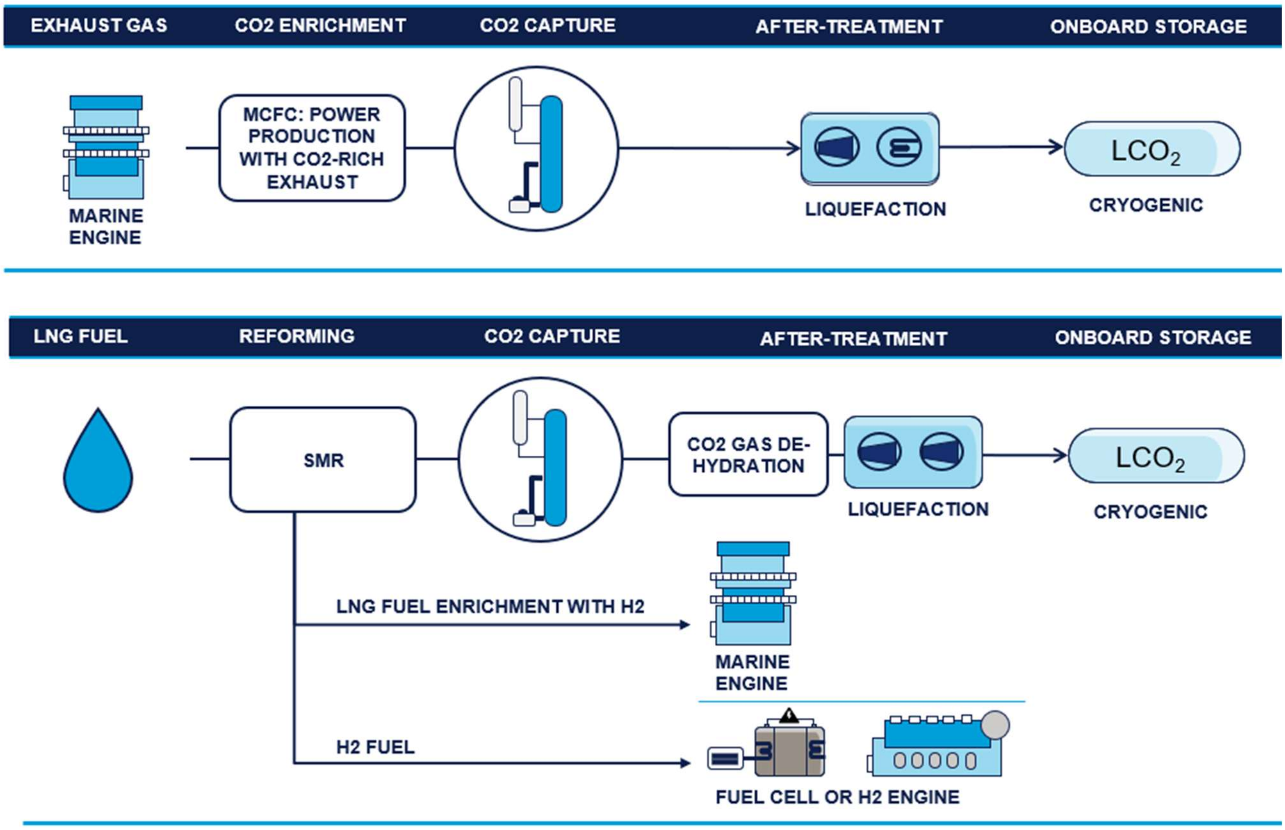

Figure 2-17. Illustration of pre-combustion OCCS technology with LNG SMR. Source: DNV.

2.3.4.8 LNG pyrolysis

Market variants are following the governing mechanisms presented in the previous paragraph and illustrated in Figure 2-18.

[43] https://www.bosch.com/research/research-fields/climate-action-and-sustainability/co2-capture/
[44] Verdox — Electric Carbon Removal

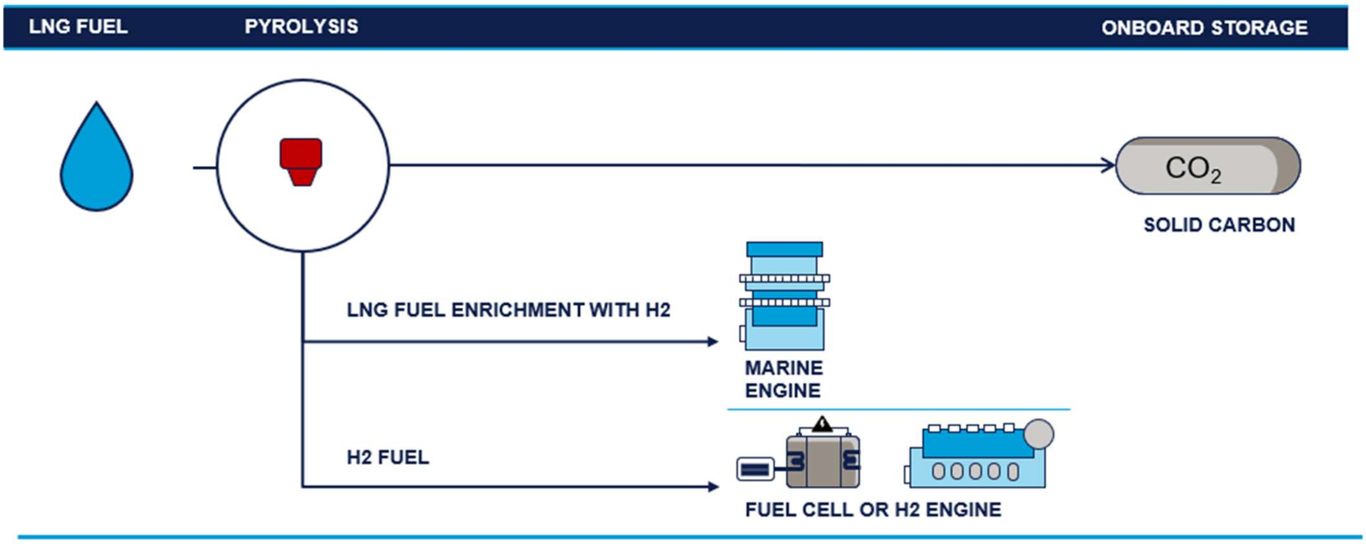

Figure 2-18. Illustration of the pre-combustion with pyrolysis OCCS technology. Source: DNV.

Market applications include the following paradigms:

- **Rotoboost**[45]: Factory-based pilot trials of an electrochemical separation system, as documented in recent literature (e.g., Nikulainen, Laukka, Portin, & Laursen, 2023).
- **Hycamite**[46]: Commissioning of a first industrial-scale facility, referred to as a Customer Sample Facility (CSF), which is expected to begin operations in Finland, based on publicly available information at the time of writing.

2.3.4.9 Oxy-fuel combustion

At the time this work is written, there appear to be no proposed market concepts or products specifically for this technology for ships.

2.3.5 Assessment of the maturity of the various OCC technologies

Table 2-13 consolidates the status of each OCCS technology, drawing on previously presented pilot projects, feasibility studies, and market-ready solutions, and applying the methodology described above. Based on the compiled inventory data and assumptions used for the TRL assessment, the following status per technology is presented.

Table 2-13 OCCS status summary.

Technology		Num. of makers	Pilots	Approvals / AiP
Chemical absorption	Liquefied CO_2	🟢	🔵	🔵
	Liquid saturated	🟡	🟢	🟢
Physical adsorption		🟡	🟡	🟡
Mineralization		🟡	🟡	🟡
Membrane		🟡	🟡	🟡
Cryogenic		🟡	🟡	🟡
Pre combustion	Pyrolysis	🟡	🟡	🟡
Oxyfuel		🟡	🟡	🟡

[45] https://www.rotoboost.com/home
[46] https://hycamite.com/

Technology	Num. of makers	Pilots	Approvals / AiP
Legend			
Limited number: Fewer than 5 cases			🟡
Moderate Number: Between 5 and 10 cases			🔵
Considerable Number: More than 10 cases			🟢

Table 2-14 OCCS TRL evaluation. Cases indicate feasibility studies, pilots, lab-scale test beds, installations and demonstration projects, depending on the TRL level.

Technology		TRL1-4	TRL5-7	TRL8-9
Chemical absorption	Liquefied CO_2	🟢	🔵	🔵
	Liquid saturated	🟡	🔵	🔵
Physical adsorption		🟡	⚪	⚪
Mineralization		🔵	🟡	🟡
Membrane		🔵	🟡	🟡
Cryogenic		🟡	⚪	⚪
Pre combustion	Pyrolysis	🟡	🟡	⚪
Oxyfuel		🟡	⚪	⚪
Legend				
Limited number: Fewer than 5 cases			🟡	
Moderate Number: Between 5 and 10 cases			🔵	
Considerable Number: More than 10 cases			🟢	

2.3.6 Conclusions on Overview of OCCS and technology categories

OCCS technologies represent an integration of multiple subsystems, from exhaust gas pre-treatment to temporary onboard CO_2 storage. These systems are categorized by the stage at which CO_2 is separated, post-combustion, pre-combustion, and oxy-fuel combustion. Post-combustion methods, such as chemical absorption, physical adsorption, mineralization, membrane separation, cryogenic separation, and electrochemical separation, are widely explored for maritime use. Pre-combustion technologies, including LNG reforming and pyrolysis, offer alternative ways by capturing CO_2 before fuel combustion, while oxy-fuel combustion remains less developed in shipping applications.

Pilot projects across the maritime sector have demonstrated OCCS feasibility under real-world marine environment conditions. Chemical absorption systems have been tested on various vessel types, showing promising results in terms of capture efficiency and operational stability, while mineralization pilots have validated the conversion of CO_2 into solid carbonates. These pilots contribute with knowledge on system performance, integration challenges, and regulatory compliance, supporting the broader consideration of OCCS as a solution for decarbonization of shipping.

Feasibility studies and techno-economic assessments further inform the viability of OCCS deployment. These analyses consider factors such as emissions reduction potential, fuel penalties, capital and operational expenditures, and system footprint. While chemical absorption remains the most mature and widely studied, other technologies are gaining traction through research initiatives and joint development projects.

Finally, it is important to notice that although OCCS technologies are being demonstrated and further developed, the realization of this technology is dependent on (a) the regulatory uptake and (b) the development of the downstream infrastructure for receival, transport and permanent storage or use of the CO_2.

3. Sustainability, Cost Analysis and Suitability

3.1 Sustainability

When evaluating the sustainability of OCCS solutions, the key factors to be addressed are:

- The GHG reduction potential, considering the emissions reduction and the energy penalty of each technology.
- The impact of use of resources, like chemicals.
- The impact of the downstream processes, for carbon offloading.
- The net lifecycle footprint.

All above factors are analysed in this section. The GHG reduction potential of the different technologies is described through literature and specific vessel cases in 3.1.1. Then, an analysis of the chemicals and solvents utilized in some of the OCCS technologies is described in paragraph 3.1.2. Finally, an analysis of the LCO_2 offloading process takes place in 3.1.3. The lifecycle footprint is analysed in 3.1.4.

3.1.1 GHG Reduction potential

In this section, we describe a framework for assessing the GHG performance of OCCS systems.

3.1.1.1 Approach

During the review of the performance of OCCS systems, it is essential to assess how OCCS operation impacts:

- The onboard systems utilization.
- The emissions of the ship.

These two factors determine the overall system efficiency and can be examined to determine OCC's influence in energy efficiency and compliance performance. Depending on the technology type, the OCCS operation could affect the utilization of onboard energy converters in ways such as:

- Increase in main engine fuel consumption due to back-pressure.
- Increase in main engine load when shaft generator is operated due to electric demands.
- Increase in aux engine load or number due to electric demands.
- Increase in boiler load due to steam demands (when demands are higher than max economizer capacity).
- Increase in freshwater generation production due to make-up water requirements.

All above impacts are relevant to most of the technology categories.

Ship emissions

When the ship operates without OCCS, the CO_2 emissions can be determined as reference, base, or baseline emissions E_{BASE}. When the ship operates with OCCS, the amount of emissions that is captured and disposed at port is $E_{DISPOSED}$. The fuel penalty, from the extra fuel needed to operate the OCCS, introduces extra emissions E_{FP}. Any leakages along the process are denoted as E_{LEAKS} and are included in the final emissions with OCCS, E_{OCC}. As shown in the below graph, the relation between base and OCCS emissions can be determined as:

$$E_{OCC} = E_{BASE} + E_{FP} - E_{DISPOSED}$$

$$E_{AVOIDED} = E_{BASE} - E_{OCC} = E_{DISPOSED} - E_{FP}$$

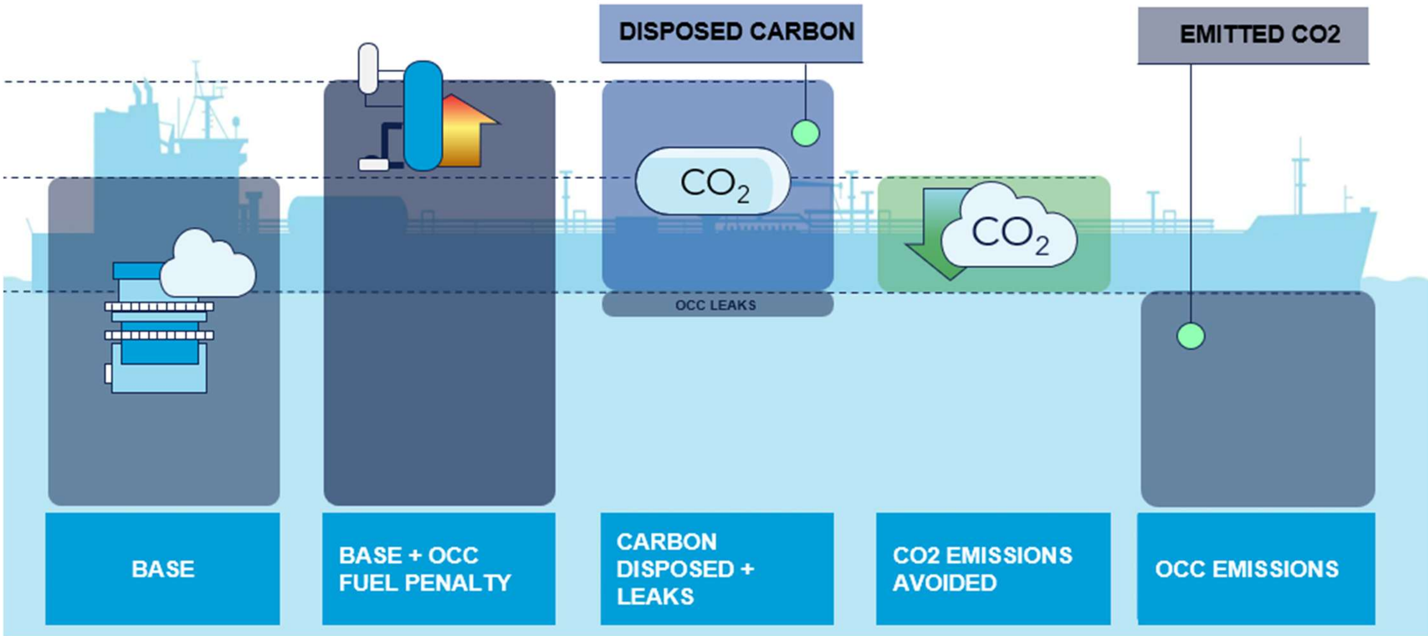

Figure 3-1. Illustration of the impact of OCCS technology on ship emissions. Source: DNV.

3.1.1.2 Technology CO2 reduction performance

Chemical absorption systems have shown high capture rates, with studies reporting reductions ranging from 30% to 90% depending on the ship type, fuel used, and system configuration, as has been shown in sections 2.3.2, 2.3.3 and Table 2-9

Membrane separation technologies, particularly when integrated with liquid absorption systems, also offer promising emissions reduction capabilities. The MemCCSea project achieved up to 80% CO_2 reduction, while Ionada's feasibility study demonstrated over 20% emissions reduction using significantly less space and power than conventional systems.

Cryogenic separation, though still in early stages of maritime adaptation, has demonstrated the ability to achieve very high CO_2 purity levels (up to 99.99%), which supports efficient downstream storage or utilization. While the low CO_2 concentration in ship exhaust limits its standalone effectiveness, projects like DecarbonICE suggest that cryogenic systems could still contribute to emissions reductions, particularly when integrated into optimized vessel designs or used in combination with other technologies.

Pre-combustion OCCS methods, such as LNG pyrolysis and reforming, offer another high-potential pathway by capturing carbon before combustion. These systems have shown emissions reductions of up to 85%, with studies on LNG-fuelled vessels reporting 51–52% reductions in integrated setups.

The energy penalty associated with OCCS technologies varies depending on the capture method and system configuration. Chemical absorption systems, which are among the most mature, typically require substantial thermal and electrical energy inputs. The heat demand for solvent regeneration ranges from approximately 1.8 to 4.0 GJ per ton of CO_2, depending on the solvent used. When combined with the electrical power demands, this translates into a fuel penalty of 9% to 30%, as reported in various feasibility studies, shown in 2.3.3 and Table 2-14. The energy is primarily consumed in operating pumps, fans, and compressors, as well as in generating steam for the reboiler. These requirements can impact the overall energy efficiency of the vessel, especially in long-haul operations.

Membrane and cryogenic separation technologies also introduce energy penalties. Membrane systems, particularly when integrated with liquid absorption, have shown fuel penalties around 14%, as shown in the relevant feasibility study 2.3.3, with some configurations requiring less power and space than traditional systems. Cryogenic systems, while avoiding the use of chemical solvents, rely on maintaining low temperatures and effective thermal insulation, which can also be energy intensive. Pre-combustion methods, such as LNG reforming and pyrolysis, involve energy losses during fuel conversion and CO_2 capture, with overall system efficiencies reported between 41% and 43%.

Table 3-1 Sustainability overview of OCCS technologies.

OCCS Technology	CO2 Reduction Performance	Energy Penalty / Demand	Notes
Chemical absorption	30–90%	Heat 1.8–4.0 GJ/ton CO2; Fuel penalty 9–30%	Mature; high heat demand
Membrane separation	20–80%	~14% fuel penalty	Needs low-temp exhaust; sensitive to impurities
Cryogenic separation	High purity CO_2 levels up to 99.99%	Energy intensive	Low CO_2 exhaust limits efficiency
Pre-combustion	Up to 85%	System efficiency 41–43%	Requires reforming/pyrolysis systems

As follows, a more detailed analysis for each technology is presented.

Chemical absorption

In chemical absorption, electric demands arise from operating pumps to circulate the liquid solution, using an exhaust gas force draft fan to compensate for pressure drops through the exhaust line, and compressing and liquefying the CO_2 product.

Regarding heat demands, thermal energy is required in the reboiler to regenerate the solvent, in addition to heat recovery. The energy demand for regeneration ranges from 4 GJ/ton CO_2 for conventional amines to 1.8 GJ/ton CO_2 for advanced solvents, as shown in Table 3-2. This heat demand is typically supplied via steam to the reboiler. Depending on the existing steam supply installation onboard a vessel, there may be the need for additional boiler installations however each case will require specific assessment and analysis, since this will depend on various factors (i.e. OCCS heat demands, capture rate, solvent used, etc.).

Physical adsorption

For maritime applications, the process effectiveness is affected by the concentration of CO_2 in the exhaust gas. Due to the low CO_2 content of the exhaust (~6% mass), the process has low efficiency and capture capacity (DNV, MARITIME CCS, 2013; R. Ben-Mansour, 2016). Furthermore, the process requires power to perform the adsorption/desorption cycles and, consequently, release the gaseous CO_2 product. In PSA, the cyclic pressurization / de-pressurization process involves the operation of gas compressors, which would introduce significant electricity demands when applied in the whole exhaust gas flow.

Mineralization

The requirements of an OCCS system which operated according to the mineralization technology can be summarized as follows:

- The process requires unreacted minerals to achieve carbon capture. The amount of minerals affects the storage requirements of the process and is analogous to the capture rate.
- Depending on the process characteristics, electricity may be needed to power up the liquid pumps that recirculate the wash-water, which serves as a carrier of the minerals.
- Finally, space onboard is required to place the minerals and the solid products of the capture process. Expected dimension for the system could range for 1m height and 1m diameter for both the absorber column and treatment unit for every 1 ton of CO_2 captured. In terms of storage for every 25 tons of mineral produced the equivalent of one TEU would be required (Wang H. , 2017).

Membrane separation

Membrane technologies are efficient for higher CO_2 concentrations (13-20%), but typical ship exhaust gas has lower CO_2 content (4-6%), posing a challenge for OCCS. Another challenge is the need of low exhaust gas inlet temperatures to the membrane modules below 50 °C, which is often hard to achieve at onboard operating conditions. The presence of impurities like SO_x, CH_4, or liquids can lower CO_2 removal efficiency, and particulate matter may clog membrane pores. Membrane properties must be optimized for the specific exhaust gas characteristics. Despite these challenges, novel concepts combining liquid absorption and membrane technologies are being developed to create more compact and efficient solutions.

Cryogenic separation

Cryogenic carbon capture is effective for high CO_2 recovery rates and purity levels, achieving up to 99.99% purity, (Song, Qingling Liu, Deng, Li, & Kitamura, 2019). However, the relatively low CO_2 content of typical ship engine exhaust gas (4-6%) poses a challenge for efficient capture. Efficient thermal insulation of the entire process is also crucial to maintain performance.

Like membrane separation, one of the challenges for onboard implementation in ships would be achieving an efficient capture process for low concentrations of CO_2 in ship engine exhausts. For the process to be energy efficient the CO_2 content of exhaust gas should be of the order of 12% and above. Further complications would be maintaining an efficient thermal insulation through the carbon capture process. Despite these challenges, cryogenic carbon capture offers significant advantages, including low energy demand and the ability to handle impurities in the gas stream.

Pre combustion marine fuel reforming

This concept involves reforming LNG into syngas before combustion, enabling CO_2 capture during the fuel conversion process. The system performance depends on the technologies considered for LNG reforming and carbon capture, as well as the storage conditions of the end-product.

LNG pyrolysis

Although related to pre-combustion approaches, LNG pyrolysis is a distinct technology that converts natural gas (NG) into H_2 and solid carbon, minimizing CO_2 emissions. The pyrolysis of NG is highly efficient in producing H_2 with minimal CO_2 emissions, as the carbon is captured in solid form rather than being released as CO_2. This method can achieve up to 85% lower emissions compared to traditional SMR.

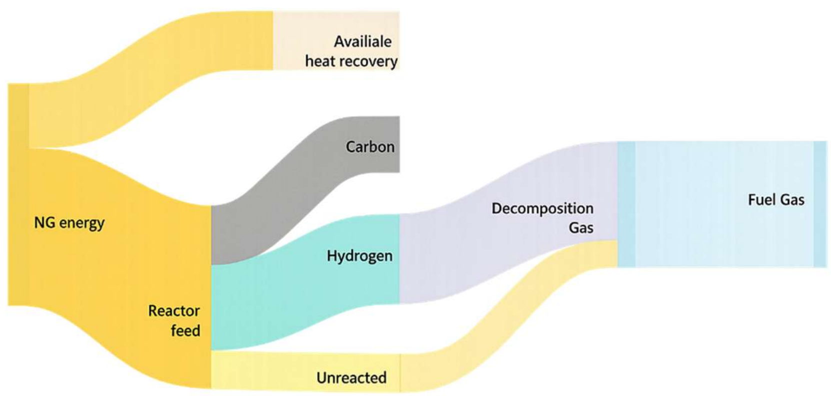

Figure 3-2: Mass flow composition in NG pyrolysis for pre-combustion carbon capture. Redrawn based on data and structure from (Nikulainen, Laukka, Portin, & Laursen, 2023).

Oxy-fuel combustion

In (Wohlthan, et al., 2024), the techno-economic performance of various oxyfuel combustion concepts for ships is assessed, considering their integration with the rest of the marine energy system through system simulation. The case study ship is a container vessel with a capacity of approximately 10,000 TEU, traveling between northern Europe and South America. The ship's operating profile includes one complete roundtrip with multiple intermediate stops, taking approximately 66 days. The baseline scenario assumes CO_2 discharge possibilities only in the home port and one South American port. The study considers oxyfuel combustion in conventional marine Diesel engines, with carbon capture after O_2 and moisture removal. The study concludes that there are fundamental techno-economic challenges of the oxyfuel combustion concept onboard ships, including the following:

- Oxyfuel combustion reduces the efficiency of the internal combustion engines due to the less favourable thermodynamic properties of the working gas.
- Onboard air separation requires a high level of electrical energy input. The latter can be avoided by separating the air onshore and transporting O_2 in a liquid state on the ship.

Electro-separation

Electrochemical methods have low theoretical energy penalties for CO_2 capture and release. Bench-scale demonstrations show promising energy efficiency, comparable to traditional methods. The stability of sorbents and electrodes is crucial for long-term operation, while the resistance to flue gas contaminants and non-toxic materials is important. The key challenge in electro separation system is the improvement of the CO_2 uptake rates and electron transfer kinetics, while the optimization of device architectures and membrane selectivity is under research.

This technology can work on any CO_2 content of the exhaust gas. In terms of power and heat consumptions, the system works at ambient temperature, and requires no heat added as such. However, as with batteries in general, temperature management could be required. Indicative performance figures indicate that such systems use about one gigajoule of energy per ton of captured CO_2, consistently.

3.1.2 Use of resources

Chemical absorption

The handling of chemicals and solvents in OCCS technologies, particularly in chemical absorption systems, involves several operational and safety considerations. Solvents such as MEA, DEA, and other amine-based compounds are commonly used due to their effectiveness in capturing CO_2. These solvents are typically regenerable, but they degrade over time and require periodic replacement. MEA is known to have degradation losses ranging from 50 to 260 grams per tonne of CO_2 captured, depending on capture efficiency and operating conditions. DEA and advanced amines such as MDEA or AMP degrade more slowly, allowing for less frequent replacement cycles, especially when reclaimers are used to recover usable solvent and minimize waste (Daniel Mullen, 2024). Additionally, common pollutants in the flue gas flow, such as NO_x and SO_x, above a certain level, may negatively affect the solvent's capturing performance.

The need for periodic solvent replacement introduces a continuous demand for chemical production, transportation, and disposal, all of which carry environmental footprints. Additionally, the system requires a continuous supply of freshwater to compensate for solvent losses, particularly in the absorber column. The degradation of solvents can lead to the formation of byproducts. These byproducts like nitrosamines and nitramines are potentially harmful to both human health and the environment, if not properly managed. Additionally, the process can generate wastewater containing degraded solvent residues, requiring further treatment.

The use of chemical solvents relates to challenges on toxicity, corrosion, and emissions of volatile compounds. Some solvents, particularly at high concentrations, can be corrosive to equipment, necessitating the use of specialized materials and increasing maintenance demands. To address these concerns, research is ongoing into the development of more stable, less toxic solvents with lower regeneration energy requirements. Sustainability also depends on the implementation of closed-loop systems for solvent recovery and recycling, as well as robust monitoring and control mechanisms to minimize leaks and emissions.

In terms of availability, commercial solvents such as MEA, DEA, and MDEA are widely available and considered commodity chemicals, making them accessible for large-scale deployment. However, advanced solvents like piperazine blends or amino acid-based formulations may have limited availability and higher costs due to proprietary constraints. DEA and MDEA offer improved stability and lower replacement rates, especially when solvent reclaimers are used. The required MEA makeup volume correlates linearly with the amount of CO_2 captured, at approximately 1.6 litres of MEA per cubic meter of liquefied CO_2 stored, based on the assumption of 1.5 kg MEA per tonne of CO_2 captured (Xiaobo Luo, 2017). This estimation refers only to makeup and does not include the total circulating solvent inventory onboard.

In addition to their widespread availability, the handling of commercial amines such as MEA, DEA, and MDEA is governed by strict IMO regulations. Proper labelling, crew training, and containment protocols are essential to ensure safe transport and onboard use. Furthermore, degradation and venting of amines may contribute to GHG emissions, adding to the overall carbon footprint of the carbon capture process[47]. The performance of chemical solvents significantly impacts system efficiency, particularly in terms of fuel penalty, health and safety, degradation, and associated costs.

Figure 3-3 provides a qualitative comparison of various solvents used in OCCS. Most conventional solvents, such as MEA, exhibit critical issues related to fuel penalty, toxicity, and performance degradation.

Table 3-2 offers an overview of solvent performance data, highlighting their advantages and disadvantages. To capture 1 ton of CO_2 per hour, the energy demand ranges from 805 to 1790 kg/h of saturated steam at 7-8 bar, which corresponds to half to full capacity of a Suezmax short-sized steam boiler[48].

	Physical Solvents	Primary Amines	Secondary Amines	Tertiary Amines	Sterically Hindered Amines	Amine Blends	Phase Change Solvents	Ionic Liquids	Salts	Ammonia	Seawater	Degree of Criticality
Maturity	5	5	5	4	4	3	1	1	4	4	1	I
Compactness	3	3	3	3	3	4	4	4	3	3	2	I
Energy Penalty	3	2	3	3	3	4	5	5	4	4	4	I
CO_2 Loading	2	3	3	4	4	5	5	5	3	3	1	I
Health and Safety	3	3	3	3	3	3	3	4	4	2	5	I
Operability Range	4	4	4	3	2	4	3	4	4	3	3	II
Impurity Tolerance	2	3	3	3	4	3	3	4	4	4	4	II
OPEX	4	2	2	3	3	2	2	2	4	4	5	II
Other Consumables	4	4	4	4	4	4	4	4	2	4	2	II

(*) Color coding is a measure of the quality of the KPI. Green (5): good, light green (4): medium-good, yellow (3): medium, orange (2): medium-bad, red (1): bad.

Figure 3-3 Comparative assessment of the different solvent classes for CO_2 capture using on board key performance indicators*. Source: (Damartzis, et al., 2022).

[47] Review of Amine emissions from carbon capture systems
[48] Reference is made to the small-scaled boilers of approximately 1500kg/h nominal capacity; the auxiliary boilers have higher capacities, i.e. 35000kg/h.

Table 3-2 Qualitative comparison of various solvents used in OCCS for chemical absorption.

Solvent Name	Regeneration (GJ/ton CO_2)	Advantages	Disadvantages	Source
Mono-ethanolamine (MEA)	3.5 - 4.0	Mature technology, fast kinetics, high selectivity	High energy demand, corrosive at high concentration, solvent degradation	Wang et al., 2023; Damartzis et al., 2022
N,N-Dimethylethanolamine (DMEA)	1.9	Low energy demand, high CO_2 loading	Limited maturity, potential solvent degradation	Wetzel et al., 2025
Piperazine (PZ)	2.4 - 3.2	High absorption rate, good stability, low viscosity	Potential for solid precipitates, solvent degradation	Khan et al., 2020; Saleem et al., 2021
Piperazine-promoted methyl-diethanolamine	2.4	Low energy demand, good stability	Potential solvent degradation	Wohlthan et al., 2024
CANSOLV	2.4 - 3.2	High capture efficiency, low parasitic energy consumption	Proprietary solvent, limited public data	Thunder Said Energy
Potassium Carbonate (K_2CO_3)	2.1 - 2.5	Low cost, high stability, low degradation	Slow kinetics, potential for equipment corrosion	Borhani et al., 2019
Diethanolamine (DEA)	2.5 - 3.0	Lower energy demand than MEA, less corrosive	Slower kinetics than MEA, potential solvent degradation	Damartzis et al., 2022
Methyl-diethanolamine (MDEA)	2.0 - 2.5	High stability, low regeneration energy	Slower kinetics, higher molecular weight	Mathias et al., 2013
Amino Acid Ionic Liquids (AA-ILs)	1.4 - 3.6	Low vapor pressure, high thermal stability	High viscosity, high production cost	Oko et al., 2018
Phase Change Solvents	2.1 - 2.5	Reduced thermal regeneration costs, high CO_2 loading	Limited maturity, potential process complexity	Papadopoulos et al., 2021

Membrane Separation

Combining the membranes with liquid absorption technologies results in a more compact plant than the traditional amine column technology. The combined solution also reduces amine amount and amine leakage on exhaust, as well as increasing the efficiency of conventional membrane systems in delivering high-purity end-product, despite the low exhaust gas CO_2 content.

Ultimately, the long-term viability of chemical-based OCCS systems focuses on balancing their CO_2 capture performance with the environmental and operational impacts of solvent use throughout the system's lifecycle.

3.1.3 LCO_2 Port offloading

LCO_2 disposal from the ship to shore requires a pressure differential or a dedicated offloading pump. Compatibility between ship and terminal pressure regimes is not only an operational concern but also a factor influencing the overall sustainability of the CCUS chain, since inefficient pressure management can increase energy use or cause CO_2 losses.

In a typical LCO_2 offloading operation, liquid CO_2 is transferred from the onboard storage tanks to a terminal buffer tank via the ship's manifolds and marine loading arms or hoses. Two hoses are used: one for liquid transfer and one for vapour return to maintain pressure balance. Although onboard systems include a reliquefaction plant that can condense returned vapour, this system may not fully stabilise tank pressure during high-rate offloading. Insufficient vapour return capacity could cause boil-off accumulation, forcing the vessel to rely heavily on re-liquefaction or, in the worst case, venting, both of which negatively affect the net environmental performance of the CCS operation.

During offloading, vapour is displaced in the terminal buffer tank as LCO_2 enters from the ship. Any power requirement is primarily linked to LCO_2 pumping. For discharge rates between 50 m^3/h and 500 m^3/h, and assuming medium-pressure LCO_2 density, the energy demand is estimated at approximately 0.99 kWh per ton of LCO_2 handled. This offloading and conditioning energy can represent up to 30% of the terminal's overall energy footprint, directly influencing the lifecycle sustainability of CO_2 transport and storage, since higher transfer-stage energy demand reduces the net amount of CO_2 avoided across the CCUS chain (Seyedvahid Vakili, 2025)

Consequently, optimising pressure control, minimising boil-off, and reducing pumping energy are key sustainability levers in the LCO_2 transport and disposal process.

3.1.4 Lifecycle footprint

To evaluate the overall impact of OCCS in decarbonizing the shipping industry, a lifecycle assessment approach to its emissions footprint is required. This involves assessing the CCUS value chain emissions from capturing and storing CO_2 onboard, to emissions from offloading, transportation, and permanent storage, or utilization. These emissions vary depending on the characteristics of the whole value chain. Currently, there are two studies in literature that address OCCS lifecycle emissions, namely the project COLOSSUS (GCMD, 2025a) and the EverLoNG project, (Reitz & Zapp, 2025).

The project COLOSSUS[49], conducted by the Global Centre for Maritime Decarbonization (GCMD) in 2025, presented the life cycle assessment of OCCS technologies using a well-to-wake (WtW) approach. The study evaluated OCCS performance across six marine fuel types and three post-capture scenarios, assuming a 40% carbon capture rate. For an HFO-fueled vessel, conventional MEA-based OCCS showed a 29% reduction in WtW GHG emissions. When combined with biofuels such as bio-LNG or biodiesel, emissions savings ranged from 69% to 121% - depending on the percentage of biofuel use. Among post-capture options, storing CO_2 in concrete offered the highest emissions reduction, up to 60%, while transport and permanent storage contributed about 9-34 gCO_2eq per kg of captured and stored CO_2. The cost of avoided carbon was estimated between euro 242-365/tCO_2 for an MR tanker (HFO fuel) for a case of permanent storage of CO_2.

The EverLoNG project conducted a Life Cycle Analysis (LCA) to evaluate the environmental impacts of implementing OCCS on LNG-fueled vessels. Two case studies were analyzed: the retrofitted semi-submersible crane vessel Sleipnir and an LNG carrier. The study assessed both Tank-to-Wake (TtW) and WtW emissions, including upstream fuel production and downstream CO_2 handling via storage or utilization. Results showed that OCCS achieved onboard CO_2 emission reductions of 72% for Sleipnir and 82% for the LNG carrier, with a respective effect of 39% and 44% full lifecycle climate change impact reductions. It was noted that CO_2 utilization pathways (e.g., methanol or LNG synthesis) showed climate impact reductions of 29-62% depending on the CO_2 pathway and ship case study.

Table 3-3 Life Cycle Assessment on OCCS emissions.

Aspect	COLOSSUS	EverLoNG
Technologies	5 OCCS technologies	OCCS using MEA-based absorption
Fuel Types	HFO, bio-LNG, biodiesel, others	LNG and MGO
Case Studies	MR tanker	Sleipnir (retrofit) and LNG carrier (NB)
CO_2 Pathways	Permanent storage, concrete production, methanol production	■ Sequestration: Northern Lights storage ■ Utilization: EOR, methanol and LNG synthesis

[49] https://www.gcformd.org/gcmds-life-cycle-study-quantifies-net-ghg-emissions-savings-for-pathways-with-onboard-carbon-capture-and-storage-occs/

Aspect	COLOSSUS	EverLoNG
Capture Rate	40%	72% (Sleipnir), 82% (LNG carrier)
Lifecycle emissions reduction	WtW GHG emission savings: ■ MEA-based OCC: 29% ■ Biofuels + OCC: 69–121% ■ Concrete fixation: up to 60%	Climate change impact: ■ MEA-based OCC: 39% (Sleipnir), 44% (LNG carrier) ■ OCC+CO_2 utilization: 29-62%

It is shown therefore, that significant emissions reduction rates are estimated to be feasible through the combined use of OCCS and alternative fuels and drop-in fuels such as biofuels. A feasibility study on a Suezmax tanker (DNV, 2024b) has also assessed the comparison of the OCCS and biofuels as decarbonization solutions on TtW approach, while OCCS and bio-LNG solutions were studied in (DNV, 2023b).

When considering the emission factors of such fuels under relevant frameworks, it is noted that according to MEPC.1/Circ.905[50] the TtW CO2 conversion factor for biofuels may be derived from the WtW GHG emissions multiplied by the fuel's lower calorific value, provided that the WtW emissions demonstrate a 65% reduction compared to fossil MGO. This guidance serves as an interim, simplified approach until a more comprehensive methodology is developed in accordance with the LCA Guidelines.

Similarly, under the FuelEU Maritime regulatory framework, biofuels produced in installations starting operation from 1 January 2021 (Art.29.10.c RED III) must meet the emission savings criteria outlined in Directive (EU) 2018/2001, which also mandates a minimum 65% GHG savings compared to the GHG intensity comparator of 94 gCO2eq/MJ (As per Annex V – Part C Methodology point 19 RED III). It is important to note that biofuels are often used in blends onboard ships, meaning the actual emissions reduction depends on the overall fuel mix consumed.

Table 3-4 illustrates the emissions reduction potential under the FuelEU Maritime framework (based on a WtW approach) for various blends of FAME and MGO biofuels, assuming compliance with the 65% savings threshold (DNV, 2025b). Depending on the biofuel blend the overall savings on WtW GHG intensity on FuelEU may range from 6-62% savings, when compared to MGO.

Table 3-4 Emissions reduction potential under the FuelEU Maritime for FAME and MGO biofuels blends. Source: (DNV, 2025b).

	MGO	B10	B20	B24	B30	B50	B100
WtW GHG intensity (gCO2eq/MJ)	0%	6%	11%	14%	17%	29%	62%

In Table 3-5 the WtW emission factors for biofuels are shown for different production pathways. These indicative values follow the default greenhouse gas emission values established under the Renewable Energy Directive (RED) and referenced in the FuelEU Maritime Guidance Document (Directorate-General for Mobility & Transport, 2025). In practice, the actual WtW GHG intensity for each fuel shall be taken from the supplier-issued Proof of Sustainability (PoS) or Proof of Compliance (PoC), as required under the FuelEU Maritime Regulation.

Table 3-5 WtW emission factors of Biofuels, compared to HFO based on example default RED GHG emission values. Source: (Directorate-General for Mobility & Transport, 2025).

Fuel type	WtW GHG intensity [gCO2eq/MJ]	Savings compared to HFO [%]
Pathway / Consumer		
Bio-ethanol (wheat straw)	17.7	81%

[50] Interim Guidance on the Use of Biofuels Under Regulations 26, 27, and 28 of MARPOL Annex VI (DCS and CII).

Fuel type	WtW GHG intensity [gCO2eq/MJ]	Savings compared to HFO [%]
Bio-diesel (waste cooking oil)	16.4	82%
Hydrotreated Vegetable Oil (waste cooking oil)	17.2	81%
Liquefied Biomethane / Otto (dual fuel medium speed)	33.6	63%
Liquefied Biomethane / Otto (dual fuel slow speed)	27.4	70%
Liquefied Biomethane / Diesel (dual fuels)	20.7	77%
Liquefied Biomethane / LBSI	31.4	66%
Bio-methanol	13.1	86%
Other Production Pathways	16.5	82%
HFO (Grades RME to RMK)	91.7	0%

The above showcase a potential emissions reduction of 63-82 % compared to HFO.

3.1.5 Conclusions on sustainability

OCCS technologies offer potential for reducing maritime GHG emissions, with chemical absorption systems currently the most mature and widely demonstrated. Other technologies, such as membrane separation, cryogenic capture, and pre-combustion methods, show promise but face integration and energy efficiency challenges.

Sustainability performance varies by vessel type, capture rate, and system configuration. Higher capture rates yield greater emissions reductions but usually come with increased fuel penalties. Lifecycle assessments confirm that OCCS, especially when combined with biofuels, can achieve substantial well-to-wake emissions reductions, which could be as high as 120% in some scenarios.

Solvent use, energy demand, offloading logistics, and compatibility with the CCUS value chain all influence the environmental footprint. Long-term viability will depend on improving solvent stability, minimizing energy penalties, and ensuring seamless integration with port and storage infrastructure.

Environmental and lifecycle considerations also play a critical role in evaluating OCCS technologies. The use of chemical solvents introduces challenges related to toxicity, corrosion, and degradation, which can impact both safety and sustainability. These systems often require continuous chemical supply, freshwater input, and wastewater treatment. Research into more stable and environmentally friendly solvents is ongoing, with several alternatives showing potential for reduced environmental impact. Long-term viability will depend on the development of closed-loop systems, improved solvent formulations, and robust monitoring to ensure safe and efficient operation throughout the system's lifecycle.

Lifecycle assessment studies such as COLOSSUS and EverLoNG demonstrate that OCCS and alternative fuels contribute separately and cumulatively to reducing well-to-wake GHG emissions. For conventional fossil fuels, OCCS alone delivers around 29%-39% WtW reduction for MEA-based systems, while biofuels alone provide reductions in the range of 6–62% for typical maritime FAME/MGO blends under FuelEU as shown in Table 3-4 and up to 63–86% depending on production pathway under RED default values as shown in Table 3-5. When OCCS is combined with biofuels, the COLOSSUS study shows that total WtW reductions increase substantially to 69–121%, depending on fuel type and blend ratio. The environmental benefits are further enhanced when CO2 is utilized or permanently stored, with concrete fixation and synthetic fuel production offering notable climate impact reductions.

3.2 Cost Economic Analysis

This chapter presents the economic framework for evaluating the feasibility and performance of OCCS across the examined vessel cases. It outlines the key operational and economic parameters that influence OCCS integration and show some comparative results.

3.2.1 Selection of case study ships

This section serves as the foundation for selecting representative vessel types to be included in the subsequent sustainability, suitability and cost analysis of OCCS technologies. By examining the operational characteristics, emission profiles, and integration potential of various ship segments within the European maritime sector, the chapter identifies candidate vessels, both deep sea and short sea, that are most suitable for OCCS deployment. These selections will guide the detailed bottom-up case studies and simulations presented in the following sections.

3.2.1.1 Overview

The European maritime transportation sector is a crucial part of the region's economy, with approximately 74% of EU merchandise imports and exports dependent on shipping, (EEA-EMSA, 2025). This sector is characterized by a diverse range of ship segments, including container ships, bulk carriers, tankers, Ro-Ro (Roll-on/Roll-off) vessels, and passenger vessels. This sector is composed of both deep sea and short sea shipping legs. Deep sea shipping involves the transport of goods across oceans and between continents, while short sea shipping refers to the movement of cargo over shorter distances within Europe, often connecting neighbouring countries and regional ports. Short sea shipping accounts for a significant portion of intra-EU trade, representing about one-third of intra-EU exchanges in terms of ton-km.

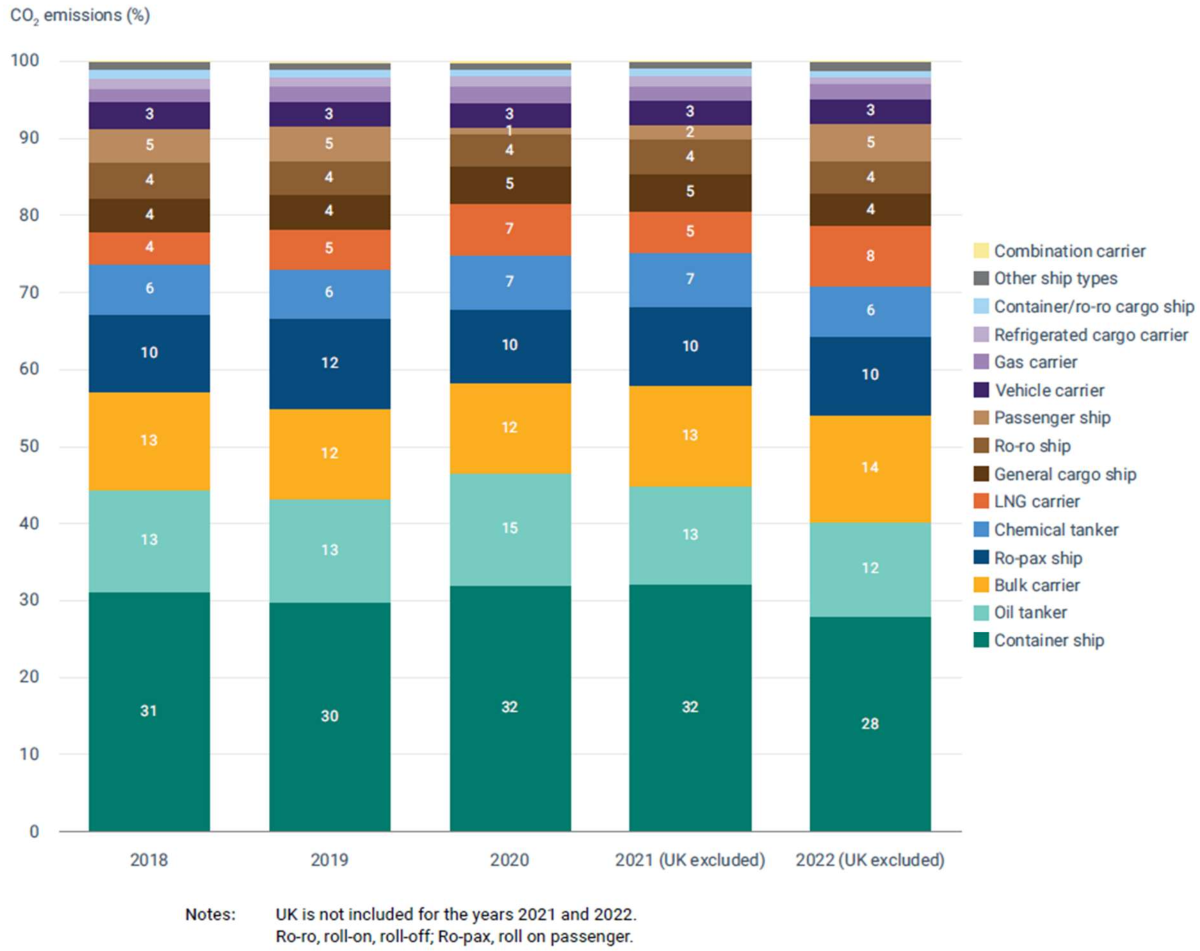

Figure 3-4 Shares in total fleet CO_2 emissions by ship type between 2018 and 2022. Source: (EEA-EMSA, 2025).

According to the European Maritime Transport Environmental Report (EEA-EMSA, 2025), CO_2 emissions from the maritime transport sector account for approximately 3-4% of all EU CO_2 emissions, and specifically, 14.2% of all CO_2 emissions from the EU transport sector in 2022. From 2018 to 2022, five types of ships constituted the majority of emissions reported under the MRV, with bulk carriers (31%), oil tankers (15%), container ships (14%), chemical tankers (11%), and general cargo ships (9%) being the primary contributors. In 2022, container ships, oil tankers, and bulk carriers alone accounted for 54% of the total maritime CO_2 emissions (Figure 3-4).

The selected vessels in this section, that are chosen for this study, are analysed in terms of:

- GHG reduction potential vs fuel penalty in 3.1.1.2.
- Technical impact analysis in 3.4.5.
- Economic impact analysis in 3.2.1.
- Economic viability against regulations in 3.3.2.

3.2.1.2 Selection of vessel types

Identifying the main contributors is an important factor in selecting the indicative vessel types for further analysis with OCCS in this work. Consequently, the focus is on the main contributing ship segments in EU emissions and their capacity to accommodate OCCS onboard when identifying the case study ships for this analysis.

Regarding EU deep sea trading, the following ship segments are identified:

- **Suezmax oil tanker**: Suezmax tankers play an important role in European crude oil transportation[51]. These tankers offer onboard space for retrofitting OCCS systems, and their long voyages provide extended periods for capturing and storing CO_2. Additionally, studies have shown that integrating OCCS on Suezmax vessels can achieve meaningful emissions reductions without major operational compromises, (DNV, 2024b).
- **Containership**: Containerships are typically characterized by frequent port calls. While the available onboard space depends on the loading factor, container vessels often operate on fixed schedules and routes, providing predictable and consistent opportunities for OCCS. Currently, most of the OCCS pilots in shipping relate to containerships (DNV, 2024d).
- **LNG Carrier:** LNG carriers are specialized vessels designed to transport LNG at cryogenic temperatures across long distances. Their complex onboard systems, including cryogenic containment and fuel gas handling, make them technologically advanced platforms for integrating OCCS solutions. Evaluating OCCS integration on this vessel type is particularly valuable due to the potential for synergies with existing cryogenic infrastructure.

[51] Riviera - News Content Hub - Analysis: tanker market reaction to the Suez Canal incident

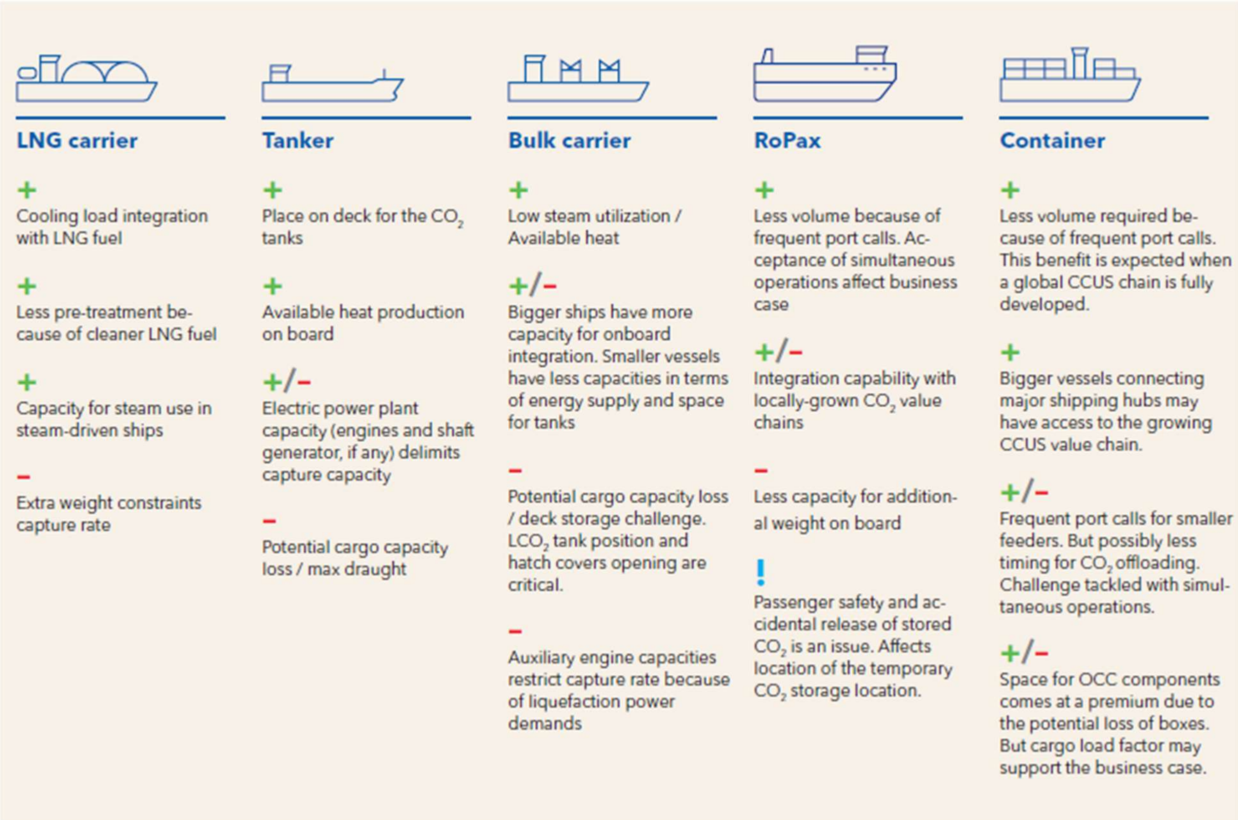

Figure 3-5 Practicalities related to the integration of OCCS for selected ship types. Source: (DNV, 2024d).

Regarding EU short sea / coastal trading, the following ship segments are identified:

- **Feeder containership**: According to the European Shortsea Network (ESN, 2025), container feeders account for approximately 19% of the total short sea shipping trade in the EU. Feeder containerships, which typically have a capacity ranging from 300 to 3,000 TEUs (Twenty-foot Equivalent Units), show operational flexibility and frequent port calls. Their smaller size allows them to access ports with shallow drafts and limited infrastructure, making them versatile in various maritime environments.
- **Ro-Pax**: RoPax ferries play a significant role in EU coastal trade. Their trade is characterized by frequent port calls. However, the dual-purpose nature of Ro-Pax vessels introduces challenges related to safety, as well as balancing the space needed for passenger amenities and vehicle storage with the requirements of OCCS equipment.
- **MR tankers:** Medium Range (MR) tankers, typically ranging from 30,000 to 52,000 DWT, are used for transporting refined petroleum products along coastal trade routes, often on regional and intraregional voyages. Their frequent and consistent operational patterns along these shorter routes provide opportunities for OCCS. Additionally, their smaller size compared to Suezmax vessels offers valuable insights into how OCCS technologies can be effectively integrated into smaller tanker vessels operating in coastal trade.

3.2.1.3 Methodology

The analysis of NB and retrofit ship cases with OCCS technologies is performed following a methodology that integrally considers the impact of the technology on ship machinery and trade.

- **Step 1 Case description and key assumptions:** The selected vessel cases are described in terms of ship characteristics, fuel types, machinery specifications, trade route and annual operational profile. Depending on the case, NB or Ship in Operation (SiO) is considered. Assumptions over the case studies of interest and the regulatory framework implementation are defined.
- **Step 2 Capture technology pre-screening**: OCCS technology pre-screening is performed, based on the maturity and readiness level, and suitability for the identified ship cases. All technology categories are considered in the screening methodology, e.g. liquid absorption with onboard liquefaction (with and without membrane separation technology), cryogenic separation, liquid saturation with CO_2, mineralization.

- **Step 3 Ship technical impact analysis:** The ship cases with and without OCCS are simulated over a range of speeds and operating modes, which are representative for the vessel operation. All simulations are conducted using DNV COSSMOS simulation environment (DNV GL, 2014).
  - **Capture rate**: The max possible capture rate is evaluated based on technical constraints onboard (availability of space and machinery capacity).
  - **Emissions reduction and fuel penalty**: The results are aggregated on voyage and annual levels, to quantify the impact on emissions and energy efficiency, space footprint, and machinery utilization.
  - **Comparison against biofuels**: Using the simulation results, a comparative assessment against base ship without the technology, and against conventional and alternative fuels, e.g. biofuels, is performed.
  - **Impact of NB or retrofit**: The study distinguishes the effect of NB versus retrofit implications. In case of retrofit, the impact on machinery power capacity and fuel type, exhaust gas pre-treatment, and vessel payload are considered. In the case of NB, an optimal onboard energy integration is performed.
  - **Dynamic processes**: The liquefied gas CO_2 tank filling and transport until disposal is simulated to indicate challenges during the process.
  - **Disposal**: An analysis is performed on the types of port offloading and ship interfacing, including for example shuttle LCO_2 service, LCO_2 terminal offloading, and other types of offloading based on the CO_2 product form.
- **Step 4 Ship economic impact analysis**: The following cost factors are accounted for in the estimation of the economic impact:
  - The annual Fuel OPEX and technology CAPEX are estimated based on past cost trends, current and foreseen prices.
  - Impact on regulatory compliance is assumed based on scenarios for technology implementation in relevant regulatory frameworks (EU ETS, GFI).
  - Combinatorial impact of above factors and any cargo capacity effect is considered.
- **Sensitivity analysis** is incorporated in all above steps, e.g. on CAPEX and OPEX of the technology, over the trade of the vessel, and the disposal cost.

3.2.1.4 Key assumptions

Furthermore, the following key assumptions are set:

- **NB vessel**: This scenario considers optimal onboard energy integration, tailored to the specific vessel. A vessel built in 2025 is considered, being OCCS ready for integration of the technology in 2030. While OCCS integration is optimized in the design phase, it may still result in a marginal reduction in DWT due to the space and weight requirements of CO_2 capture, liquefaction, and storage systems. However, NBs offer better flexibility in equipment placement (e.g., deck-mounted CO_2 tanks), minimizing cargo impact compared to retrofits. To support future OCCS integration, the NB CCS-ready vessel incorporates several preparatory measures in line with classification society guidelines. These include documenting and implementing structural modifications required for the future installation of CO_2 containment systems, ensuring that reinforcements and materials are suitable for the expected low-temperature conditions. Additionally, spaces intended for OCCS equipment are planned and prepared from the newbuilding stage, and any auxiliary systems or equipment that can facilitate future integration are installed during construction. These provisions ensure that the vessel is structurally and operationally prepared for efficient OCCS retrofitting with minimal disruption to cargo operations.
- **Retrofitted vessel**: In this scenario, the examined vessel built in 2025, will undergo a retrofit, assumed to take place in 2030. In this case, vessel is not considered to be optimally designed around the OCCS technology, which may lead to more pronounced impacts on cargo capacity and operational efficiency due to integration constraints.
- The financial assessment will be conducted over a 25-year vessel lifetime.

3.2.1.5 Technology Selection Criteria

The selection of OCCS technology depends on several vessel-specific factors, including:

- Voyage profile (duration, speed distribution, port operations).
- Available deck and machinery space.
- Engine load stability.
- Waste heat recovery potential.

The selection of the technology is based on the analysis from section 2. Table 2-14 and Table 3-19 can be used as a comparative basis for the technology screening. The vessel's operational profile, onboard space, and stable engine load conditions are factors that are taken into consideration.

A range of OCCS technologies are considered during the pre-screening phase, including chemical absorption, cryogenic separation, membrane-based systems, mineralization, and liquid saturation. Each presents distinct advantages and integration challenges depending on vessel type, operational profile, and maturity level.

For the purposes of this study, chemical absorption is selected as the reference OCCS technology across all examined vessel types, Suezmax tankers, large container ships, LNG carriers, RoPax ferries, and feeder container vessels. This choice is guided by the relatively high TRL and the availability of marine pilot experience. Their modularity and adaptability to varying ship sizes and voyage durations make them a practical baseline for simulation and economic analysis.

For the analysis of OCCS technology in terms of energy efficiency a state-of-the-art system is considered for both the NB and retrofit vessels with:

- Solvents reducing additional heat demands for the chemical solvent regeneration (assumed at 2GJ/ton of CO_2).
- Compression stage assuming energy demand at the order of 300kWh/ton of CO_2.

Each vessel exhibits diverse operational characteristics. Suezmax tankers and LNG carriers offer long-haul voyage profiles and sufficient deck space, supporting OCCS integration. Container ships and feeder vessels provide predictable engine loads and modular design flexibility, while RoPax ferries, despite frequent port calls and variable loads, benefit from regular docking schedules that facilitate CO_2 offloading.

Regarding the alternatives, such as cryogenic and membrane systems, these may offer competitive advantages in specific contexts. The focus on chemical absorption in this phase is intended to provide a baseline for comparative analysis, while acknowledging that future assessments may incorporate other technologies as they evolve.

3.2.2 Selected vessels overview

The reader can find the full techno-economic analysis per vessel in the Appendix as follows:

- Appendix B - Suezmax cost economic analysis.
- Appendix C - 15,000 TEU Dual Fuel LNG container cost economic analysis.
- Appendix D - RoPax cost economic analysis.
- Appendix E - LNGC cost economic analysis.
- Appendix F - 1,700 TEU Feeder container cost economic analysis.
- Appendix G - MR Tanker cost economic analysis

3.2.2.1 Suezmax vessel

For the Suezmax vessel, the main dimensions and machinery are shown in Table 3-6.

Table 3-6 Suezmax case study – Vessel specifications.

Suezmax case study – Vessel specifications	
First year in service	2025
DWT	Appr. 160,000 tons
Lightweight	Appr. 25,000 tons
Propulsion system	1 x 2-Stroke Diesel engine of abt. 13.5 MW
Electricity supply	3 x 4-stroke Diesel engines of 1.3 MW each
Heat supply	1 x composite boiler / 2 x auxiliary boilers

The analysis of the vessel's voyage operating profile is shown in Figure 3-6, where the percentage of time at low speeds (below 7 knots), speeds in the range of 7 – 14 knots, and higher than 14 knots are shown, along with the percentage of time the vessel spends at anchorage and at operations. The vessel trade is considered for an average round trip of 40 days, meaning approximately 9 round trips per year. Operation profile data are extracted from AIS. No cargo heating operations are considered.

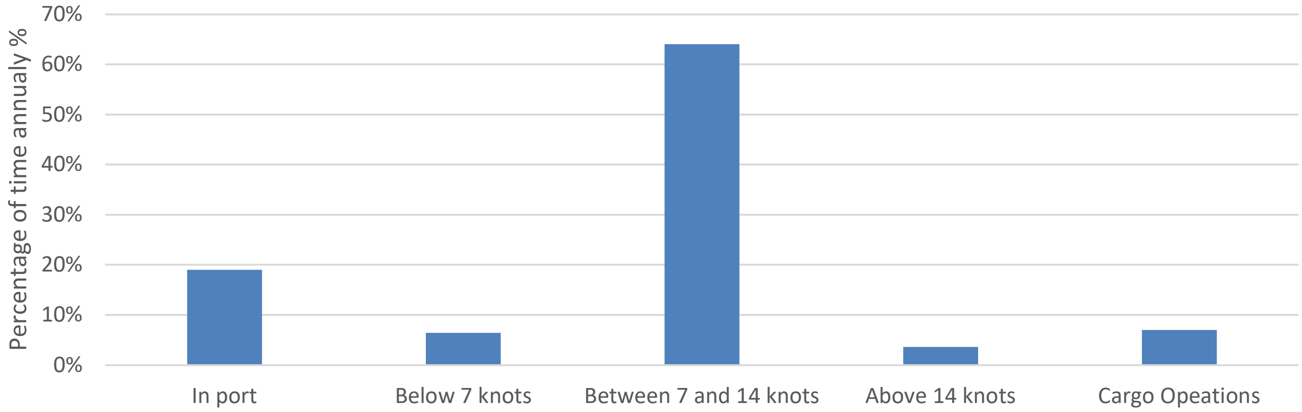

Figure 3-6 Suezmax case study – Operating profile.

3.2.2.2 15,000 TEU Dual Fuel LNG container

For the 15,000 TEU dual fuel LNG container vessel, the main dimensions and machinery are shown below.

Table 3-7 Container case study – Vessel specifications.

15,000 TEU container case study – Vessel specifications	
First year in service	2025
DWT	Appr. 160,000 tons
Lightweight	Appr. 45,000 tons
Propulsion system	1 x 2-Stroke Dual fuel engine of abt. 45 MW
Electricity supply	4 x 4-stroke Dual fuel of abt. 4 MW each
Heat supply	1 x Auxiliary Boiler / 1 x Main Engine Exhaust Gas Economizer / 2 x Auxiliary Engines Economizers (AEECOs)

The operational profile of a typical 15,000 TEU container vessel is analysed below, detailing the distribution of time spent underway, at anchor, and during port operations as shown in Figure 3-7.

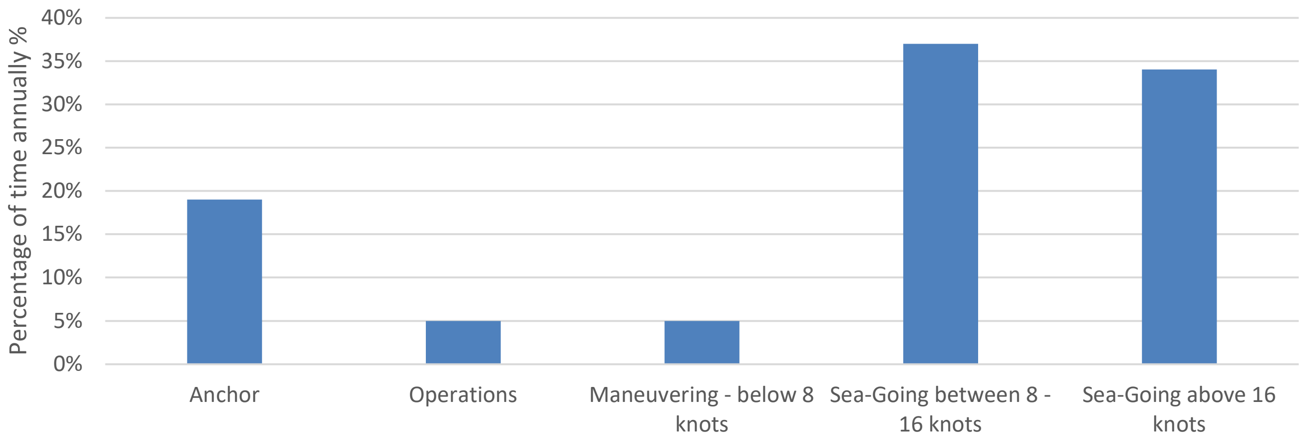

Figure 3-7 Container case study - operating profile.

3.2.2.3 Ro-Pax

For the Ro-Pax vessel, the main dimensions and machinery are shown below. During its port calls, the vessel is supplied with electrical power by means of a shore-side electricity supply (High Voltage External Connection).

Table 3-8 Ro-Pax case study – Vessel specifications.

Ro-Pax case study – Vessel specifications	
First year in service	2025
DWT	Appr. 1,700 tons
Lightweight	Appr. 4,000 tons
Propulsion system	2 x 4-Stroke Diesel engine of abt. 3.2 MW each
Electricity supply	4 x 4-stroke Diesel engine of abt. 560 kW each (sea-going) shore connection
Heat supply	Oil fired Aux. Boiler

The vessel operates on a short-distance route between neighbouring ports. Its schedule involves several frequent, brief intraday coastal transits, the number of which depends on the season of the year. These transits are followed by extended periods moored at its primary terminal, where it remains docked for several hours during nighttime. During these layovers, the vessel connects to a shore-side electrical supply system, which allows it to shut down its auxiliary engines and draw energy from the local grid. This setup significantly reduces local emissions, noise, and fuel consumption while docked. The shore power connection ensures that essential onboard systems, such as lighting, ventilation, and communications, remain fully operational without relying on fossil fuels.

The vessel's auxiliary boiler remains in operation throughout the majority of the day to maintain the temperature of the fuel oil storage, settling, and service tanks. This function, however, is assumed by the main engine economiser when the vessel is underway.

Figure 3-8 presents the vessel's operational profile over the course of a full calendar year, derived from AIS data. The analysis indicates that the vessel remains moored at port for more than half the time. The remaining operational time is distributed between port manoeuvring activities and sea-going transit, with the latter typically conducted at an average speed of approximately 16 knots.

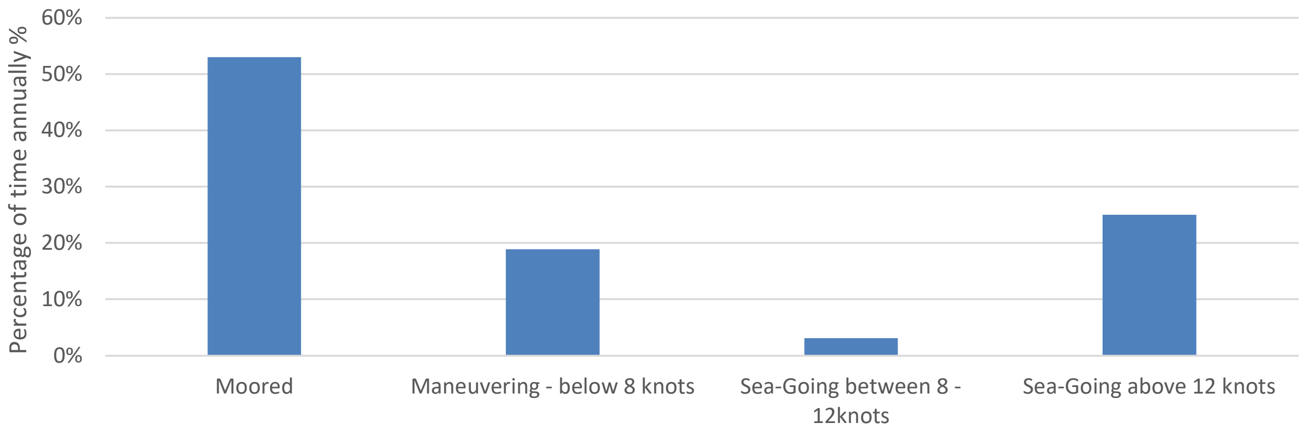

Figure 3-8 RoPax case study - operating profile.

3.2.2.4 174,000 m³ LNGC

For the LNGC vessel, the main dimensions and machinery are shown below.

Table 3-9 LNGC case study – Vessel specifications.

174,000 m3 LNGC case study – Vessel specifications	
First year in service	2025
DWT	Appr. 90,000 tons
Lightweight	Appr. 35,000 tons
Propulsion system	2 x 2-Stroke Dual fuel engine of abt. 12.5 MW each
Electricity supply	2 x 4-stroke Dual fuel engines of 3 MW each 2 x 4-stroke Dual fuel engines of 4.5 MW each
Heat supply	2 x auxiliary boilers / 1 x Main Engine Exhaust Gas Economizer

The operational profile of a typical 174,000 m³ LNGC is analysed below, detailing the distribution of time spent underway, at anchor, and during port operations as shown in Figure 3-9. Results are aggregated for laden and ballast voyages.

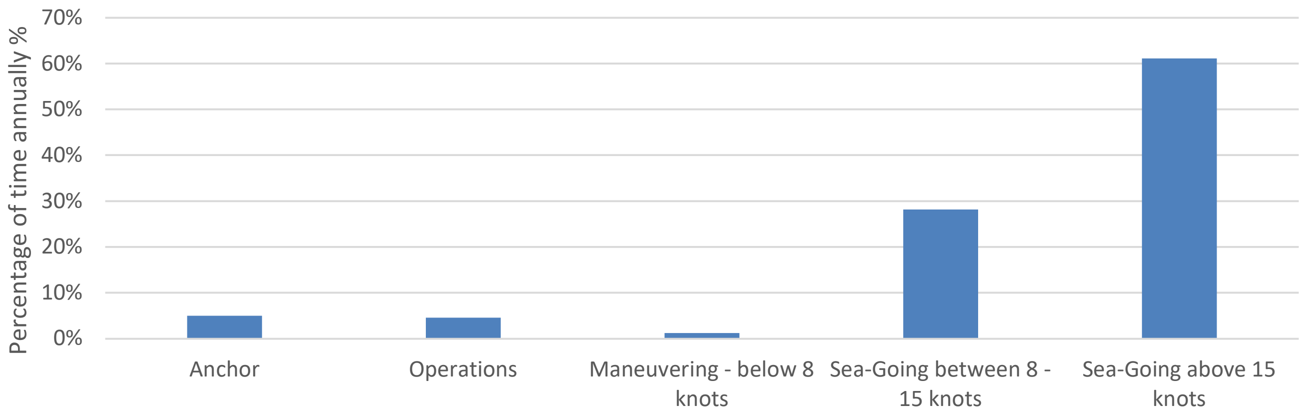

Figure 3-9 LNGC case study - operating profile.

3.2.2.5 1,700 TEU Feeder Container

For the 1,700 TEU feeder container vessel, the main dimensions and machinery are shown below.

Table 3-10 Feeder Container case study – Vessel specifications.

1,700 TEU feeder container case study – Vessel specifications	
First year in service	2025
DWT	Appr. 25,000 tons
Lightweight	Appr. 8,500 tons
Propulsion system	1 x 2-Stroke Diesel engine of abt. 15.0 MW
Electricity supply	3 x 4-stroke Diesel engines of 1.5 MW each
Heat supply	1 x auxiliary boiler / 1 x Main Engine Exhaust Gas Economizer

The operational profile of a typical feeder container is analysed below, detailing the distribution of time spent underway, at anchor, and during port operations as shown in Figure 3-10. Results are aggregated for laden and ballast voyages

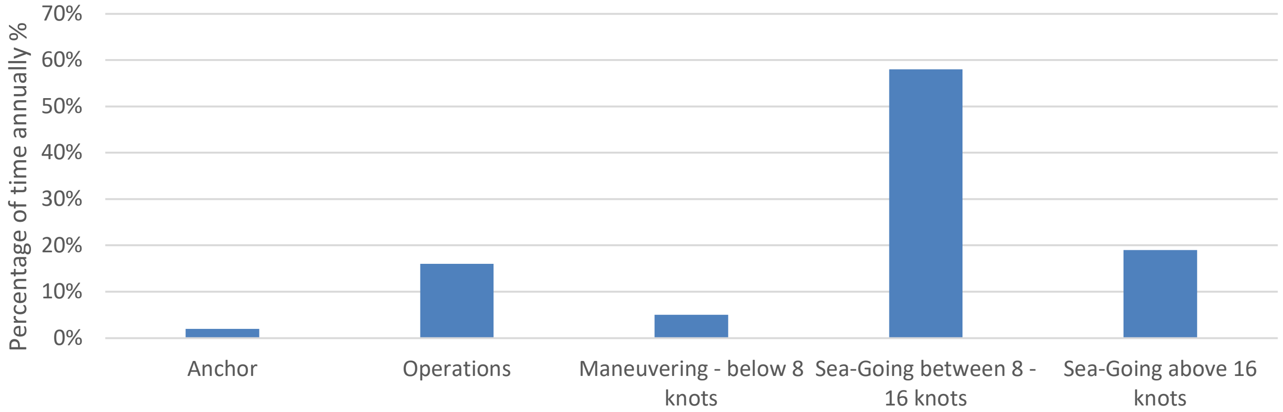

Figure 3-10 Feeder container case study - operating profile.

3.2.2.6 MR tanker

For the MR tanker vessel, the main dimensions and machinery are shown below.

Table 3-11 MR tanker case study – Vessel specifications.

MR tanker case study – Vessel specifications	
First year in service	2025
DWT	Appr. 40,000 tons
Lightweight	Appr. 8,500 tons
Propulsion system	1 x 2-Stroke Diesel engine of abt. 7.5 MW
Electricity supply	3 x 4-stroke Diesel engines of 1.0 MW each
Heat supply	1 x auxiliary boiler / 1 x Main Engine Exhaust Gas Economizer

The operational profile of a typical MR tanker vessel is analysed below, detailing the distribution of time spent underway, at anchor, and during port operations as shown in Figure 3-11. Results are aggregated for laden and ballast voyages

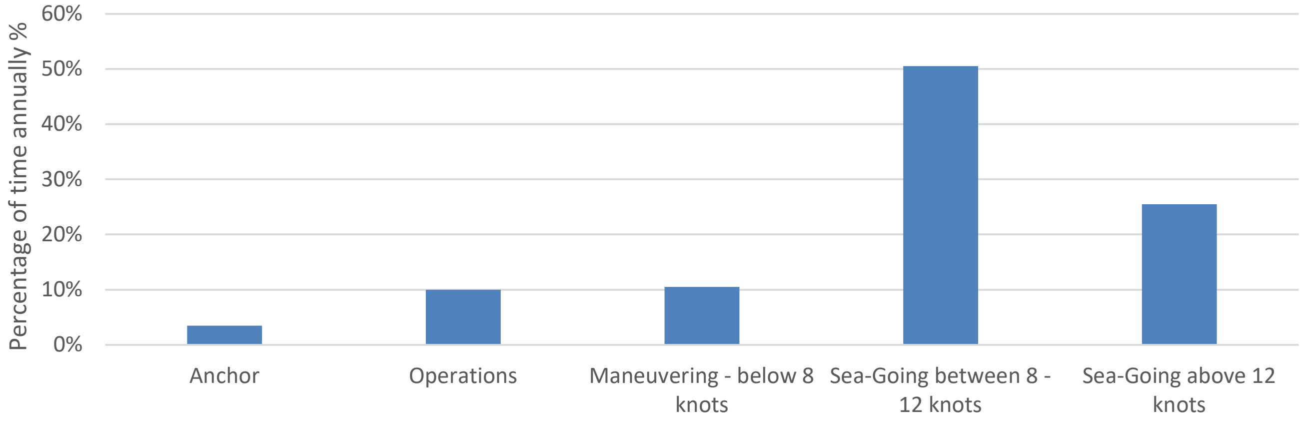

Figure 3-11 MR tanker case study - operating profile.

3.2.2.7 Conclusions

This section has identified and analysed the most representative ship types within the European maritime sector for the integration of OCCS systems. The selection was based on their contribution to CO_2 emissions and their operational suitability for OCCS deployment. Deep sea vessels such as Suezmax oil tankers, large container ships, and LNG carriers were prioritized due to their significant emissions profiles and voyage characteristics that support extended OCCS operation. Short sea vessels, including feeder container ships, Ro-Pax ferries, and MR tankers, were also considered for their frequent port calls and consistent operational patterns, although certain segments like Ro-Pax vessels present spatial and safety integration challenges. Chemical absorption technology was selected as the OCCS solution across the examined vessels, paired with medium-pressure LCO_2 storage.

3.2.3 Performance Indicators

In the lack of respective standardization, the terminology regarding OCCS performance varies between different publications. The key focus areas are the effect of OCCS performance on fuel consumption, the so-called fuel penalty (DNV, 2024), the capture unit performance and the effect of OCCS on ship emissions (GCMD, 2024; DNV, 2024).

3.2.3.1 Fuel penalty performance indicator

The fuel penalty is defined based on the difference between consumptions with OCCS, FOC_{OCC}, and the base case consumptions FOC_{BASE}, (DNV, 2024), which are the consumptions of the vessel without the OCCS system. The fuel penalty FP can therefore be determined on the basis of the reference case consumptions, establishing the effect of the complete OCCS system over the ship energy conversion system:

$$FP = \frac{FOC_{OCC} - FOC_{BASE}}{FOC_{BASE}} \times 100\%$$

3.2.3.2 Technology capture capacity

The technology capture capacity in tons of CO_2 capture per hour (CO_2 tons/h), reflects the efficiency and effectiveness of the OCCS system in mitigating carbon emissions. This metric is crucial for evaluating the performance of different carbon capture technologies, as it directly impacts the overall energy consumption and operational costs. Higher capture capacities typically indicate more efficient systems, capable of processing larger volumes of exhaust gases and capturing greater amounts of CO_2 within a given timeframe. This comes with additional energy consumption and operational costs as will also be shown in the following sections.

3.2.3.3 Technology capture rate performance indicator

In (EverLoNG, 2024), the capture rate is defined at the carbon capture unit level as the CO_2 captured by the unit versus the CO_2 supplied by the exhaust to the system. A similar ratio is described in ISO 27919-1:2018, as CO_2 capture efficiency. The same terminology is observed in the studies of (BV, 2023) and (OGCI, GCMD, Stena Bulk, 2024).

When focusing on the capture unit (CU) performance, the capture rate is defined as the ratio between emissions captured versus emissions supplied to the capture unit:

$$CAPTURE\ RATE = \frac{E_{CAPTURED\ AT\ CU}}{E_{SUPPLIED\ TO\ CU}} \times 100\%$$

It is noted that this ratio represents a performance metric of the capture technology. It does not represent the final effect of the integral OCCS system over total ship emissions. Furthermore, the term does not reflect the effectiveness of the CO_2 handling and storage system, which may involve leakages, leading to a difference between the emissions captured at the capture unit versus emissions disposed at port. Over the period of a voyage, it is expected that, for most OCCS technologies, the following expression would be applicable:

$$E_{CAPTURED} = E_{DISPOSED} = E_{CAPTURED\ AT\ CU} - E_{LEAKS}$$

3.2.3.4 Ship emissions reduction performance indicators

In (OGCI, GCMD, Stena Bulk, 2024), the net CO_2 avoided are determined as follows:

$$Net\ CO2_{AVOIDED} = \frac{Amount\ of\ CO2\ captured - Additional\ emissions}{Reference\ vessel\ emissions} \times 100\%$$

The term additional emissions is associated with the energy penalty of the OCCS operation. The above equation can also be expressed using the terminology:

$$Net\ CO2_{AVOIDED} = \frac{E_{AVOIDED}}{E_{BASE}} \times 100\% = \frac{E_{DISPOSED} - E_{FP}}{E_{BASE}} \times 100\%.$$

A similar performance term is provided in (Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2022) , as the effective emissions reduction compared to the base ship CO_2 emissions. Furthermore, the above definition is relevant to the ISO 27917:2017, the CO_2 emission reduction refers to the net decrease of CO_2 emissions compared to a base case, where the reduced emissions may be referred to as CO_2 avoided.

In (OGCI, GCMD, Stena Bulk, 2024), the gross CO_2 captured is defined as:

$$Gross\ CO2_{CAPTURED} = \frac{Amount\ of\ CO2\ captured}{Reference\ vessel\ emissions + Additional\ emissions} \times 100\%$$

In (DNV, 2024d), an aligned definition of the captured amount per the total ship emissions level is presented. In (Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2022), the capture rate is identified as the amount of captured CO_2 versus the base emissions plus the emissions associated with the energy penalty.

Summarizing on the literature, the Net Capture Rate or Net Avoided Rate or Effective Emissions Reduction Rate or Emissions Abatement Rate can be determined at ship-level in comparison with base emissions:

$$EFFECTIVE\ EMISSIONS\ REDUCTION\ RATE = \frac{E_{CAPTURED} - E_{FP}}{E_{BASE}} \times 100\%.$$

The effective emissions reduction rate represents the portion of base emissions (without OCCS) that can effectively be captured and disposed of at port, reduced by the emissions for running the OCCS system.

The Gross CO_2 capture rate represents the impact of OCCS over the emissions that correspond to vessel's consumption with OCCS in operation:

$$GROSS\ CAPTURE\ RATE = \frac{E_{CAPTURED}}{E_{BASE}+E_{FP}} \times 100\%.$$

3.2.3.5 Energy impact of OCC

A performance metric for the energy impact of OCCS onboard can be defined in MWh/ton (as in ISO 27919-1:2018), accounting for all energy processes that cover OCCS demands in terms of electricity and heat for CO_2 capture and onboard storage.

3.3 Emission reduction performance through selected ship cases

For each selected vessel from 3.2.1, the OCCS technology is examined for sweeps of different CO_2 capture capacities, in order to properly assess the effect to the potential emission reductions and fuel penalty across the spectrum of the different capture rates. The capture rates to be examined for each vessel are selected in terms of LCO_2 storage and maintaining the operation of the Auxiliary Gensets and boilers within manufacturer and redundancy limits (load below 90%, 1 Aux Diesel Generator on standby). The selected capture rates for further evaluation are shown in Table 3-12 below.

Table 3-12 Examined cases with chemical absorption and Liquid CO_2 Medium Pressure and corresponding OCCS capture rate.

Vessel	Suezmax	RoPax	1700 TEU Feeder Container	MR Tanker	15000 TEU Container	LNGC
Fuel	Conventional				LNG	LNG
CO_2 capture capacity TPH	1 / 2 / 3	0.25 / 0.50 / 0.75 / 1	1 / 2	1 / 2	2 / 4 / 6	1 / 2 / 3

For the evaluation of OCCS system in terms of energy efficiency, a state-of-the-art chemical absorption system is considered for both newbuild and retrofit vessel configurations. In both cases, the OCCS system is assumed to be installed in the year 2030, reflecting the anticipated market maturity and broader commercial availability of advanced capture technologies by that time. This assumption enables a consistent basis for comparing performance across vessel types and integration scenarios.

In the case of OCCS with chemical absorption this translates into the below:

- Solvents requiring reduced additional heat demands for the chemical solvent regeneration (assumed at 2GJ/ton of CO_2).
- Compression stage assuming energy demand at the order of 300kWh/ton of CO_2.

In the case of the optimized newbuilding, additional considerations take place:

- Properly sized AEECOs for the OCCS, sized to the capacity of the exhaust gas enthalpy from the Auxiliary Engines.
- Installation of Power Take Off (PTO), which is sized to cover vessel's electrical demands during sailing, including OCC

Each examined case has different application of the above. A quick view into the examined cases is shown in Table 3-13.

Table 3-13 Examined cases and technologies.

Vessel	Retrofit	Newbuilding with PTO	Newbuilding with AEECOs
Suezmax	X	X	X
Container vessel	X	X	-
RoPax	X	-	-
LNGC	X	X	X
Feeder Container	X	X	X
MR tanker	X	X	X

The emission reduction potential against the additional fuel penalty for each examined vessel case is shown in the following graphs. The results indicate that optimized CCS ready newbuild configurations with integrated PTO and AEECOs outperform retrofits in terms of energy efficiency and emissions reduction. This is due to the fact that simple retrofits incur higher fuel penalties. Vessel-specific characteristics, such as exhaust gas availability and electrical demand profiles, influence OCCS effectiveness.

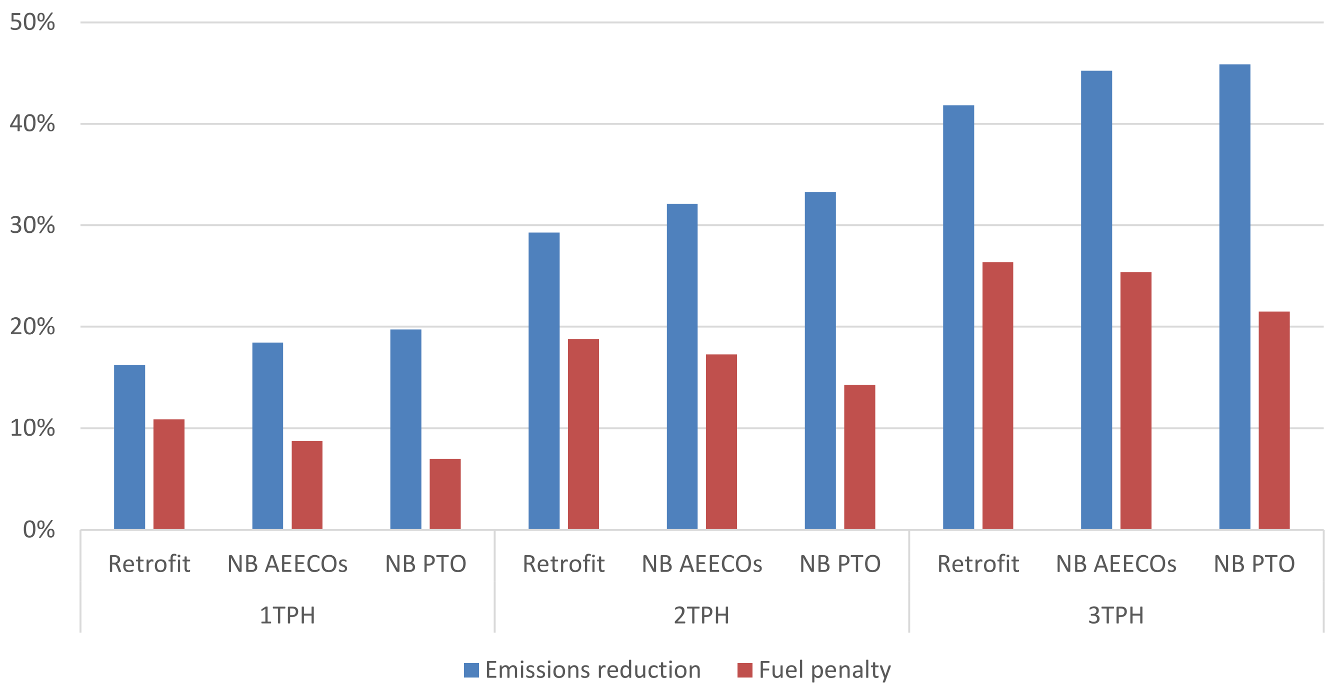

Figure 3-12 Suezmax case study - Emissions reduction vs Fuel penalty.

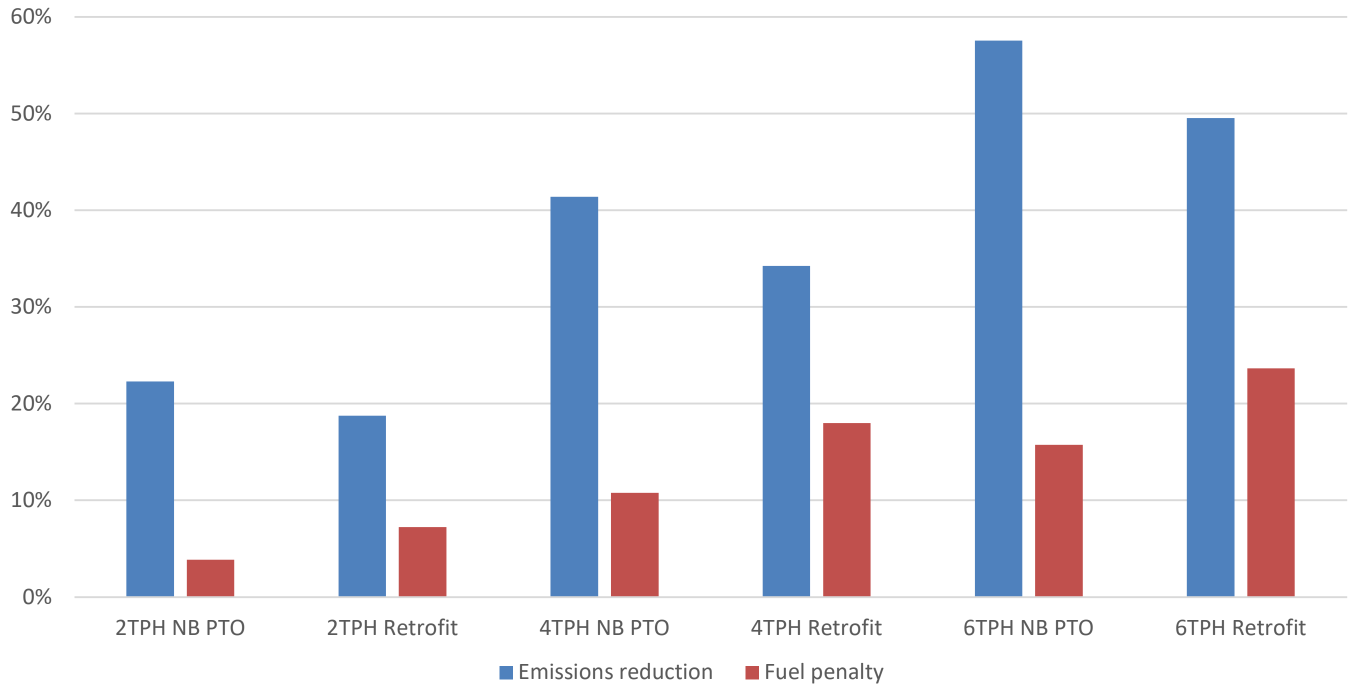

Figure 3-13 Container case study - Emissions reduction vs Fuel penalty.

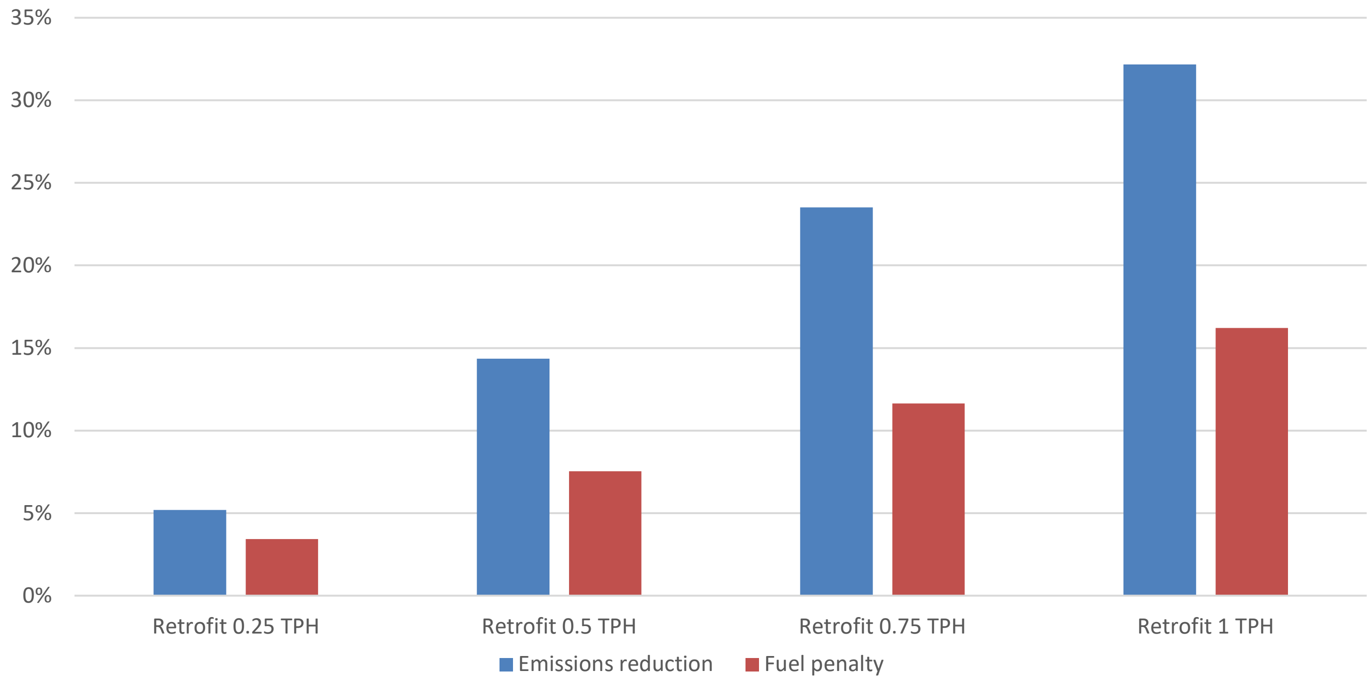

Figure 3-14 RoPax case study - Emissions reduction vs Fuel penalty.

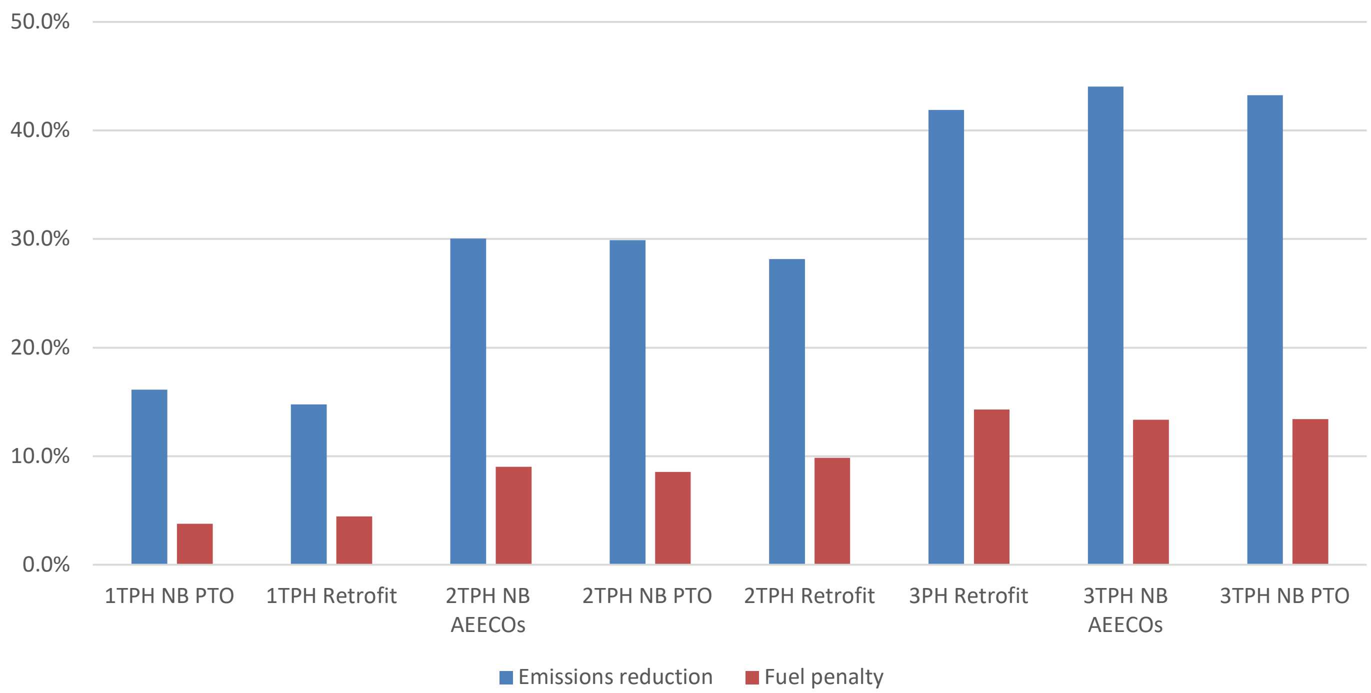

Figure 3-15 LNGC case study - Emissions reduction vs Fuel penalty.

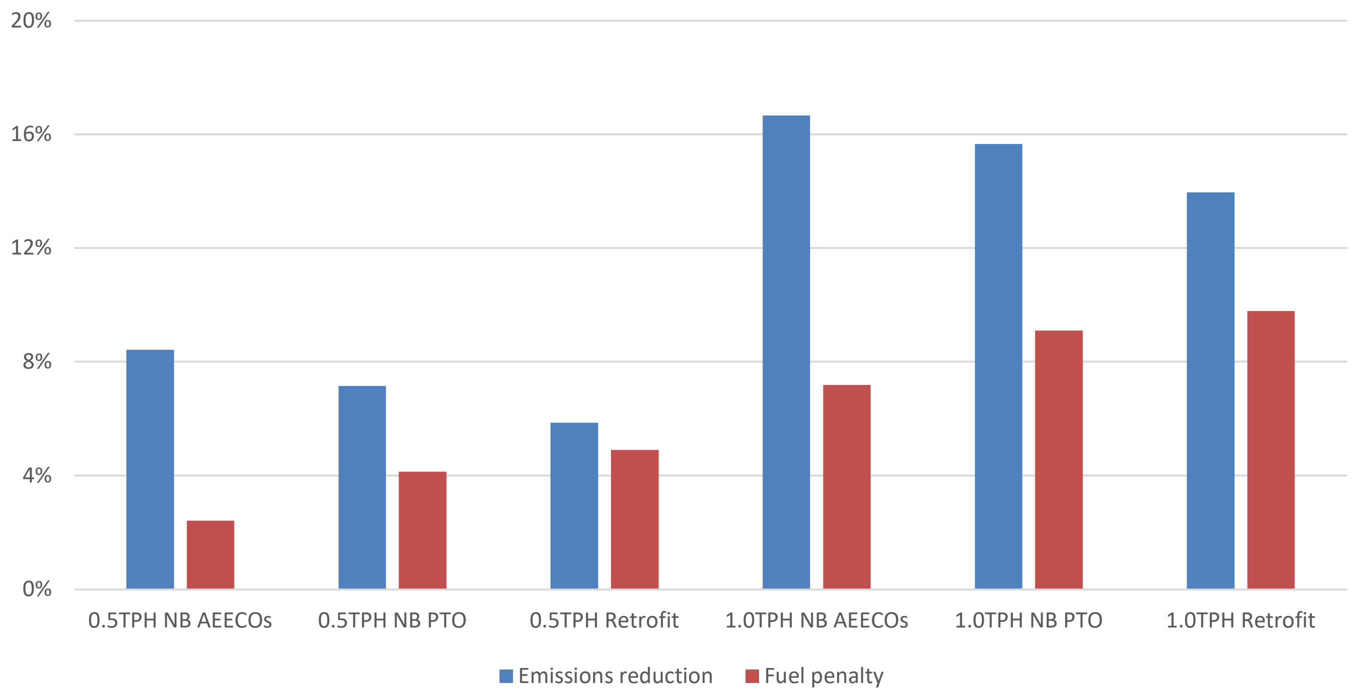

Figure 3-16 Feeder Container case study - Emissions reduction vs Fuel penalty.

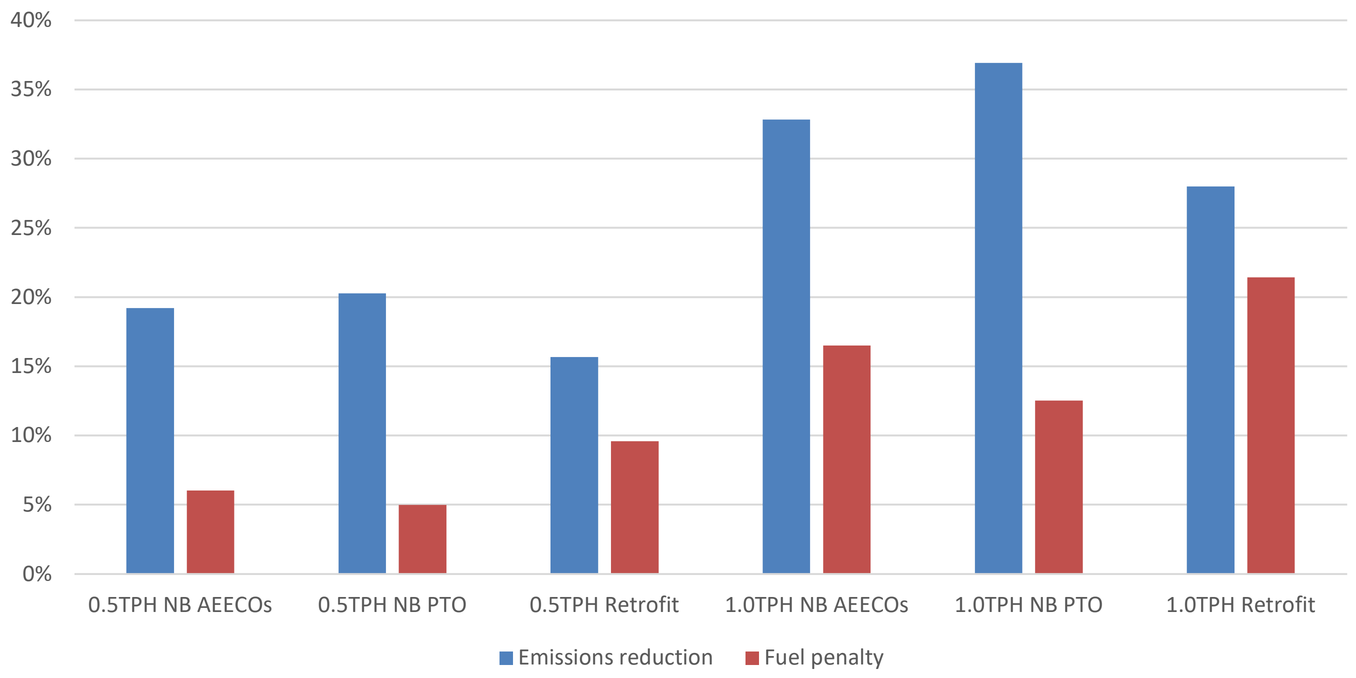

Figure 3-17 MR tanker case study - Emissions reduction vs Fuel penalty.

3.3.1 Economic impact analysis

The economic analysis includes:

- **CO_2 Abatement Cost**: CO_2 abatement cost analysis presents the cost associated with reducing one metric ton of CO_2 emissions compared to the baseline scenario for each of the examined cases.
- **CAPEX**: Equipment costs for OCCS, PTO, and economizers.
- **OPEX**: Fuel costs, maintenance, solvent replacement, and CO_2 disposal.

The CO_2 abatement cost[52] assessment is conducted for both the newbuilding and the retrofit cases and evaluated under three implementation cost scenarios: low, base, and high. All financial figures are discounted to the base year 2025, with a discount rate of 8% applied (Xiaobo Luo, 2017), (Sadi Tavakoli, 2024).

CAPEX is assumed within a range of 180–720 euro per ton of CO_2 treated annually. For differential fuel expenditure, a price range of euro per ton is used for MGO, Very Low Sulphur Fuel Oil (VLSFO) and LNG fuels (DNV, 2024a).

The CO_2 disposal cost is assumed to range between 54–117 euro per ton of CO_2 (DNV, 2024a). The solvent cost is estimated at approximately 2,000 EUR per ton. Other maintenance costs are assumed to be 3% of CAPEX to account for potential uncertainties (Marco Visonà, Techno-economic analysis of onboard CO2 capture for ultra-large container ships, 2024).

Cost for PTO and AEECO follows the available data from (DNV, Energy Efficiency Measures and Technologies, 2025a).

[52] The CO_2 abatement cost presented in the following figures reflects the levelized cost of abatement (LCOA), expressed in €/tCO_2 abated. This metric is calculated over a 25-year vessel lifetime by discounting all CAPEX, OPEX, energy-penalty fuel costs and total CO_2 captured into a single lifetime-average cost-effectiveness value.

Table 3-14 Cost-economic assumptions for CAPEX.

Cost Scenario	Low	Base	High
OCCS CAPEX	€180/ton CO_2 treated annually	€450/ton CO_2 treated annually	€720/ton CO_2 treated annually
PTO CAPEX	€405/ kW	€405/ kW	€405/ kW
AEECO	€ 135,000 per unit	€202,500 per unit	€ 270,000 per unit

Table 3-15 Cost-economic assumptions for OPEX.

Cost Scenario	Low	Base	High
CO_2 disposal cost	€54/ton CO_2 offloaded	€85.5/ton CO_2 offloaded	€117/ton CO_2 offloaded
MGO price	€357/ton	€543/ton	€730/ton
VLSFO price	€302/ton	€460/ton	€617/ton
HFO price	€234/ton	€357/ton	€480/ton
LNG price	€341/ton	€497/ton	€652/ton
Maintenance	3%	3%	3%
Solvent cost	€2,070/ton		

The CO_2 abatement cost in euros for each case is shown in the below figures.

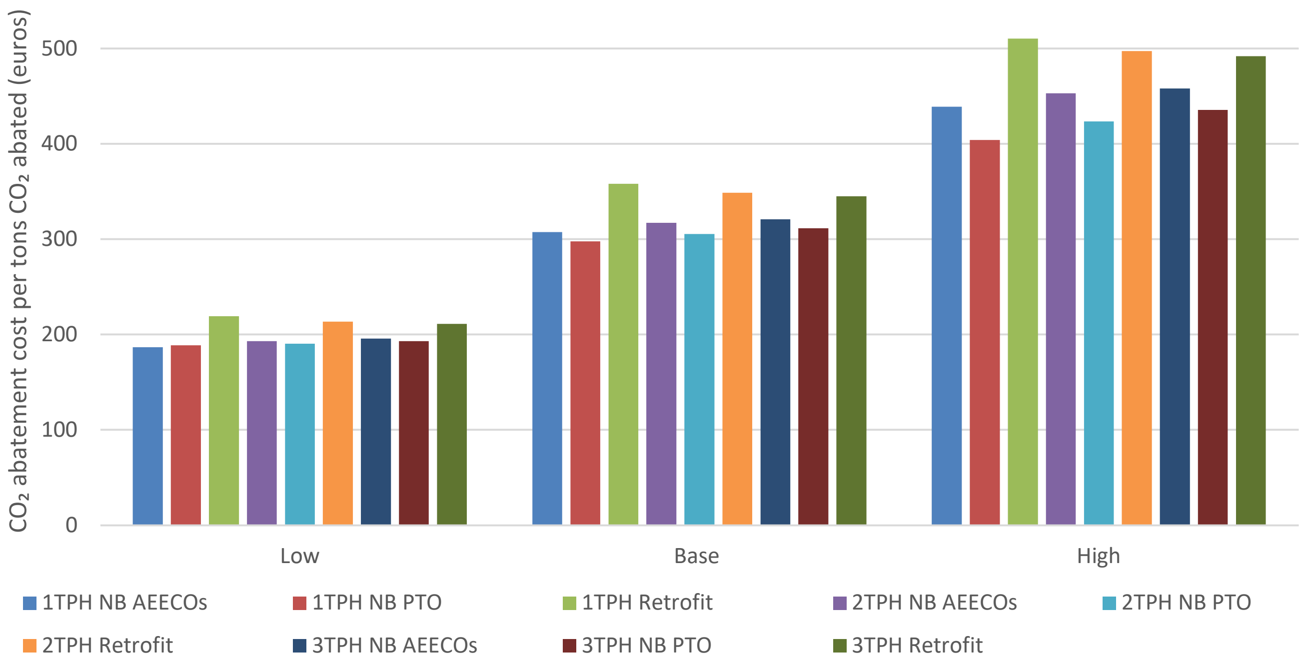

Figure 3-18 Suezmax case study - CO_2 abatement cost per tons CO_2 abated.

Figure 3-19 Container case study - CO_2 abatement cost per tons CO_2 abated.

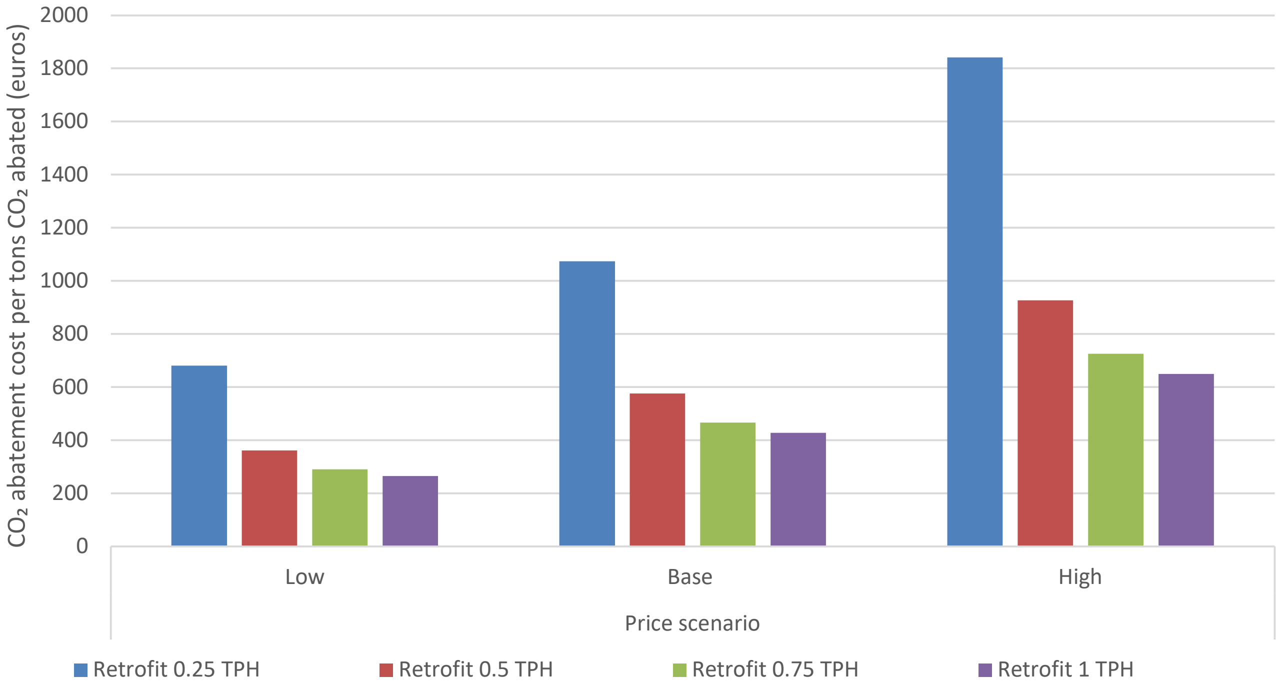

Figure 3-20 RoPax case study - CO_2 abatement cost per tons CO_2 abated.

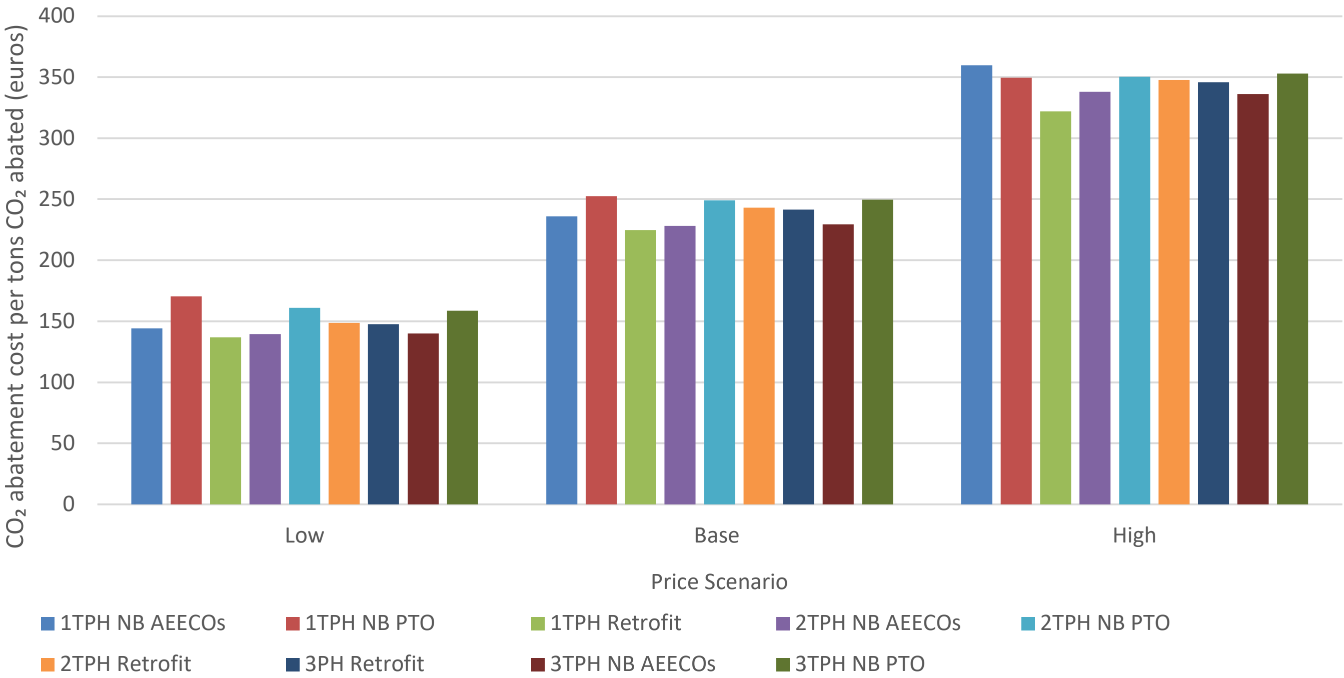

Figure 3-21 LNGC case study - CO_2 abatement cost per tons CO_2 abated.

Figure 3-22 Feeder container case study - CO_2 abatement cost per tons CO_2 abated.

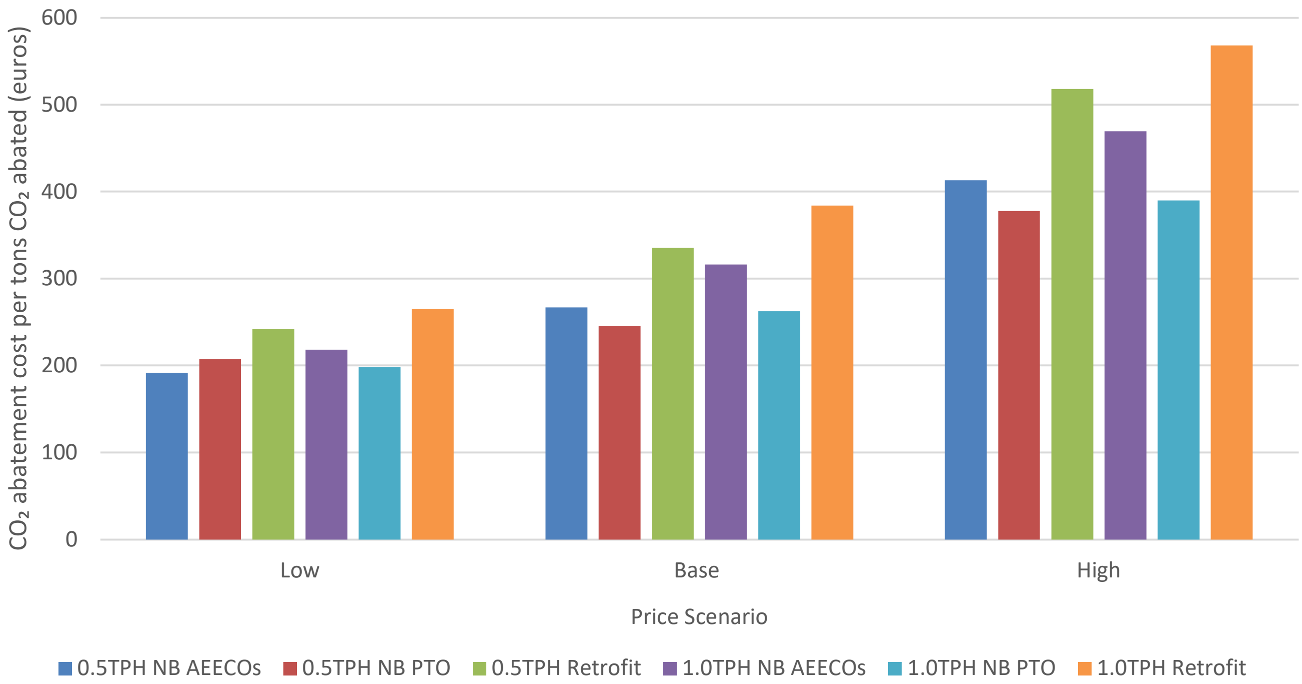

Figure 3-23 MR tanker case study - CO_2 abatement cost per tons CO_2 abated.

Additionally, a sensitivity analysis is conducted to assess the impact of each cost component on the overall CO_2 abatement cost. This analysis is done for a selected capture rate for each vessel case, namely 2 TPH for the Suezmax, 4 TPH for the Container, 0.75 TPH for the RoPax, 3 TPH for the LNGC, 1TPH for the feeder container. The chosen capture rates reflect a balance between emissions-reduction performance, fuel penalty, and the OCCS impact on the vessel's lightweight (between 1.5% and 2%), allowing each case to be matched with the most suitable technology size. Results are shown in the figures below.

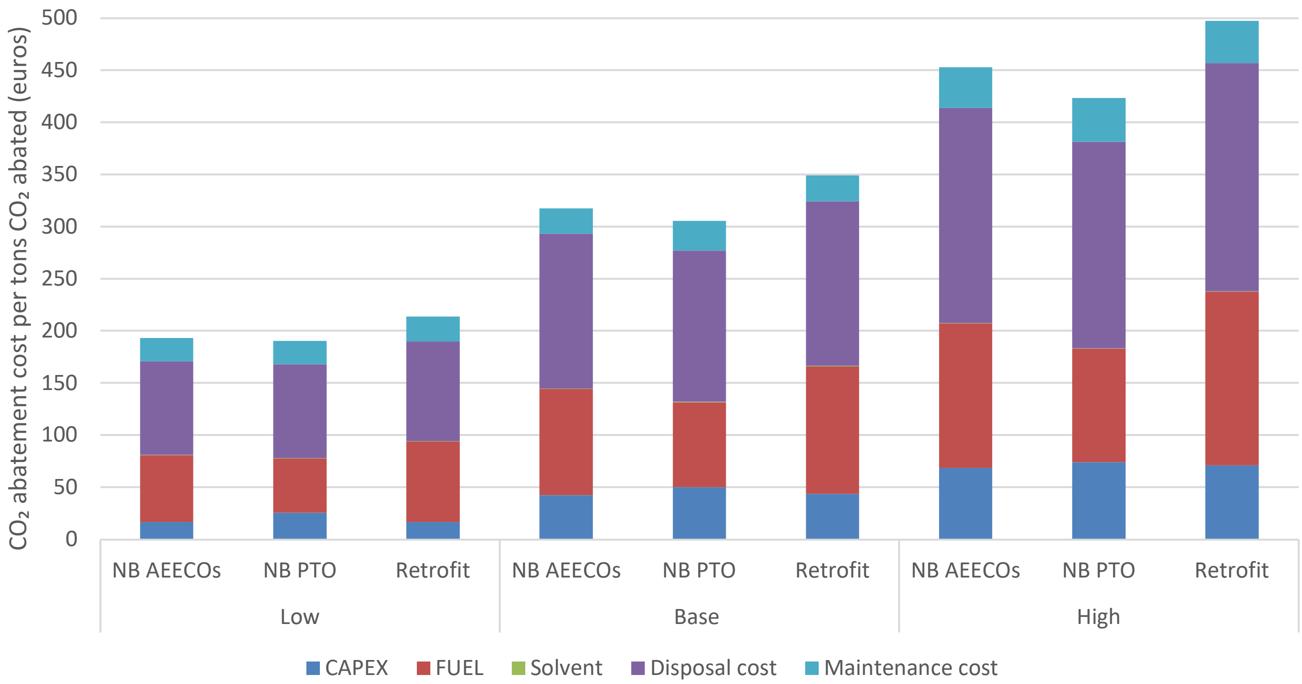

Figure 3-24 Suezmax case study – CO_2 abatement cost per ton of abated CO_2. Sensitivity analysis for 2TPH.

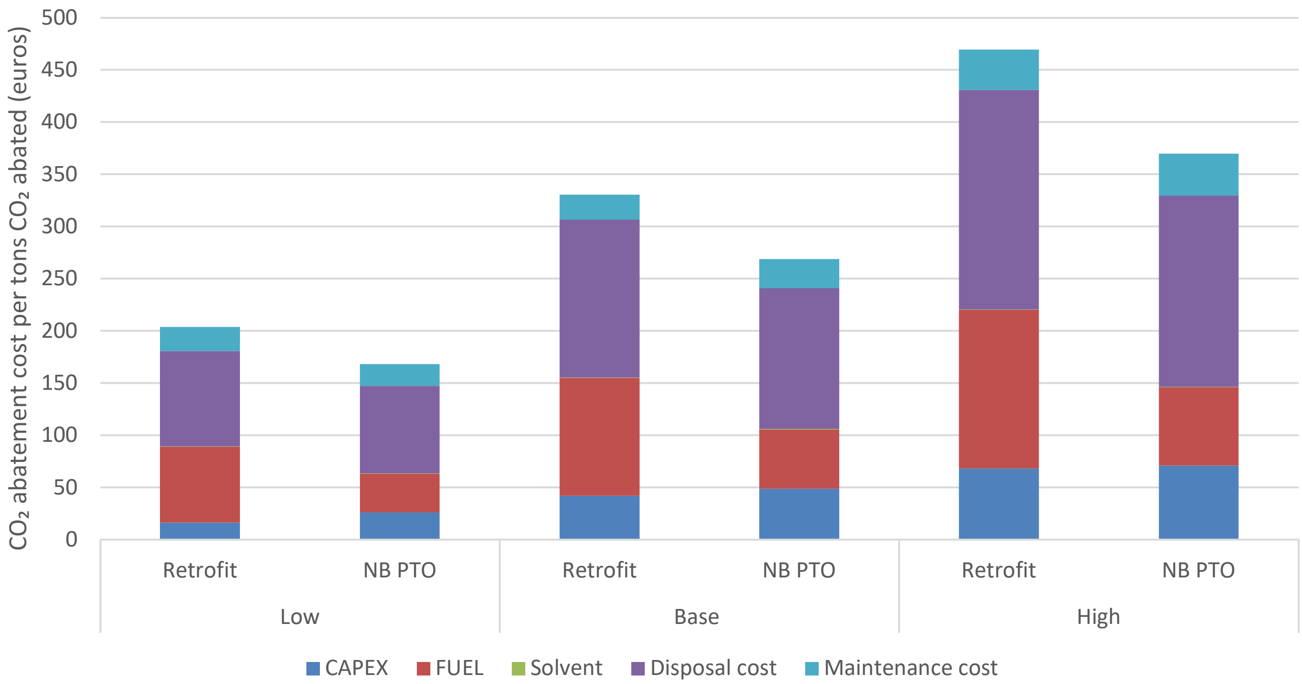

Figure 3-25 Container case study - CO_2 abatement cost per ton CO_2. Sensitivity analysis for 4TPH.

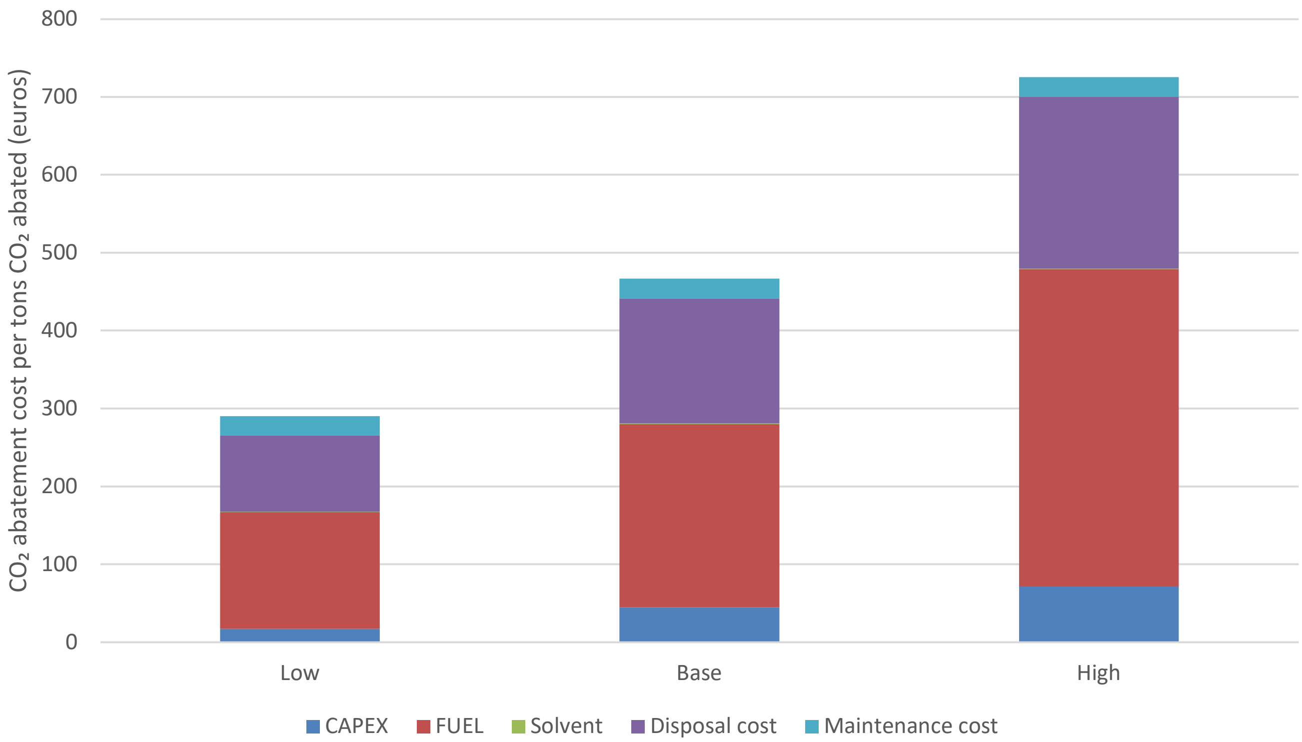

Figure 3-26 RoPax case study - CO_2 abatement cost per ton CO_2. Sensitivity analysis for 0.75TPH.

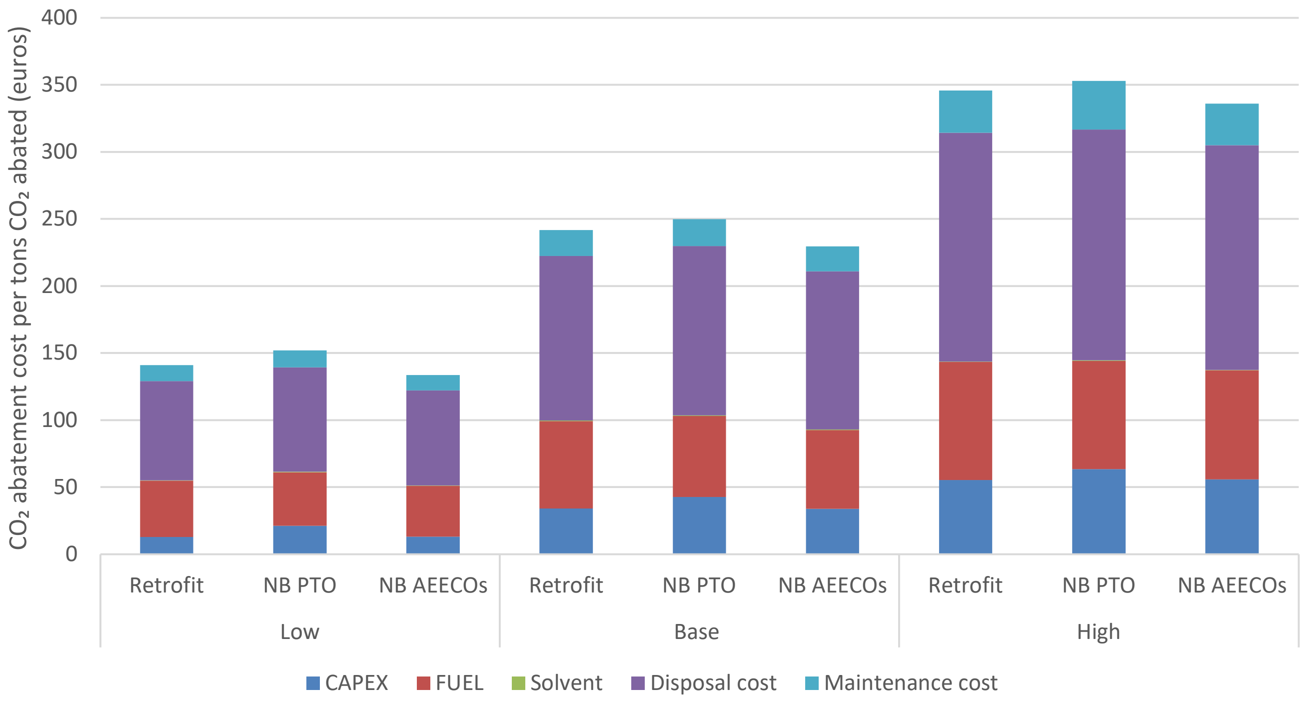

Figure 3-27 LNGC case study - CO_2 abatement cost per ton CO_2. Sensitivity analysis for 3TPH.

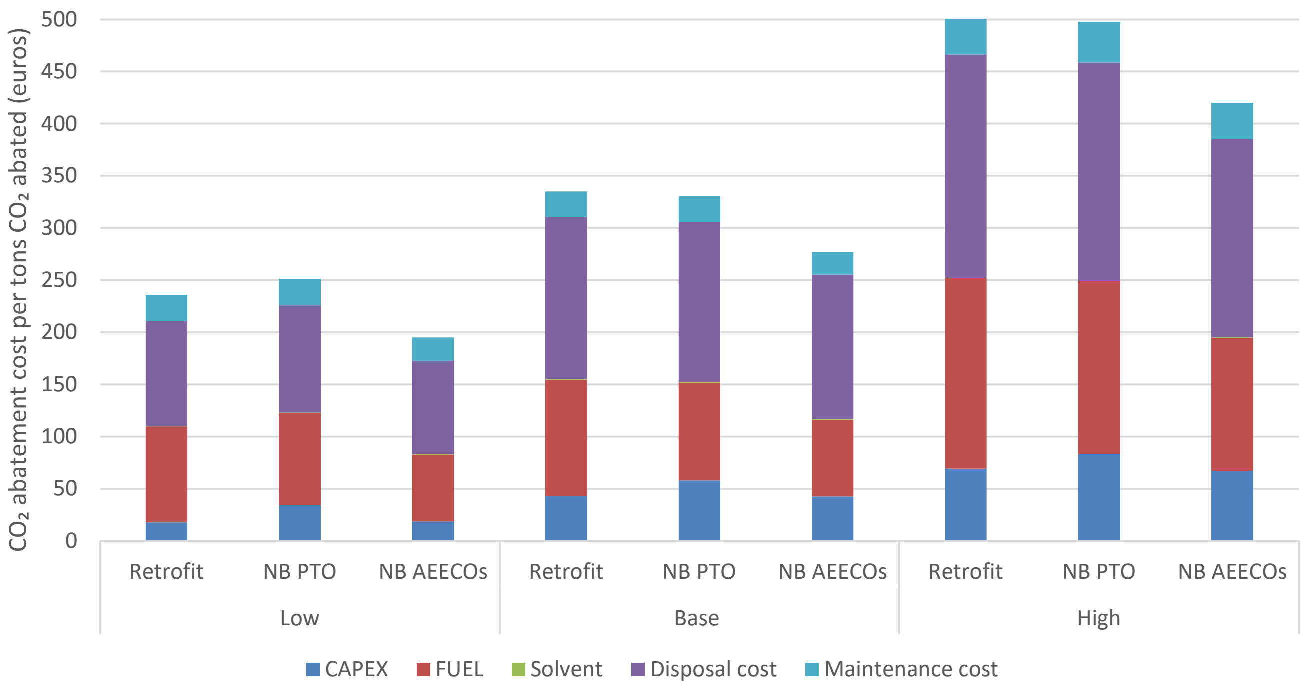

Figure 3-28 Feeder Container case study - CO_2 abatement cost per ton CO_2. Sensitivity analysis for 1TPH.

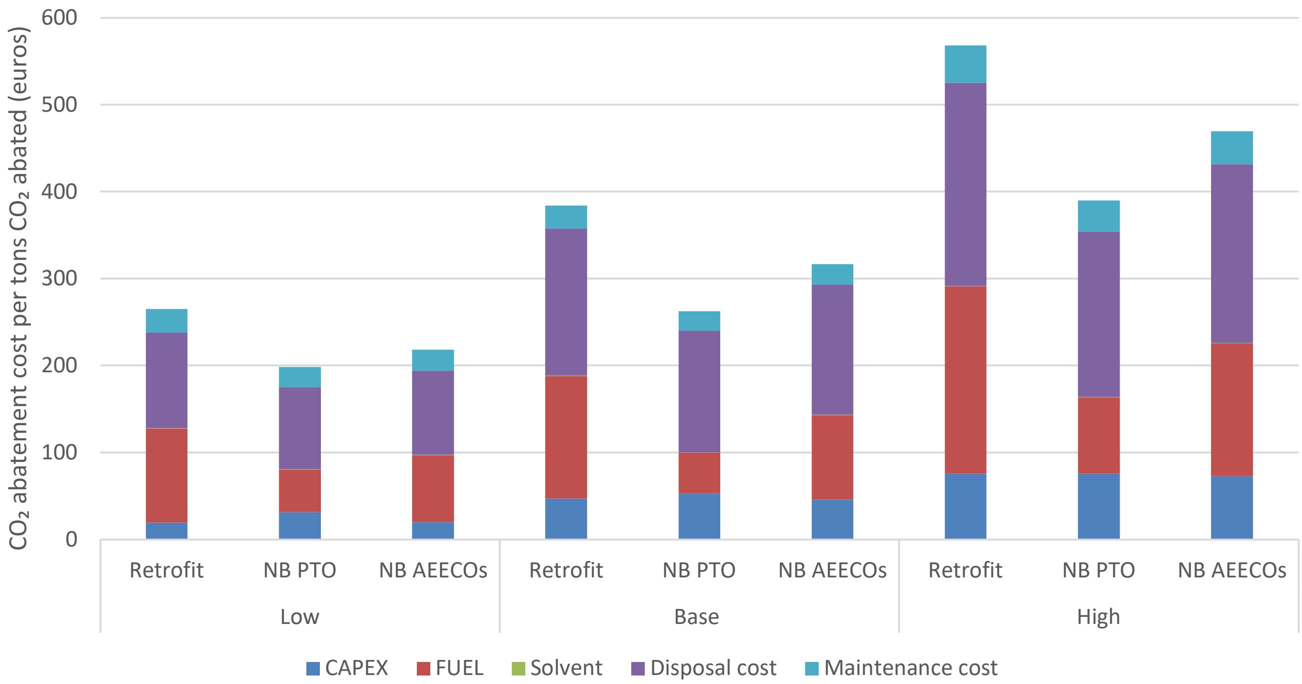

Figure 3-29 MR tanker case study - CO_2 abatement cost per ton CO_2. Sensitivity analysis for 1TPH.

The results indicate that the CO_2 disposal cost and fuel OPEX exert the most significant influence on the abatement cost. These are followed by the technology CAPEX and maintenance costs, which have a moderate impact. In contrast, the cost of solvents contributes minimally to the overall CO_2 abatement cost.

3.3.2 Economic viability

This chapter analyses key scenarios related to EU ETS compliance and decarbonization strategies. It covers projected allowance savings under low and high EU exposure, evaluates the cost and performance of OCCS compared to biofuels and bio-LNG, and examines how OCCS integrates into the IMO GFI metric. The chapter concludes with summary tables and figures presenting the underlying assumptions and results.

3.3.2.1 EU ETS impact

To evaluate the financial implications of compliance with the EU ETS[53], a comparative analysis was conducted across the vessels, for their distinct operational profiles and OCCS configurations. For each vessel, two exposure scenarios were considered, Low EU Exposure and High EU Exposure, reflecting varying proportions of annual voyages involving EU ports.

According to (DNV, Energy Transition Outlook CCS to 2050, 2025c), the regional average carbon price[54] level applied to ETS-1 sectors is projected to reach approximately €128/tCO_2 by 2030, €188/tCO_2 by 2040, and €213/tCO_2 by 2050. Therefore, carbon pricing was assumed at €170 per ton of CO_2, and the analysis focused on the saving on EU ETS allowance savings based on vessel-specific capture rates. This approach enables a direct comparison of the economic viability of OCCS deployment under different regulatory exposure levels. The results provide insight into the cost-effectiveness of OCCS systems across a range of operational conditions, supporting strategic decision-making for emissions compliance and fleet optimization. Detailed scenario assumptions and vessel-specific results are presented in the respective Appendix for each vessel, while Table 3-16 summarizes the key findings across all vessels.

[53] OCCS is currently not included within the scope of FuelEU Maritime compliance, with a provision for potential review of inclusion by 31 December 2027. As no methodological framework for integrating OCCS into the regulation has yet been established, FuelEU Maritime requirements were not incorporated into the present analysis

[54] The carbon price assumption used in the EU ETS analysis is applied exclusively to estimate avoided allowance expenditures and is not used in the computation of the CO_2 abatement cost, which is a technology-intrinsic cost indicator, whereas carbon pricing relates to regulatory exposure. These two metrics therefore serve different purposes and are not intended to be directly compared.

Table 3-16 EU ETS scenarios % of time in EU voyages.

EU ETS scenarios % of time in EU voyages		
Scenario	Low EU Exposure	High EU Exposure
Suezmax – 2 TPH	22% Into or out of EU/ European Economic Area (EEA)	55% Into or out of EU/EEA
Container – 4 TPH	20% Into or out of EU/EEA	60% Into or out of EU/EEA
RoPax – 1 TPH	70% within the EU/EEA, 30% Out of EU/EEA	100% within the EU/EEA
LNGC – 3 TPH	20% Into or out of EU/EEA	80% Into or out of EU/EEA
Feeder container – 1 TPH	-	100% within the EU/EEA
MR tanker – 1 TPH	50% Into or out of EU/EEA	100% within the EU/EEA

Table 3-17 EU ETS allowance savings in € thousands on a yearly basis.

EU ETS allowance savings in € thousands on a yearly basis			
Scenario		Low EU Exposure	High EU Exposure
Suezmax – 2 TPH	NB PTO	173	434
	NB AEECOS	171	428
	Retrofit	165	413
Container – 4 TPH	NB PTO	388	1,163
	Retrofit	331	992
RoPax – 1 TPH	Retrofit	434	620
LNGC – 3 TPH	NB PTO	276	1,103
	NB AEECOS	277	1,107
	Retrofit	271	1,086
Feeder container – 1 TPH	NB PTO	-	920
	NB AEECOS	-	901
	Retrofit	-	877
MR tanker – 1 TPH	NB PTO	198	893
	NB AEECOS	187	837
	Retrofit	170	783

3.3.2.2 Scenario-Based Assessment of OCCS and Biofuels/Bio-LNG Under the IMO GFI Metric

At MEPC 83, the GFI metric was introduced as a key component of the IMO Net-Zero Framework. This metric measures the WtW GHG emissions per unit of energy used on board a ship, including energy from fuel, electricity, wind, and solar sources. In the IMO 2024 LCA Guidelines, MEPC.391(81), OCCS is referenced within paragraph 5.2 in the TtW GHG emission factor equation. In this equation the emission credit from OCCS (e_{OCCS}) term is introduced and represents the CO_2 emissions avoided through onboard capture and sequestration. Emissions from the capture process (e_{cc}), transport (e_t), storage (e_{st}), and additional emissions related to OCCS (e_x) must be subtracted from the total CO_2 sequestered (c_{SC}) to account the avoided emissions.

$$e_{OCCS} = c_{SC} - e_{cc} - e_t - e_{st} - e_x$$

At the time this report is compiled, a detailed methodological guidance on how OCCS should be assessed or accounted for within the GFI metric is not in place. To explore these implications, this report presents three hypothetical scenarios that model the integration of OCCS under the Net-Zero Framework. The scenarios are not intended to represent definitive assessments but rather to show the potential impact of the gaps on the methodological approach. Furthermore, adjustments of the above mentioned formula are expected as part of future regulatory developments, to ensure no double-counting of fuel penalty.

- The retrofit of the OCCS system with nominal treatment capacities indicated at Table 3-16 are evaluated, a comparison of their performance in terms of emissions reduction and cost implications with equivalent scenarios involving the use of biofuels as an alternative decarbonization strategy is made. The cost analysis takes into consideration the period from 2028 to 2035, using 2028 as a base with a discount rate of 8% (Xiaobo Luo, 2017), (Sadi Tavakoli, 2024).
- The period 2028-2035 is selected for the GFI scenarios, as it represents the timeframe for which relevant data are available and reasonable assumptions can be made. It should be noted that this timeframe of 8 years applies only to the present GFI scenarios analysis.
- For the OCCS scenario, the OPEX costs encompass several components: the cost of CO_2 disposal, increased fuel consumption due to the system's energy penalty, and expenses related to consumables, such as chemical solvents. In the biofuel scenario, the analysis includes the differential fuel costs compared to the baseline vessel. Across all scenarios, baseline, OCCS, and biofuels, the costs associated with remedial units required for compliance with the IMO Net Zero Framework's GFI targets are accounted for.
- Fuel prices are based on estimated high and low prices for fuels in the period 2030 to 2050 (DNV, 2024a). For biofuels, two pricing scenarios were evaluated: one based on the minimum price, and another based on the average price.
- The relevant emission factors were extracted from the IMO LCA guidelines and where data were not available, assumptions were used in the analysis based on:
    - the LNG Well-to-Tank (WtT) emission factor of 18.5 g/CO_2eq/MJ for LNG, assumed as equal to the default FuelEU value (Annex II of Regulation (EU) 2023/1805)
    - an assumed liquefied bio-methane WtT emission factor of -35.83 g/CO_2eq/MJ as found on (Directorate-General for Mobility & Transport, 2025) - table 4.9, page 44.
    - a biofuel production pathway of Bio-diesel (waste cooking oil), assumed with a 14.9 gCO_2eq/MJ WtW emission intensity.

The assumptions table outlines the key parameters used in the techno-economic and environmental assessment of OCCS under the IMO Net Zero framework's GFI.

Table 3-18 Key parameters and assumptions for GFI impact scenarios.

Category	Assumption	Unit / Notes
Years of Assessment	2028–2035	8-year horizon
Discount Rate	8%	
Operational Expenses of OCC	€85.5/ton	CO_2 disposal cost
	€2070/ton	Amine solvent cost
Fuel Prices Source: (DNV, 2024a)	€543/ton	MGO
	€497/ton	LNG
	€690-€1410/ton	Biofuel
	€720-€1895/ton	Bio-LNG
Fuel WtW Intensity [gCO_2eq/MJ]	93.9	MGO
	14.9	Biofuel
	77.2	LNG Diesel (dual fuel slow speed)
	85.3	LNG Otto (dual fuel slow speed)
	94.8	LNG Otto (dual fuel medium speed)
	20.7	Bio-LNG (dual fuel slow speed)
	28.3	Bio-LNG Otto (dual fuel slow speed)
	37.4	Bio-LNG Otto (dual fuel medium speed)
LCA Emissions – OCCS		
Storage site emissions	2.3 kgCO_2/tCO_2 stored	Source: (GCMD, 2025a)
Transportation emissions	34 gCO_2eq/kg of CO_2 captured and stored	Source: (GCMD, 2025a)

The scenarios related to the OCCS potential impact on the ship's attained GFI were defined as follows:

- Scenario 1: The attained GFI is calculated by subtracting the mass of CO_2 captured on board from the total TtW CO_2 emissions associated with the fuel consumed. This approach includes the additional fuel required to operate the OCCS system, since this fuel penalty contributes to the ship's total emissions. This assumption does not include the full lifecycle emissions of the procedure such as the ones arising from the transportation and permanent storage of the captured CO_2.
- Scenario 2: The attained GFI is derived using the WtW emission factors defined in the LCA guidelines. For fuels used in conjunction with OCCS, the TtW emission factor is modified using the e_{OCCS} term. A key assumption in this scenario is that the OCCS fuel penalty is not included in the total fuel energy term of the attained GFI formula.
- Scenario 3: The attained GFI is calculated based on the WtW emission factors of the LCA guidelines, where for OCCS the TtW factor is adjusted by the eOCCS term. However, in this scenario the energy penalty e_{CC} is omitted from the e_{OCCS} formula. Instead, the OCCS energy penalty is accounted in the ship fuel energy calculation.

Scenarios 2 and 3 were formulated to address how the OCCS energy penalty is treated, with the aim of avoiding potential cases where this penalty might be counted again and ensuring consistency between the related energy and emissions of the ship.

Below graphs present the results of costs assessment, summarizing the annual operational expenses associated with the implementation of the OCCS solution, alongside the costs of the remedial units under the proposed GFI framework. Additionally, the alternative solution of biofuels, is evaluated to achieve the same attained GFI as the estimated lower value from the 3 OCCS scenarios.

In the Suezmax case, the first instance of annual OPEX savings is observed in year 2028 for the case of biofuels minimum price, while for the mid-price scenario it is estimated that up to 2034 the differential OPEX does not showcase savings. For the OCCS case it is assumed that in the end of 2031 the retrofit is implemented on board, as the differential OPEX savings begin from 2032 and onwards.

In the Container vessel case, the first instance of annual OPEX savings is observed in year 2031 for the case of bio-LNG minimum price, while for the mid-price scenario it is estimated that up to 2035 the differential OPEX does not showcase savings, similar to the Suezmax tanker case. The OCCS is assumed to be implemented in the end of 2030 as a retrofit with the differential OPEX savings beginning from 2031 and onwards.

For the Feeder container and MR Tanker case studies, the OCCS retrofit is assumed to take place in 2029-2030 and 2032 respectively. The alternative of biofuels presents the first OPEX savings for the average price scenario from 2032 and onwards for the Feeder container, whereas for the MR tanker the OPEX is relatively attractive after 2035 on an average projected biofuel price.

It should be noted that in the RoPax case, as the methodological treatment of both OCCS and shore connection power within the IMO's GFI framework remains to be further defined, a scenario-based GFI impact analysis was excluded. The decision was driven by the potential high degree of uncertainty associated with assumptions that would be required to model the combinatorial effect of the above solutions.

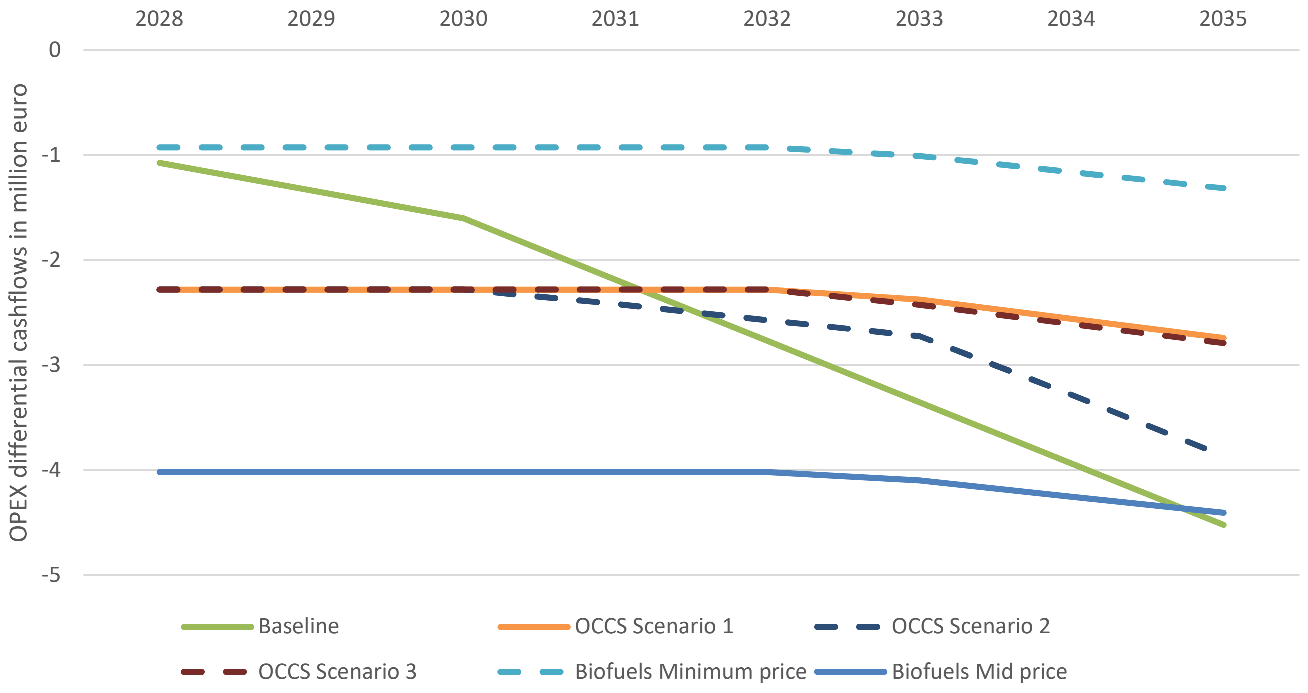

Figure 3-30 Suezmax case study - OCCS comparison to biofuels. Annual differential OPEX cashflows.

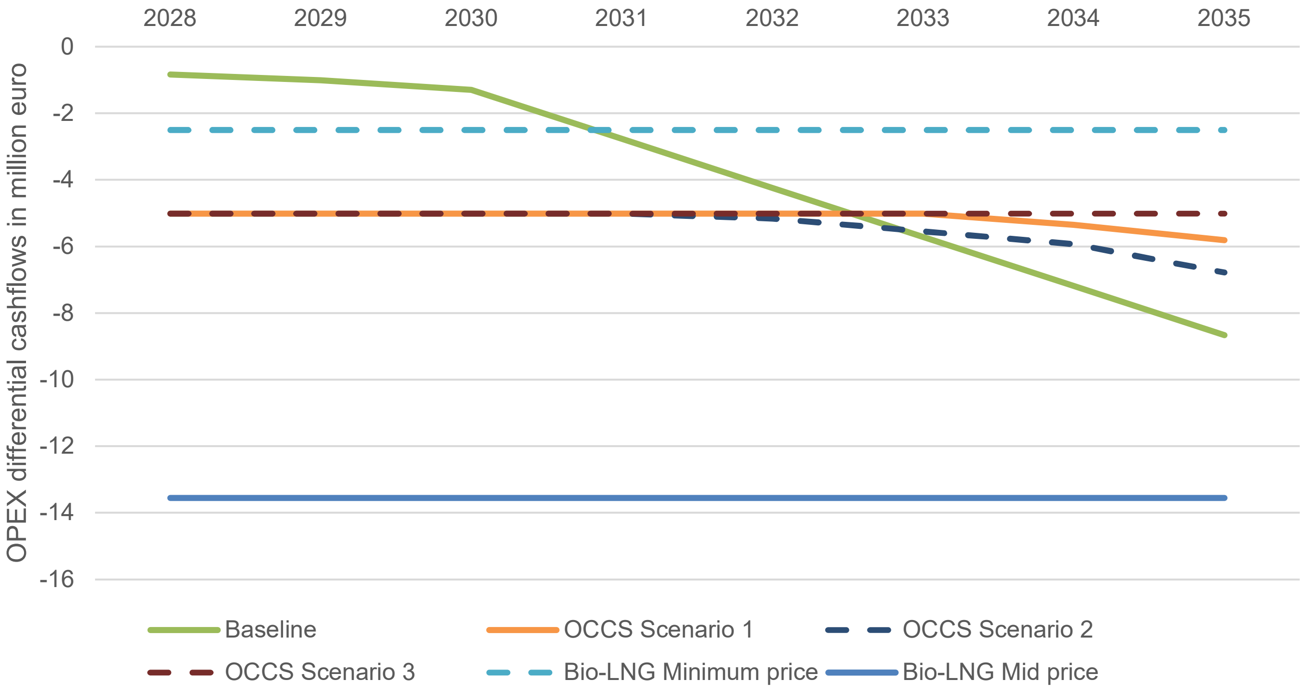

Figure 3-31 Container case study - OCCS comparison to bio-LNG. Annual differential OPEX cashflows.

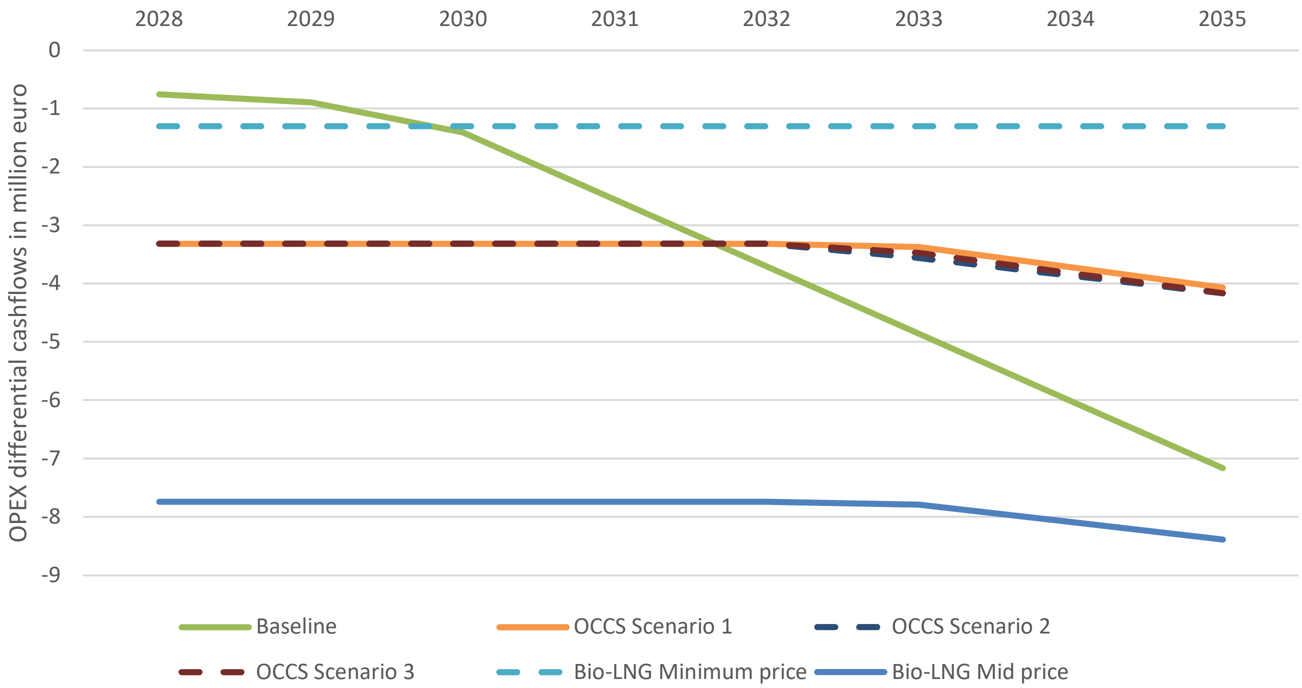

Figure 3-32 LNGC case study - OCCS comparison to bio-LNG. Annual differential OPEX cashflows.

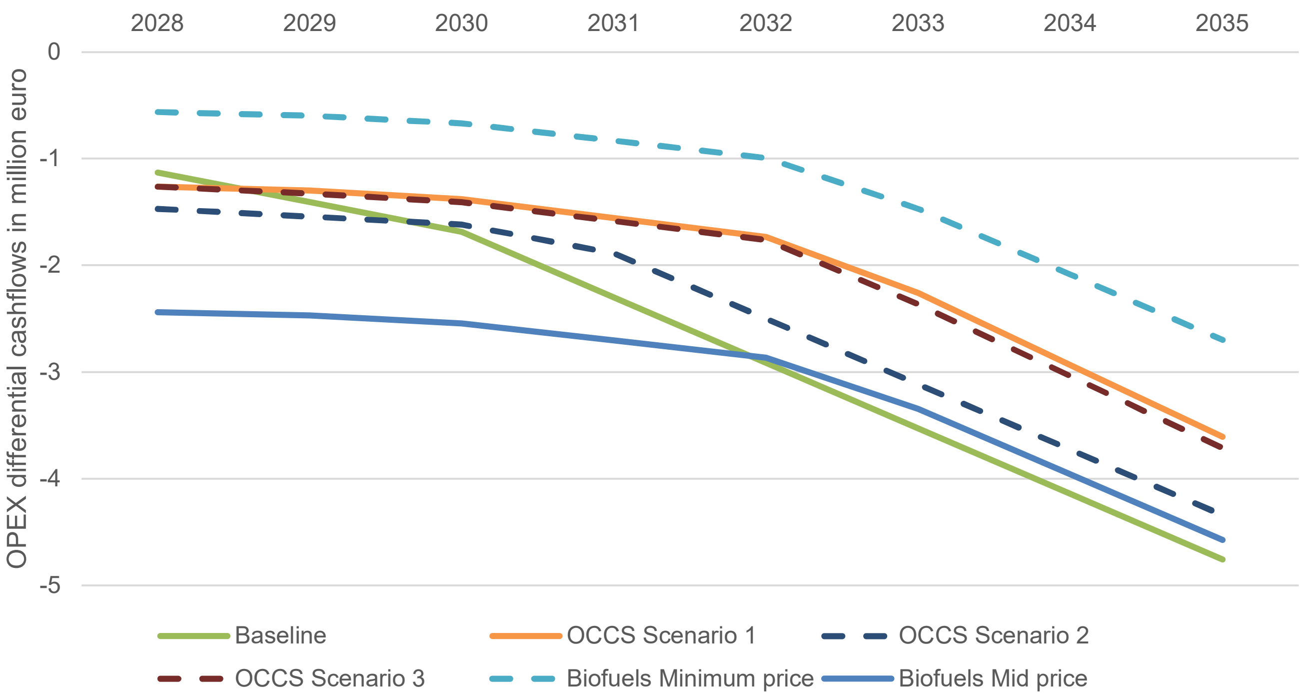

Figure 3-33 Feeder container case study - OCCS comparison to biofuels. Annual differential OPEX cashflows.

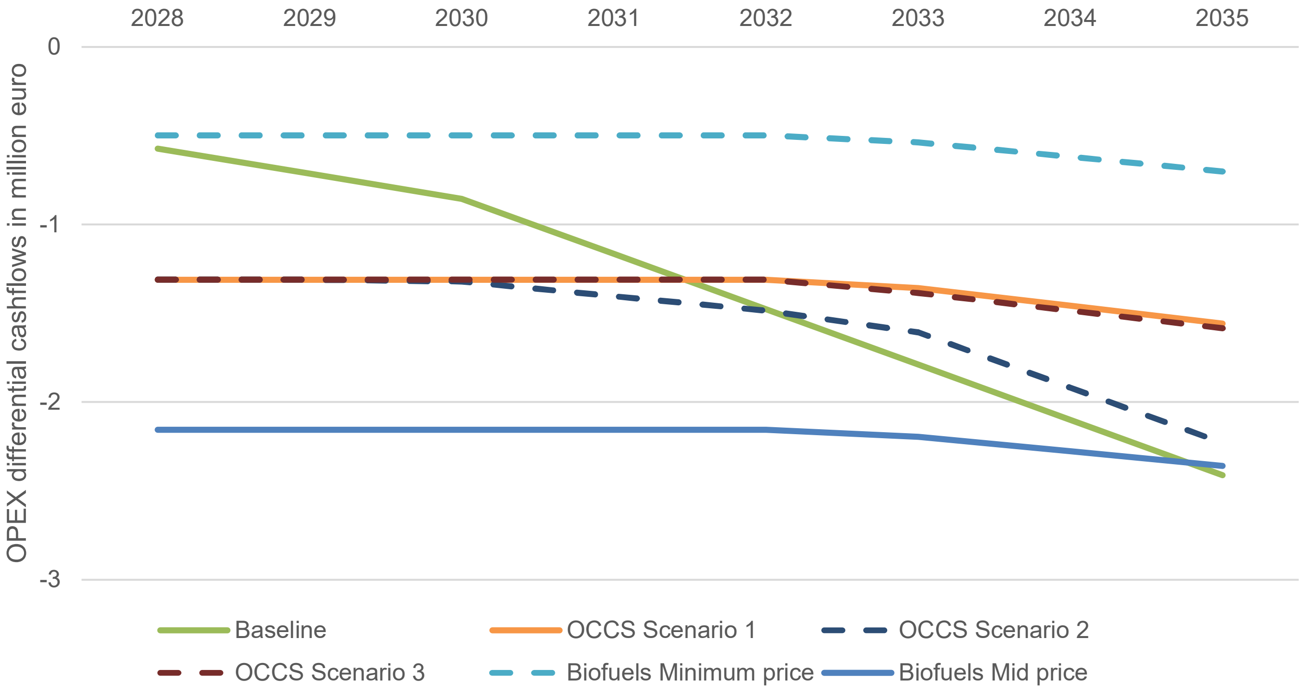

Figure 3-34 MR Tanker case study - OCCS comparison to biofuels. Annual differential OPEX cashflows.

The following graphs illustrate the attained GFI for each case scenario.

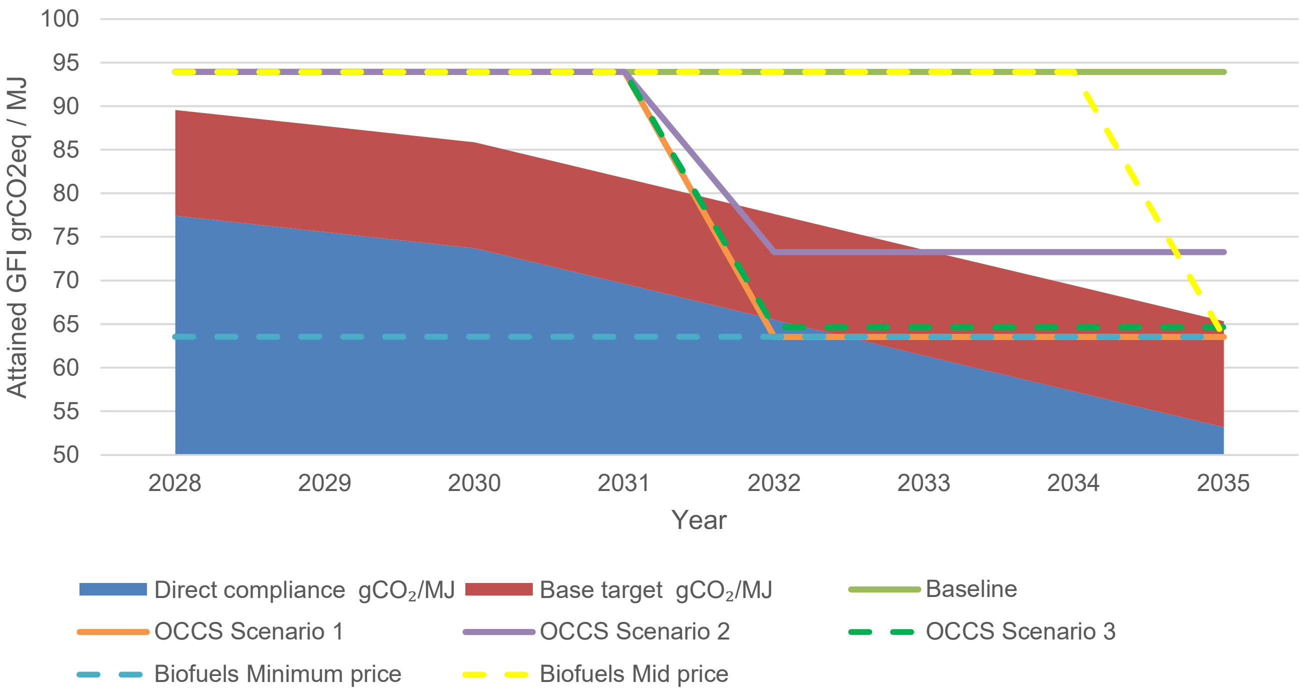

Figure 3-35 Suezmax case study - OCCS comparison to biofuels. Attained GFI scenario analysis trajectory.

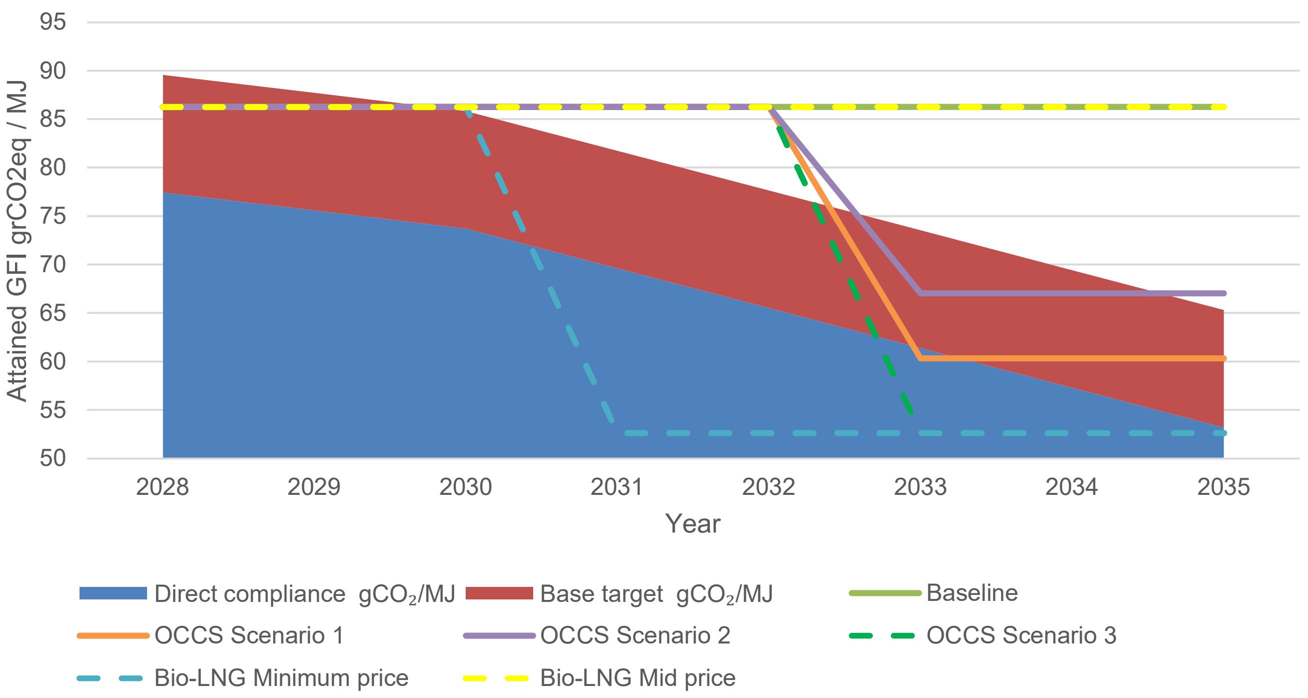

Figure 3-36 Container case study - OCCS comparison to bio-LNG. Attained GFI scenario analysis trajectory.

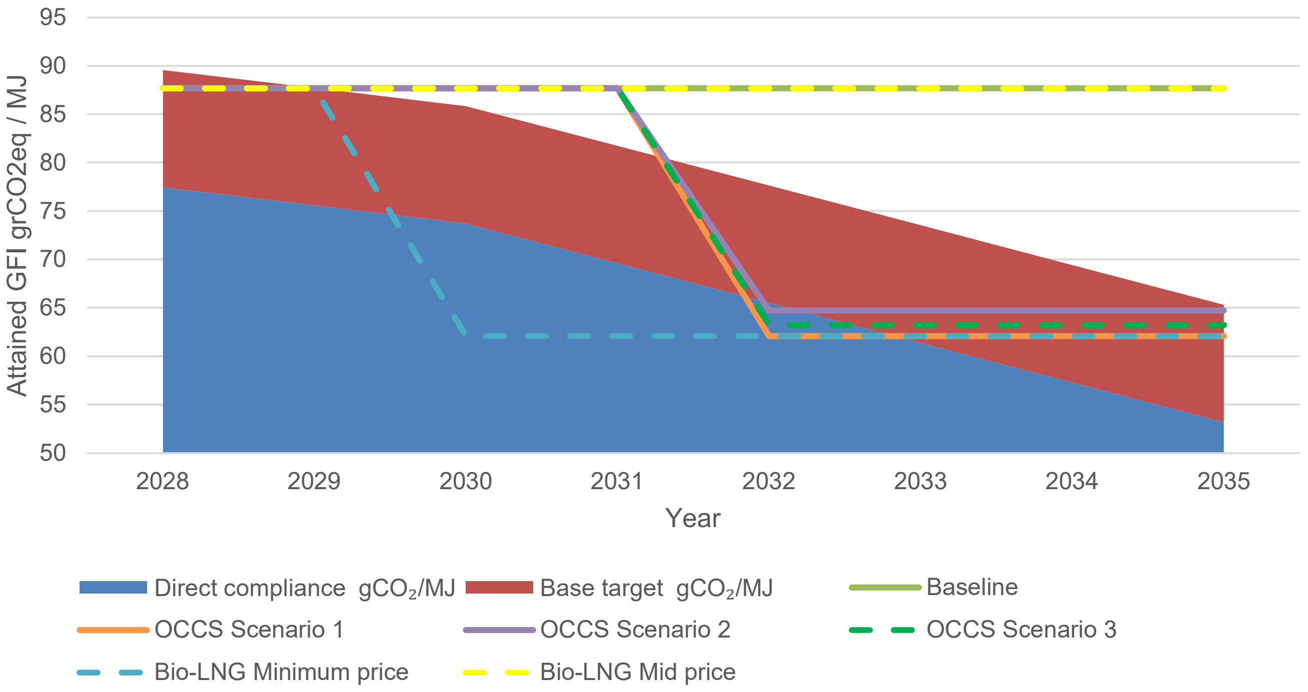

Figure 3-37 LNGC case study - OCCS comparison to bio-LNG. Attained GFI scenario analysis trajectory.

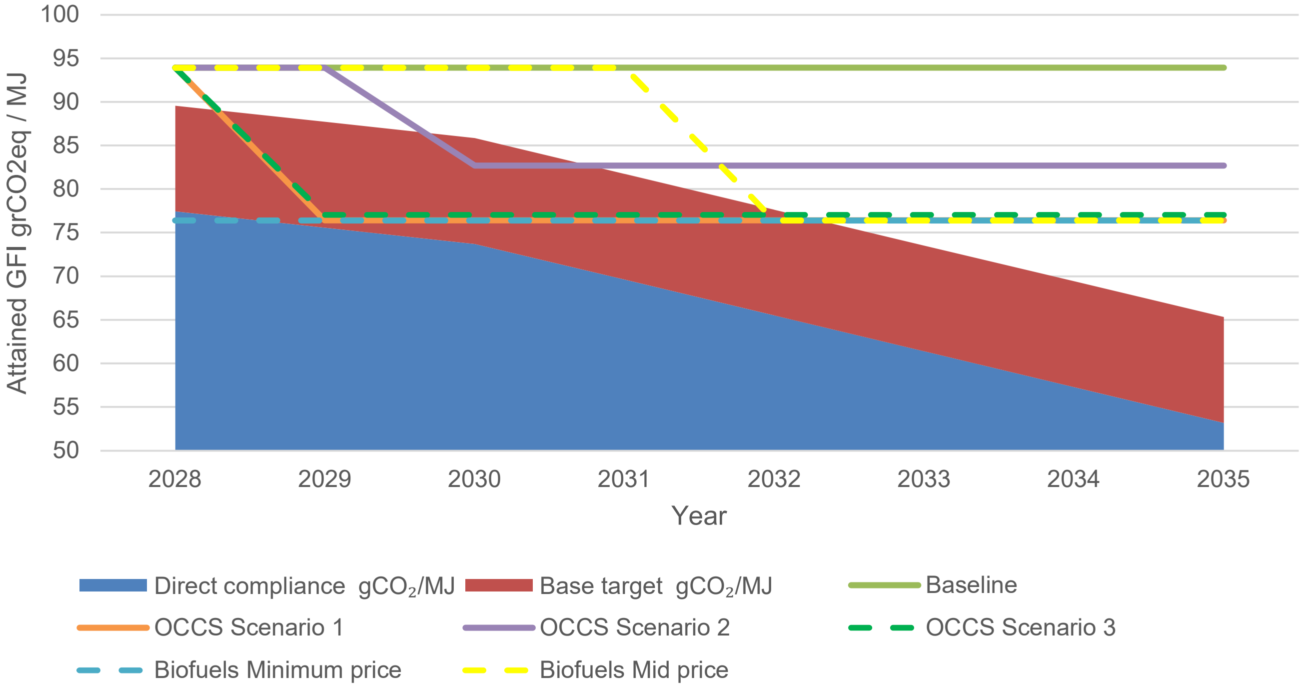

Figure 3-38 Feeder container case study - OCCS comparison to biofuels. Attained GFI scenario analysis trajectory.

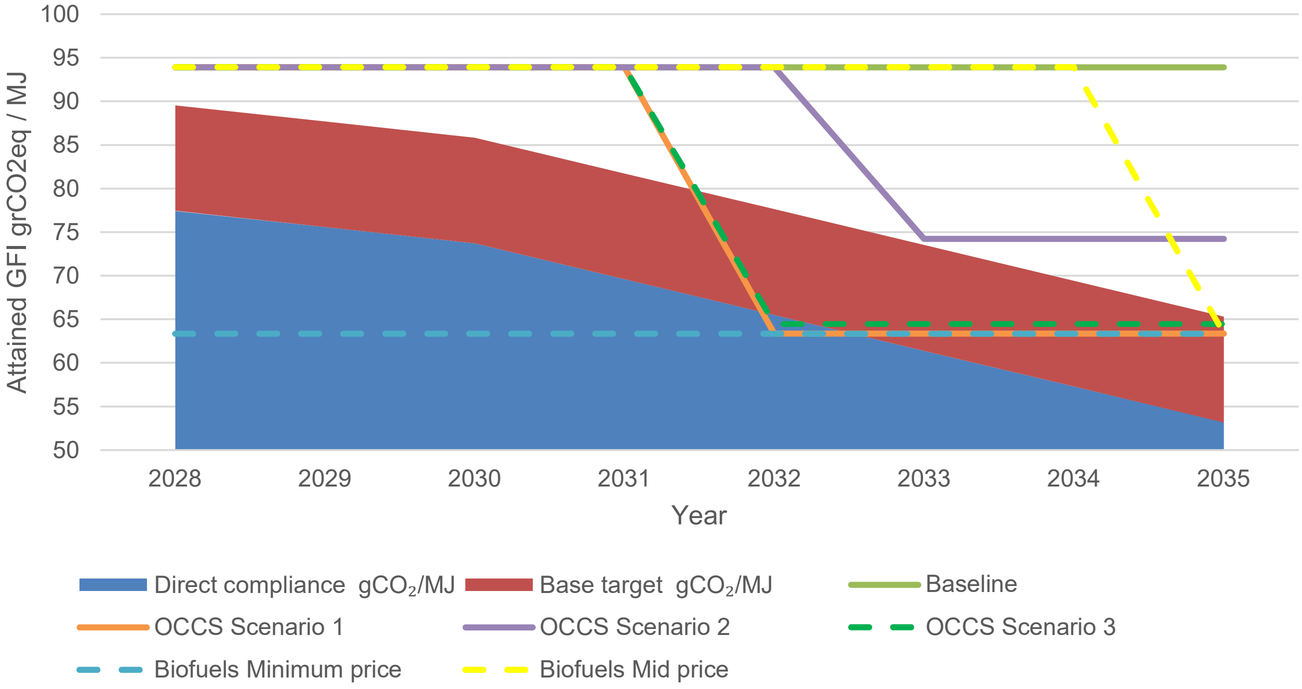

Figure 3-39 MR Tanker case study - OCCS comparison to biofuels. Attained GFI scenario analysis trajectory.

In Figure 3-40 - Figure 3-44 the discounted differential OPEX cashflows on the above analysis are accumulated for the years covering 2028-2035 (blue stack) while the red bars represent the margin of the discounted differential OPEX of OCCS and biofuels against the baseline vessel. Under this particular price scenarios, the usage of biofuels and bio-LNG, seem to be beneficial when the minimum fuel price is projected, contrary to their performance on the mid price scenario.

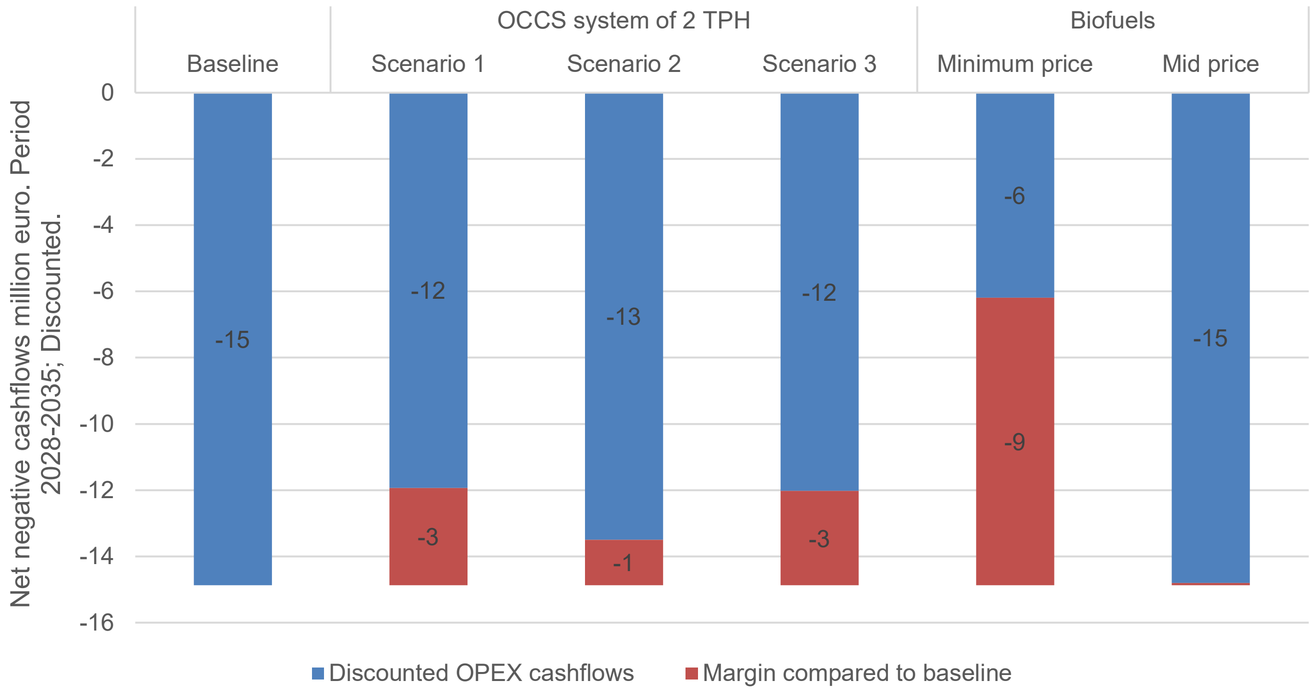

Figure 3-40 Suezmax case study - OCCS comparison to biofuels. Discounted Differential OPEX cashflows from 2028 to 2035.

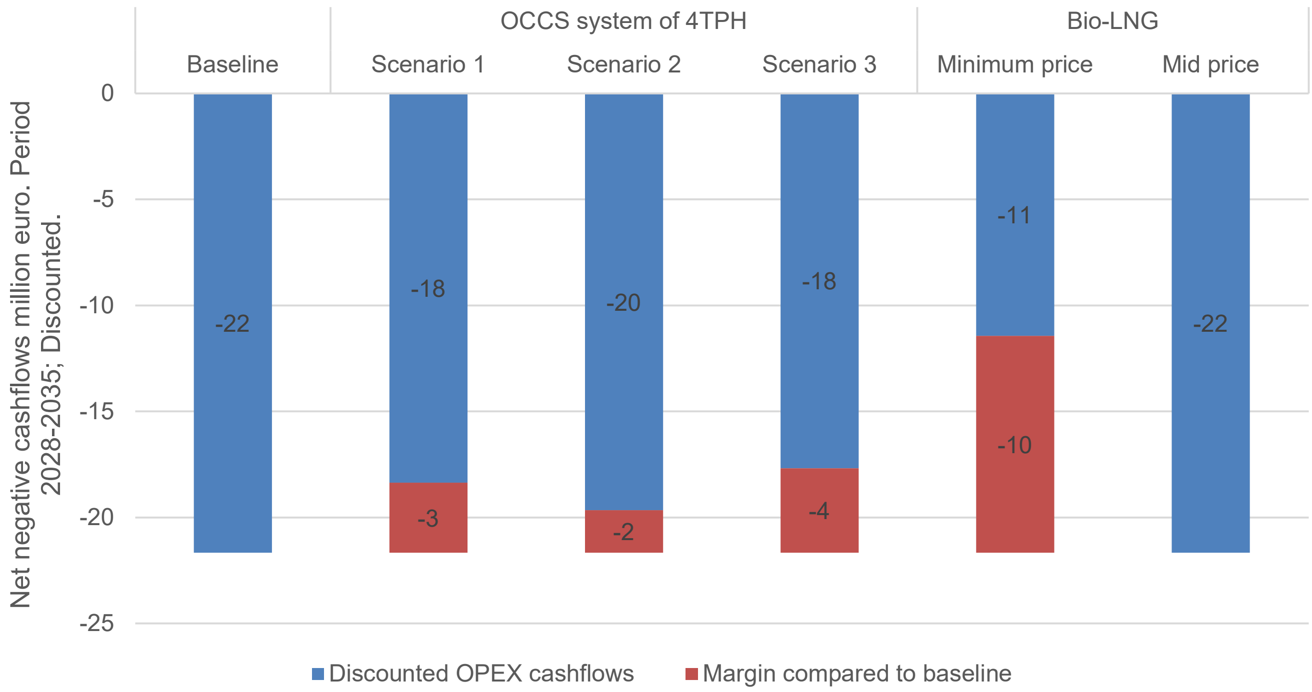

Figure 3-41 Container case study - OCCS comparison to bio-LNG. Discounted Differential OPEX cashflows from 2028 to 2035.

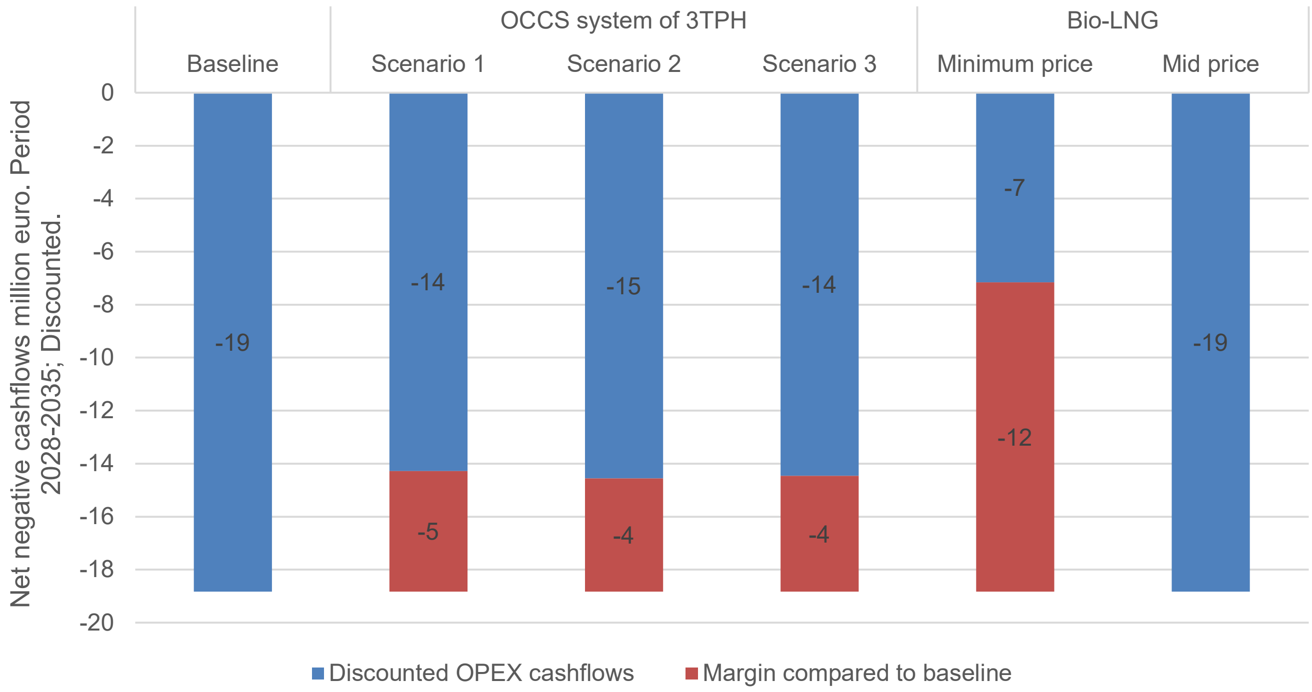

Figure 3-42 LNGC case study - OCCS comparison to bio-LNG. Discounted Differential OPEX cashflows from 2028 to 2035.

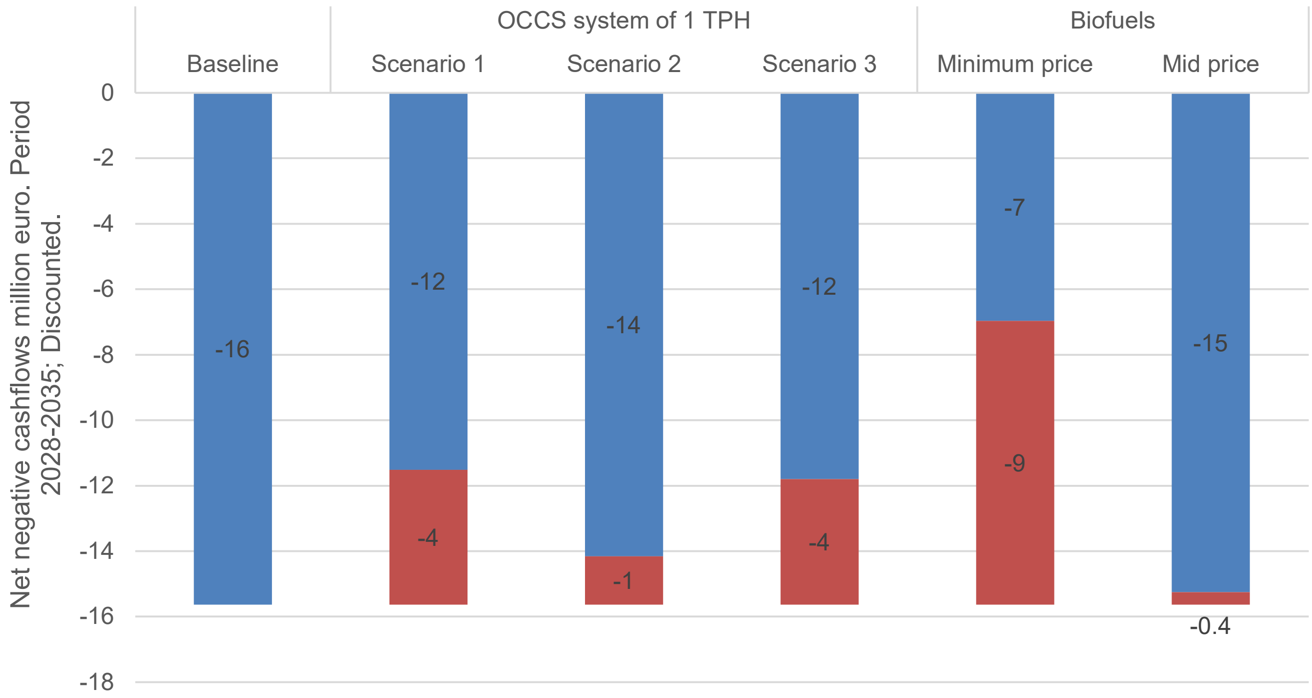

Figure 3-43 Feeder container case study - OCCS comparison to biofuels. Discounted Differential OPEX cashflows from 2028 to 2035.

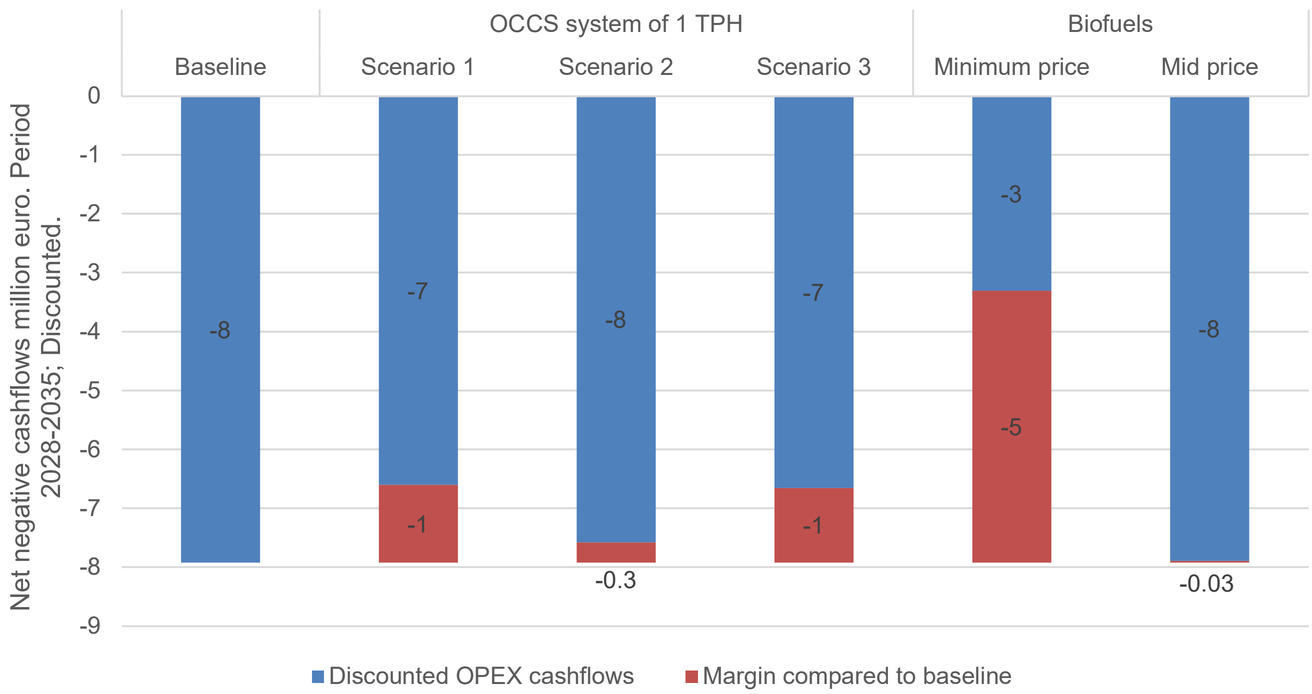

Figure 3-44 MR Tanker case study - OCCS comparison to biofuels. Discounted Differential OPEX cashflows from 2028 to 2035.

3.3.3 Conclusions on Cost Economic Analysis

The economic viability of OCCS was assessed across the selected vessel types of 3.2.1.2 under varying cost scenarios and regulatory frameworks. The analysis incorporated capital and operational expenditures, CO_2 abatement costs, EU ETS allowance savings, and the potential implications of the IMO Net-Zero Framework's GFI metric. OCCS-ready newbuild vessels show the lowest CO_2 abatement costs, while retrofits generally incur higher costs due to integration complexity and fuel penalties.

The results indicate that for OCCS across all examined vessel types, the most favourable CO_2 abatement costs observed for the Container (4 TPH), LNGC (3 TPH) and Suezmax (2 TPH) cases. These vessels benefit from higher capture capacities, more stable operational profiles, and, in the case of newbuildings, lower integration penalties. Their CO_2 abatement values are the lowest across the fleet, reflecting the cost advantages of PTO/AEECO-based newbuilding configurations compared to retrofits, whose abatement costs are higher due to fuel penalties and installation complexity. In general, fuel prices and CO_2 disposal costs are the most influential factors in total abatement cost, followed by CAPEX and maintenance. OCCS becomes increasingly competitive under mid- to long-term fuel price projections, especially when compared to biofuels, which are more cost-effective only under minimum price scenarios.

The timing of positive cashflow is derived from the GFI scenario analysis covering the years 2028–2035, where annual OPEX and ETS-related costs were modelled dynamically. Under these assumptions, the Container (4 TPH) and LNGC (3 TPH) vessels are the first to reach positive differential OPEX, typically from 2031 onwards, depending on the fuel-price scenario. The Suezmax (2 TPH) and MR tanker (1 TPH) cases become positive between 2032–2033, whereas the Feeder container (1 TPH) reaches positive differential OPEX slightly later, also within the same timeframe. These cashflow results do not represent lifetime CO_2 abatement costs behaviour but only reflect the eight-year scenario window applied for the GFI analysis. Overall, vessels with higher fuel consumption and higher EU-ETS exposure exhibit earlier economic breakeven, confirming OCCS as a promising long-term compliance option for these segments.

When interpreting the above results, it should be recognized that the economic performance of OCCS presented herein reflects the regulatory context and cost assumptions available at the time of analysis. Potential future inclusion of OCCS within global or regional GHG compliance mechanisms could influence the perceived financial performance of the technology. While the current assessment characterizes system behaviour based on the best available information and assumptions, the long-term economic viability of OCCS could be further shaped by future regulatory developments and the extent to which verified CO_2 avoidance is incentivized.

3.4 Suitability

When evaluating the implementation of an OCCS solution on a vessel, several factors determine the suitability and the performance of the system for a retrofit or a NB vessel. These indicators relate to practical considerations for onboard implementation and can be categorized as follows:

- Technology related feasibility parameters.
- Ship related feasibility parameters.
- Value chain related feasibility parameters.

Each category may include various considerations, as analysed in the paragraphs that follow.

3.4.1 Technology-related parameters

- **Compactness**: Minimizing system dimensions and weights while ensuring maximum performance is crucial for onboard integration. Some systems combine different technologies, like membranes with liquid absorption, to achieve compactness.
- **Resistance to corrosion**: The marine environment is highly corrosive, necessitating careful material selection to meet relevant rules and standards.
- **Operating conditions**: Depending on the technology, operating conditions may require specific considerations regarding Class rules, such as high-pressure and cryogenic operations.
- **Use of chemicals and consumables**: Capture systems may rely on chemical agents or solid materials for CO_2 capture. The need of consumables must be factored into the techno-economic, safety, and risk assessments.
- **Capture system capacity**: The capture capacity in TPH represents the nominal potential for CO_2 capture.
- **Power and heat energy system use**: Onboard ships have limited resources like power and heat. The carbon capture unit must operate efficiently without incurring too high an energy penalty.
- **Sensitivity to impurities**: Some capture technologies are sensitive to impurities like SO_x and particulate matter. Proper pre-treatment equipment should be considered, adding complexity and weight.
- **Sensitivity to ship motions**: Scrubbing performance can be affected by ship motions. Packing material properties play a significant role in efficiency degradation due to motion.

- **Integration capacity**: Compactness and optimal utilization of onboard resources can lead to improved onboard performance (without compromising safety).
- **CO_2 product characteristics**: CO_2 can be captured in gaseous or solid form. High purity capture processes are needed for gaseous CO_2, prior to onboard liquefaction.
- **Overflows**: Scrubbing columns may experience overflow, posing health and safety risks that require assessment and management.

3.4.2 Ship-related parameters

- **Optimized design for vessel trade**: The OCCS system capacity can be optimized for maximum utilization subject to the vessel's trade and intended machinery operation (engine loading).
- **Space availability, strength, stability and seakeeping ability**: Limited space on ships may result in potential cargo capacity loss. The addition of an OCCS system requires recalculations for structural strength and stability. Open deck space is advantageous for positioning OCCS infrastructure.
- **Handling different exhaust gas streams**: OCCS can clean exhaust from the main engine or other equipment. By-pass valves and proper connections should be considered in the design.
- **Fuel flexibility**: A desirable characteristic is its ability to operate with different fuels throughout the vessel's lifetime.
- **Effect on engine Back-Pressure**: The system requires an exhaust gas force draft fan, which adds a penalty to the capture process.
- **Leakage avoidance**: Leakages of chemicals or CO_2 pose health risks. Safety systems, like gas detection systems and others, are necessary to mitigate risks.
- **Intermediate CO_2 storage**: CO_2 handling and storage equipment require marine equipment certification.
- **CO_2 tank sizing and footprint constraints**: The sizing of onboard CO_2 storage tanks presents a significant challenge due to the usually large volume required for captured gas, especially on long voyages. Tank dimensions must be balanced against available space, vessel stability, and operational needs, often requiring trade-offs with cargo capacity or retrofitting solutions.

3.4.3 Value chain-related parameters

- **Loading/unloading systems**: Infrastructure for CO_2 receival and further sequestration or use is needed to ensure OCCS technology uptake. The infrastructure includes port discharging facilities, intermediate storage, transport, and permanent storage solutions.
- **CO_2 storage forms**: Specifications of the CO_2 product purity and quality may be imposed from the CO_2 value chain side. These would affect the performance and footprint of the OCCS technology, such as the need for after-treatment systems.
- **Supply chain compatibility**: To ensure efficient disposal of CO_2, the ship OCCS systems will need to be compatible with the rest of the CCUS value chain.
- **Solvent management systems**: If chemical absorption is used for OCCS, the supply chain must support solvent regeneration, recycling, and disposal. This includes handling amines or other capture agents and ensuring environmental compliance.
- **Compression and liquefaction units**: Depending on the form of CO_2 storage (compressed gas, liquid, or solid), specialized equipment may be needed onboard and at receiving terminals to manage phase transitions and maintain containment integrity.
- **Integration with sequestration or utilization facilities**: The final leg of the CCUS chain, whether geological storage or industrial reuse, must be aligned with the specifications and delivery format of the captured CO_2.

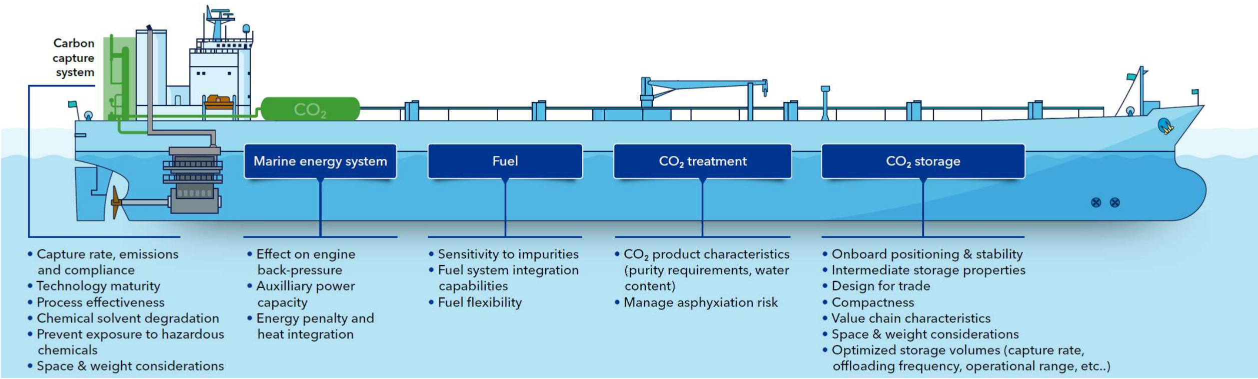

Figure 3-45. OCCS design implications. Source: DNV.

3.4.4 Assessment on suitability

A summary of advantages and disadvantages of OCCS technologies is provided in Table 3-19. The potential impacts on stability, energy consumption, space demands, risks for personnel, and effective emissions reduction are evaluated comprehensively using a high-level assessment. This assessment is based on an extensive compilation of literature from various reputable sources, (Damartzis, et al., 2022), (Nikulainen, Laukka, Portin, & Laursen, 2023), (DNV, 2024d), (Yaseen A. A., 2025). The presented capture rates are based on results of projects on the different technologies, which are further described in the section that follows.

Table 3-19 Advantages and disadvantages of OCCS technologies.

Capture Method	Stability Impact	Marine energy system use	Space Demands	Risks for Personnel	Maintain-ability	Emissions Reduction
Chemical absorption	**Moderate impact**	**Moderate to high impact**	**High impact**	**High impact**	**High impact**	Effective emissions reduction depends on capacity. Capture rate at unit level up to 90%. Issues with NO_x impurities.
	🟡	🟡🔴	🔴	🔴	🔴	
	Equipment size and weight may affect stability	Solvent regeneration heat duty and electricity requirements for liquefaction influence footprint.	Requires significant space for absorbers and strippers. Dependent on capture capacity.	Solvent/by-products pose hazards (corrosion, toxicity).	Solvent degradation and corrosion issues.	
Mineralization	**High impact**	**Low impact**	**High impact**	**Low impact**	**Low impact**	Effective emissions reduction depends on capacity. Capture rate at unit level up to 95%.
	🔴	🟢	🔴	🟢	🟢	
	Because of space demands, dependent on capacity.	Low requirements for energy.	Storage needed for minerals and capture by-products	Minimal risks for personnel.		
Membrane separation	**Low impact**	**High impact**	**Low impact**	**Low impact**	**High impact**	Effective emissions reduction
	🟢	🔴	🟢	🟢	🔴	

Capture Method	Stability Impact	Marine energy system use	Space Demands	Risks for Personnel	Maintain-ability	Emissions Reduction
	Compact designs. However, extensive pre-treatment may be needed, adding weight.	Energy required for pressure drop mitigation, potential gas cooling and pre-treatment.	Highly compact, flexible placement.	Applicable in case of chemical solvent use.	Membrane fouling and degradation over time.	depends on capacity. Capture rate at unit level up to 85%
Cryogenic separation	**Low impact**	**High impact**	**Low impact**	**Low impact**	**Moderate impact**	Effective emissions reduction depends on capacity. Capture rate at unit level up to 99%
	🟢	🔴	🟢	🟢	🟡	
	Compact design minimizes impact on ship stability.	Energy to maintain low temperatures.	Compact design minimizes space requirements.	Potential issues with ice formation and blockages.	Requires robust refrigeration units.	
Pre-combustion	**High impact**	**Moderate impact**	**High impact**	**High impact**	**High impact**	Capture rate at unit level up to 90%
	🔴	🟡	🔴	🔴	🔴	
	Heavy equipment and free surfaces affect stability.	Low energy requirements, at the expense of less volumetric energy content of produced fuel H_2.	Space for syngas production and H_2 storage.	Risk from H_2 systems Technical defects may cause propulsion loss.	As for H_2 systems. Engine capacity for rich-H_2 fuel use.	
Oxy-fuel combustion	**High impact**	**Moderate to high impact**	**High impact**	**High impact**	**High impact**	Easy capture of CO_2 due to high concentration in exhaust gases. Reduction in NO_x emissions.
	🔴	🟡/🔴	🔴	🔴	🔴	
	The addition of ASUs and O_2 storage tanks can affect the ship's stability due to the added weight and space requirements	Energy-intensive for ASUs to produce pure O_2 and the subsequent compression and liquefaction of CO_2	Many components are required, dependent on capacity.	O_2 presence: risk of fires and explosions.	As for gas handling systems.	
Legend						
Low impact			🟢			
Moderate impact			🟡			
High impact			🔴			

3.4.5 Suitability analysis for selected cases

This section provides a more in-depth analysis of the selected vessels as shown in Table 3-13, focusing on the onboard temporary storage systems and their implications for equipment placement, weight distribution, vessel stability, and the associated operational risks.

When installing an OCCS considerations related to the following items should be made:
- Absorber and regeneration stacks.
- Liquefaction plant.
- LCO_2 tanks.
- Required space and installation location for the relevant components.
- Additional weight.
- Effect on vessel's structural integrity.
- Effect on vessel's stability.
- Piping and rerouting.
- Maintenance.
- Conflict with cargo operations.

3.4.5.1 Space and Layout Considerations

The OCCS system comprises three main components: the absorber and regeneration stacks, the liquefaction plant, and the LCO_2 storage tanks. Placement strategies vary by vessel type:

- LCO_2 Tanks could be installed on the main deck (Suezmax, MR Tanker, LNGC), within the aft cargo hold (Container, Feeder), or on the uppermost deck (RoPax). Their location is influenced by available space, structural support, and hazardous area classification.
- Absorber and Regeneration Units are generally positioned close to the funnel to minimize interference with operations and leverage existing structural support.
- Liquefaction Plants are often located near the engine room or on a designated space on deck, with a potential placement being close to the OCCS capture system, requiring dedicated space and safety systems due to the presence of pressurized CO_2.

If the installation location of the LCO_2 storage tanks is classified as a hazardous area, additional safety measures must be implemented. This includes ensuring that all associated electrical equipment, such as sensors and instrumentation, are certified for use in explosive atmospheres (e.g., EX-certified).

To mitigate the need for hazardous area compliance, an alternative approach may involve installing the tanks above deck, outside the classified zone. However, this solution requires further structural analysis, as it introduces additional loads, up to 10% additional weight of the storage tank, and necessitates reinforcement of the supporting structure, potentially impacting the vessel's overall weight and stability.

For the liquefaction plant, given the presence of pressurized CO_2 and potential leak scenarios, the same safety requirements, such as dedicated ventilation, gas detection, and explosion-proof equipment, are expected to apply same as LCO_2 storage tanks. To comply with these standards and mitigate risks, the liquefaction plant may need to be installed in a segregated, purpose-built compartment adjacent to or outside the ER, rather than within the general machinery space.

In retrofit cases, structural modifications such as deck reinforcements or relocation of existing equipment (e.g., bollards, foam cannons) may be necessary.

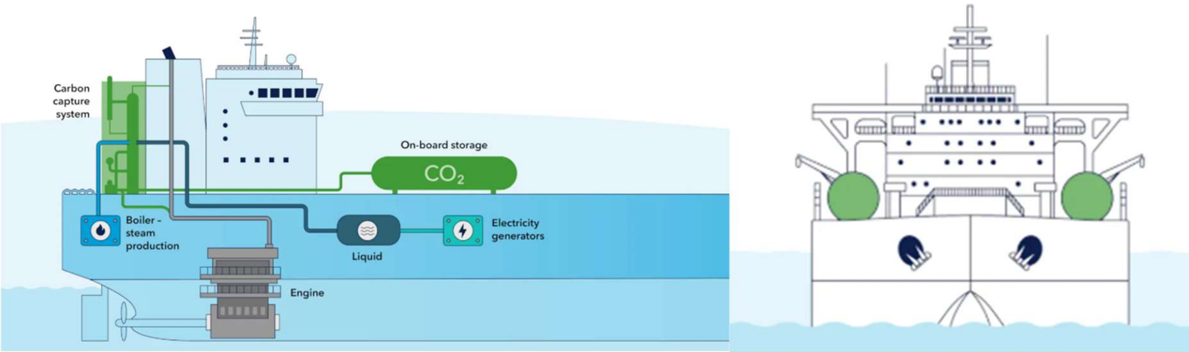

Figure 3-46 Potential location of OCCS system & LCO_2 storage tanks onboard a Suezmax vessel. Source: DNV TMS Study[55].

3.4.5.2 Newbuilding vs Retrofit Integration

Newbuildings offer the advantage of integrating OCCS from the design phase (OCCS ready), allowing for optimized layout, weight distribution, and minimal disruption to vessel operations. In contrast, retrofitting requires careful planning to accommodate OCCS within existing constraints. This often involves:

- Reinforcing decks or cargo holds.
- Updating the vessel's loading computer and inclining test.
- Ensuring compliance with hazardous area regulations.

The retrofit complexity varies by vessel type, with RoPax and container vessels typically requiring more substantial structural adaptations.

3.4.5.3 LCO_2 onboard storage tanks

The estimations for the required capacity of the LCO_2 tank is assuming the examined round trip voyage profile for each selected vessel from 3.2.2, considering a margin of +10% (unforeseen delays/ extended cargo operations). LCO_2 storage tanks are filled up to 95% of their volume. LCO_2 density is assumed at 1,110 kg/m^3. For the Suezmax and RoPax examined case, two LCO_2 storage tanks have been assumed, while for the two Container cases and the MR tanker[56] one LCO_2 storage tank has been assumed. For LNGC four LCO_2 storage tanks have been assumed[57].

Table 3-20 Suezmax case study - LCO_2 Storage Tanks specifications.

Suezmax case - LCO_2 Storage Tanks specifications				
OCCS Capture rate	CO_2 captured per 40 days+10% margin (m^3)	LCO_2 total required capacity (m^3)	Tank capacity tons (per LCO_2 tank)	Tank DxL (m) (per storage tank)
1 TPH	880	930	470	6x19
2 TPH	1560	1650	830	7x22
3 TPH	2210	2350	1180	8x26

Table 3-21 Container case study - LCO_2 Storage Tank specifications.

Container case - LCO_2 Storage Tank specifications				
OCCS Capture rate	CO_2 captured per 35 days+10% margin (m^3)	LCO_2 total required capacity (m^3)	Tank capacity tons	Tank DxL (m) (per storage tank)
2 TPH	1550	1480	1630	9x28
4 TPH	3100	3000	3250	11x34
6 TPH	4300	4150	4560	12x40

[55] https://www.dnv.com/expert-story/maritime-impact/on-board-carbon-capture-and-storage-equipment-feasibility-study/
[56] What would an Onboard Carbon Capture and Storage (OCCS) system look like on the Stena Impero? - GCMD
[57] Investigating Carbon Capture and Storage for an LNG carrier

Table 3-22 RoPax case study - LCO_2 Storage Tanks specifications.

RoPax case - LCO_2 Storage Tanks specifications				
OCCS Capture rate	CO_2 captured per 15 days+10% margin (m^3)	LCO_2 total required capacity (m^3)	Tank capacity tons (per LCO_2 tank)	Tank DxL (m) (per storage tank)
0.25 TPH	39	50	30	2x7
0.50 TPH	73	80	40	2x8
0.75 TPH	91	100	50	3x9
1.00 TPH	109	120	60	3x9

Table 3-23 LNGC case study - LCO_2 Storage Tanks specifications.

LNGC case - LCO_2 Storage Tanks specifications				
Capture rate of OCCS	CO_2 captured per 40 days+10% margin (m^3)	LCO_2 total required capacity (m^3)	Tank capacity tons (per tank)	Tank D x L (m) (per storage tank)
1 TPH	870	900	250	5x16
2 TPH	1750	1850	500	6x18
3 TPH	2600	2750	750	7x21

Table 3-24 Feeder container case study - LCO_2 Storage Tanks specifications.

Feeder container - LCO_2 Storage Tanks specifications				
Capture rate of OCCS	CO_2 captured per 15 days+10% margin (m^3)	LCO_2 total required capacity (m^3)	Tank capacity tons (per tank)	Tank D x L (m) (per storage tank)
0.5 TPH	190	200	220	5x15
1 TPH	340	360	395	5x17

Table 3-25 MR tanker case study - LCO_2 Storage Tanks specifications.

MR tanker case - LCO_2 Storage Tanks specifications				
Capture rate of OCCS	CO_2 captured per 15 days+10% margin (m^3)	LCO_2 total required capacity (m^3)	Tank capacity tons (per tank)	Tank D x L (m) (per storage tank)
0.5 TPH	165	180	200	4x14
1 TPH	323	340	375	5x17

3.4.5.4 Chemical Solvents onboard storage capacities

As mentioned in 3.1.2, the required MEA makeup volume correlates linearly with the amount of CO_2 captured, at approximately 1.6 liters of MEA per cubic meter of liquefied CO_2 stored, based on the assumption of 1.5 kg MEA per tonne of CO_2 captured (Xiaobo Luo, 2017). This value represents a conservative design basis for degradation-related makeup and does not include the total circulating solvent inventory onboard. The CCS system contains a circulating solvent volume, typically 50–200 m³ of water and MEA solution (Aleksander Krótki, 2023), that remains in continuous operation and does not require additional storage.

Table 3-26 Suezmax case study – MEA storage tanks estimation.

Suezmax case - LCO_2 Storage Tanks specifications			
OCCS Capture rate	CO_2 captured per 40 days+10% margin (m^3)	LCO_2 total required capacity (m^3)	MEA makeup required onboard storage capacity (m^3)
1 TPH	880	930	1.51
2 TPH	1560	1650	2.67
3 TPH	2210	2350	3.81

Table 3-27 Container case study - MEA storage tanks estimation.

Container case - LCO_2 Storage Tank specifications			
OCCS Capture rate	CO_2 captured per 35 days+10% margin (m^3)	LCO_2 total required capacity (m^3)	MEA makeup required onboard storage capacity (m^3)
2 TPH	1550	1480	2.39
4 TPH	3100	3000	4.86
6 TPH	4300	4150	6.72

Table 3-28 RoPax case study - MEA storage tanks estimation.

RoPax case - LCO_2 Storage Tanks specifications			
OCCS Capture rate	CO_2 captured per 15 days+10% margin (m^3)	LCO_2 total required capacity (m^3)	MEA makeup required onboard storage capacity (m^3)
0.25 TPH	39	50	0.08
0.50 TPH	73	80	0.13
0.75 TPH	91	100	0.16
1.00 TPH	109	120	0.19

Table 3-29 LNGC case study - MEA storage tanks estimation.

LNGC case - LCO_2 Storage Tanks specifications			
Capture rate of OCCS	CO_2 captured per 40 days+10% margin (m^3)	LCO_2 total required capacity (m^3)	MEA makeup required onboard storage capacity (m^3)
1 TPH	870	900	1.46
2 TPH	1750	1850	2.99
3 TPH	2600	2750	4.45

Table 3-30 Feeder container case study - MEA storage tanks estimation.

Feeder container - LCO_2 Storage Tanks specifications			
Capture rate of OCCS	CO_2 captured per 15 days+10% margin (m^3)	LCO_2 total required capacity (m^3)	MEA makeup required onboard storage capacity (m^3)
0.5 TPH	190	200	0.32
1 TPH	340	360	0.58

Table 3-31 MR tanker case study - MEA storage tanks estimation.

MR tanker case - LCO_2 Storage Tanks specifications			
Capture rate of OCCS	CO_2 captured per 15 days+10% margin (m³)	LCO_2 total required capacity (m³)	MEA makeup required onboard storage capacity (m³)
0.5 TPH	165	180	0.29
1 TPH	323	340	0.55

3.4.5.5 Weight and Structural Impacts

The effect of the OCCS weight to each vessel's lightship is shown in the below tables. It should be noted that the effect in the weight is approximately the same regardless of whether it is an optimized newbuilding or a retrofit. In the context of the present study, the lightweight increase is intended to remain below 2% wherever possible, allowing the retrofit to be carried out without the need for an inclining test. For the newbuilding vessel, this anticipated lightweight increase should be considered already at the design and construction stage.

Table 3-32 Suezmax case study - OCCS weight distribution (tons).

Suezmax case - OCCS Weight distribution in tons per examined capture rates			
Capture rate	**1 TPH**	**2 TPH**	**3 TPH**
OCCS System weight - Structure only	230	380	515
Increase compared to baseline LWT	0.9 %	1.5 %	2.1%

Table 3-33 Container case study - OCCS weight distribution (tons).

Container case - OCCS Weight distribution in tons per examined capture rates			
Capture rate	**2 TPH**	**4 TPH**	**6 TPH**
OCCS System weight - Structure only	330	620	885
Increase compared to baseline LWT	0.7%	1.4%	2.0%

Table 3-34 RoPax case study - OCCS weight distribution (tons).

RoPax case - OCCS Weight distribution in tons per examined capture rates				
Capture rate	**0.25 TPH**	**0.50 TPH**	**0.75 TPH**	**1.00 TPH**
OCCS System weight - Structure only	54	68	84	98
Increase compared to baseline LWT	1.3%	1.7%	2.1%	2.5%

Table 3-35 LNGC case study - OCCS weight distribution (tons).

LNGC case - OCCS Weight distribution in tons per examined capture rates			
Capture rate	**1 TPH**	**2 TPH**	**3 TPH**
OCCS System weight - Structure only	280	440	620
Increase compared to baseline LWT	0.9%	1.4%	2.0%

Table 3-36 Feeder container case study - OCCS weight distribution (tons).

Feeder container case - OCCS Weight distribution in tons per examined capture rates		
Capture rate	**0.5 TPH**	**1 TPH**
OCCS System weight - Structure only	110	140
Increase compared to baseline LWT	1.3%	1.6%

Table 3-37 MR tanker case study - OCCS weight distribution (tons).

MR tanker case - OCCS Weight distribution in tons per examined capture rates		
Capture rate	**0.5 TPH**	**1 TPH**
OCCS System weight - Structure only	100	140
Increase compared to baseline LWT	1.1%	1.6%

Mineralization OCCS weight impact

For reference purposes, the weight impact for the OCCS is also presented for the mineralization case. In mineralization processes, calcium carbonate ($CaCO_3$) is a commonly considered end product due to its stability and ease of handling. The fundamental chemical reaction governing this transformation involves the combination of CO_2 with calcium oxide (CaO) and water (H_2O), resulting in the formation of $CaCO_3$. Stoichiometrically, one mole of CO_2 reacts to produce one mole of $CaCO_3$. Given the molar masses of CO_2 (44 g/mol) and $CaCO_3$ (100 g/mol), this translates to a mass conversion ratio of approximately 2.27:1. Therefore, for every 1 ton of CO_2 mineralized, approximately 2.27 tons of $CaCO_3$ are generated. This conversion factor is essential for estimating the material output of mineralization systems and for assessing the implications on storage, transport, and potential reuse of the solidified carbon product.

Based on the above the effect of the mineralization OCCS will be shown in the below matrices. Density of $CaCO_3$ is assumed at 2.71 tons/m³.

Table 3-38 Suezmax case study - LCO_2 Storage Tanks specifications.

Suezmax case – Mineral $CaCO_3$ Storage Tanks specifications			
OCCS Capture rate	CO_2 captured per 40 days+10% margin (m³)	$CaCO_3$ required weight (tons)	$CaCO_3$ total required capacity (m³)
1 TPH	880	2040	752
2 TPH	1560	3616	1334
3 TPH	2210	5123	1890

Table 3-39 Container case study - LCO_2 Storage Tank specifications.

Container case - Mineral $CaCO_3$ Storage Tank specifications			
OCCS Capture rate	CO_2 captured per 35 days+10% margin (m³)	$CaCO_3$ required weight (tons)	$CaCO_3$ total required capacity (m³)
2 TPH	1550	3595	1325
4 TPH	3100	7185	2650
6 TPH	4300	9970	3676

Table 3-40 RoPax case study - LCO_2 Storage Tanks specifications.

RoPax case - Mineral $CaCO_3$ Storage Tanks specifications			
OCCS Capture rate	CO_2 captured per 15 days+10% margin (m^3)	$CaCO_3$ required weight (tons)	$CaCO_3$ total required capacity (m^3)
0.25 TPH	39	90	33
0.50 TPH	73	170	62
0.75 TPH	91	210	78
1.00 TPH	109	252	93

Table 3-41 LNGC case study - LCO_2 Storage Tanks specifications.

LNGC case - Mineral $CaCO_3$ Storage Tanks specifications			
Capture rate of OCCS	CO_2 captured per 40 days+10% margin (m^3)	$CaCO_3$ required weight (tons)	$CaCO_3$ total required capacity (m^3)
1 TPH	870	2016	743
2 TPH	1750	4056	1496
3 TPH	2600	6027	2223

Table 3-42 Feeder container case study - LCO_2 Storage Tanks specifications.

Feeder container - Mineral $CaCO_3$ Storage Tanks specifications			
Capture rate of OCCS	CO_2 captured per 15 days+10% margin (m^3)	$CaCO_3$ required weight (tons)	$CaCO_3$ total required capacity (m^3)
0.5 TPH	190	440	162
1 TPH	340	788	290

Table 3-43 MR tanker case study - LCO_2 Storage Tanks specifications.

MR tanker case - Mineral $CaCO_3$ Storage Tanks specifications			
Capture rate of OCCS	CO_2 captured per 15 days+10% margin (m^3)	$CaCO_3$ required weight (tons)	$CaCO_3$ total required capacity (m^3)
0.5 TPH	165	382	141
1 TPH	323	748	276

3.4.5.6 Impact on Stability

The installation of OCCS systems introduces changes to the vessel's stability profile, due to the added weight and its vertical and longitudinal distribution. Across all vessel types, the OCCS components, particularly the LCO_2 storage tanks and absorber columns, raise the vessel's vertical centre of gravity (VCG), which can reduce the metacentric height (GM) and increase sensitivity to rolling motions.

For newbuildings, these effects are addressed during the design phase. The OCCS system's weight and distribution are incorporated into the initial lightship definition and stability calculations. The inclining test reflects the vessel's final configuration, ensuring compliance with regulatory requirements from the outset.

In retrofit scenarios, the OCCS system alters the existing lightship characteristics. A new inclining test is often required to accurately determine the updated GM and ensure continued compliance. The impact varies by vessel type:

- On Suezmax and MR tankers, the effect is moderate. The deck structure is typically robust, and the added weight is distributed symmetrically. With the installation of the OCCS components and when the LCO_2 tanks are full, the vessel's center of gravity shifts slightly higher, and a bit aft compared to the vessel without the OCC.
- For container vessels, the flexibility in container placement allows for some compensation of the OCCS weight. The impact on GM is expected to be small to insignificant in practice, provided that voyage-specific stability assessments are conducted.
- In RoPax vessels, the stability impact is more critical. Installing heavy tanks on the uppermost deck significantly raises the VCG, reducing GM and increasing roll amplitudes. While relocating tanks to lower decks (e.g., vehicle decks) could improve stability, this introduces safety concerns due to proximity to passengers and the need for hazardous area compliance.
- LNG carriers and feeder vessels also require careful assessment due to limited flexibility in weight redistribution. The OCCS weight must be reflected in the loading computer and considered in every voyage's stability plan.

In all cases, the evaluation must include the weight of liquids within the system (e.g., solvents, absorbents, and liquefied CO_2) under normal operating conditions. The updated mass distribution must be incorporated into the vessel's loading computer to ensure accurate trim and stability calculations.

3.4.5.7 Impact on Cargo Capacity

The OCCS system affects cargo capacity through both space occupation and deadweight increase, with the extent of impact varying by vessel type and installation configuration.

On container and feeder vessels, LCO_2 tanks are typically installed in the aft cargo hold. This results in the loss of container slots, up to 175 TEU in the large case of the 15,000 TEU Containership, translating to a 1–3% reduction in cargo capacity. The impact is more pronounced in retrofit cases, where structural constraints limit flexibility.

For RoPax vessels, tanks placed on deck preserve vehicle space but may still reduce usable volume due to safety zones or access restrictions. If tanks are installed within vehicle decks, the loss can be equivalent to up to 100 cars, directly affecting commercial payload.

In tankers and LNG carriers, the OCCS components are generally placed on deck or in non-cargo areas, minimizing direct interference with cargo operations. However, the added weight still affects the vessel's draft and available deadweight.

The total added weight, including structural components, piping, insulation, and stored LCO_2, ranges from 1,200 to 5,900 tons, depending on vessel size and capture rate. This increase reduces the vessel's available deadweight for cargo, fuel, and provisions. The effect is particularly relevant on routes with strict draft limitations or where fuel efficiency is critical.

To mitigate these impacts some measures could be considered as follows:

- Ballast water configurations may be adjusted to maintain acceptable trim and draft.
- Deadweight increase studies can be conducted to assess the feasibility of offsetting the added weight through structural modifications or operational changes.
- Voyage planning must account for reduced cargo margins, especially in high-capacity or draft-restricted ports.

In newbuilds, these challenges can be addressed through integrated design solutions, such as optimized ballast arrangements and structural accommodations. In retrofit cases, a detailed engineering assessment is essential to evaluate trade-offs and ensure compliance with both technical and commercial requirements.

3.4.6 Conclusions on Suitability

Integrating OCCS requires balancing technical feasibility, operational constraints, and alignment with the broader CCUS value chain.

Each vessel type presents unique challenges in terms of space, weight, and safety. Larger vessels like Suezmax tankers and LNG carriers are generally more suitable due to their size and operational profiles, which allow for better integration of LCO_2 storage and capture systems. Container ships can accommodate OCCS with moderate cargo loss (1-3% TEU), while RoPax vessels face tighter constraints due to limited deck space and safety considerations. Feeder vessels and MR tankers may support OCCS at lower capture rates, provided structural and stability impacts are managed.

A key trade-off is between capture rate and cargo capacity. Higher capture rates require larger tanks and more equipment, which can reduce cargo space and increase draft. Newbuilds offer the most flexibility, enabling optimized integration from the design phase. Retrofits, while feasible, require detailed engineering and may involve compromises in layout, stability, or cargo. Selecting the right OCCS solution requires a holistic assessment of vessel design, operational profile, and value chain integration.

3.5 Top-down approach

This section presents a top-down generalization of the bottom-up sustainability, suitability and economic analysis conducted for selected vessel types. The objective is to extend the insights gained from the six representative vessels to the broader fleet, which includes a diverse range of vessel categories such as VLCCs, bulk carriers, chemical tankers, cruise ships, and general cargo vessels.

3.5.1 Additional vessel segments performance indicator

The approach is based on operational similarity, machinery scale, voyage duration, and emissions contribution, using the assessed vessels as reference cases.

Each unassessed vessel type is mapped to the most technically and operationally similar assessed vessel. The extrapolated values for capture rate, emissions reduction, and fuel penalty are scaled based on key parameters, including main engine power, voyage duration and frequency, space availability for OCCS equipment, and operational profile characteristics such as port call frequency and speed distribution. This mapping ensures that extrapolated performance indicators remain technically plausible and contextually relevant.

For example, VLCCs are mapped to Suezmax tankers due to their comparable propulsion systems and long-haul trade patterns, resulting in an estimated capture rate of 2-5 TPH, emissions reduction potential of 20–50%, and a fuel penalty of 10-30%. Similarly, chemical tankers are aligned with MR tankers, reflecting their machinery scale and regional trade exposure. Bulk carriers are mapped to container vessels, given their stable engine loads and long voyages, while cruise ships, and car carriers are linked to RoPax ferries due to shared constraints in space, safety, and HVAC complexity.

The extrapolated performance indicators are summarized in Table 3-44.

Table 3-44 Top down approach - Vessel performance indicators.

Vessel Segment	Mapped Reference	Capture Rate (TPH)	Estimated Emissions Reduction (%)	Fuel Penalty (%)
Aframax Tanker	MR Tanker	0.5–1	15–35	5–20
Bulk Carrier	Container	1–2.5	20–50	5–25
Car Carrier	RoPax	0.25–1	5–30	5–15
Chemical Tanker	MR Tanker	0.5–1	15–35	5–20
Cruise Ship	RoPax	0.25–1	5–30	5–15
General Cargo	Feeder	0.5–1	15–45	5–15
Handymax Bulk Carrier	Feeder	0.5–1	15–45	5–15
Panamax Bulk Carrier	Container	2–6	20–50	5–25
ULCV	Container	2–6	20–50	5–25
VLCC	Suezmax	2–5	20–50	10–30

3.5.2 Feasibility analysis

To assess the broader applicability of OCCS across the EU fleet, a qualitative feasibility matrix has been developed. This matrix evaluates each vessel type based on three dimensions:

- Feasibility: Overall technical and operational suitability for OCCS integration.
- Challenges: Key barriers to implementation, including space constraints, safety risks, and machinery limitations.
- Characteristics: Operational characteristics that will influence OCCS deployment, such as voyage duration, emissions intensity, and port infrastructure compatibility.

Table 3-45 Top-down feasibility matrix analysis.

Vessel Type	OCCS Feasibility	Challenges	Characteristics
Aframax Tanker	Medium	Similar to MR, slightly more space	Moderate voyage duration
Bulk Carrier (general)	Medium	Deck space, cargo interference	Long voyages, stable load
Car Carrier	Medium-Low	Deck height limitations, safety zones	Predictable routes, frequent port calls
Chemical Tanker	Medium	Machinery complexity, cargo compatibility	Frequent port calls
Container vessel	Medium-High	Cargo loss, retrofit complexity	Predictable routes, modular design
Cruise Ship	Low	Passenger safety, HVAC integration	Shore power, regular port calls
Feeder Container	Medium	Limited space, frequent port calls	Flexible operations, short voyages
General Cargo	Medium-Low	Limited space, variable operations	Short-sea trade, flexible routing
Handymax Bulk Carrier	Medium-Low	Space constraints, lower power	Short-sea bulk trade
LNG Carrier	High	Cryogenic systems, hazardous area rules	Synergies with existing infrastructure
MR Tanker	Medium	Payload impact, retrofit constraints	Regional trade, consistent patterns
Panamax Bulk Carrier	Medium	Cargo hold interference, weight distribution	Long-haul, stable engine load
RoPax	Medium	Safety zones, passenger space conflict	Frequent port calls, shore power
Suezmax	High	Deck space, weight impact	Long voyages, stable engine load
ULCV	High	Structural integration, cargo interference	High emissions, long voyages
VLCC	High	Structural reinforcement, tank sizing	Ample space, long-haul trade

3.5.3 Integration considerations

As seen from Table 3 42, OCCS feasibility varies significantly by vessel segment, driven by operational characteristics, machinery scale, and integration constraints. Deep-sea vessels such as VLCCs, Suezmax tankers, ULCVs, and LNG carriers show as the most promising candidates for OCCS deployment. Their long-haul operations, high emissions intensity, and available deck space support large-scale capture systems with minimal disruption to cargo operations. Container vessels, particularly ULCVs and 15,000 TEU ships, benefit from modular design, allowing OCCS to be integrated with moderate cargo loss. LNG carriers offer unique synergies with existing cryogenic infrastructure, facilitating integration of liquefaction and storage systems.

Short-sea and regional segments such as MR tankers and feeder containers present viable opportunities for OCCS integration, nevertheless with moderate engineering effort. These vessels typically operate on consistent patterns and frequent port calls, supporting lower-capacity OCCS systems and enabling regular CO_2 offloading. RoPax ferries are constrained by passenger safety and space limitations, are characterized from regular docking schedules and shore power compatibility, which may support hybrid OCCS-port disposal strategies. Chemical tankers require tailored engineering due to machinery complexity and cargo compatibility, but OCCS may be viable at lower capture rates.

In contrast, segments such as cruise ships and car carriers face significant barriers to OCCS integration. Cruise ships are challenged by HVAC interference, passenger safety regulations, constrained port operations and timetables, and limited deck space, making OCCS deployment challenging without major design changes. Car carriers are constrained by internal layout and ventilation systems, limiting OCCS to modular configurations.

Machinery and energy integration is essential for efficient OCCS operation. The system’s energy demands, primarily for solvent regeneration, compression, and liquefaction, must be met without overloading the vessel’s power and heat supply. OCCS ready newbuilds can incorporate PTO systems and AEECOs to recover waste heat and optimize energy use. Retrofitted vessels may require additional boilers or upgraded generators to meet OCCS demands, which can increase fuel consumption and operational costs.

Newbuilds offer the opportunity to design OCCS-ready vessels with pre-allocated space, structural reinforcements, and integrated energy systems. This approach minimizes cargo impact and simplifies compliance with classification society rules. Retrofitting, while feasible, often involves more pronounced compromises in layout, efficiency, and cost.

In conclusion, OCCS integration must be tailored to each vessel’s design and operational profile. Early planning, modular system design, and alignment with regulatory and safety standards are key to ensuring successful deployment and maximizing emissions reduction potential.

3.5.4 Regulatory and Trade Sensitivity

The feasibility and attractiveness of OCCS deployment across vessel segments is strongly influenced by the evolving regulatory landscape and trade exposure. Vessels operating on EU-exposed routes, such as RoPax ferries, MR tankers, and feeder containers, are expected to benefit significantly from OCCS integration due to the direct cost savings on emissions allowances under the EU ETS. For example, MR tankers and RoPax vessels with consistent regional operations can achieve substantial annual savings when OCCS is deployed, particularly under high EU exposure scenarios.

Conversely, deep-sea vessels less exposed to EU ETS may benefit from OCCS under global regulatory schemes – currently absent. Such case vessels typically have high fuel consumption and emissions intensity, making them suitable for OCCS as a compliance strategy under future lifecycle-based metrics.

The economic viability of OCCS is also sensitive to fuel price scenarios. Under high fuel cost conditions, the fuel penalty associated with OCCS becomes more impactful, potentially offsetting emissions savings. However, when combined with biofuels or bio-LNG, OCCS can deliver synergistic benefits, achieving deeper decarbonization and improved lifecycle performance.

OCCS deployment should be prioritized on vessels with high regulatory exposure, predictable trade patterns, and favourable emissions profiles. Strategic alignment with EU and IMO frameworks, coupled with sensitivity to fuel economics, is essential for maximizing OCCS impact and ensuring long-term viability.

3.5.5 Recommendations

Further bottom-up analysis is recommended for unassessed segments such as chemical tankers, cruise ships, and car carriers. These vessel types present unique integration challenges that may be addressed through specialized OCCS configurations or alternative decarbonization pathways. OCCS deployment should also be aligned with regulatory exposure.

Incorporating OCCS-ready design standards, including pre-allocated space, structural reinforcements, and integrated energy systems such as PTO and AEECOs on newbuild vessels would enable seamless future OCCS installation and ensures compliance with classification society requirements. In parallel, supporting infrastructure for CO_2 offloading, solvent management, and integration with the CCUS value chain must be developed to ensure scalability and operational compatibility.

Finally, OCCS strategies should remain adaptive to fuel price fluctuations and technology maturity. Continuous monitoring of energy markets, solvent performance, and emerging capture technologies, such as membranes and cryogenics, will be essential for refining deployment plans and investment decisions. These recommendations collectively support a phased, segment-specific, and regulation-aligned approach to OCCS adoption across the EU maritime sector.

3.5.6 Top-down analysis conclusions

The top-down generalization presented in 3.5 demonstrates that OCCS has scalable potential across a wide range of vessel types. By building on detailed bottom-up analyses and extrapolating performance indicators to additional segments, the study aims to provide a comprehensive view of OCCS feasibility, integration challenges, and opportunities. Deep-sea vessels such as VLCCs, ULCVs, LNG carriers, and Suezmax tankers emerge as potential candidates for OCCS deployment, offering favourable conditions for integration and emissions reduction. Medium-feasibility segments, including MR tankers and feeder containers, show promise with tailored engineering and modular solutions.

The analysis highlights the importance of aligning OCCS deployment with regulatory exposure, where emissions reductions translate into direct financial benefits. Integration considerations, ranging from space and weight constraints to machinery compatibility and cargo trade-offs, underscore the need for vessel-specific design strategies, especially in retrofit scenarios. Newbuild vessels offer the greatest flexibility for OCCS readiness, enabling optimized energy systems and structural accommodations.

4. CCUS Value Chain

The effectiveness of OCCS is contingent upon the existence of a functioning and integrated CCUS value chain (Figure 4-1). Without established pathways for offloading, transporting, and permanently storing or utilizing the captured CO_2, OCCS cannot serve as a complete emissions reduction solution. This dependency underscores the need for coordinated development of terminal infrastructure, maritime logistics, and access to certified storage or utilization facilities. The following sections examine the status of the broader CCUS value chain, focusing on its relevance to OCCS deployment:

- First, an overview of global CO_2 storage projects and infrastructure is presented, including terminal capabilities, key hubs, cross-border initiatives, and alignment with EU and international strategies. A more extensive list of CCUS value chain projects is provided in
- Table 0-2 in Appendix A.
- Second, CO_2 transportation and distribution networks are briefly described, highlighting their role in connecting maritime capture points to downstream facilities.
- Third, the specifications of captured CO_2, derived from upstream capture and conditioning processes, are outlined, with emphasis on compatibility between onboard-produced CO_2 and the requirements of the rest of the value chain.
- Fourth, methods for offloading CO_2 from ships are described, focusing on the technical and operational considerations specific to OCCS systems.
- Finally, permanent storage and utilization pathways are discussed, covering geological storage options and emerging utilization trends.

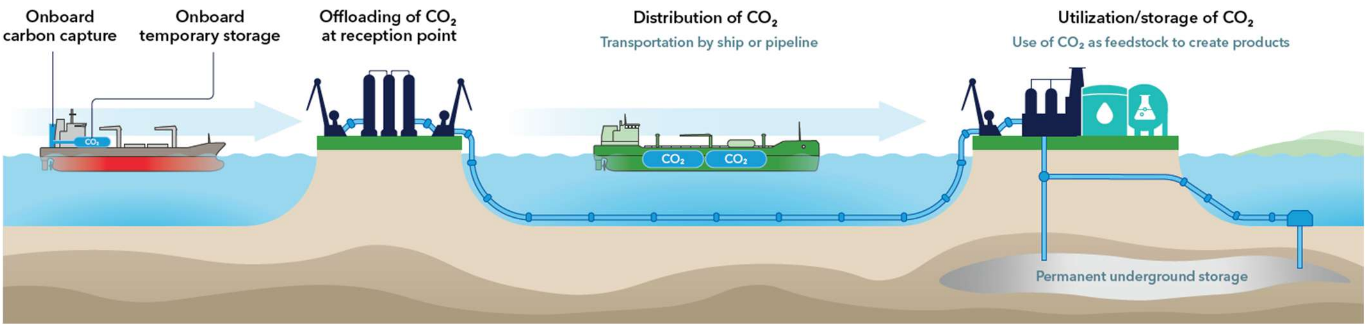

Figure 4-1 Steps of the CCUS value chain (Source: “The Potential of Onboard Carbon Capture in Shipping”, DNV White Paper 2024).

4.1 Global storage projects status

4.1.1 CCUS value chain developments

DNV’s ETO 2025 (DNV, Energy Transition Outlook CCS to 2050, 2025c) report projects CCS to capture 6% of global emissions by 2050, requiring significant investment in CO_2 offloading and storage infrastructure. Key needs include port facilities for loading/unloading liquefied CO_2 and integration with shipping and pipeline networks. Captured CO_2 is typically stored via onshore geological sequestration (deep formations), offshore geological sequestration (beneath seabed), or enhanced oil recovery (EOR), where CO_2 injection aids hydrocarbon recovery while storing carbon.

Global CCS capacity is forecasted to more than quadruple by 2030, driven mainly by North America and Europe, with early deployment focused on natural gas processing and EOR. Broader adoption is expected across sectors, including CCS-integrated gas power generation. Despite strong momentum, policy uncertainty and financing constraints remain key barriers to large-scale deployment.

The following figure presents a map of the existing and planned global CCUS projects in 2030, from the Alternative Fuel Insight (AFI)) database (excluding enhanced oil recovery), by annual storage capacity (size of bubble) and location. The proximity of CCUS projects to major shipping hubs worldwide is evident, including in example North Europe, Middle East, Australia, Singapore, US-Mexico Gulf and Canada.

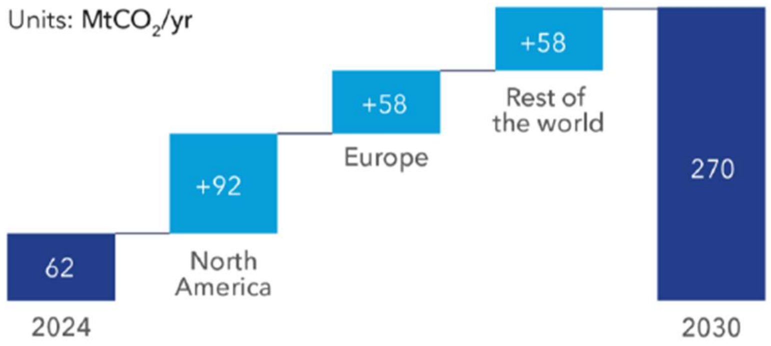

Figure 4-2 Existing and estimated global carbon storage capacity by 2030. Source: (DNV, Energy Transition Outlook CCS to 2050, 2025c).

Figure 4-3 Existing and planned global carbon storage projects in 2030 which are proxime to shipping hubs. Source: (DNV, 2024d).

4.1.2 Projected CO_2 capture from OCCS

For reference, shipping emits around 880 million tonnes of CO_2 per year. According to DNV's ETO 2025 report, a gradual uptake of OCCS between 2030 and 2040 could result in around 4 $MtCO_2$ captured annually, increasing to approximately 110 $MtCO_2$ per year by 2050, (DNV, Energy Transition Outlook CCS to 2050, 2025c).

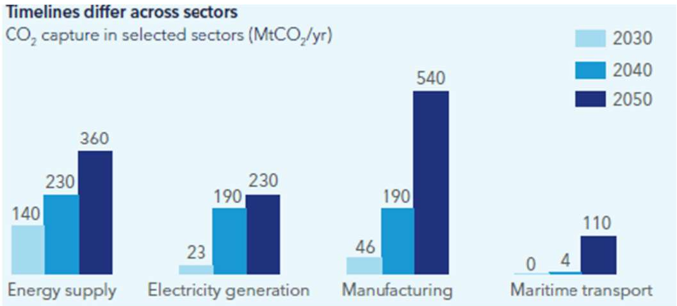

Figure 4-4 CO_2 volumes per industrial sector. Source: (DNV, Energy Transition Outlook CCS to 2050, 2025c).

4.1.3 Developments related to CO_2 disposal

Based on the inventory, the following table summarizes CCUS projects which are closer to EU shipping hubs. As it can be noticed, there is a wide coverage of different regions alongside the EU, indicating future potential uptake of OCCS related services, subject to the further development of these projects.

Table 4-1. Non exhaustive list of projects related to the development of CO_2 terminals related projects in EU.

Area	Country	Project name	Proxime Ports
North EU	Belgium	Antwerp@C CO_2 Export Hub	Port of Antwerp-Bruges
		Zeebrugge Multi-molecule Hub	Port of Zeebrugge
		Ghent Carbon Hub	North Sea Port and ArcelorMittal
	Poland	ECO$_2$CEE	Gdansk LNG terminal
	Germany	CO$_2$nnectNow	Wilhelmshaven LNG terminal
	Netherlands	CO$_2$next	Port of Rotterdam
	Iceland	Coda Terminal	Port of Coda
	France	D'Artagnan: Dunkirk CO_2 Hub Phase I	Port of Dunkirk
		GOCO$_2$	Montoir-de-Bretagne LNG terminal
	Denmark	Norne Carbon Storage Hub	Port of Aalborg
South EU	France	Rhône CO_2 project	Fos LNG terminal; Port of Fos; Marseille
	Greece	APOLLOCO$_2$ project	Port of Piraeus

In parallel with the above, EverTop, a 13,806 TEU Neopanamax container ship operated by Evergreen Marine Corp, was the first vessel fitted with SMDERI's OCCS technology. It completed three verified disposals following capture voyages. On August 21, 2023, it offloaded CO_2 via ship-to-shore transfer at Yangshan Deepwater Port in Shanghai. In March 2024, a second disposal was carried out at the Port of Rotterdam, where the CO_2 was transferred to a shore facility. The third disposal took place on June 19, 2025, again in Shanghai, involving a ship-to-ship transfer to Dejin 26, which transported the CO_2 inland for conversion into low-carbon calcium carbonate.

4.2 Transportation

CO_2 transportation from the emitters to dedicated reception facilities is an important segment of the CCUS value chain. This transport can be achieved through pipelines, which are well-suited for continuous, high-volume transfer of compressed gaseous CO_2 over land, or via ships, which offer greater flexibility for reaching offshore or remote storage sites and are particularly advantageous for cryogenic liquid CO_2 due to its higher density and ease of bulk handling.

Unlike pipeline transport, ship-based CO_2 logistics operate in batches, necessitating liquefaction, buffer storage at both ends, specialized vessels, and conditioning prior to injection. Transport may be directed to shore-based terminals or offshore facilities, with injection occurring either directly from the ship or via fixed structures. Alternative transport modes, such as dry ice, could leverage existing container infrastructure but would require adjustments across the CCS value chain. Pressure regimes, low, medium, and high, play a critical role in determining ship design, liquefaction costs, and overall logistics. Low-pressure systems enable larger tanks and reduced shipping costs, while high-pressure systems offer savings in liquefaction but require heavier containment and result in lower CO_2 density (DNV, Energy Transition Outlook CCS to 2050, 2025c).

For small-scale CCS projects or regions with existing infrastructure, trucks and trains offer viable transport options. While trains provide lower emissions, they are constrained by fixed routes; trucks offer greater flexibility but typically result in higher emissions. Both modes operate under low to medium pressure regimes using insulated, non-refrigerated tanks, and share logistical similarities with ship-based transport. The choice of transport method depends on technical, economic, and logistical factors, and in some cases, multiple modes may be integrated within a single value chain.

In addition to these conventional forms, CO_2 can also be transported as a saturated liquid, such as in carbonated water or brine, which may be relevant in specific industrial or enhanced oil recovery (EOR) contexts. Furthermore, solid or mineralized CO_2, such as carbonates formed through mineralization processes, represents a stable and non-volatile form that may be transported as bulk solids, though this is typically more relevant for utilization or disposal rather than injection-based storage.

The choice between these transport methods and CO_2 states depends on geographic, economic, and logistical factors, including distance, infrastructure availability, and the end-use or storage method. Each form presents unique challenges and opportunities in terms of energy requirements, safety, and compatibility with downstream systems. Upon arrival at the reception facility, the CO_2 must undergo preparation and conditioning to align with the technical requirements of downstream processes. For compressed gas, this involves pressure and temperature adjustments to meet pipeline or injection specifications. Cryogenic liquid CO_2 requires controlled warming and pressure regulation to avoid phase changes that could damage infrastructure. CO_2 saturated liquids may need degassing or purification depending on the application, while solid or mineralized CO_2 may require mechanical processing or chemical treatment if it is to be repurposed.

These specifications are essential not only for maintaining the integrity and safety of the infrastructure but also for enabling seamless integration between different components of the value chain. Proper conditioning ensures that the CO_2 can be reliably handled, stored, or repurposed without compromising system performance or environmental safety. Table 4-2 presents an overview of the different pressure and temperature regimes for liquid CO_2 cargo tank designs.

Table 4-2 Pressure and temperature regimes for liquid CO_2 cargo tank designs.[58]

Cargo designation	Cargo vapour pressure (operation) bara	Equilibrium temperature °C	Density of liquid CO_2 kg/m3	Density of vapour CO_2 kg/m3
Low pressure	5.7 to 10	-54.3 to -40.1	1 170 to 1 117	15 to 26
Medium pressure	14 to 19	-30.5 to -21.2	1 078 to 1 037	36 to 50
High pressure	40 and above	5.3 and above	894 and lower	116 and higher

4.3 Captured CO_2 specifications

The compatibility between the nodes of the CCUS value chain is an important element of OCCS implementation. While large-scale transportation favours low-pressure (LP) regimes, due to the higher density and mass transport capacity, currently the LCO_2 specifications of the Northern Lights project serves as an industry benchmark and is dedicated to medium pressure (MP) carriage of liquefied CO_2 for offshore sequestration. The critical parameters and risks associated with LCO_2 specifications are:

- Corrosion risk, which is inhibited by compounds like NO_x, sulphur traces, free water and H_2.
- Dry ice formation, when the triple point is affected by impurities.
- Maintainability and operational risks related to the vapor phase generation in the presence of volatile compounds.

Table 4-3. Liquid CO_2 Quality Specifications of Northern Lights Project. Source: https://norlights.com/how-to-store-CO₂-with-northern-lights/.

Component	Unit	Limit for CO_2 Cargo within Reference Conditions
Carbon Dioxide (CO_2)	mol-%	Balance (Minimum 99.81%)
Water (H_2O)	ppm-mol	≤ 30

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Component	Unit	Limit for CO_2 Cargo within Reference Conditions
Oxygen (O_2)	ppm-mol	≤ 10
Sulphur Oxides (SO_x)	ppm-mol	≤ 10
Nitrogen Oxides (NO_x)	ppm-mol	≤ 1.5
Hydrogen Sulfide (H_2S)	ppm-mol	≤ 9
Amine	ppm-mol	≤ 10
Ammonia (NH_3)	ppm-mol	≤ 10
Formaldehyde (CH_2O)	ppm-mol	≤ 20
Acetaldehyde (CH_3CHO)	ppm-mol	≤ 20
Mercury (Hg)	ppm-mol	≤ 0.0003
Carbon Monoxide (CO)	ppm-mol	≤ 100
Hydrogen (H_2)	ppm-mol	≤ 50
Methane (CH_4)	ppm-mol	≤ 100
Nitrogen (N_2)	ppm-mol	≤ 50
Argon (Ar)	ppm-mol	≤ 100
Methanol (CH_3OH)	ppm-mol	≤ 30
Ethanol (C_2H_5OH)	ppm-mol	≤ 1
Total VOC	ppm-mol	≤ 10
Mono-Ethylene Glycol (MEG)	ppm-mol	≤ 0.005
Tri-Ethylene Glycol (TEG)	ppm-mol	Not allowed
BTEX	ppm-mol	≤ 0.5
Ethylene (C_2H_4)	ppm-mol	≤ 0.5
Hydrogen Cyanide (HCN)	ppm-mol	≤ 100
Aliphatic Hydrocarbons (C_3+)	ppm-mol	≤ 1,100
Ethane (C_2H_6)	ppm-mol	≤ 75
Solids, particles, dust	Micro-meter (μm)	≤ 1

4.4 Offloading methods related to OCC

In this paragraph the possible methods for disposal of the CO_2 at port site are described, depending on the product type: (a) Cryogenic Liquefied CO_2 (LCO_2), (b) Compressed gas, (c) liquid at atmospheric conditions (CO_2 absorbed in aqueous solution), (d) mineral, (e) solid.

4.4.1 Cryogenic liquid CO_2

There is limited experience in the industry related to the disposal of LCO_2 from OCCS. Although accomplished pilots have demonstrated only ship-to-truck disposal, the industry can leverage experience with other cryogenic substances, such as LNG used as fuel, to describe ship-to-shore and ship-to-ship transfer options as well, (LR 2024):

- **Ship-to-Shore Transfer:** This method involves transferring LCO_2 from the ship to shore-based facilities using specialized cryogenic equipment. In a terminal equipped with OCCS de-bunkering, offloading arms would be expected to connect the LCO_2 tank onboard the ship with the shore infrastructure, which includes a buffer tank linked to a CO_2 network. Alternatively, flexible hoses can be used to transfer LCO_2 from the ship to the shore-side buffer tank, while a vapor return line maintains the ship tank pressure during loading. The process requires unloading until a minimum heel level of 4% is reached in the ship tank, ensuring the tank remains cold, as mandated by IGC code. Depending on the pressure of the tank, the cold temperature may vary indicatively between -55 to -35°C. The LCO_2 collected in the terminal buffer tank would be further processed for either pipeline or ship-based large-scale transfer for sequestration or utilization. Ports must have the necessary infrastructure to handle and temporarily store CO_2 safely. It is noted that this is at the concept level.

- **Ship-to-Truck Transfer:** This method involves transferring LCO_2 from the ship to truck. Although the process resembles the Ship-to-Shore transfer, this method is more flexible for ports that do not have the offloading and temporary storage equipment in place. At the time this work is written, the process has been demonstrated in pilot scale with LCO_2 produced onboard from chemical absorption CO_2 capture[59].
- **Ship-to-Ship Transfer:** In this method, LCO_2 is transferred from one ship to another, which then transports it to a storage or utilization facility. This approach can be useful when direct access to shore-based facilities is limited or when the receiving ship is equipped to handle larger volumes of CO_2. An important element for further analysis is the investigation of potential simultaneous operations, during the offloading process, which is an element that requires dedicated risk analysis. Same as in the case of ship-to-shore transfer, a heel level would be required in the ship tank, as well as a vapour return line between the ships to maintain pressure and temperature conditions. Risks related to contamination of the ship tank, because of mixing with a potentially dirty vapour return, may have to be considered during the design of such systems.

4.4.2 Compressed gas

Though this is a potential option for onboard capture, there is no concept for offloading at compressed gas conditions[60]. An equivalent system in the maritime industry is the one of compressed gas N_2, which could be used as reference and for indication only.

4.4.3 Liquid saturated with CO_2

When the by-product of the OCCS technology is liquid saturated with CO_2, the concept involves temporarily storing this by-product in a dedicated onboard tank, which is not integrated in the vessel's hull. This tank can be offloaded at the port and subsequently transported for utilization. The offloading process can be conducted using port cranes.

4.4.4 Solids and minerals

In the case where CO_2 is captured through mineralization processes, like in the calcium looping process, the resulting mineral is offloaded at port, for regeneration of the mineral for reuse onboard the vessel, or to be recycled as construction material[61].

4.5 Permanent storage and utilization

The final step in the CCUS value chain is the permanent storage or utilization of captured CO_2. In the case of storage, the CO_2, typically in compressed gaseous or supercritical form, is injected deep underground into geological formations such as depleted oil and gas fields or deep saline aquifers, where it can be securely contained for thousands of years. Cryogenic liquid CO_2 may be converted to a supercritical state prior to injection, requiring careful thermal and pressure management to ensure phase stability and reservoir compatibility. In some cases, CO_2-saturated liquids, such as carbonated brines, may be directly injected into saline formations, leveraging solubility trapping mechanisms. Alternatively, solid or mineralized CO_2, such as carbonates formed through mineral carbonation, can be stored in surface or subsurface repositories. This form offers the highest permanence and lowest risk of leakage, though it typically requires more energy and processing upfront.

[59] China achieved first recycling of CO2 emitted by a retrofitted container ship - iMarine
[60] In 2022, DNV awarded Knutsen NYK Carbon Carriers (KNCC) with Approval in Principle (AiP) for their compressed CO2 carrier in cylinders. The PCO2 concept involved storing CO2 at high pressures (35-45 bar) and temperatures ranging from 0-10°C. Instead of using large cylindrical tanks, the PCO2 system utilizes bundles of vertically stacked small-diameter pressure cylinders. The AiP from DNV validates the safety and reliability of the PCO2 containment system. This endorsement can provide confidence in the system's ability to safely store and transport CO2 under high pressure, which is crucial for onboard applications.
[61] Seabound wants to trap carbon emissions from ships | CNN

Depleted fields offer advantages such as proven containment structures and existing infrastructure, but they also pose challenges including limited capacity, legacy well leakage risks, and reduced monitoring effectiveness due to residual hydrocarbons. Saline aquifers, on the other hand, offer greater pore space, fewer well penetrations, and better conditions for seismic monitoring, though they require new infrastructure and carry higher initial uncertainty due to limited subsurface data.

Enhanced Oil Recovery (EOR) represents a hybrid approach, where CO_2 is injected into mature oil fields to extract additional hydrocarbons. While considered a utilization method, a significant portion of the CO_2 remains permanently stored. EOR has been practiced since the 1970s, primarily in the US and Middle East, and has contributed valuable operational experience in handling large volumes of CO_2 underground.

Carbon mineralization offers another promising pathway for permanent CO_2 storage. Below-ground methods, such as the in-situ approach pioneered by Carbfix in Iceland, involve injecting carbonated water into basalt formations, where CO_2 reacts with minerals to form solid carbonates. Above-ground techniques include ex-situ production of carbonated aggregates for concrete, surficial mineralization using ground rock dust spread on land or coastlines, and industrial by-product mineralization using materials like steel slag. These approaches complement geological storage by offering long-term stability and opportunities to repurpose industrial waste.

Beyond storage, captured CO_2 can be utilized in various industrial processes. Compressed or supercritical CO_2 is commonly used in EOR, as already seen above, while gaseous or liquid CO_2 can serve as a feedstock in the production of synthetic fuels, chemicals, or as a curing agent in concrete and other building materials. Mineralized CO_2 can be directly incorporated into construction products, offering both sequestration and material performance benefits. This step ensures that the captured carbon does not re-enter the atmosphere, thereby contributing to long-term climate change mitigation. The choice of CO_2 form and storage or utilization pathway significantly influences the overall efficiency, safety, and sustainability of the CCUS system. To support shipping's transition, reception points near major ports and bunkering hubs could be developed, especially for regular trade routes. These locations would make it easier to offload CO_2 and connect to storage infrastructure, helping integrate shipping into the global carbon reduction effort.

4.6 Cost Considerations Across the CCUS Value Chain

The CCUS industry is undergoing a structural shift toward a model in which emitters are primarily responsible for the development and operation of capture facilities. These emitters typically pay a tariff to third-party operators who manage the transport and storage of CO_2. This separation of responsibilities reflects the growing complexity and specialization within the CCUS value chain, and it has significant implications for cost distribution and risk allocation.

Capture remains the most cost-intensive component of the CCUS chain. Capture costs per tonne of CO_2 vary widely due to differences in CO_2 concentration, facility scale, transport requirements, and site-specific conditions. A critical distinction must be made between the cost of CO_2 captured (COC) and the cost of CO_2 avoided (COA), the latter accounting for emissions generated during the capture process itself. For example, in gas-fired power plants, COA can be approximately 25% higher than COC due to energy consumption during regeneration. High-purity CO_2 sources, such as bioethanol production (≥90 mol% CO_2), incur relatively low capture costs (€ 27–32/tCO_2), while low-concentration sources like power generation (3–15 mol%) can range from € 54 to 108/tCO_2.[62]

The scale of the capture facility influences also cost efficiency. Larger plants benefit from economies of scale, particularly in applications with low CO_2 concentrations that require processing large volumes of flue gas. For instance, increasing capture capacity in natural gas power plants from 0.07 to 0.66 MtCO_2/year can reduce costs from € 67 to 108/tCO_2.[63] Modular capture systems, which are gaining traction, may offer cost advantages for small-to-medium installations through standardization, though their cost benefits diminish at larger scales due to the need for replication. Additional cost factors include whether the capture system is retrofitted or newly built, the availability of utilities like steam and cooling water, and regional variations in labour and material costs. Capture systems designed for liquefied CO_2 transport (via ship, rail, or truck) typically incur higher costs than those optimized for pipeline transport, due to added equipment and energy demands.

Transport costs are highly variable and depend on distance, volume, transport mode, and terrain. Pipeline transport is generally the most cost-effective option for large volumes over short to medium distances, with compression and

[62] Energy Transition Outlook: CCS to 2050
[63] Energy Transition Outlook: CCS to 2050

pipeline costs ranging from € 5 to 25/tCO_2[64]. In contrast, ship, train, and truck transport methods tend to be more expensive and are often chosen for smaller volumes or longer distances. Pipeline transport is largely CAPEX driven, while truck and train transport are dominated by OPEX. Ship transport presents a more balanced CAPEX-OPEX profile. Multimodal transport systems, while sometimes necessary, introduce additional complexity and cost. Reusing existing infrastructure, such as natural gas pipelines, can reduce capital costs but may require significant investment in inspection and retrofitting.

According to DNV's ETO 2025 Report, (DNV, Energy Transition Outlook CCS to 2050, 2025c), ship-based CO_2 transport is more costly than pipelines due to its complexity. In 2025, transport and storage costs can reach about € 81/tCO_2 for cement production in Europe, reflecting offshore storage and multimodal logistics. However, these costs are projected to decline significantly, dropping below € 45/tCO_2 by 2040.

Storage costs are generally lower than capture and transport but still vary based on geological and logistical factors. Key cost components include site characterization, drilling and operation of injection wells, and long-term monitoring. Onshore storage is typically less expensive than offshore storage, which is more prevalent in Europe and can be 1.5 to 3 times more costly. Storage in saline aquifers ranges from € 4–32/tCO_2, while depleted oil and gas fields offer lower costs (€ 2–13/tCO_2) due to existing infrastructure and reduced characterization requirements. Despite limited detailed cost data, storage remains the most cost-stable segment of the CCUS chain, except in cases involving complex offshore or multimodal configurations.[65]

In CCUS projects where third-party operators manage transport and storage, tariffs paid by emitters often exceed the actual infrastructure costs. These tariffs account for project and business model contingencies, operator margins, and early-phase inefficiencies. A global analysis by Xodus estimates average transport and storage tariffs at around € 67/tCO_2, though regional variations are significant. European projects tend to be more expensive due to offshore storage, CO_2 shipping, and urban constraints, while regions with onshore storage and pipeline infrastructure benefit from lower costs.

Overall CCS costs vary widely depending on project complexity. Simple onshore projects near storage sites can cost as little as € 27/tCO_2, while projects involving low-concentration CO_2 sources and long-distance shipping can reach € 90–270/tCO_2. In Asia, shipping alone may add up to € 90/tCO_2. Looking ahead, operational cost reductions of 20–30% are expected by 2040, driven by digitalization, advanced materials, and smarter manufacturing. However, commercial viability remains a challenge, as current carbon prices are generally insufficient to support investment without substantial government backing, especially outside of select low-cost European projects.[66]

4.7 Challenges and remarks

The uptake of OCCS depends on its integration with the wider CCUS value chain. For captured CO_2 from vessels to be stored or utilized, it must be offloaded at ports equipped for handling and connected to transport networks leading to storage or utilization sites. Key challenges include the absence of standardized specifications, fragmented regulations, and limited international alignment on CO_2 transport and acceptance protocols.

The growing development of CO_2 terminals and CCUS hubs near major shipping corridors is expected to accelerate OCCS adoption as part of the global decarbonization effort. Between 2030 and 2040, captured volumes from shipping are projected to rise gradually from near zero to around 4 MtCO_2 per year. By 2050, this figure could increase nearly thirtyfold, reflecting the combined impact of infrastructure readiness, regulatory support, and integration with the broader CCUS network.

Cost drivers across the CCUS value chain are dominated by capture expenses, influenced by CO_2 concentration, facility scale, and transport mode, with pipeline generally most cost-effective for large volumes. Regarding transport of LCO2 volumes, the cost is estimated at the order of € 45/tCO_2, with potential to drop by 2040.

[64] Energy Transition Outlook: CCS to 2050
[65] Energy Transition Outlook: CCS to 2050
[66] Energy Transition Outlook: CCS to 2050

4.8 Conclusions on CCUS value chain

The successful deployment of OCCS systems relies also on the availability of a fully integrated and interoperable CCUS value chain. OCCS effectiveness depends on the ability to offload, transport, and permanently store or utilize the CO_2 in a safe, efficient, and economically viable manner.

As seen in the present chapter, current developments in CO_2 storage, particularly near major shipping hubs, show promising alignment with maritime decarbonization goals. However, challenges remain in harmonizing technical standards, especially pressure and temperature regimes, between ship-based systems and land-based infrastructure. Transport logistics, offloading methods, and CO_2 conditioning must be tailored to the physical state of the captured CO_2, with cryogenic liquid, compressed gas, and mineralized forms each requiring specific handling protocols. In addition, the composition of the captured CO_2 must meet downstream purity specifications to ensure compatibility with storage sites and utilization pathways.

Additionally, cost remains a critical factor, with CO_2 disposal cost representing a factor associated with uncertainties and affecting the viability of OCCS investments. Tariff structures, infrastructure readiness, and regional disparities further influence project viability. As the CCUS ecosystem matures, coordinated investment in port infrastructure, regulatory alignment, and digital integration will be essential.

5. Safety and Environmental Regulations, Standards and Guidelines

This section of the report examines regulations, standards, initiatives, and guidelines implicitly or explicitly related to OCCS, as developed by various international bodies, including the IMO, the EU, Classification Societies, and other relevant organizations. Such entities are actively working to shape the regulatory framework that will govern the safe and effective use of OCCS technology in the maritime sector. As OCCS technology is new for shipping, its implementation necessitates the development of comprehensive regulations to ensure both safety and environmental compliance. By examining the efforts of these organizations, insight can be gained into the current state of OCCS regulations and the challenges that lie ahead.

Standards and requirements for CO_2 handling and storage systems are already established in the land-based, offshore, and shipping industries to manage the associated CO_2 risks. Standards that are directly applicable to OCCS systems, or relevant to risks that may arise in OCCS applications, are identified. Consequently, an overview of the regulations pertinent to OCCS systems is provided. The study is structured according to the components, overall system, and procedures of an OCCS system to elucidate the relevance of each regulation. Subsequently, the existing practices are assessed in relation to the CCUS value chain experience (since the experience with the complete OCCS value chain is limited), the management of waste and liquefied gases onboard, and the insights garnered from OCCS pilot projects thus far. Finally, an evaluation is conducted to pinpoint regulatory gaps, highlighting essential elements necessary for adopting and implementing OCCS technology in the shipping sector.

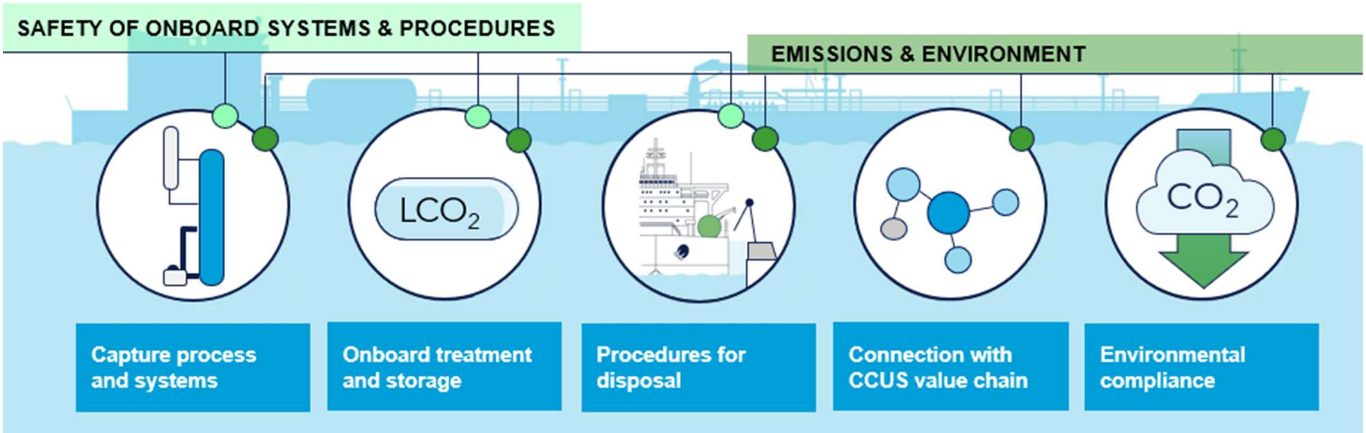

Figure 5-1. OCC-related regulations categories. Source: DNV.

5.1 International

In this section an overview of the status of international regulations on the application of OCCS takes place.

5.1.1 IMO

The IMO is actively advancing a regulatory framework to facilitate the safe and effective deployment of OCCS technologies. This initiative reflects the IMO's commitment to fostering innovation in maritime decarbonization, ensuring that emerging solutions like OCCS are integrated responsibly and efficiently into the global shipping industry. By establishing clear guidelines and safety standards, the IMO aims to support the adoption of OCCS while safeguarding crew welfare, vessel integrity, and environmental protection. This regulatory development is part of the IMO's broader strategy to reduce GHG emissions from international shipping.

As a latest development, at MEPC 83 in April 2025, the Committee agreed on a work plan for the development of this framework. The plan addresses both shipboard and land-based considerations related to OCCS, ensuring their integration into existing and future regulatory instruments. The work is scheduled for completion by 2028. To further advance this initiative, the Committee re-established the Correspondence Group on Measurement and Verification of Non-CO_2 GHG emissions and Onboard Carbon Capture. This group was tasked with refining methodologies for measuring and verifying actual methane (CH_4) and nitrous oxide (N_2O) emission factors, assessing fuel slippage values for LNG fuels, and developing the OCCS regulatory framework in line with the approved work plan. The group is expected to submit a written report to MEPC 84.

In parallel with the regulatory work at MEPC, safety-related developments are also progressing under the IMO's Maritime Safety Committee. At Maritime Safety Committee (MSC) 110, within the context of an existing output focused on developing a safety regulatory framework to support GHG reduction from ships using new technologies and alternative fuels, the Committee recommended that the CCC Sub-Committee include, as a high-priority item in its work plan, tasks related to the development of a safety instrument addressing OCCS and OCCU-related gaps and barriers. This work is scheduled to begin in September 2026, running concurrently with MEPC's efforts and resulting in interim guidance to be finalized by 2028. The recommendation is detailed by MSC 110 (in MSC 110/21) as well as in the workplan agreed by CCC 11 (CCC 11/16).

The integration of OCCS into ship operations intersects with several existing IMO instruments, as outlined in the following sections.

5.1.1.1 Environmental Regulations

IMO London Protocol

The London Convention and Protocol aim to control effectively all sources of marine pollution. The London Convention and Protocol are currently one of the leading international regulatory frameworks for carbon capture and sequestration in sub-sea geological formations and marine geoengineering, including ocean fertilization[67]. An amendment to Article 6 of the London Protocol was proposed by contracting parties in 2009 to allow for cross-border transportation of CO_2 for sub-seabed storage. The amendment also set guidelines regarding impurities in the CO_2 stream and requirements for obtaining storage permits. The amendment emphasized that CO_2 capture, and storage is a viable option to reduce atmospheric CO_2 levels and should be regulated under the London Protocol. It specified that CO_2 streams could be considered for dumping only if they are disposed of in sub-seabed geological formations, consist predominantly of CO_2 with incidental associated substances, and no waste is added for disposal purposes (IMO, 2019).

To enter into force the amendment must be ratified by two thirds of contracting parties. This is as of today pending though an interim solution has been established. Countries can provisionally apply the amendment by submitting a declaration of provisional application and notifying the IMO of any agreements. This interim solution helps facilitate CCUS projects by enabling cross-border CO_2 transportation and storage (Global CCS Institute, 2024). It remains to be clarified how the London Protocol is to be utilized for captured CO_2 in various territorial and international waters (DNV, 2024d).

MARPOL

The MARPOL Convention is the primary international agreement for the prevention of marine pollution from ships, and it includes guidelines relevant to the carriage of amines, such as MEA, used in OCCS systems. A key development under MARPOL is MEPC.340(77), which provides guidelines for the testing, survey, certification, and approval of exhaust gas cleaning systems (EGCS), particularly relevant for water removal and discharge processes associated with OCCS.

Additionally, MARPOL Annex VI sets limits on emissions, like for sulphur oxides (SO_x), nitrogen oxides (NO_x), and particulate matter (PM) emitted from ship exhausts. In this context, there is gap in addressing the impact of OCCS technologies on indices like the CII and the EEXI requirements.

GHG compliance

Reducing GHG emissions from ships is vital to global climate efforts, with multiple regulatory frameworks at international, regional, and national levels driving the sector's decarbonization. OCCS could play a key role by directly capturing CO_2 emissions from ships, helping meet these targets. The text outlines relevant emission-reduction regulations and explores how OCCS might fit into this evolving landscape, while also addressing the challenges of integrating such technology into existing and future frameworks.

[67] Source: https://www.imo.org/en/OurWork/Environment/Pages/CCS-Default.aspx

In July 2023 IMO adopted the “2023 IMO Strategy on Reduction of GHG Emissions from Ships” - Resolution MEPC.377(80). The 2023 IMO GHG Strategy represents a framework for Member States, setting out the future vision for international shipping, the levels of ambition to reduce GHG emissions, and guiding principles. It sets reduction targets for GHG emissions in international shipping, aiming to achieve net-zero GHG emissions by or around 2050. Further targets include reducing the carbon intensity of international shipping by at least 40% by 2030 and 70% by 2040 compared to 2008 levels. Additionally, it targets the uptake of zero or near-zero GHG emission technologies, fuels, and energy sources to represent at least 5%, striving for 10% of the energy used by international shipping by 2030.

The IMO’s regulatory response to the 2023 IMO GHG Strategy, is the newly approved by MEPC 83 (April 2025) Net-Zero Framework (NZF). Set to take effect from January 2028, the NZF (New Chapter 5 of MARPOL ANNEX VI) introduces new MARPOL Annex VI regulations, including a global fuel standard. Central to the framework is the GFI metric, which measures WtW emissions per unit of energy, guiding ships toward cleaner energy use. The NZF supports the IMO’s 2050 net-zero goal by promoting zero or near-zero GHG fuels and technologies, while allowing non-compliant ships to contribute to an IMO Net-Zero Fund.

To support the goals of the 2023 IMO GHG strategy, the IMO has additionally developed several regulatory instruments:

- **EEDI**: The Energy Efficiency Design Index (EEDI) applies to new ships and sets CO_2 emission limits per tonne-mile based on technical design parameters. It has been in force since January 1, 2013. While EEDI provides a robust framework for evaluating design efficiency, future integration of OCCS may introduce uncertainties, particularly regarding how captured CO_2 and the associated fuel penalty will be accounted for. At the new building stage, integrating OCCS with the EEDI would help decide the optimal design for energy efficiency.

- **EEXI**: The EEXI measures the energy efficiency of ships already in operation and applies to vessels of 400 gross tonnage and above. Although EEXI currently does not incorporate OCCS, similar considerations to those of EEDI may become relevant if OCCS is applied to retrofitted ships. Evaluating the fuel penalty and captured emissions will be essential for ensuring accurate assessments.

- **CII**: The CII evaluates a ship’s operational efficiency by measuring CO_2 emissions in grams per cargo-carrying capacity and nautical mile. It applies to ships of 5,000 gross tonnage and above. As OCCS becomes more prevalent, it will be important to determine how captured emissions are reflected in CII calculations. This could involve custody transfer systems, direct measurements, or alternative accounting methods to ensure fair and accurate reporting. Additionally, during the vessel's operational stage, the CII would provide ongoing assessment and incentives for maintaining low emissions. This comprehensive approach would leverage existing efficiency standards to drive notable environmental benefits and systematically reduce GHG emissions.

- **SEEMP:** The Ship Energy Efficiency Management Plan (SEEMP) is an IMO-mandated framework aimed at improving the energy efficiency of ships. It consists of three parts: Part I outlines general efficiency measures, Part II focuses on fuel consumption data collection, and Part III is specifically designed to monitor and improve a ship’s CII. While SEEMP does not directly mandate the use of OCCS systems, it provides a regulatory and strategic framework that supports their adoption. OCCS technologies can be integrated into a ship’s operations to help meet the increasingly stringent carbon intensity targets set by SEEMP Part III. This can potentially improve their CII rating and ensure compliance with future environmental regulations.

- **GFI:** The GFI is a metric that quantifies the WtW GHG emissions per unit of energy consumed by a ship, encompassing not only conventional fuels but also alternative energy sources like electricity, wind, and solar power. Ships are required to report their attained GFI annually as part of the IMO’s Data Collection System (DCS). In parallel, a GHG pricing scheme is being developed, marking a shift toward a new regulatory era. This scheme will require ships to either transition to low-emission fuels, which are significantly more expensive than conventional fossil fuels, or contribute financially to the IMO Net-Zero Fund. However, there are still methodological gaps between GFI and the IMO’s LCA guidelines for OCCS, meaning that current assessments must rely on assumptions to account for OCCS within GFI calculations.

The IMO has formalized its LCA Guidelines through Resolution MEPC.391(81), establishing a comprehensive framework for evaluating the GHG intensity of marine fuels using WtW approach. This methodology encompasses both upstream emissions; from fuel production to delivery onboard (WtW), and downstream emissions; from fuel combustion to exhaust (TtW). The guidelines currently account for emissions of CO_2, methane (CH_4), and nitrous oxide (N_2O).

A significant development within these guidelines is the introduction of the concept of Emission Credit from (e_{occs}). Specifically, paragraph 5.2 of MEPC.391(81) incorporates EOCCS into the TtW emission factor calculation, acknowledging the potential for onboard CO_2 capture and long-term storage to contribute to emission reductions. However, the methodological framework for EOCCS remains under development, and the current guidance stipulates that the EOCCS value is to be set to zero until further notice. The proposed EOCCS calculation framework includes the following components:

- csc: Credit equivalent to the amount of CO_2 captured and stored for a long-term period (defined as 100 years).
- ecc: Emissions associated with the onboard process of capturing, compressing, and temporarily storing CO_2.
- et: Emissions related to the transport of CO_2 to a long-term storage site.
- est: Emissions from the long-term storage process, including potential fugitive emissions during injection and storage over 100 years.
- ex: Any additional emissions arising from the CCS process.

Although EOCCS credits are not yet applicable in emission factor calculations, their inclusion in the LCA framework reflects the IMO's recognition of onboard carbon capture technologies. It also underscores the importance of quantifying the energy penalty and associated emissions of operating such systems onboard ships. These factors will be critical in future assessments of the net benefit of CCS technologies within maritime decarbonization strategies. At present, the GFI metric serves as the primary operational tool, while the LCA guidelines provide a foundational structure for future alignment and integration of OCCS technologies.

5.1.1.2 Safety Regulations

SOLAS

SOLAS regulations not explicitly name OCCS technologies.

IGC Code

The IGC Code is applicable to ships transporting liquefied gases with a vapor pressure exceeding 2.8 bar at 37.8°C absolute, as well as other substances listed in Chapter 19. This code establishes the design, construction, and equipment standards for such vessels. In the context of the OCCS system, the IGC Code is particularly relevant due to the potential need to store captured CO_2 in liquefied form. It provides guidance on the safe storage and transfer of LCO_2, especially through the use of Type C independent tanks.

Key risks associated with storing LCO_2 include respiratory hazards, cryogenic burns, exposure to extremely low temperatures, asphyxiation, and issues related to the CO_2 triple point. Additionally, risks such as tank construction integrity, transfer procedures, potential structural damage or BLEVE (Boiling Liquid Expanding Vapor Explosion), and personnel injuries must be considered. Proposed revisions to the IGC Code aim to enhance safety by introducing advanced monitoring systems for CO_2 cargoes, with a focus on thermodynamic behaviour, pressure regulation, and impurity control to prevent solidification and structural failures during transport.

IGF Code

The International Code of Safety for Ships Using Gases or Other Low-flashpoint Fuels (IGF Code) provides a comprehensive framework for the safe arrangement and installation of machinery, equipment, and systems on vessels that utilize gas or low-flashpoint liquids as fuel. This code is particularly relevant for ships not covered by the IGC Code and aims to minimize risks to the ship, its crew, and the environment. In the context of OCCS technology, the IGF Code offers valuable guidance, especially when the system involves storing captured CO_2 in liquefied form. The criteria outlined in the code can inform the design and installation of OCCS systems, ensuring they meet international safety standards. This is especially pertinent when considering LCO_2 offloading arrangements.

The IGF Code provides insights that can help address potential risks associated with such systems, including thermal expansion, pipeline cracks, and the presence of impurities. Furthermore, the code may also be applicable to vessels employing pre-combustion carbon capture methods, where gas fuels are part of the process. As can be seen from the above, the IGC code is for ships dedicated to carriage of gas, while the IGF code is more suitable for ships where the gas carried is related to the operation of the ship (e.g. in the form of fuel).

IBC Code

The International Code for the Construction and Equipment of Ships Carrying Dangerous Chemicals in Bulk (IBC Code) establishes international standards for the safe transport of hazardous chemicals and NO_x ious liquid substances in bulk by sea, as listed in Chapter 17. It covers chemicals and noxious liquids carried as cargo and not fuel. It specifies ship design, construction requirements, and necessary equipment to minimize risks to vessels, crews, and the environment, taking into account the specific properties of the transported substances. In the context of OCCS technology, the IBC Code is relevant for the handling and sea transportation of MEA (monoethanolamine), a chemical agent commonly used in carbon capture processes.

IMDG Code

The International Maritime Dangerous Goods (IMDG) Code sets out the requirements for the maritime transport of dangerous goods in packaged form, that is in sealed containers like cylinders or tanks rather than in bulk. It is relevant to the OCCS system in cases where LCO_2 is stored or offloaded in such packaged form, as well as for chemical consumables that fall within the scope of the IMDG Code. The associated risks include packaging-related hazards, transport safety concerns, and issues related to the CO_2 triple point. Additionally, the IMDG Code applies to chemical solvents such as MEA, which is classified as a hazardous substance due to its corrosive properties. The IMDG Code governs the storage, handling, and transportation of these substances onboard, under the premise that the packages are handled as sealed units and not processed onboard. This ensures that operations are conducted safely and in compliance with international maritime safety standards.

IMO STCW Convention

The International Convention on Standards of Training, Certification and Watchkeeping for Seafarers (STCW Convention) prescribes the minimum standards for training, certification, and watchkeeping for seafarers to ensure safe and effective maritime operations. In the context of the OCCS system, the STCW Convention is relevant for establishing training standards for onboard personnel involved in LCO_2 offloading procedures. It ensures that crew members are adequately trained to handle the specific operational and safety challenges associated with liquefied CO_2, including its toxicity and the importance of proper watchkeeping. The associated risks include insufficient training, inadequate watchkeeping practices, and exposure to toxic substances, all of which underscore the need for strict adherence to STCW requirements in OCC-related operations.

Proposals and Initiatives

Various proposals and documents on studies for OCCS have been submitted during the IMO meetings, underscoring the work and growing interest around the development of OCCS technologies for the maritime industry, and the efforts taking place to highlight the need for an OCCS regulatory framework. Key suggestions include:

- Development of non-mandatory safety guidelines specific to OCCS technologies.
- Incorporation of CO_2 reduction from carbon capture into existing regulatory mechanisms such as the EEDI, EEXI, and CII frameworks.
- Amendments to the EEDI Survey and Certification Guidelines to facilitate the integration of OCCS systems.
- Review of current regulations and formulation of a structured work plan to accommodate OCCS within the broader IMO regulatory framework.
- Establishment of a comprehensive regulatory framework addressing emissions, transportation, storage, and disposal aspects of OCCS, with recommendations to adopt a development approach similar to that used for EGCS.
- Compilation and analysis of existing regulatory instruments relevant to OCCS, aimed at identifying overlaps, gaps, and opportunities for harmonization within IMO's ongoing work.

5.1.2 Industry Organisations

The organizations SIGTTO (Society of International Gas Tanker and Terminal Operators), OCIMF (Oil Companies International Marine Forum), CDI (Chemical Distribution Institute), and ICS (International Chamber of Shipping) released the joint publication "Ship to Ship Transfer Guide for Petroleum, Chemicals and Liquefied Gases (2013)", which provides guidance relevant to ship-to-ship (STS) transfer operations of liquefied gases. While not directly applicable to the current market status, their recommendations become highly relevant if STS transfers are adopted in the future for LCO_2 or similar cargoes. These operations carry potential risks such as operational hazards, compatibility issues between vessels, leaks, and the risk of asphyxiation due to gas release.

Additionally, in “Recommendations for Liquefied Gas Carrier Manifolds (2018)”, SIGTTO and OCIMF offer detailed recommendations on the layout, strength, and fittings of gas carrier manifolds, which are critical components in the safe transfer of liquefied gases. These guidelines are particularly relevant when considering the design and arrangement of offloading equipment for LCO_2 or other cryogenic cargoes. The associated risks include manifold compatibility issues, operational challenges during transfer, potential leakages, and the danger of asphyxiation. These industry standards help ensure that transfer operations are conducted safely and efficiently, minimizing hazards to personnel and the environment.

Furthermore, SIGTTO’s more recent publication “Carbon Dioxide Cargo on Gas Carriers (2024)” specifically addresses the unique properties and handling considerations of LCO_2 onboard gas carriers. This document provides valuable insights into containment, transfer, and safety measures tailored to CO_2, reinforcing the importance of industry standards in ensuring that transfer operations are conducted safely and efficiently, minimizing hazards to personnel and the environment.

5.1.3 Classification Societies

5.1.3.1 The International Association of Classification Societies

The International Association of Classification Societies (IACS) provides technical standards and rules that are highly relevant to the implementation of OCCS technology on ships. These rules cover requirements for general arrangements, machinery, electrical and control systems, safety systems, as well as containment and piping systems. In the context of OCCS, IACS standards are particularly applicable to LCO_2 offloading setups, where risks such as asphyxiation, material compatibility, corrosion, toxicity, and explosive decompression must be carefully managed. If the OCCS system includes components such as an exhaust gas scrubbing unit, for example, an absorber or a regenerator/stripper, then IACS Unified Requirement (UR) M46: Ambient Conditions – Inclinations (Rev.2 Dec 2018) becomes relevant. This regulation provides specific requirements for equipment that may be affected by ship inclinations, ensuring operational reliability under varying sea conditions. For storage systems, IACS rules similarly apply, detailing requirements for containment systems and associated machinery and control systems used in LCO_2 offloading arrangements. Key risks in this area include storage integrity, containment performance, and the presence of impurities in the CO_2 stream. In terms of chemical use, IACS UR M81 is particularly relevant. It outlines safety measures, design requirements, and protective equipment standards to mitigate risks associated with chemical treatment fluids used in Exhaust Gas Cleaning Systems, including the handling of hazardous residues. Finally, IACS’ Council launched the Safe Decarbonisation Panel (SDP) in 2022 to support the maritime industry's decarbonisation efforts[68]. OCCS is among the technologies to be considered by SDP, in an initial list that included others such as ammonia, H_2 and batteries.

5.1.3.2 American Bureau of Shipping (ABS)

ABS published its first formal requirements for OCCS systems in July 2023[69]. The ABS rules focus primarily on post-combustion carbon capture technologies, particularly wet scrubbing systems, while also allowing for a wide range of alternative and emerging solutions. The ABS OCCS framework covers the design, installation, and classification approval of systems that capture, process, and store CO_2 from ship exhaust. It includes provisions for chemical absorption systems, such as amine-based scrubbers, as well as non-solvent-based technologies like membrane separation, cryogenic distillation, and pre-combustion carbon removal. One component of the ABS rules is the integration of OCCS with existing equipment, including SO_x scrubbers, Selective Catalytic Reduction (SCR) units,

[68] (IACS, 2022)
[69] Requirements for Onboard Carbon Capture and Storage

Exhaust Gas Recirculation (EGR) systems, and Exhaust Emissions Monitoring Systems (EEMS). The rules also address the onboard storage of captured CO_2, requiring that storage tanks, whether pressurized or cryogenic, meet structural, safety, and monitoring requirements. These include pressure relief systems, leak detection, ventilation, and fire protection. ABS also considers the operational implications of CO_2 handling, including crew safety, training, and emergency response procedures. The ABS OCCS requirements are focused on classification approval and do not replace or override statutory requirements imposed by flag administrations or international conventions such as SOLAS and MARPOL.

5.1.3.3 Bureau Veritas (BV)

BV has not yet issued a dedicated OCCS class notation, however it has published a series of reports and white papers that provide an overview of the technical, operational, and regulatory considerations for implementing OCCS technologies on ships. In May 2024, BV released a detailed report titled Onboard Carbon Capture: An Overview of Technologies to Capture CO_2 Onboard Ships[70], which evaluates the technical and commercial viability of various OCCS technologies. The report explores the integration of systems such as amine-based chemical absorption, cryogenic separation, and membrane technologies. It also addresses key challenges, including space constraints, energy consumption, and the safe handling and storage of CO_2 onboard. While a formal OCCS class notation is still under development, BV applies its existing rules for gas containment systems, hazardous materials handling, and emission abatement technologies to assess OCCS installations.

5.1.3.4 Det Norske Veritas (DNV)

DNV released a dedicated set of guidelines in October 2023[71], followed by the formal introduction of the OCCS class notation in its Rules for Classification in July 2024[72], which entered into force in January 2025. These rules provide a structured framework for the safe design, integration, and operation of OCCS technologies on both newbuilds and retrofitted vessels. The OCCS rules encompass the full lifecycle of carbon capture systems, beginning with exhaust pre-treatment. This includes particulate removal, temperature regulation, and flow control. The core capture process typically involves chemical absorption using amines, although DNV also permits alternative technologies such as physical absorption and cryogenic separation, provided they meet equivalent safety and performance standards. DNV's rules specify requirements for tank design, structural integrity, insulation, pressure relief systems, and fire protection. These systems must be equipped with leak detection, monitoring instrumentation, and emergency venting protocols to ensure operational safety. The rules also cover transfer systems for offloading CO_2 to shore-based infrastructure, including piping arrangements, valve control, and emergency shutdown capabilities. The rules also mandate comprehensive HAZID/HAZOP and failure mode and effects analysis (FMEA) during the design phase. OCCS systems must be fully integrated with shipboard machinery and automation systems, and operators are required to implement crew training programs, personal protective equipment (PPE) protocols, and emergency response procedures. Compliance with broader IMO conventions, such as SOLAS and MARPOL, is also required to ensure regulatory alignment. As to DNV OCCS Class Notation, the LCO_2 part of the OCCS should be designed and approved with basis in the IGC Code/DNV Rules for Gas Carriers. This basis will be applicable for all types of vessels to DNV Class. The DNV Class Rules for the OCCS Notation will be revised accordingly in 2026.

5.1.3.5 Lloyd's Register (LR)

In August 2024, LR issued its first Class notation for OCCS, titled Emission Abatement Carbon Capture & Storage (EACCS)[73]. It was first assigned to the Pacific Cobalt, a 50,000-dwt chemical tanker retrofitted with a prefabricated OCCS unit developed by Value Maritime. This class notation provides a framework for the design, construction, installation, and survey of OCCS systems. The EACCS class notation addresses a range of technical and operational aspects, including materials selection, structural integrity, containment systems, piping, refrigeration plants, electrical and control systems, and vessel integration. It also includes requirements for safety systems, such as gas detection, emergency shutdown, and fire protection. In addition to the full OCCS notation, LR also offers a "READY" descriptive note, which certifies that a vessel has been pre-engineered and outfitted to accommodate future OCCS installation. This includes preparatory work on structural layout, interfacing, materials, and safety systems.

[70] Onboard Carbon Capture | Marine & Offshore
[71] DNV has launched new guidelines for Onboard Carbon capture Systems on board ships
[72] DNV rules create new in-operation class framework, enable hydrogen vessels and on-board carbon capture
[73] LR class notation for onboard carbon capture system | LR

5.1.3.6 Registro Italiano Navale (RINA)

RINA has not yet published a dedicated OCCS class notation, however it has integrated OCC-related requirements into its broader marine classification rules and climate change initiatives. Through its Rules for the Classification of Ships and associated technical publications, RINA provides guidance on the design, installation, and integration of emission abatement systems, including those capable of capturing CO_2 from ship exhaust. These rules cover aspects such as system safety, materials compatibility, pressure containment, and integration with shipboard machinery. In addition to classification rules, RINA's 2024 publication on CCUS[74] highlights the role of onboard capture as a transitional solution for hard-to-abate emissions, particularly in deep-sea shipping. The publication emphasizes the need for safe CO_2 handling, onboard storage protocols, and shore-based infrastructure readiness, aligning with international best practices and IMO regulatory developments.

5.1.4 International Organization for Standardization

As of 2025, there are no ISO standards directly related to OCCS systems in maritime applications. This absence reflects the relatively nascent stage of OCCS deployment at sea, where the maritime environment introduces variables such as vessel motion, limited space, variable fuel types, and the need for integration with existing shipboard systems, all of which require specialized guidance. On the other hand, ISO has made significant progress in standardizing carbon capture and storage for land-based industries such as ISO 27913:2016, which outlines requirements for CO_2 pipeline transportation.

More specifically, ISO 27913:2024, titled “Carbon dioxide capture, transportation and geological storage - Pipeline transportation systems”, is the principal international standard governing the safe and reliable transport of CO_2 from capture sites to storage or utilization locations. It applies to land-based and offshore rigid metallic pipelines, including newly constructed and repurposed systems. The standard is developed by ISO Technical Committee TC 265, which focuses on carbon capture, transport, and storage technologies.

A central focus of ISO 27913 is the quality and composition of the CO_2 stream. The standard outlines requirements for CO_2 purity, with impurities such as water vapor, oxygen, nitrogen, sulphur compounds, and hydrocarbons can pose significant risks to pipeline integrity. The standard mandates quality assurance protocols and compatibility assessments, especially when CO_2 streams from multiple sources are combined.

Beyond stream composition, ISO 27913 provides detailed technical guidance on pipeline integrity and operational safety. It incorporates risk assessment methodologies, material selection criteria tailored to the unique properties of dense-phase and supercritical CO_2, and specifications for pressure containment, leak detection, and emergency shutdown systems. The standard also supports the conversion of existing pipelines for CO_2 service, offering a cost-effective pathway for infrastructure reuse. These provisions are designed to complement general pipeline codes such as ISO 13623 and ASME B31.4, while addressing the specific challenges associated with CO_2 transport.

Importantly, ISO 27913 also considers the interface between pipeline systems and geological storage sites. It ensures that CO_2 is delivered under controlled conditions suitable for injection into long-term storage formations, with requirements for flow regulation, monitoring, and verification. While the detailed standards for storage operations are covered under related ISO documents, such as ISO 27914 for site selection and ISO 27916 for storage quantification, ISO 27913 ensures seamless integration across the CCS value chain.

5.2 European Union

The European Union has set ambitious climate targets as part of its commitment to achieving climate neutrality by 2050. Central to this vision is the European Green Deal, which outlines a comprehensive roadmap for reducing GHG emissions across all sectors of the economy. The EU aims to cut net GHG emissions by at least 55% by 2030 compared to 1990 levels, an objective that underpins the legislative package known as Fit for 55. Additionally, EU ETS has been extended to cover CO_2, CH4 and N2O emissions from ships entering EU ports, and the FuelEU Maritime Regulation mandates the uptake of renewable and low-carbon fuels, with a goal to reduce the GHG intensity of energy used on board ships by 80% by 2050 compared to 2020 levels.

[74] Carbon Capture, Use and Storage (CCUS) - RINA.org

5.2.1 Fit for 55

As mentioned above, the Fit for 55 package is the EU's plan to cut GHG emissions by 55% by 2030 compared to 1990 levels. It includes new rules for energy, transport, and industry, and for the first time, it brings the shipping sector into the EU ETS. Ships over 5,000 gross tonnage now need to pay for their CO_2eq emissions, with full implementation by 2026. The EU allows derogation of emissions from OCCS under the EU ETS, as long as the CO_2 is permanently stored and the process is properly monitored and verified in accordance with EU standards.

5.2.2 EU ETS

As part of the 'Fit for 55' package, the EU Emissions Trading System (EU ETS) is currently the only regulatory framework offering incentives for the implementation of OCCS in maritime shipping. The European Commission's Guidance Document No.1 on "The EU ETS and MRV Maritime General guidance for shipping companies[75]" outlines key principles for how OCCS can be integrated into emissions accounting for ships, with key elements including:

- CO_2 Capture and Reporting: Ships capturing CO_2 emissions to prevent atmospheric release can reduce their GHG emissions for EU ETS purposes. However, total emissions before capture must be reported under the MRV Maritime Regulation.
- Geological Storage Requirement: Captured CO_2 must be transferred to a compliant geological storage site, in line with the CCS Directive (Directive 2009/31/EC). Emission reductions are only eligible if the CO_2 is handed over to a certified transport operator or directly to a storage site. Temporary onboard storage may limit the amount of emissions that can be deducted.
- Additional Emissions: Emissions from energy sources used in the CO_2 capture process must be included in the ship's monitoring plan and emissions report.
- Accounting for Captured CO_2: CO_2 emissions captured and transported for permanent storage or chemically bound are multiplied by zero. For voyages starting or ending outside the EEA, only 50% of captured CO_2 emissions are multiplied by zero, meaning half of these emissions can be accounted as zero.

Importantly, the CCS Directive provides the legal framework for the safe geological storage of CO_2 across the EU and EEA. It applies to both stationary installations and mobile sources like ships, ensuring that captured CO_2 is stored in a manner that prevents environmental harm. The recent updates to the CCS Directive's guidance documents (2024[76]) emphasize streamlined permitting, risk-based financial provisions, and the identification of suitable geological formations for storage. These updates align OCCS practices with those used in industrial carbon management, reinforcing the principle that only permanently stored CO_2 qualifies for emission reductions under the EU ETS.

Further items to consider for the inclusion of OCCS within EU ETS could be the terms and conditions of carbon utilization as well as information on the method that will be used for determining the captured and handed over emissions.

5.2.3 FuelEU Maritime

FuelEU Maritime, another part of the Fit for 55 package, is effective from January 1, 2025, for ships trading within the EEA and aims to promote renewable and low-carbon fuels in maritime transport. Currently, OCCS is not considered under FuelEU Maritime compliance, with a provision for potential review by December 31 2027, as mentioned in Article 30 of Regulation (EU) 2023/1805 related to possible inclusion of new GHG abatement technologies.

According to the "*Questions and Answers on Regulation (EU) 2023/1805 on the use of renewable and low-carbon fuels in maritime transport, and amending Directive 2009/16/EC*"[77], as drafted by the services of the Directorate-General for Mobility and Transport, OCCS is not included in the FuelEU Maritime Regulation as the latter focuses on promoting renewable and low-carbon fuels. While OCCS could support the continued use of fossil fuels, it may become significant for biogenic and synthetic renewable carbon. Its exclusion was due to lack of maturity, demonstrated results, and an international framework for traceability of captured CO_2.

[75] (EUROPEAN COMMISSION, 2024)
[76] The European Commission publishes revised Guidance Documents to the CCS Directive - European Commission
[77] (Directorate-General for Mobility and Transport of the European Commission, 2024)

5.2.4 CCS and CCUS Related Regulations and Initiatives

This section provides an overview of the regulatory frameworks and initiatives relevant to CCS and CCUS in the European Union. It includes references to the Industrial Carbon Management strategy, the CCS Directive, and the Renewable Energy Directive (in relation to fuel production from captured carbon), as well as selected elements from the European Commission's 2026 work programme connected to CCS policies.

5.2.4.1 Industrial Carbon Management Strategy

The European Commission's Industrial Carbon Management Strategy, published in 2024, outlines a comprehensive framework for the deployment of CCUS technologies across the EU. It supports the EU's climate neutrality goal by 2050 and complements the Fit for 55 legislative package.

The Industrial Carbon Management Strategy (COM/2024/62), adopted by the European Commission on 6 February 2024, sets out a plan to scale up carbon management in the EU by creating a unified CO_2 market and encouraging investment in related technologies.

The European Union aims climate neutrality by 2050 and a 55% reduction in greenhouse gas emissions by 2030, positioning industrial carbon management as an essential aspect. The strategy encompasses three main pathways: carbon capture and storage (CCS), carbon removal from biogenic or atmospheric sources, and carbon capture for utilization (CCU), with CO_2 transport infrastructure being an important element. By 2040, fossil fuel consumption is projected to decline by 80% compared to 2021, requiring captured CO_2 volumes to reach 280 Mt annually, scaling to 450 Mt by 2050, with at least 50% sourced from biogenic or atmospheric origins to achieve negative emissions. A unified policy and investment framework for industrial carbon management can potentially complement mitigation for hard-to-abate emissions.

Furthermore, EU's supporting CCUS regulatory framework includes the CCS Directive (2009), TEN-E Regulation, and the EU Emissions Trading System (ETS), complemented by funding mechanisms like the Innovation Fund and the proposed Net Zero Industry Act (NZIA). Targets include 50 Mt of annual storage capacity by 2030, with Member States projecting up to 34.1 Mt of captured CO_2, primarily from cement, steel, and hydrogen sectors.

CCU offers additional decarbonization potential by converting CO_2 into fuels, chemicals, and materials, reducing fossil feedstock dependency and promoting circular economy principles. Under the revised Renewable Energy Directive[78], energy from renewable fuels of non-biological origin and recycled carbon fuels can only count toward EU renewable energy and transport targets if they achieve at least 70% greenhouse gas emissions savings compared to fossil fuels. The European Commission will define a methodology through delegated acts to calculate these savings, ensuring life-cycle emissions are considered, including indirect effects from diverting inputs like waste, and preventing double credit for captured fossil CO_2 already accounted for under other laws. The recast Gas Directive complementing the updated Renewable Energy Directive outlines a terminology and certification framework for low-carbon hydrogen and low-carbon fuels. A similar requirement is outlined in the recast Gas Directive, for ensuring that credit for avoided emissions is not granted for CO_2 from fossil sources that have already received an emission credit under other legal provisions.

However, deployment faces barriers including high energy requirements, regulatory gaps, infrastructure risks, and insufficient investment incentives. Innovation programs such as Horizon Europe and the European Innovation Council are critical to scaling CCU technologies and ensuring environmental integrity through robust accounting frameworks.

5.2.4.2 European Commission Work Programme 2026

As part of the European Commission's 2026 Work Programme, a new legislative initiative is included to potentially support the development of CO_2 transportation infrastructure and markets[79]. The proposal is scheduled for the third quarter of 2026 and a public consultation was launched in October 2025[80] to gather stakeholder input. The initiative aims to support the development of a cost-effective EU CO_2 value chain by exploring measures that reduce barriers and improve coordination. It will consider options to facilitate cross-border CO_2 transport, enhance interoperability,

[78] DIRECTIVE (EU) 2023/2413 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 18 October 2023 amending Directive (EU) 2018/2001, Regulation (EU) 2018/1999 and Directive 98/70/EC as regards the promotion of energy from renewable sources, and repealing Council Directive (EU) 2015/652.
[79] Commission work programme 2026 - European Commission
[80] Legislative initiative on CO2 transportation infrastructure and markets

and provide legal clarity, while assessing both legislative and supportive approaches. Potential actions may include guidance on infrastructure access, financing, governance, and permitting, as well as mechanisms to encourage reuse of existing assets and long-term planning. The initiative also seeks to improve investor confidence and coordination across the value chain, potentially providing flexibility during the early ramp-up phase and taking into account different transport modes.

5.3 Other regional and national regulations

Below, we present a brief overview of how each country's regulatory landscape may impact OCCS. The list is non exhaustive, with a focus on major shipping hubs regions and countries.

United States

The USA has several legislative and programmatic initiatives promoting CCUS technologies, including tax credits and funding programs. CCS is also gaining interest at the US state level, driven by supportive federal policies. States are increasingly implementing federal laws and passing state-level legislation to build governance frameworks for CCS, covering transport, storage, pore space, liability, and other aspects (Global CCS Institute, 2024). These initiatives could support the development of infrastructure necessary for OCCS. Additionally, the US California Air Resources Board (CARB) has implemented the At-Berth Regulation for California ports. Currently OCCS is not included under CARB compliance. A potential future integration of OCCS within the maritime environmental regulatory framework could be enhanced by harmonization and standardization of OCCS emissions reporting. For example, alignment under the IMO and EU's MRV system and FuelEU Maritime initiative, could assist with a consistent and transparent approach to mitigate discrepancies in OCCS captured emissions accounting.

Singapore

Although Singapore currently lacks a specific regulatory framework for CO_2 transportation and handling, existing regulations, such as the Environmental Protection and Management Act and the Carbon Pricing Act, provide a foundation. Collaborative efforts with neighbouring countries indicate activities related to CO_2 policy making, such as the signing of the Green Economy Agreement with Australia (Australian Government - Department of Foreign Affairs and Trade, 2022), which aims to facilitate collaborative efforts between the two nations to achieve net-zero emissions, and the signing of a Letter of Intent with Indonesia (Press release MTI, 2024) to conduct cross-border CO_2 transport.

United Kingdom

The UK has established a robust regulatory framework under the Climate Change Act and Energy Act, which includes provisions for carbon budgeting, licensing of offshore carbon storage, and strict monitoring protocols. Furthermore, The UK's GHG emissions Trading Scheme Order 2020 establishes monitoring and reporting requirements for entities regulated under the UK ETS, covering CO_2 capture, transport via pipelines, and geological storage (Global CCS Institute, 2024). These regulations ensure the safe and efficient operation of CO_2 transport and storage networks, which are essential for OCCS.

Norway

Norway is a pioneer in CCS technologies, with regulations governed by the Petroleum Activities Act and the Pollution Control Act. The Longship project, exemplifies Norway's commitment to capturing and storing CO_2, providing a model for OCCS implementation (Global CCS Institute, 2024).

Australia

Australia's regulatory landscape for CO_2 handling, transportation, and storage is shaped by several initiatives promoting CCUS technologies. Programs like the Low Emissions Technology Demonstration Fund, the CCS Flagships program and the Future Gas Strategy (Australia Government - Department of Industy, Science and Resources, 2024) support the development and deployment of carbon capture technologies. Additionally, Australia is the first country in the Asia Pacific region to establish a domestic permitting regime for transboundary CO_2 export and import for geological storage, pursuant to the provisions of the London Protocol (Global CCS Institute, 2024).

Japan
Japan has been actively developing its regulatory framework for CCS. In 2024, Japan's Parliament passed the CCS Bill, establishing a licensing system and safety regulations for storage businesses and CO_2 pipeline transportation (Fukushima & Konno, 2024).

South Korea
South Korea has a comprehensive regulatory framework for CCS under the Carbon Capture and Storage Act, which includes guidelines for CO_2 capture, transportation, and storage. The Ministry of Trade, Industry, and Energy oversees these projects (Global CCS Institute, 2024).

China
China's CCS policy framework is part of its broader efforts to reduce GHG emissions. The 30/60 climate policy framework aims for peak carbon emissions by 2030 and climate neutrality by 2060. The Implementation Plan for Green and Low-Carbon Technology Demonstration includes CCS projects. China's existing regulatory framework for oil and gas exploration provides a foundation for CCS regulation, but gaps remain in areas like pore space ownership, monitoring, site selection, and post-closure responsibility (Global CCS Institute, 2024).

Germany
Germany's regulatory framework is governed by the Carbon Dioxide Storage Act. The 2024 amendment facilitates the application of CCS/CCU, transport, and offshore storage, focusing on emissions that are difficult to reduce (Global CCS Institute, 2024).

France
France's "National Low Carbon Strategy" outlines the roadmap for achieving carbon neutrality by 2050, recognizing CCUS as a key technology for carbon sequestration. The strategy supports the development of pilot and commercial CCS and CCU units (Global CCS Institute, 2024).

Netherlands
The Netherlands has secured multi-lateral agreements to advance carbon capture, transport, and geological storage of CO_2. The Dutch "Climate Act" mandates a 55% reduction in GHG emissions by 2030 and net zero by 2050. Moreover, the Dutch government introduced the SDE++ (Netherlands Enterprise Agency, 2020) scheme in late 2020 to make CCS projects more financially viable by covering the costs of CO_2 capture, transport, and storage relative to EU ETS prices.

Denmark
Denmark's "Climate Act" sets ambitious targets for GHG emissions reduction and aims for a climate-neutral society by 2050. Additionally, Denmark has launched the Danish CCUS Fund (Danish Energy Agency), a subsidy scheme for up to 20 years to support the capture, transport, and storage of CO_2. Denmark is positioning itself as a hub for CCUS, with several licenses approved for large-scale CCS projects.

Sweden
Sweden aims for zero net emissions of greenhouse gases by 2045. The regulatory framework for CCS is governed by the Environmental Code, with financial support provided for bio-CCS projects. In April 2024, the Swedish Government submitted a €3 billion state aid notification to the European Commission to support CCS projects aimed at reducing biogenic CO_2 emissions from biomass combustion or processing (European Commision - Press Release, 2024).

Greece
Greece's national regulations for CCS are primarily governed by the transposition of the EU CCS Directive into Greek law. Recent legislative updates have introduced new licensing processes for CO_2 exploration and storage permits (European Commission, 2023).

Middle East

Regulatory frameworks are essential for CCS deployment in the Middle East. While many countries are still developing these frameworks, some are making progress. Oman is leading in regulatory development, working with the Global CCS Institute and forming a CCUS Core Team (Global CCS Institute - Media Releases, 2023), Qatar and Egypt have established basic frameworks, and the UAE is emphasizing the need for regulations. Currently, only three countries in the Middle East -Iran, Iraq, and Saudi Arabia- are Contracting Parties to the London Protocol (Global CCS Institute, 2024).

5.4 GAP analysis

As described in the previous sections, at the timing of the writing of present study, there are still some uncertainties or lack of dedicated guidelines and regulations to the implementation of OCCS technologies in the maritime sector. The summary of these gaps is seen in

Table 5-2. Colour coding of the identified gaps is shown in Table 5-1.

Table 5-1 Colour coding of gap analysis.

Gap assessment	Colour status
No gap or changes	● (green)
Small gaps / minor changes	● (light blue)
Medium gaps / few changes	● (orange)
Large gaps / many changes	● (grey)

Table 5-2 Regulatory gap analysis on OCCS for shipping.

Subject	Code	Comment on Code/Standard – Gaps
Safety - OCCS Technology	IACS Classification Society Rules	■ No unified requirements for OCC-specific equipment (e.g., absorbers, regenerators). ■ Classification Societies have rules, which could assist with unification.
	IGC Code	■ Current IGC Code provisions are not OCC-specific and may not fully address any relevant risks, like cryogenic burns, asphyxiation, and BLEVE due to CO_2's unique properties.
	IBC Code	■ This code provides relevant safety, transport and design standards for chemicals like MEA, but none are tailored specifically for OCCS systems.
	SOLAS	■ OCCS are not explicitly defined or mentioned. ■ No OCC-specific redundancy or failover system requirements.
	CDI / ICS / OCIMF / SIGTTO Ship-to-Ship Transfer Guide for Petroleum, Chemicals, and Liquefied Gases 2013	■ CO_2 as a cargo is not mentioned. ■ Lack of procedures for handling CO_2-specific risks (e.g. solidification, asphyxiation). ■ There is no guidance for custody transfer or emissions tracking.
Safety - Procedures	SOLAS	■ OCCS are not explicitly defined or mentioned.

Subject	Code	Comment on Code/Standard – Gaps
	SIGTTO / OCIMF Recommendations for Liquefied Gas Carrier Manifolds, 2018	■ There are no standards for CO_2 – specific manifold design. ■ The recommendations do not address material compatibility with CO_2 impurities. ■ There is a lack of guidance for retrofitting OCCS systems.
	IACS Classification Society Rules	■ Survey and maintenance protocols for OCCS components (e.g., absorbers, tanks) are not detailed.
Handling/ Training Requirements (Human Element)	IMO STCW Convention	■ No dedicated training standards for OCCS operations, especially for handling cryogenic CO_2 and chemical solvents like MEA.
Handling/ Training Requirements (Human Element)	IACS Classification Society Rules	■ Inconsistent crew training and Personal Protective Equipment (PPE) protocols across societies.
Safety – Onboard Storage	IACS Classification Society Rules	■ Inadequate standards for LCO_2 storage on non-gas carriers (IGC Code not fully applicable). ■ Limited guidance on impurities in CO_2 stream and their impact on storage integrity.
	IGC Code	■ Proposed updates aim to improve safety via better monitoring, pressure control, and impurity management.
	IGF Code	■ Captured CO_2 is not a fuel, nor does it have a low flashpoint fuel, so its storage and handling are not relevant to the IGF Code. ■ The IGF Code does not comprehensively address the cryogenic storage of LCO_2, which has unique thermodynamic and safety properties (e.g., risk of asphyxiation, rapid phase change, and thermal expansion). ■ The IGF Code lacks detailed provisions for offloading captured CO_2, especially in ship-to-ship or ship-to-terminal scenarios.
	IMO IMDG Code	■ No mention of CO_2 triple point risks in packaged form ■ Current rules only address general chemical transport, not continuous OCCS operations.
	USA	■ U.S. regulations are designed for land-based CO_2 sources. There is no explicit legal framework for handling CO_2 captured onboard ships and delivered to shore for permanent storage.
Safety – Permanent Storage	UK	■ Currently, there are no UK-wide standards for: ○ CO_2 offloading procedures, ○ Port infrastructure compatibility, ○ Handling of CO_2 impurities.
	ISO	■ ISO 27913:2024 considers the interface between pipeline systems and geological storage sites. ISO 27914 covers site selection and ISO 27916 storage quantification.
	USA	■ U.S. law lacks a dedicated regulatory pathway for CO_2 delivered by ships, whether from domestic or international sources.

Subject	Code	Comment on Code/Standard – Gaps
		■ There are no standardized permitting processes for ports to receive, offload, and temporarily store liquefied CO_2 from ships.
	IMO	■ Need for selection of which instrument to handle carriage of captured (i.e. non-cargo) CO_2.
(Non-Shipping) Transportation	EU	■ Absence of standardized port infrastructure and unclear legal status of captured CO_2 (commodity vs. waste) hinder the integration of ship-based CCS into existing EU and international regulatory frameworks.
	ISO	■ ISO 27913:2024 covers the safe and reliable transport of CO_2 from capture sites to storage or utilization locations. It applies to land-based and offshore rigid metallic pipelines, including newly constructed and repurposed systems.
	London Protocol	■ The 2009 amendment allowing cross-border CO_2 transport is still not in force, due to insufficient ratifications. ■ There is still regulatory uncertainty around CO_2 captured and transported in various territorial and international waters for storage.
Environmental pollution and waste handling	MARPOL	■ No specific safety framework for solvents, cryogenic CO_2, or emergency venting.
	EU	■ Fragmented treatment across regions (e.g., EU ETS, FuelEU Maritime). No unified international approach to OCCS regulation.
GHG Emissions - Vessel Design	EEDI	■ No accounting method for captured CO_2, since it is unclear how OCCS affects the EEDI score. ■ OCCS systems increase fuel consumption, but this is not reflected in the current EEDI framework. ■ No guidance on how to incorporate OCCS into ship design for EEDI compliance.
	EEXI	■ Retrofitted OCCS systems are not considered in EEXI calculations. ■ Additional energy used by OCCS systems may worsen EEXI scores unless properly accounted for. ■ No framework for evaluating OCC's impact on existing ship efficiency.
GHG Emissions - Vessel Operation	CII (SEEMP, IMO DCS)	■ Current CII does not deduct captured CO_2 from reported emissions. ■ Lack of standards for verifying and reporting captured CO_2 volumes. Custody transfer systems, direct measurements, or alternative accounting methods could ensure fair and precise reporting. ■ OCCS may increase fuel use, negatively impacting CII unless offset by captured CO_2. ■ OCCS could be incorporated into a ship's operation to achieve the SEEMP Part III targets.
	GFI – LCA	■ Current LCA Guidelines provide a basis for incorporating OCCS into "Well to Wake" emission factors and GFI calculations, but the methodology is not yet finalized, which may lead to inconsistencies in lifecycle impact assessments.

Subject	Code	Comment on Code/Standard – Gaps
		■ If OCCS energy use is included in both the total ship energy and the e_{CC} term (CO_2 capture, liquefaction and storage penalty), it may result in double penalization of OCCS technologies, distorting their comparative performance. However, If the total ship energy does not include the OCCS energy penalty, then the e_{CC} term will only represent "Tank to Well" impact. Although additional fuel consumption for OCCS is reported in IMO DCS, care is needed to avoid double counting when applying e_{CC} terms. ■ Whether captured CO_2 is stored, reused, or vented is not considered. ■ Emissions and sustainability aspects from MEA or other capture agents are not addressed. ■ LCA guidelines present a high-level calculation method, which needs to be refined.
	EU ETS	■ Emissions are deductible if CO_2 is handed over to a certified storage operator, in line with the CCS Directive (Directive 2009/31/EC) or if the CO_2 emissions are permanently stored in products in line with the Directive 2003/87/EC. ■ Lack of terms and conditions of carbon utilization.
	FuelEU Maritime	■ OCCS is not currently recognized as a compliance measure, due to lack of maturity, demonstrated results, and an international framework for traceability of captured CO_2.
	CARB (US)	■ OCCS currently is not included in CARB's At-Berth Regulation.

5.5 Conclusions on regulations

The OCCS regulatory framework is still under development. The IMO has initiated a work stream to create OCC-specific regulations, with a target completion date of 2028. Existing IMO instruments such as MARPOL, SOLAS, and various safety codes (IGC, IGF, IBC, IMDG) provide partial coverage for OCC-related risks, but none fully address the unique challenges of onboard CO_2 capture, storage, and offloading.

A regulatory gap analysis highlights several areas needing attention. Safety standards for OCCS equipment and procedures are incomplete, and training requirements for crew handling OCCS systems are lacking. Emissions reporting frameworks such as EEDI, EEXI, and CII do not yet account for captured CO_2 or the energy penalties of OCCS systems. Lifecycle assessment methods are still under development, and current tools may penalize OCCS technologies due to methodological inconsistencies.

The European Union allows abatement of CO_2 through OCCS under ETS the EU Emissions Trading System (EU ETS), which emission reductions if captured CO_2 is permanently stored or chemically bound in a product and properly verified. However, OCCS is not yet recognized under the FuelEU Maritime regulation, mainly due to concerns about technological maturity and traceability. A review is planned by the end of 2027 to reconsider its inclusion.

Classification societies like DNV, ABS, and Lloyd's Register have introduced OCCS class notations, offering technical standards for system design, safety, and integration. Despite these efforts, there is no harmonized approach across societies. Additionally, there have been no unified OCC-specific requirements issued from the IACS.

To support the safe and effective deployment of OCCS, regulators must develop dedicated safety and operational guidelines, harmonize international standards, and establish clear protocols for emissions accounting and crew training. Without these measures, OCCS cannot be fully integrated into the maritime decarbonization strategy.

6. Risk Assessment using Onboard Carbon Capture and Storage Technologies

As described in Chapter 4 of the present study, although progress has been made in recent years, the safety regulations landscape for OCCS technology still needs further development. Therefore, in the context of the present study, a HAZID/HAZOP analysis took place for different vessel types under different trade patterns (deep sea and coastal). The intention of these HAZID/HAZOP studies is to identify the gap regarding the safety and risk assessment for vessels using OCCS.

The vessels that were considered for the HAZID/HAZOP analysis were the following:

- MR tanker with chemical absorption.
- Suezmax vessel with chemical absorption.
- RoPax vessel with mineralization.
- 1,700 TEU Container with mineralization.

6.1 OCCS safety

When installing carbon capture and storage systems onboard seagoing vessels, one of the primary concerns is the potential for CO_2 leakage. CO_2 is a colourless and odourless gas that can displace oxygen in confined spaces, posing a significant asphyxiation risk to crew members. Ensuring that the OCCS system is properly sealed and regularly maintained is crucial to preventing leaks. Additionally, monitoring systems must be in place to detect any CO_2 release promptly and initiate emergency protocols to protect the crew.

Another safety issue is the structural integrity of the vessel. The installation of OCCS equipment adds significant weight to the ship's structure. This necessitates a thorough engineering assessment to ensure that the vessel can handle these additional loads without compromising its trim, stability or structural strength. Reinforcements may be required in certain areas to support the OCCS system as well.

Corrosion is another issue that can affect the safety and longevity of OCCS systems onboard vessels. CO_2 can be corrosive, especially when mixed with impurities, which can lead to the deterioration of pipes, tanks, and other components. This can result in leaks and equipment failures if not addressed. Using corrosion-resistant materials and implementing regular maintenance schedules can help mitigate this risk. Additionally, operational safety requires comprehensive training for the crew to ensure they are familiar with the OCCS system's operation and emergency procedures.

Combustion

CO_2, whether in its gaseous or liquid state, is non-combustible and does not support combustion. As a gas, CO_2 is chemically stable and acts as a fire suppressant by displacing oxygen, which is essential for sustaining flames. In its liquid form, achieved under high pressure or low temperature, CO_2 retains these inert characteristics and is similarly effective in smothering fires by cooling and reducing oxygen concentration.

Dispersion

In both its gaseous and liquid states, CO_2 exhibits distinct dispersion behaviors. As a gas, CO_2 is heavier than air and tends to accumulate in low-lying areas, especially in confined or poorly ventilated spaces, which can pose asphyxiation risks. Its dispersion is influenced by factors like wind, temperature, and terrain. In its liquid form, CO_2 is stored under high pressure, and when released, it rapidly expands and cools, forming a dense, cold gas cloud that remains close to the ground and disperses slowly. It is essential to consider this behavior in applications like OCC, where the analysis of CO_2 dispersion helps in designing safe transport and leak detection systems, ensuring that any accidental release does not pose hazards to people or the environment.

Asphyxiation

As mentioned in 5.1.2, CO_2 while non-toxic and non-combustible, poses a serious asphyxiation hazard in high concentrations, particularly in enclosed or poorly ventilated areas. Because CO_2 is heavier than air, it can accumulate in low-lying spaces, displacing oxygen and creating an asphyxiant environment. Exposure to elevated CO_2 levels can lead to symptoms such as dizziness, headaches, shortness of breath, and, at very high concentrations, unconsciousness or death due to oxygen deprivation. Proper ventilation, leak detection systems, and safety protocols are essential to prevent accidental exposure and ensure worker safety.

Viscosity

Viscosity is a key physical property of CO_2 that plays an important role in the design and operation of OCCS systems. It affects how easily CO_2 flows through pipelines and porous geological formations during transport and injection. In its gaseous state, CO_2 has relatively low viscosity, which facilitates efficient flow but requires careful pressure management to avoid turbulence or flow instability. When CO_2 is compressed into a supercritical or liquid state, common in OCCS applications, its viscosity increases, though it remains lower than that of water or oil. This low viscosity in the supercritical phase is advantageous for deep geological injection, as it allows CO_2 to penetrate reservoir rock more easily, reducing the energy required for pumping. Accurate knowledge of CO_2 viscosity under varying temperature and pressure conditions is essential for modeling flow dynamics and optimizing system performance.

Corrosivity

CO_2 itself is not highly corrosive under normal conditions, but it can contribute to corrosive environments, especially when it comes into contact with water. When CO_2 dissolves in water, it forms carbonic acid (H_2CO_3), a weak acid that can lower the pH of the solution and lead to corrosion of metals, particularly carbon steel. This is a significant concern in OCCS systems, where CO_2 is often transported and stored under high pressure and may contain moisture. Over time, the acidic environment can degrade pipelines, valves, and storage infrastructure if not properly designed or protected. To mitigate this, materials resistant to acid corrosion, such as stainless steel or corrosion-resistant alloys, are often used, and dehydration of CO_2 streams is a common practice before compression and transport.

Toxicity

Although CO_2 (CAS no.: 124-38-9) is not classified as a toxic gas in the traditional sense, it can be hazardous to health at elevated concentrations due to its effects on the body's respiratory and nervous systems. Under normal atmospheric conditions (~0.04% CO_2), it is harmless. However, when concentrations rise above 0.5% - 1%, symptoms such as headaches, dizziness, and shortness of breath can occur. At levels above 5%, CO_2 can cause more severe effects like confusion, increased heart rate, and unconsciousness. Prolonged exposure to concentrations above 10% can be fatal. More specifically, the occupational exposure limit for CO_2 in the EU is 5,000 ppm as an 8-hour long-term exposure limit. In OCCS, where CO_2 is handled in large volumes and under pressure, strict monitoring and safety protocols are essential to prevent accidental exposure and ensure occupational health.

Chemicals in the OCCS system

For OCCS with liquid absorption, as already seen in 3.1.2, the use of chemical solvents presents hazards related to toxicity, corrosion, and potential chemical leakages. Amines such as MEA (CAS no.: 141-43-5) and DEA (CAS no.: 111-42-2) are essential for CO_2 removal but can be hazardous if mishandled. They are corrosive and can irritate skin, eyes, and the respiratory tract. Short-term exposure may cause coughing, headaches, and nausea, while prolonged contact can lead to dermatitis and sensitization. In OCCS systems, strict containment, PPE, and monitoring are critical to prevent exposure during maintenance or loading operations.

6.2 HAZID Objectives, Process, Scope and Assumption

6.2.1 Objectives

A HAZID is a structured approach based on documents, drawings, and a set of guidewords as basis to identifying risks and hazards involved with operation or the use of equipment and/or systems. In the context of the present study this will apply for the OCCS technology and the selected vessels. The key objectives of the HAZID are as follows:

- To identify hazards and hazardous events that may give rise to serious and immediate risk to personnel, environment, and assets.
- To identify causes and consequences of hazardous events.
- To identify preventive and mitigating measures (e.g., measures to prevent the hazardous events from occurring and engineering or operational controls to help prevent escalation) that are already included in design for managing the risks associated with the identified hazards.
- To assess risks semi-quantitatively by using a risk matrix.
- To recommend any potential new measures to be implemented in design and/or during operation.

The relationship among the hazard, hazardous event, cause, consequence, and preventive & mitigating measures is shown in Figure 6-1.

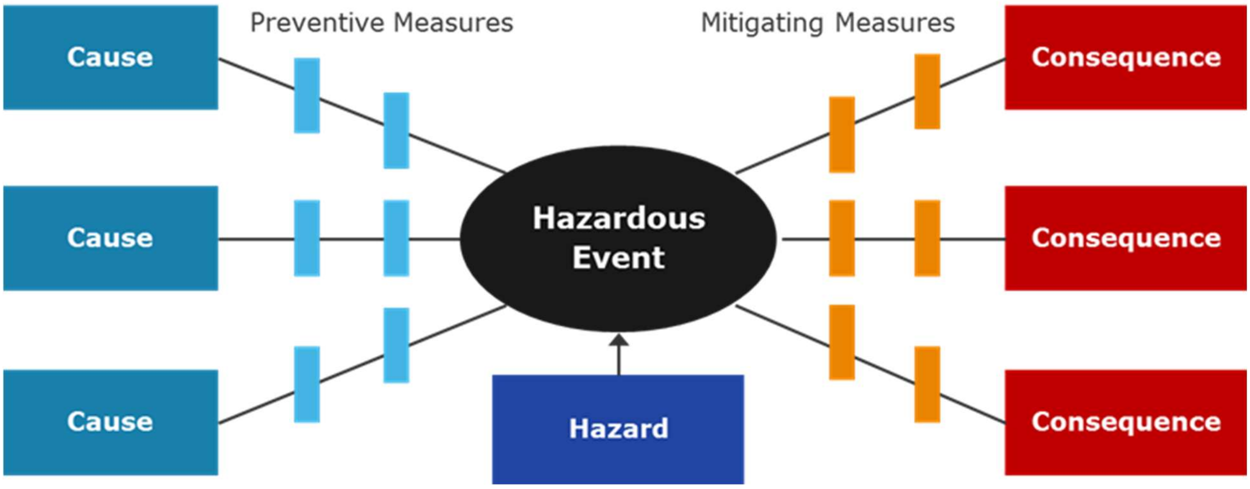

Figure 6-1 Bow-tie Diagram.

6.2.2 Common Scope

The selected vessels for the HAZID/HAZOP workshop are understood to be in full compliance with all the relevant regulatory and classification requirements. The scope of the HAZID/HAZOP, for all examined vessels, focuses on hazards scenarios on the vessel systems with carbon capture technology encompassing the following sequence of operations during the vessel's lifecycle:

- Onboard installation.
- Operations:
  - Voyage.
  - Carbon off-loading process (ship-to-ship, ship-to-shore, ship-to-barge).
  - Cargo operations / Bunkering operations as parallel operation to carbon off-loading.
  - Gas freeing process.
  - Lay-up/Idle.

6.2.3 HAZID Methodology

For this study, the SWIFT-methodology (Structured What-If Technique) has been selected for the HAZID. The Structured What-If Checklist (SWIFT) study technique has been developed as an efficient technique for providing effective hazards identification when it can be demonstrated that circumstances do not warrant the rigor of techniques like for instance HAZOP. SWIFT can also be used in conjunction with or complementary to other techniques. The

Structured What If Checklist (SWIFT) is a thorough, systematic, multidisciplinary team oriented analytical technique. This technique is based on following ISO documents:

- ISO 31000: 2018, Risk Management – Principles and Guidelines, (Standardization, 2018)
- ISO 31010: 2010, Risk Management – Risk Assessment Techniques, (Commission, 2010)

SWIFT is a systems-oriented technique which examines complete systems, subsystems or activities. To ensure comprehensive identification of hazards, SWIFT relies on a structured brainstorming effort by a team of experienced experts with supplemental questions from a checklist.

The procedure applied in this HAZID workshop follows the steps outlined below and illustrated in Figure 6-2.

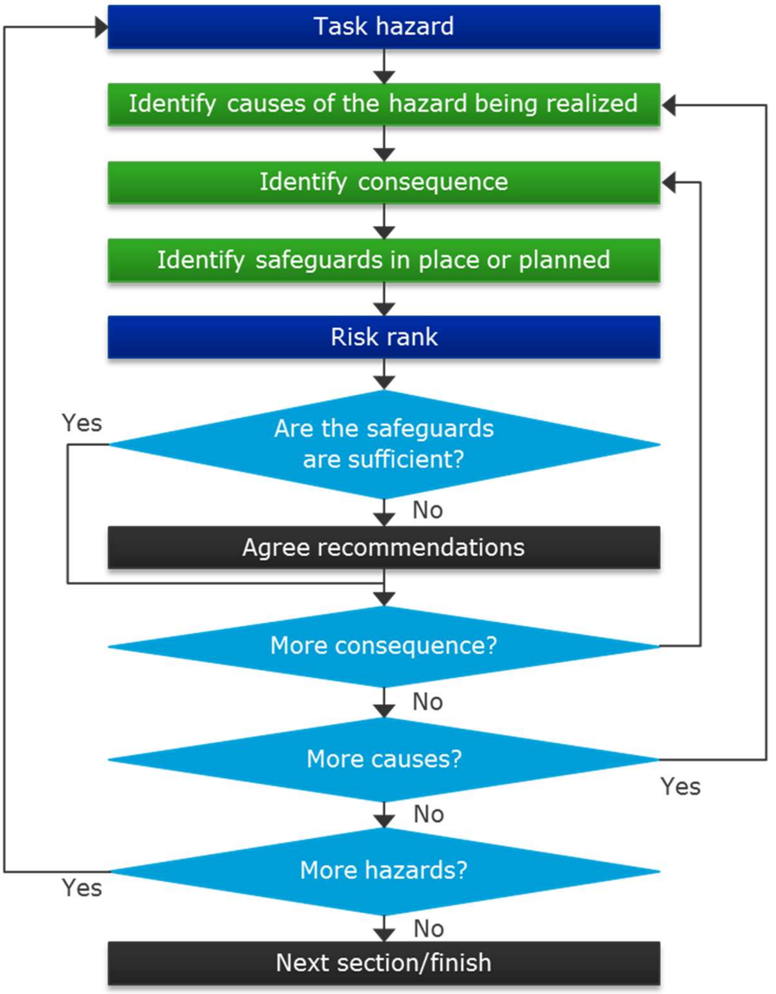

Figure 6-2 Process flow for the HAZID Procedure.

Step 1: Identification of HAZID Nodes

To assess the specifics of each individual area or operation, the areas and operations associated with the exhaust gas cleaning system were broken down into the series of nodes as listed in Table 6-1. For each node, the following steps are performed.

Step 2: Node Briefing

For all HAZID team members to obtain a common understanding of the design and intended operation of the node, the discipline lead gave a brief introduction of the node in question.

Step 3: Identification of Hazards, their Causes, and Consequences:

- In order to commence discussion on potential hazard associated with the carbon capture system, hazard sources should be identified. The HAZID team considered each node in turn to identify potential hazards associated with each node. For each hazard, potential causes along with the potential consequences were identified.
- For each hazard identified, all possible causes of the hazard being realized were identified and discussed if relevant. However, double jeopardy which is multiple independent events occurring at the same time was not considered during the HAZID workshop.
- For each hazardous event, all possible consequences in terms of health and safety were identified and discussed without taking credit for safeguards. Consequence was not limited by the HAZID node definitions or scope boundaries in evaluating the consequences of a given event.

Step 4: Identification of Safety Measures:

- The next part of the HAZID was for each hazardous event to identify existing or planned safety measures expected to prevent an incident from occurring, as well as those intended to control its development or mitigate its consequences.

Step 5: Determination of Severity, Frequency, and Risk

- Risk ranking is the categorization of the identified hazards rather than the estimation of their associated risks. This allows to undertake the relevant risk analysis. Risk ranking for each identified accident event was performed using the risk matrix.

Step 6: Identification of Recommendations (Action Items)

- If the current provision of preventive or mitigating measures was identified to be insufficient to manage the hazard, or that further assessments are required to obtain a better understanding of the hazard, recommendations were raised during the workshop. These recommendations were assigned to responsible parties.

The HAZID workshop was conducted based on decomposition of the system into smaller manageable parts, HAZID nodes. Nodes were reviewed and agreed at the start of the HAZID workshop and are listed in Table 6-1.

Table 6-1 HAZID Nodes.

Node	Description
1	Design
2	Operation: Voyage
3	Carbon off-loading process as standalone procedure
4	Off-loading simultaneous to (Ship to ship)
5	Gas-freeing (applicable for chemical absorption case only)
6	Lay up/idle

Risk ranking was performed for the identified hazards, using the risk matrix represented in Table 6-2. For the risk ranking, the following assumptions were applied:

- The focus of the workshop was on safety of people, asset and the environment. Hazards were risk ranked according to safety of personnel, asset and the environment.
- The frequency index selected is the likelihood of the final outcome, not for the cause or the initial event.
- The risk ranking is applied for the residual risk after existing safeguards are applied.
- Where more than one final credible event outcome is possible, the index for the worst credible consequence is selected.
- Whenever there are different opinions on the index to use, the worst credible index is to be used.

Table 6-2 Risk Matrix.

				Severity				
				1	2	3	4	5
				None	Minor	Significant	Severe	Catastrophic
People				None / insignificant	Single or minor injuries	Multiple or severe injuries	Single fatality or multiple severe injuries	Multiple fatalities
Asset				None / insignificant	Local equipment damage	Non-severe ship damage	Severe damage	Total loss
Environment				None / insignificant	Minor air or water pollution (short time)	Significant air or water pollution.	Severe pollution	Catastrophic pollution
Likelihood	5	Frequently	Occurs several times per year per facility or ship (10–1 < pf)					
	4	Very likely	Occurs several times per year per operator (10–2 < pf < 10–1)				High	
	3	Likely	Has been experienced by most operators (10–3 < pf < 10–2)			Medium		
	2	Unlikely	An incident has occurred in industry or related industry (10–4 < pf < 10–3)		Low			
	1	Extremely remote	Failure is not expected (pf < 10–4)					

The risk matrix classifies hazardous events by their severity and frequency into low-risk hazardous events (Low, green region) which can be considered broadly acceptable, and high-risk hazardous events (High, red region) which are not acceptable unless additional safeguards are provided to reduce the risk. For medium-risk hazardous events (Medium, yellow region), it should be demonstrated that all reasonable practical measures to reduce the risks are taken. The information is summarized in Table 6-3.

Table 6-3 Risks and Acceptance Criteria.

Risk	Acceptance criteria
High Risk	Action must be taken to reduce risk to at least the medium level.
Medium Risk	Risk reduction measures must be taken if their respective costs are not disproportionately high as compared to their attained benefits (ALARP principal); actions need to be taken to manage and measure risk.
Low Risk	Monitoring actions required to identify whether the risk rises to medium level.

For each hazard, the following aspects were discussed and recorded:

- Node.
- Guideword.
- Major Causes.
- Subsequent causes.
- Potential Consequences.
- Existing or planned safety measures.
- Risk Ranking.
- Proposed Additional Safety Measures (Actions/Recommendations).
- Comments and Notes.

All the HAZID recommendations and relevant discussion were recorded in the HAZID worksheet (ref.Appendix A). The HAZID worksheet was altered after the workshop session to incorporate comments to the log, including editorial updates.

6.2.4 Hazards

A short list of the risks considered during the HAZID for the OCCS technology is shown below:

- Design Hazards:
  - Location of captured CO_2 storage tanks.
  - Material & construction.
  - Events leading to CO_2 release.
  - Accidental leakages of CO_2 from tanks and systems.
  - Accidental leakages of process chemicals from tanks and systems.

- Exhaust systems related Hazards:
  - Flue gas exceeding design temperature at inlet.
  - Leakage of flue gas into the contact cooler container.

- Mechanical and Process Hazards:
  - High-pressure systems: CO_2 compression and storage involve high-pressure equipment, posing risks of leaks, rupture, or explosion.
  - Rotating machinery: Compressors, pumps, and fans can cause injury if not properly guarded.
  - Corrosion and erosion: Chemical solvents and exhaust gases degrade materials, leading to leaks or failures.
  - Backpressure and flow disruptions: Can cause system inefficiencies, flooding, or shutdowns.
  - Vibration and ship/plant motion: May affect mechanical integrity and alignment of components.

- Thermal and Fire Hazards:
  - High-temperature operations: Reboilers and heat exchangers operate at elevated temperatures, posing burn and fire risks.
  - Flammable solvents: Some capture solvents (e.g., MEA) are flammable or degrade into flammable byproducts.
  - Static discharge: Risk of ignition in areas with solvent vapours or flammable refrigerants.

- Chemical Hazards:
  - Toxic solvents: Amines and other chemicals can be harmful if inhaled or contacted.
  - Solvent degradation products: Can form corrosive or toxic compounds (e.g., nitrosamines).
  - Acid gas exposure: High CO_2 concentrations can displace oxygen and cause asphyxiation.
  - SO_x and particulates: Can degrade solvents and clog scrubbers or filters.

- Environmental and Ventilation Hazards:
  - Gas leaks: CO_2 and solvent vapors can accumulate in enclosed spaces, creating asphyxiation or explosion zones.
  - Ventilation failure: Poor airflow can lead to buildup of hazardous gases.
  - Overboard discharge: Improper handling of wash water or solvent waste can pollute marine or terrestrial environments.

- Low temperature in the case of cryogenic storage.

- Electrical and Control Hazards:
  - Power failure: Can disrupt capture operations and disable safety systems.
  - Instrumentation failure: Faulty sensors or control systems can lead to unsafe conditions.
  - Ignition risks: Static electricity or electrical faults can ignite flammable vapours.

- Operational and Human Factors:
  - Maintenance errors: Complex systems increase the risk of human error during inspection or repair.
  - Training gaps: Crew or operator qualifications may be insufficient for handling chemical capture systems.
  - Emergency response: Delays or missteps in responding to leaks, fires, or system failures can escalate hazards.
  - Accessibility issues: Poor layout or design can hinder maintenance and emergency access.

6.2.5 Assumptions for the HAZID studies

For the smooth execution of the HAZID workshops some critical assumptions were made, based on current documentation. Their importance dictated the need for them to be considered as "assumptions" instead of "recommendations" and it was agreed for them to be treated as "safeguards" during the workshop. The most common of these assumptions are listed below:

- The vessels are/will be designed and built in compliance with classification and statutory regulations.
- The structural integration of the OCCS within the vessel will be designed and tested according to class rules.
- All materials will comply with class rules.
- For any electrical equipment installed in hazardous area, they will comply with the appropriate requirements.

6.2.5.1 Chemical absorption case

The examined Suezmax and MR tanker vessels are equipped with chemical absorption with amines and onboard storage of liquefied CO_2 with system pressures between 12 and 20 bar. Details for the Suezmax and MR tanker vessel regarding their main dimensions and machinery are shown in 3.2.2. The OCCS system follows the techno-economic analysis and is assumed to have a CO_2 capture rate of 2 TPH for the Suezmax and 1 TPH for the MR tanker. The proposed location of the LCO_2 storage tanks and the OCCS capture plant onboard the Suezmax and the MR tanker is mentioned in Appendix B and Appendix G respectively.

In addition to the assumptions listed above, other assumptions from the workshop are listed below:

- For the case of chemical absorption, state-of-the-art solvents are used, reducing additional heat demands for the chemical solvent regeneration.
- For the case of chemical absorption, state-of-the-art compression stage, assuming the lowest possible energy demand (for reference only - at the order of 300kWh/ton of CO_2).
- The risk mitigation measures for auxiliaries for cooling during the CO_2 refrigeration process are sufficiently covered by Classification Rules and International Codes.
- For both the Suezmax and MR tanker vessels, the LCO_2 storage tanks have been assumed to be on deck, due to space availability for these vessel types.
- LCO_2 transfer pumps and tank cooling spray rails have been assumed to be located inside of the LCO_2 storage tank.

A typical PID diagram for the chemical absorption case can be seen below.

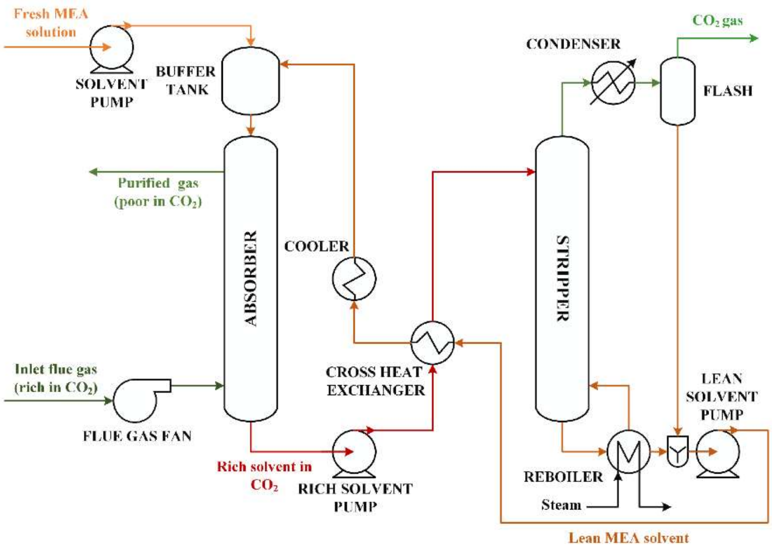

Figure 6-3 PID diagram for chemical absorption with MEA (Alexandru-Constantin Bozonc, 2022)

6.2.5.2 Mineralization case

The examined RoPax and 1,700 TEU feeder container vessel are assumed to be equipped with mineralization CCS and onboard storage of solid mineral. Details for the vessels regarding their main dimensions and machinery are shown in 3.2.2. The OCCS system follows the techno-economic analysis and is assumed to have a CO_2 capture rate of 1 TPH both vessels. The proposed location of the mineral storage tanks and the OCCS capture plant onboard the RoPax vessel is shown in Figure 6-4 respectively. The mineralization product is assumed to be $CaCO_3$. The systems' weights have been analysed in Table 3-34 and Table 3-36 respectively.

The mineralization OCCS is examined under two variants, the first one being of wet type (RoPax vessel) and the second one of dry type (Feeder container vessel).

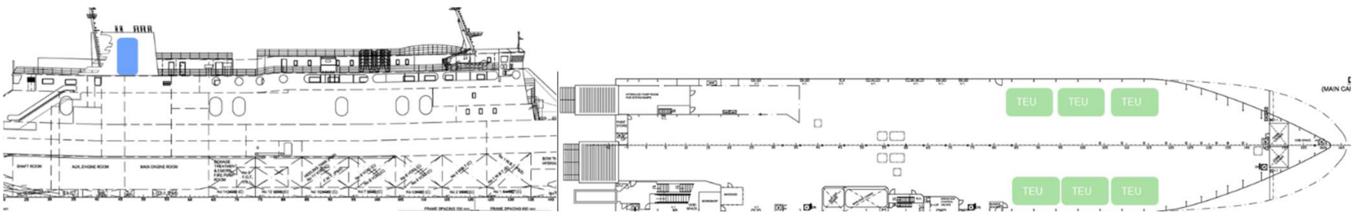

Figure 6-4 RoPax vessel – Wet type Mineralization OCCS locations (source: courtesy of Levante Ferries. Used with permission.)

Wet type

In wet type systems, the process involves an absorber where flue gas is brought into contact with a liquid containing a sorbent. This sorbent selectively captures carbon dioxide (CO_2) from the gas stream. As the process continues, solid byproducts are filtered out and collected as sediment. The liquid used in the system is recirculated until it reaches saturation, at which point make-up liquid is added to maintain effectiveness. Disposal primarily involves handling the accumulated sediments and managing the loading of additional make-up liquids. Common chemical agents used in wet scrubbers include sodium hydroxide (NaOH), water (HOH), ammonia (NH_3), and calcium hydroxide ($Ca(OH)_2$). A typical PID diagram for the wet type process is shown in the figure below.

Dry Type

Dry scrubber systems operate using a packed bed reactor filled with solid materials that are selective to CO_2. As the flue gas passes through the reactor, the packing material absorbs CO_2 until it becomes saturated. Once saturation is reached, the entire reactor unit is offloaded at port in a containerized form for disposal or regeneration. The minerals typically used in dry scrubbers include calcium oxide (CaO), magnesium oxide (MgO), dolomite ($CaMg(CO_3)_2$), and forsterite (Mg_2SiO_4). A typical PID diagram for the dry type process is shown in the figure below.

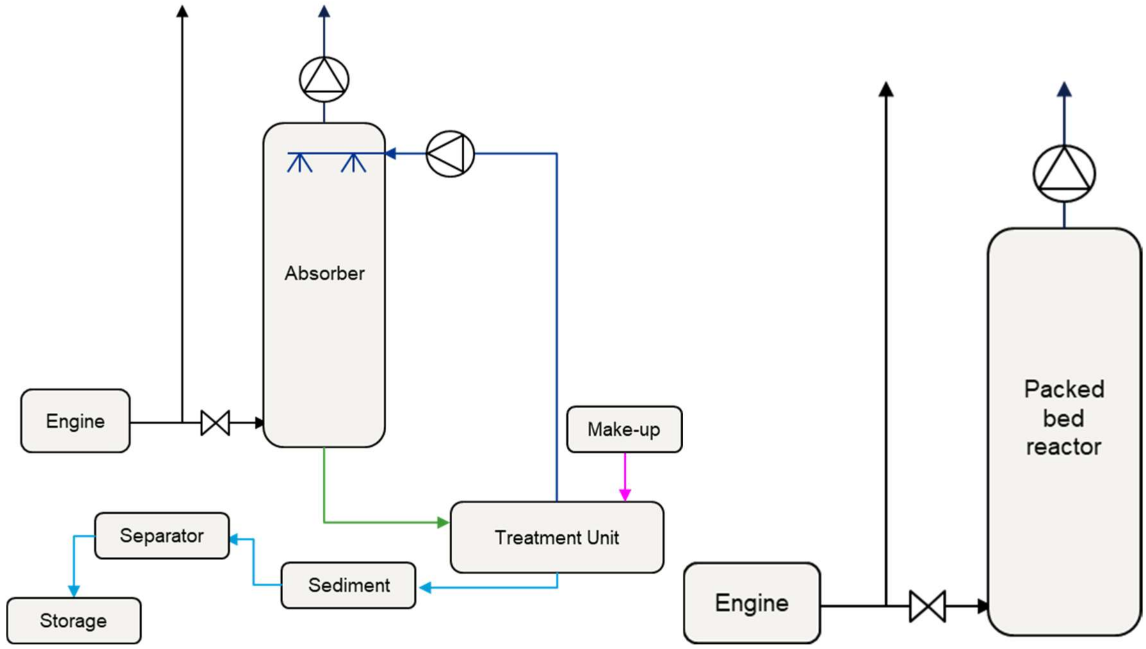

Figure 6-5 Mineralization PID diagram - wet type (left) and dry type (right). Source: DNV.

6.3 HAZID Results – Findings and Recommendations

Key risks were assessed, and required safeguards per relevant codes and standards were identified. Risk rankings for the different vessel types are included in the appendix. In the absence of specific codes, further research was advised. All recommendations are listed in Appendix H and may guide future safety standards and vessel design improvements.

When supported by appropriate mitigation strategies, the onboard deployment of OCCS systems can be managed within a medium risk threshold. These appropriate mitigation strategies were highlighted and described in thorough detail during the workshop, covering both design and operational aspects on OCCS onboard integration.

6.3.1 Suezmax and MR tanker vessels using chemical absorption with CO_2 onboard liquefaction

This chapter summarizes and highlights the results from the risk study. For a full overview of all the hazardous events, reference is made to the HAZID worksheet given in Appendix H. The assessment identified and examined 78 hazardous events for the total of nodes as shown in Table 6-1. The hazards' distribution depending on mode of operation and ranking are as follows.

Table 6-4 Number of hazardous events per node and risk level.

Operation mode	Low Risk	Medium Risk	High Risk	Total per mode
Design	14	24	0	38
Operation: Voyage	0	19	0	19
Carbon off-loading process as standalone procedure	6	7	0	13
Off-loading simultaneous to ship to ship	0	1	0	1
Gas-freeing	4	0	0	4
Lay up/idle	2	1	0	3

Out of the 78 hazardous events, 52 were ranked as of medium risk and 26 as of low risk. No high-risk hazards were identified. Therefore, there were no major risks against the installation and operation of the chemical absorption OCCS on the Suezmax and the MR tanker vessels.

Table 6-5 Recommendations list per node for chemical absorption OCCS.

Node	Recomendation
1.1: Design: Pre-treatment stage	RC1: For vessels with scrubber installed, the proper water handling in the scrubber should be considered and analyzed
	RC 2: For vessels with scrubber installed, control/monitoring of the level water of the scrubber (U - Type)
	RC 3: Warning signs and restricted access in the high temperature designated areas
1.2: Design: Capture system - Absorber	RC 4: Corrosive-resistant materials (high grade steel)
	RC 5: Proper quality of chemicals used
1.3: Design: Capture system - Regenerator column	RC 6: Proper sizing of the compressor
	RC 7: Leakage detectors in the drip trays and where leakages are more likely to occur (e.g. under pumps)
	RC 8: Chemical sensor in the steam
	RC 9: Measurement of the difference of the pressure of the two streams
	RC 10: Ensuring proper assembly and use of durable materials
	RC 11: Establish procedures for regular inspection and maintenance of components
	RC 12: Control of steam pressure
1.4: Design – Gas Piping	RC 4: Corrosive-resistant materials (high grade steel)
	RC 13: Detailed analysis during NB or retroffiting of the system
	RC 14:Detailed calculations of pressure drop of gas routing
1.5: Design – Liquefaction Plant	RC 7: Leakage detectors in the drip trays and where leakages are more likely to occur
	RC 15:CO_2 gas & liquid management plan as worst case scenario
	RC 16: Dispersion analysis based on the worst case scenario (max CO_2 flow)
	RC 17: Safety ventilations requirements to ensure proper air exchange in compartments as per IGF code
	RC 18: Use of anti-clogging agents
	RC 19: Pressure could be controlled in the stripper, making the need to bypass the absorber column not necessary
	RC 20: Welded connections, flange connections to be equipped with spill protection
	RC 21: NDT requirements - leak test requirements
	RC 22: Stress and fatigue analysis for subcooled liquid flows
	RC 36: Crew to undertake relevant training and be familiarized with procedures for human error prevention around the OCCS system installed onboard
1.6: Design: Storage	RC 4: Corrosive-resistant materials (high grade steel)
	RC 23: Regulatory framework uncertainty in IGF and IGC in LCO_2 tank system (to be further studied)
	RC 24: Operational optimization of the system
	RC 25: Voyage planning to take into consideration the amount of LCO_2 to be stored during the voyage and until the next LCO_2 offloading
	RC 37: To examine redundancy options of the BOG management system (associated with containment system type and capacity, complexity, positioning of the tank and pressure regime low pressure). It should be noted that the continuous operation of the system is not a requirement
2: Voyage	RC 24: Operational optimization of the system

	RC 25: Voyage planning to take into consideration the amount of LCO_2 to be stored during the voyage and until the next LCO_2 offloading
	RC 26: Structure and fatigue analysis to take sloshing effect into consideration
3: Carbon off-loading process as standalone procedure	RC 27: ESD philosophy to account for this phenomenon
	RC 28: Use of strainers in the manifolds
	RC 29: To prevent the return of contaminated vapor from the barge, the onboard LCO_2 tank will be pressurized. The liquefaction system should be operated to maintain the required tank pressure and ensure vapor containment.
	RC 30: Low pressure alarm and if the pressure in the LCO_2 falls down to 0.5 bar above triple point shut-down/ESD
	RC 31: CCTV at the manifolds for monitoring
	RC 32: Guarantee of the vapour return conditions of high purity at land side
	RC 33: Water spray system should be provided for the LCO_2 tank if there is combustible cargo for the vessel in question
4: Off-loading simultaneous to (Ship to ship)	RC 34: Safety zones; limitations of operation boundaries (no other processes encroach to the areas of LCO_2 discharge)
5: Gas-freeing	RC 35:Operation manual to cover this and be available during the procedure
	RC 36: Crew to undertake relevant training and be familiarized with procedures for human error prevention around the OCCS system installed onboard

Most of the hazardous events identified as medium risk relate to the potential for leaks, equipment failures, pressure deviations, and operational errors within the capture, regeneration, liquefaction, and storage subsystems. Accordingly, the most critical recommendations centre on:

- Leak prevention and detection, including installation of leakage detectors (RC7, RC21), spill protection on flanged connections (RC20), and chemical sensors in steam or high-risk zones (RC8).
- Material integrity and corrosion resistance, such as specifying high-grade steel for corrosive environments (RC4) and ensuring durable construction and proper assembly (RC10).
- Pressure and flow-related controls, involving correct compressor sizing (RC6), steam pressure control (RC12), differential pressure monitoring (RC9), and thorough pressure-drop assessment for gas routing (RC14).
- Operational safeguards and system stability, such as establishing structured inspection and maintenance procedures (RC11), incorporating redundancy or robustness in BOG-handling and critical systems (RC37), and implementing appropriate ESD philosophy and shutdown limits during offloading (RC27, RC30).
- Crew competence and human-factor mitigation, addressed through targeted training and familiarization with OCCS procedures (RC36).

6.3.2 RoPax vessel and 1,700 TEU container using mineralization with $CaCO_3$ onboard storage

For a full overview of all the hazardous events, reference is made to the HAZID worksheet given in Appendix I. The assessment identified and examined 38 hazardous events for the total of nodes as shown in Table 6-6. The hazards' distribution depending on mode of operation and ranking are as follows:

Table 6-6 Number of hazardous events per node and risk level.

Operation mode	Low Risk	Medium Risk	High Risk	Total per mode
Design	8	14	0	22
Operation: Voyage	3	6	0	9
Carbon off-loading process as standalone procedure	4	1	0	5

Off-loading simultaneous to (Ship to ship)	0	1	0	1
Lay up/idle	1	0	0	1

Out of the 38 hazardous events, 22 were ranked as of medium risk and 16 as of low risk. No high-risk hazards were identified. Therefore, there were no major risks against the installation and operation of the mineralization OCCS on the RoPax and the feeder container vessels.

Table 6-7 Recommendations list per node for mineralization OCCS.

Node	Recomendation
1.1 Design: Absorber	RC1: Proper water handling/monitoring in scrubber (wet type)
	R2: Existence of inspection hatches
	RC3: Leak detection under components and piping (high-high bilge)
	RC4: Proper consideration during the design in case of absence of Exhaust Gas Economizer
1.2 Design: Liquid Medium Treatment Unit (Wet Type)	RC3: Leak detection under components and piping (high-high bilge)
	RC5: Separated location of the components
	RC6 Redudancy monitoring of the dosing equipment
	RC7: Examine the need for component redudancy
1.3: Design – Dosing System for CaO and Hydroxides (wet type)	-
1.4: Design: Gas Piping	RC8: Maintenance and inspection per analyzed number of operations
1.5: Design: Onboard Storage	RC9: Optimized container removal in terms of logistic
	RC10: Keep all transfer and dosing operations fully enclosed
	RC11: Aqeuate platform/space for storage (unhindered operations)
1.6: Design: General layout	RC12: New analysis/position of downflooding points taking into consideration the OCCS components/layout
2: Operation: Voyage	RC1: Proper water handling/monitoring in scrubber (wet type)
	R2: Existence of inspection hatches
	RC3: Leak detection under components and piping (high-high bilge)
	RC5: Separated location of the components
	RC6 Redudancy monitoring of the dosing equipment
	RC7: Examine the need for component redudancy
	RC9: Optimized container removal in terms of logistic
	RC10: Keep all transfer and dosing operations fully enclosed
3: Mineral off-loading process as standalone procedure	RC9: Optimized container removal in terms of logistic
	RC10: Keep all transfer and dosing operations fully enclosed
4: Off-loading simultaneous to (Ship to shore)	RC 13: Safety zones; limitations of operation boundaries (no other processes encroach to the areas of mineralized CO_2 discharge)
5: Lay-up/idle	-

The medium-risk events identified for the mineralization-based OCCS system predominantly relate to leakage risks, component failures, improper handling of wet-type scrubbing media, and operational issues associated with dosing and storage. The most critical recommendations therefore focus on:

- Leak detection and containment, including high-high bilge monitoring beneath critical components and piping (RC3), ensuring enclosed transfer and dosing operations (RC10), and maintaining well-controlled water management in wet scrubbers (RC1).
- Component reliability and redundancy, such as implementing redundancy or monitoring for dosing equipment (RC6, RC7) and ensuring appropriately separated or compartmentalized equipment layouts (RC5).
- Operational accessibility and safe logistics, including optimized container removal and handling procedures (RC9) and ensuring adequate platform and storage space for uninterrupted and safe operations (RC11).
- Design alignment with vessel configuration, including reassessment of downflooding points considering OCCS integration (RC12) and ensuring proper design considerations when exhaust heat recovery is absent (RC4).

7. Overall Conclusions on Onboard Carbon Capture Technologies

The maritime industry accounts for approximately 3% of global CO_2 emissions from human activities and faces mounting pressure to decarbonize under increasingly stringent international and regional regulations. The IMO has set ambitious targets for reducing greenhouse gas emissions, including a 40% reduction in carbon intensity by 2030 and net-zero emissions by around 2050. In parallel, the EU's Fit for 55 package and the inclusion of shipping in the ETS further accelerate the need for effective solutions. While alternative fuels such as ammonia, hydrogen, and methanol are gaining attention, their low energy density, high cost, and limited global availability pose significant challenges. Against this backdrop, OCCS has emerged as a promising transitional technology, enabling vessels to continue using conventional fuels while significantly reducing CO_2 emissions.

OCCS technologies have been successfully demonstrated in pilot projects and feasibility studies, but their readiness for widespread adoption varies across technology categories. Post-combustion chemical absorption systems are the most mature, with capture rates of 30–90%, while membrane separation, cryogenic capture, and mineralization offer potential advantages but remain at lower technology readiness levels. Pre-combustion methods, such as LNG reforming and pyrolysis, introduce additional complexity and require integration with hydrogen-based propulsion systems. Despite these challenges, OCCS provides a unique advantage: it can be retrofitted to existing vessels and incorporated into newbuild designs, offering flexibility for shipowners navigating the transition to low-carbon operations.

From an environmental perspective, OCCS can reduce well-to-wake emissions by 29–44% independently and up to 120% when combined with biofuels. It also eliminates the need for immediate fuel switching, mitigating risks associated with fuel availability and infrastructure gaps. However, sustainability depends on minimizing energy penalties, currently estimated at 9–30%, and managing solvent degradation and byproducts.

Economic viability remains a critical consideration. OCCS-ready newbuilds demonstrate lower abatement costs compared to retrofits, which incur higher integration complexity and fuel penalties. While initial capital expenditure is significant, long-term competitiveness improves under carbon pricing mechanisms such as the EU ETS and IMO's GHG Fuel Intensity metric. Comparative analyses indicate that OCCS can outperform biofuels under mid- to long-term cost scenarios, particularly as carbon costs rise and technology matures. Nevertheless, uncertainties in CCUS infrastructure tariffs and regulatory frameworks must be addressed to provide investment confidence.

Furthermore, the success of OCCS is closely tied to the development of a robust CCUS value chain, including port infrastructure for LCO_2 offloading and permanent storage facilities. Without these downstream elements, the climate benefits of OCCS cannot be fully realized.

Safety and regulatory compliance are essential for OCCS adoption. Risk assessments confirm that OCCS can operate within acceptable thresholds when supported by robust engineering safeguards, hazardous area classification, and crew training. However, regulatory gaps persist, particularly in environmental performance measures and lifecycle emissions accounting. Ongoing IMO work plans and EU initiatives aim to close these gaps, but coordinated international efforts will be required to ensure harmonized standards and avoid fragmented compliance regimes.

In summary, OCCS represents a promising technology for achieving substantial reductions in maritime emissions, albeit with the trade-off of increased fuel consumption. Its ability to utilize existing fuel infrastructure, combined with its significant emissions reduction potential, constitutes a key advantage over other decarbonization alternatives. However, the current absence of disposal infrastructure and limited regulatory incentives remain major challenges - though these are expected to evolve as the regulatory landscape and supporting infrastructure develop in the future.

Table 7-1 OCCS conclusions summary table.

Subject	Observations	Mitigations/Suggestions
OCCS Technology	▪ OCCS systems integrate multiple subsystems, including exhaust gas pre-treatment, capture units, and temporary onboard CO_2 storage. ▪ Technologies are categorized by the stage of CO_2 separation: post-combustion, pre-combustion, and oxy-fuel combustion. ▪ Post-combustion methods (chemical absorption, physical adsorption, mineralization, membrane separation, cryogenic separation, electrochemical separation) are the most widely explored for maritime use. ▪ Chemical absorption remains the most mature and widely studied, with proven pilots and operational stability. ▪ Mineralization pilots have validated CO_2 conversion into solid carbonates, but space and weight impacts remain significant. ▪ Membrane and cryogenic systems offer compactness but face efficiency challenges due to low CO_2 concentration and impurities. ▪ Pre-combustion technologies (LNG reforming, pyrolysis) provide alternative pathways but introduce complexity and require hydrogen handling. ▪ Technology readiness levels vary widely; most concepts remain at pilot or feasibility stage, or low commercial implementation. ▪ Successful deployment depends on downstream CCUS infrastructure for CO_2 transport, conditioning, and permanent storage.	▪ Prioritize chemical absorption for near-term deployment due to higher TRL and operational experience. ▪ Combine membranes with absorption systems to improve efficiency and reduce footprint. ▪ Optimize heat recovery and energy integration to minimize fuel penalty. ▪ Develop modular mineralization systems and explore reuse of mineralized products. ▪ Advance pre-combustion technologies through targeted R&D and safe hydrogen handling protocols. ▪ Accelerate TRL progression via collaborative pilots, joint development projects, and standardization of performance metrics. ▪ Promote innovation in compact designs and hybrid systems to address space limitations on smaller vessels. ▪ Coordinate OCCS development with CCUS infrastructure planning to ensure full value chain readiness.
Sustainability	▪ OCCS technologies demonstrate significant potential for reducing emissions, with chemical absorption systems achieving reductions around 30% and, in exceptional cases, 70%. ▪ Chemical absorption variants and mineralization technologies are currently the most mature and widely demonstrated. ▪ Other technologies (membrane separation, cryogenic capture, pre-combustion methods) show promise but face integration and energy efficiency challenges.	▪ Optimize solvent selection and regeneration processes to reduce heat demand and degradation. ▪ Implement heat recovery and waste energy utilization to minimize fuel penalties. ▪ Develop closed-loop solvent management systems to reduce environmental risks. ▪ Conduct full lifecycle assessments (WtW) to validate net climate benefits. ▪ Collaborate with ports and CCUS stakeholders to accelerate infrastructure development for LCO_2 offloading and storage.

	■ Sustainability performance varies by vessel type, capture rate, and system configuration; higher capture rates yield greater emissions reductions but increase fuel penalties. ■ Lifecycle assessments confirm OCCS can achieve substantial well-to-wake emissions reductions, up to 120% when combined with biofuels. ■ Solvent use, energy demand, offloading logistics, and compatibility with the CCUS value chain strongly influence environmental footprint. ■ Long-term viability depends on improving solvent stability, minimizing energy penalties, and ensuring seamless integration with port and storage infrastructure.	■ Combine OCCS with biofuels and renewable energy sources to maximize emissions reduction potential. ■ Explore reuse of mineralized products to improve circularity and reduce resource consumption.
Suitability	■ Integrating OCCS systems onboard requires balancing technical feasibility, operational constraints, and alignment with the CCUS value chain. ■ Chemical absorption is the most mature technology, but vessel-specific constraints (space, weight, safety) strongly influence suitability. ■ Larger vessels (Suezmax tankers, LNG carriers) are generally more suitable due to available space and stable operating profiles. ■ Container ships can accommodate OCCS with moderate cargo loss (1–3% TEU), while RoPax vessels face tighter constraints due to limited deck space and safety considerations. ■ Feeder vessels and MR tankers may support OCCS at lower capture rates, provided structural and stability impacts are managed. ■ Higher capture rates require larger tanks and more equipment, reducing cargo space and increasing draft. ■ Newbuilds offer the most flexibility for optimized integration; retrofits are feasible but involve compromises in layout, stability, and cargo capacity. ■ Selecting the right OCCS solution requires a holistic assessment of vessel design, operational profile, and CCUS infrastructure readiness.	■ Design OCCS-ready newbuilds with reserved spaces and structural reinforcements for tanks and capture units. ■ Conduct detailed stability analysis and update loading computer after installation; reinforce decks for concentrated loads. ■ Use modular OCCS units and compact technologies (e.g., membrane-assisted absorption) to minimize footprint. ■ Install explosion-proof equipment and ventilation systems in hazardous zones. ■ Upgrade auxiliary power and steam systems for retrofits; integrate PTO and AEECOs in newbuilds for energy efficiency. ■ Collaborate with ports and CCUS stakeholders to ensure compatibility for LCO_2 offloading and storage. ■ Apply capture rate optimization to balance emissions reduction with cargo capacity and operational efficiency.
Economic viability	■ Economic viability of OCCS depends on CAPEX, OPEX, CO_2 abatement costs, and regulatory incentives. ■ OCCS-ready newbuild configurations show the lowest abatement costs, while retrofits incur higher costs due to	■ Promote OCCS-ready newbuild designs to minimize integration complexity and reduce CAPEX. ■ Implement energy recovery systems and optimized solvent technologies to lower OPEX and fuel penalties.

	integration complexity and fuel penalties. ■ Fuel prices and CO_2 disposal costs are the most influential factors in total abatement cost, followed by CAPEX and maintenance. ■ OCCS becomes increasingly competitive under mid- to long-term fuel price projections, especially compared to biofuels, which remain cost-effective only under minimum price scenarios. ■ Scenario-based analysis under IMO GFI highlights the need for methodological clarity in lifecycle emissions accounting. ■ Uncertainty around CCUS infrastructure tariffs and disposal costs complicates long-term financial planning.	■ Leverage EU ETS incentives and carbon credit schemes to improve OCCS business cases. ■ Develop standardized techno-economic models for OCCS to support transparent cost comparisons with alternative fuels. ■ Encourage collaborative financing models and public-private partnerships for CCUS infrastructure development. ■ Conduct sensitivity analyses on fuel prices, carbon costs, and capture rates to guide investment decisions. ■ Explore hybrid decarbonization strategies combining OCCS with biofuels or renewable energy to enhance cost-effectiveness.
CCUS value chain	■ OCCS success depends on a integrated and interoperable CCUS value chain for offloading, transport, and permanent storage or utilization of CO_2. ■ Current developments in CO_2 storage near major shipping hubs show promising alignment with maritime decarbonization goals. ■ Technical compatibility challenges persist between ship-based systems and land-based infrastructure, particularly regarding pressure and temperature regimes. ■ Offloading methods and CO_2 conditioning must be tailored to the physical state of captured CO_2 (cryogenic liquid, compressed gas, mineralized solids). ■ Cost of disposal, relevant to OCCS cases, is expected at the order of 45 €/ton, with potential to drop by 2040. ■ Tariff structures, infrastructure readiness, and regional disparities influence project viability. ■ Coordinated investment in aligning CCUS port infrastructure with OCCS volumes, and regulatory alignment, are essential for scalability.	■ Accelerate development of port infrastructure for LCO_2 offloading and conditioning facilities through public-private partnerships. ■ Standardize technical specifications for CO_2 pressure, temperature, and purity to ensure interoperability across the CCUS chain. ■ Develop technical solutions and business models for CCUS integration with OCCS operations. ■ Promote collaborative business models involving shipowners, ports, and storage operators to share investment and operational costs. ■ Implement tariff structures and financial incentives to reduce uncertainty and encourage early adoption. ■ Explore interim solutions such as shuttle LCO_2 barges or floating storage units for ports lacking permanent infrastructure.
Safety and Environmental Regulations	■ OCCS not fully integrated into IMO and EU environmental performance measures. ■ Safety standards exist for components but lack for full OCCS systems. ■ Fragmented regulatory landscape increases complexity. ■ No clear derogation benefits under different metrics.	■ Accelerate IMO work on OCCS-specific guidelines, including safety, operational procedures, and verification protocols. ■ Harmonize international and regional frameworks to avoid fragmented compliance regimes. ■ Update emissions reporting standards to account for captured CO_2 and OCCS energy penalties.

	■ Limited guidance for testing and verification. ■ Lack of unified international standards creates uncertainty for shipowners and technology providers.	■ Develop standardized lifecycle assessment methodologies for OCCS to ensure fair treatment in compliance metrics. ■ Expand OCCS-related class notations and push for unified requirements under IACS.
Risk Assessment	■ OCCS introduces new -but manageable through safeguards- hazards onboard, including CO_2 leakage and asphyxiation risks during capture, storage, and offloading. ■ High-pressure systems and cryogenic operations pose risks of rapid decompression, frostbite, and equipment failure. ■ Chemical absorption systems involve handling amine-based solvents, which can degrade into harmful byproducts and cause corrosion. ■ Mineralization processes require frequent dosing and handling of reactive minerals, creating contamination and operational risks. ■ Integration of OCCS increases complexity in hazardous zones, requiring compliance with explosion-proof standards and gas detection. ■ Crew unfamiliarity with OCCS systems may lead to operational errors during normal and emergency conditions. ■ Offloading operations introduce additional hazards, including pressure imbalance and vapour release.	■ Install robust leak detection systems, ventilation standards, and emergency shutdown protocols for CO_2 containment areas. ■ Use corrosion-resistant materials and protective coatings for piping and tanks; schedule regular inspections and maintenance. ■ Apply hazardous area classification and install explosion-proof electrical equipment for liquefaction units and LCO_2 tanks. ■ Provide comprehensive crew training programs covering OCCS operation, emergency response, and chemical handling procedures. ■ Introduce automated monitoring and control systems to minimize human error and ensure safe operating conditions. ■ Establish clear offloading procedures with vapour return lines and pressure balancing to prevent overpressure incidents.

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Appendix A OCCS Project Inventory

Table 0-1 Inventory: Projects related to OCCS technologies.

Project	Type	Objective / TRL	Scope & ship type / Fuel	Companies	Technology / Impact, outcome & challenges
Project: AL Group / DNV techno-economic OCCS study	**Type:** Private Partnership (JDP)	**Objective**: Techno economic study of CCS on board AL's 7,100TEU containership and Kamsarmax bulk carrier NBs.	**Scope**: Feasibility study of CCS on board AL's NB vessels, 7,100 TEU containership and Kamsarmax bulk carrier using DNVs FuelPath model to assess the economic potential of different fuel and technology strategies.	**Companies**: AL Group, DNV	**Technology**: Chemical absorption; CO_2 liquefaction
		TRL: 1-4	**Fuel:** Fossil.	**Impact:** Feasible design.	
Project: Crowley / Carbon Ridge OCCS pilot project	**Type:** MARAD META Programme[81]	**Objective**: Install Carbon Ridge's technology on Crowley's Storm container ship	**Scope**: Installation, integration, operation, and optimization of the OCCS system on a containership. Achieve capture capacity of 1 metric ton of CO_2 per day, housed in two 40-foot containers. Liquefy and store onboard in 20-foot ISO-certified tank.	**Companies**: Crowley, Carbon Ridge Inc	**Technology**: Chemical absorption
		TRL: Estimated at 7-8	**Fuel:** Fossil	**Impact:** Expected 75% reduction in footprint when compared to conventional OCCS, with less than 5% energy penalty; 99.9% elimination of PM, NO_x and SO_x emissions.	
Project: EverLoNG	**Type:** EU funded through ACT Programme[82]	**Objective**: Advance OCCS technology and address technical, economic, and	**Scope**: Develop, demonstrate, and optimize OCCS systems on LNG-fuelled vessels. Test system performance parameters. Integrate with existing maritime infrastructure. Assess environmental and economic feasibility. Provide recommendations for regulatory framework updates for large-scale technology adoption.	**Companies**: Consortium of more than 10 partners[83]	**Technology**: Chemical absorption; CO_2 liquefaction

[81] Maritime Environmental and Technical Assistance MARAD META Programme
[82] Financial contributions by: 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.
[83] Partners: ÅKP AS / GCE Blue Maritime Cluster, Anthony Veder, BV, Carbotreat B.V., Conoship, DNV, Forschungszentrum, Jülich GmbH, Heerema Marine, Contractors, LRS, Los Alamos National Laboratory, MAN, Nexant Energy and Chemical Advisory, Scottish Carbon Capture & Storage (University of Edinburgh), SINTEF AS, TNO, Norge AS, TotalEnergies EP, VDL AEC Maritime.

Project	Type	Objective	Scope & ship type	Companies	Technology
		TRL	Fuel	Impact, outcome & challenges	
		regulatory challenges			
		TRL: From 4 to 7	**Fuel:** LNG	**Impact:** Performance assessment (order of magnitude of 70% capture rate of the OCCS unit) under ship motions; Key challenge: NO_x emissions in exhaust / corrosivity.	
Project: Green Marine	**Type:** European Union Funding (Horizon Europe)	**Objective**: Accelerate climate neutrality in waterborne transport by retrofitting fleets with cost-effective emission control solutions. Achieve TRL 8 and study scale up.	**Scope**: Develop retrofitting protocols and a software tool catalogue to support decision-makers. Demonstrate innovative solutions including carbon capture mineralization, HVAC energy savings through air-reuse, carbon and water capture with membranes, and use of excess engine heat to produce syngas. Test solutions on land-based engines before demonstrating on a vessel. Retrofit and demonstrate activities on MV Coruisk, a RoRo RoPAX ferry vessel.	**Companies**: Consortium of about 10 partners[84]	**Technology**: Membrane separation; Chemical absorption; Mineralization (Ca/Mg)
		TRL: Target TRL 8	**Fuel:** Fossil	**Impact:** Ongoing work.	
Project: HyMethShip	**Type:** European Union Funding (Horizon 2020)	**Objective**: Achieve significant CO_2 emissions reductions: 85% in lab conditions, 75% in a small-scale prototype. Reduce NO_x , SO_x , and PM emissions. Ensure system	**Scope**: Design and manufacture membrane reactors for large-scale demonstration. Improve ceramic membrane production. Develop a hydrogen direct injection system. Implement spark ignition engine control. Perform LCA impact analysis of the concept.	**Companies**: Consortium of more than 10 partners[85]	**Technology**: Pre-combustion carbon capture system, hybridized with membranes

[84] Cyprus Marine & Maritime Institute, Smart Material Printing, University Polytechnic of Marche, BlueXPRT, SINTEF, PDM, CalMac Ferries Limited, University of Strathclyde, CarbonCapture Machine
[85] Chalmers University of Technology, Colibri, Exmar Marine, Fraunhofer IKTS, INNIO Jenbacher, Graz University of Technology, HOERBIGER Wien, LEC (Project Coordinator), Lloyd's Register, MEYER Werft, MUW Screentec, SE.S, SSPA Sweden

Project	Type	Objective / TRL	Scope & ship type / Fuel	Companies	Technology / Impact, outcome & challenges
		efficiency of 49%. Risk-based analysis and environmental and economic viability.			
		TRL: Target 6	**Fuel:** Methanol	**Impact:** Reduced LCA footprint of 92% for acidification, 98% for climate change (GWP20, GWP100), 93% for marine eutrophication, 88% PM reduction,92% in photochemical ozone formation, and 90% in terrestrial eutrophication by 90% compared to ICE with fossil. **Challenge:** Methanol leaks. Relatively high impact on toxicity.	
Project: JDP on LNGC OCCS feasibility	**Type:** Private Partnership (JDP)	**Objective**: OCCS feasibility study on board a 174,000 m^3 LNG carrier	**Scope**: Analyse performance of a conventional OCCS technology for existing LNG carrier. Evaluate max possible capture rate and emissions reduction potential. Compare costs against alternative solutions for decarbonization.	**Companies**: SK Shipping, HD-HHI (Hyundai), TotalEnergies, Marubeni, DNV	**Technology**: Chemical absorption; CO_2 liquefaction
		TRL: Estimated at 1-4	**Fuel:** LNG	**Impact:** Up to 7% savings over the vessels lifetime compared to other decarbonization options.	
Project: JIP / AiP on OCCS for a Ultra-large containership	**Type:** Private Partnership (JIP)	**Objective**: AiP from DNV for OCCS system of HD Hyundai companies.	**Scope**: Retrofitting an LNG dual fuel, 15,000 TEU ultra-large container ship built by HD Hyundai Group. Integration of carbon capture and liquefaction systems from Hyundai Heavy Industries Power Systems and HD KSOE. HD Hyundai Marine Solution handled the basic design, HD Hyundai Engineering & Technology managed 3D modelling and detailed design, and DNV provided verification based on international regulations and classification rules.	**Companies**: Consortium of about 10 partners[86]	**Technology**: Chemical absorption
		TRL: Estimated at 7-8	**Fuel:** LNG/ Marine Diesel Oil (MDO)	**Impact:** Demonstration of approved OCCS technology.	
Project: JDP on pre-combustion OCCS for	**Type:** Private Partnership (JDP)	**Objective**: Fuel cell and pre-combustion OCCS study.	**Scope**: Evaluation of the use of hydrogen fuel cells, ammonia and methane cracking technology and CCS. Outcomes to determine the technologies' emissions reduction for container feeders.	**Companies**: Lloyd's Register, ROTOBOOST, Amogy	**Technology**: Fuel pyrolysis / Carbon production

[86] DNV, HD Hyundai Marine Solution, HD Hyundai Engineering & Technology, HD Korea Shipbuilding & Offshore Engineering (HD KSOE), Hyundai Heavy Industries Power Systems.

Project	Type	Objective	Scope & ship type	Companies	Technology
		TRL	Fuel	Impact, outcome & challenges	
container feeder		**TRL:** Estimated at 1-6	**Fuel:** LNG	**Impact:** Demonstration of benefits from pre-combustion OCCS.	
Project: JDP on Carbon Clean OCCS technology	**Type:** Private Partnership (JDP)	**Objective**: Explore opportunities for OCCS projects, optimally marinizing Carbon Clean's CycloneCC technology.	**Scope**: Develop and optimize Carbon Clean's modular carbon capture technology, CycloneCC, for use onboard ships. Address challenges of space constraints and efficiency in the marine environment. Leverage Samsung Engineering's expertise in engineering, procurement, construction, and project management.	**Companies**: Carbon Clean, Samsung Engineering	**Technology**: Chemical absorption, amine solvent. Rotating Packed Bed (RPB) technology
		TRL: Estimated at 1-6	**Fuel:** Fossil	**Impact:** Demonstration of OCCS concept feasibility.	
Project: K-Line, CC-Ocean pilot	**Type:** Private Partnership (JDP)	**Objective**: Install OCCS at the container feeder vessel MV CORONA UTILITY.	**Scope**: The project involves collaboration between Mitsubishi Heavy Industries, "K" Line, and Class NK, focusing on the installation, operation, and performance evaluation of the CO_2 capture system on the vessel CORONA UTILITY, operated by Tohoku Electric Power.	**Companies**: Mitsubishi Heavy Industries (MHI), K- Line, Class NK	**Technology**: Chemical absorption
		TRL: Estimated at 7-8	**Fuel:** Fossil	**Impact:** Demonstration of OCCS concept feasibility.	
Project: Langh Tech OCCS Pilot project	**Type:** Private Partnership (Pilot project)	**Objective**: Retrofit ships with OCCS to lower emissions of CO_2 (60% reduction), SO_x , and NO_x , with traditional fuels. .	**Scope**: Pilot project of OCCS installation was run during 2024. First commercial installations to take place early in 2025 onboard four bulk carriers.	**Companies**: Langh Tech, Langh Ship, Atal Solutions, BAM Shipping, Damen Shipyards Group	**Technology**: To be confirmed
		TRL: Estimated at 7-9	**Fuel:** Fossil	**Impact:** Onboard demonstration of multi-gas cleaning technology (CO_2, SO_x , NO_x , PM)	
Project: LINCCS	**Type:** Funded by Research Council of Norway, Innovation	**Objective:** Accelerating the adoption of large-scale, cost-effective	**Scope:** As part of this project, the R&D Facility of Wärtsilä in Moss was developed. This research centre replicating a ship's engine room to test OCCS solutions.	**Companies**: Consortium	**Technology**: Chemical absorption

Project	Type	Objective	Scope & ship type	Companies	Technology
		TRL	Fuel	Impact, outcome & challenges	
	Norway and SIVA	carbon capture and storage (CCS) in European energy-intensive industries. Reducing costs by connecting the entire CCS value chain from capture to storage.		of 13 partners[87]	
		TRL: Estimated at 5-6	**Fuel:** Fossil	**Impact:** Land-based test bed of Wartsila Moss, testing of OCCS chemical absorption technology at high capture rates above 70%.	
Project: LR GCMD Study	**Type:** Private Partnership (JDP)	**Objective**: Evaluate the feasibility and technical requirements for safely offloading onboard captured CO_2 from ships.	**Scope**: Investigation of logistical, regulatory, and operational challenges associated with CO_2 offloading at ports, assessing necessary infrastructure, storage solutions, and potential pathways for large-scale maritime carbon capture implementation.	**Companies**: Lloyd's Register, Arup	**Technology**: LCO_2 terminal and disposal
		TRL: Estimated at 1-4, if pilot materializes: 7-8	**Fuel:** Fossil	**Impact:** Review of methods for OCCS LCO_2 offloading. Discussion of cost models and processes.	
Project: Maritime Carbon Capture and Storage (MCCS)	**Type:** Research and Innovation Eurostars fund (UK/Norway)	**Objective**: Assess the feasibility, challenges, and emissions reduction potential of	**Scope**: Evaluation of the technical, operational, and economic aspects of OCCS, analyzing different capture methods, integration with ship systems, and regulatory considerations to enable large-scale adoption in commercial shipping. Assessment of chemical absorption, PSA, and membranes for a VLCC.	**Companies**: DNV GL, Process Systems Enterprise Ltd. (PSE)	**Technology**: Chemical absorption, PSA, membranes (Post-combustion)

[87] AkerSolutions, Equinor, Wartsila, AkerBP, TotalEnergies, Wintershall Dea, Var Energi, AGR, OpenGoSim, Cognite, Aize, Sustainable Energy, SINTEF

Project	Type	Objective / TRL	Scope & ship type / Fuel	Companies	Technology
		OCCS technology.			
		TRL: 1-4	**Fuel:** HFO, MDO	**Impact:** Holistic review of emissions reduction, fuel penalty, commercial and technical feasibility of conventional OCCS technologies. Benefits from onboard heat integration. Reduction of emissions by 65%, significant energy penalty at the order of 30%, for a 18million euro CAPEX investment. Carbon price for breakeven at 180 euro/ton CO_2 captured.	
Project: Maritime Efficient & Easy Carbon Capture (ME2CC)	**Type: Funded** by Maritime Masterplan 2024)	**Objective**: Create a scalable, compact OCCS system using patented techniques to reduce dimensions and footprint, while maintaining low pressure drop.	**Scope**: Retrofit Samskip Kvitbjorn with Value Maritime's CO_2 capture system. Capture, store, and deliver CO_2 for reuse or sequestration.	**Companies**: Value Maritime, Samskip Holding, B2B Marine, Fusie Engineers, Devoteq, Brusche Process Technology, Heatmaster, Yard Energy Group	**Technology**: Chemical absorption; Liquid solvent CO_2 saturation
		TRL: Estimated at 7-8	**Fuel:** Fossil	**Impact:** Value chain demonstration.	
Project: MemCCSea	**Type:** European Union Funding (Accelerating CCS Technologies ACT, Horizon 2020)	**Objective**: Develop hyper-compact membrane systems for flexible, cost-effective post-combustion CO_2 capture for over 90% recovery of main engine's CO_2 emissions, 50% overall CO_2 reduction,	**Scope**: Simulation-based integration of the CCS system on the case ship. Review of solvents. Development of ceramic membrane contactors, polymeric-based membranes (permeators), and novel carbon nano-based materials as fillers for mixed matrix membranes (MMM). Modelling of transport processes in ceramic and gas membranes, integrating gas-liquid membrane contactor modules on ships, and optimizing the marinized system through model-based assessments. Techno-economic assessment and feasibility study of the CCS system for optimal marinized operation.	**Companies**: CPERI – CERTH, DNV GL, Fraunhofer, NETL, NTNU, DBI, EURONAV	**Technology**: Membrane separation; Chemical absorption; CO_2 liquefaction

Project	Type	Objective / TRL	Scope & ship type / Fuel	Companies	Technology / Impact, outcome & challenges
		10-fold reduction of system volume and 25% less OPEX compared to conventional amines			
		TRL: 5-6	**Fuel:** Fossil	**Impact:** Assessment of membrane technology on ship performance. Significant emission reduction by 80% with 14% fuel penalty, for a 6.7-million-euro CAPEX investment.	
Project: McKinsey Moller Maersk Zero carbon centre	**Type:** Private Partnership (JDP)	**Objective**: Assess the feasibility, benefits, and challenges of OCCS technology for maritime decarbonization through case studies, evaluating different vessel types, fuel options, and integration approaches.	**Scope**: Analyze the technical, economic, and operational implications of implementing OCCS on container, bulk, and tanker vessels, considering retrofit and NB scenarios, energy requirements, and emissions reduction potential.	**Companies**: Maersk, MAN, ABS, MHI, NYK, Seaspan, TotalEnergies	**Technology**: Chemical absorption (post-combustion)
		TRL: Estimated at 1-4	**Fuel:** Fossil	**Impact:** Advancement in carbon capture technology	
Project: Neptune Lines / Ermafirst OCCS Pilot project	**Type:** Private Partnership (Pilot project)	**Objective**: Install OCCS on Neptune Lines' Tharros RoRo vessel	**Scope**: Receive Class approval for the conversion, install a capture unit onboard, and demonstrate OCCS performance.	**Companies**: Erma First, Neptune Lines	**Technology**: Chemical absorption; Liquid solvent CO_2 saturation
		TRL: Estimated at 7-8	**Fuel:** Fossil	**Impact:** Onboard demonstration of the performance of OCCS chemical absorption.	

Project	Type	Objective / TRL	Scope & ship type / Fuel	Companies	Technology / Impact, outcome & challenges
Project: Remarccable	**Type:** Private Partnership (Engineering study)	**Objective**: Investigate feasibility and demonstrate OCCS installation on Stena Impero	**Scope**: Phase 1: Conceptual design and front-end engineering design study. Phase 2: Engineering, procurement, and construction of a prototype system, if Phase 1 is successful. Phase 3: System integration and conduction of sea trials.	**Companies**: OGCI, GCMD, Stena Bulk, American Bureau of Shipping, Alfa Laval, Deltamarin, Lloyd's Register, Seatrium, TNO	**Technology**: Chemical absorption; CO_2 liquefaction
		TRL: Estimated at 1-4, if pilot materializes: 7-8	**Fuel:** HFO, MGO/MDO	**Impact:** Estimated 9.2% fuel penalty for 19.7% annualized net CO_2 avoided. Abatement cost of €692/tCO_2, which can drop to 177 euro/ton via onboard heat integration. No major technical barriers for OCCS implementation. Challenges: High abatement cost; Lack of infrastructure for CO_2 offloading.	
Project: Seabound / Hapag Lloyd OCCS Project	**Type:** Pilot project, UK Clean Maritime Demonstration Competition Round 3	**Objective**: Demonstrate and optimize Seabound's calcium looping-based carbon capture system on a Hapag-Lloyd chartered container ship. Achieve up to 95% CO_2 capture efficiency	**Scope**:-Install, test, and validate the prototype carbon capture system onboard a 240-meter container ship -Full-scale development, following succesful pilot implementation	**Companies**: Seabound, Lomar, Hapag-Lloyd	**Technology**: CO_2 mineralization / Calcium looping
		TRL: Estimated at 7-9	**Fuel:** Fossil	**Impact:** Estimated 78% carbon capture efficiency (capture rate at unit) and ~1 ton of CO_2 captured per day. Over 90% of sulphur capture efficiency.	
Project: SinOceanic Shipping, Wilhelmsen	**Type:** Private Partnership (Feasibility study)	**Objective**: Establish the foundation for a business case	**Scope**:Design and implementation of CCS technology onboard. '-Commercial and regulatory implications assessment. '-Logistical aspects for scalable CCS design examination.	**Companies**: SinOceanic Shipping, Wilhelmsen, DNV	**Technology**: Chemical absorption; Liquid solvent CO_2 saturation

Project	Type	Objective	Scope & ship type	Companies	Technology
		TRL	Fuel	Impact, outcome & challenges	
OCCS Pilot project		for CCS on a 4,000 TEU container ship, ready for contracting by 2025. Assess feasibility of CCS on a container ship and Explore potential for scaling up to larger vessels in the future up to 16,000 TEU.			
		TRL: Estimated at 1-4	**Fuel:** Fossil	**Impact:** Advancement in CCS technology and successfully demonstrating the technology on a container ship will reduce perceived risks	
Project: SMDERI, Evergreen OCCS Pilot project	**Type:** Private Partnership (Pilot project)	**Objective**: Install SMDERI OCCS system onboard Evergreen's neopanamax container vessel.	**Scope**: -Installation and operational testing of the OCCS system on the vessel. -Offloading and recycling the captured CO_2.	**Companies**: SMDERI, Evergreen	**Technology**: Chemical absorption; CO_2 liquefaction
		TRL: Estimated at 7-9	**Fuel:** Fossil	**Impact:** - Confirmation of safety compliance and offloaded CO_2 quantity by Class NK - Determination of CII's CO_2 emissions deduction from Panama Flag	
Project: Solvang / Wartsila OCCS pilot	**Type:** Enova funding	**Objective**: Install a full-scale OCCS on the vessel Clipper Eris. Demonstrate feasibility, efficiency, and	**Scope**: Implement and validate the OCCS system on the vessel.	**Companies**: Solvang, Wärtsilä, MAN Energy Solutions, SINTEF	**Technology**: Chemical absorption; CO_2 liquefaction

Project	Type	Objective / TRL	Scope & ship type / Fuel	Companies	Technology / Impact, outcome & challenges
		impact on reducing maritime CO_2 emissions			
		TRL: Estimated at 7-9	**Fuel:** HFO	**Impact:** Demonstration of OCCS pilot Advancement in onboard carbon capture technology, making it more efficient and scalable for deep-sea shipping Significant reduction in CO_2 emissions with an expected CO_2 capture rate of 70-80%	
Project: STDR Marine, DNV OCCS Feasibility	**Type:** Private Partnership (Feasibility study)	**Objective**: OCCS feasibility study for a 85,000 DWT Kamsarmax bulk carrier	**Scope**: Techno-economic analysis of OCCS implementation for a 85,000 DWT bulk carrier of STDR Marine	**Companies**: STDR Marine, DNV	**Technology**: Post combustion onboard carbon capture
		TRL: Estimated at 1-4	**Fuel:** Fossil	**Impact:** Advancement in carbon capture technology, making it more efficient and scalable for bulk carriers	
Project: TMS Tankers, DNV OCCS feasibility study	**Type:** Private Partnership (Feasibility study)	**Objective**: Assess the feasibility of retrofitting a chemical-absorption-based OCCS system on a Suezmax vessel.	**Scope**: OCCS equipment feasibility study for retrofit an OCCS system onboard a Suezmax Tanker. Different scenarios explored with regards to heat integration, solvent performance, and their combinations. The study compared the cost-effectiveness of OCCS with biofuels, finding that OCCS can be more cost-effective for reducing CO_2 emissions. Analysis of the components needed for an OCCS system, including absorber and regeneration stacks, a liquefaction plant, and CO_2 storage tanks.	**Companies**: TMS Tankers Ltd, DNV	**Technology**: Chemical absorption; CO_2 liquefaction
		TRL: 1-4	**Fuel:** Fossil	**Impact:** Estimated CO_2 emission reduction ranging from 11% to 38% depending on the technology and setup used, at 5-24% fuel penalty. CO_2 breakeven value 135-225 euro/t of CO_2 captured annually.	

Project	Type	Objective / TRL	Scope & ship type / Fuel	Companies / Impact, outcome & challenges	Technology
Project: Value Maritime OCCS system installation projects	**Type:** Private Partnership (Pilot project)	**Objective**: Installation of Value Maritime’s OCCS system onboard M/T Pacific Cobalt	**Scope**: Installation and full integration of Value Maritime CO_2 Battery technology: Chemical absorption with liquid saturation technology at a capacity of 200 CO_2 tons in a single voyage.	**Companies**: Eastern Pacific Shipping, Value Maritime	**Technology**: Chemical absorption; Liquid solvent CO_2 saturation
		TRL: Estimated at 7- 9	**Fuel:** Fossil	**Impact:** OCCS demonstration.	
		Objective: Installation of Value Maritime’s OCCS system onboard JR Shipping's container feeder vessel, MV Energy	**Scope**: Installation and full integration of Value Maritime CO_2 Battery technology.	**Companies**: Value Maritime, JR Shipping	
		TRL: Estimated at 7- 9	**Fuel:** Fossil	**Impact:** OCCS demonstration.	
		Objective: Installation of Value Maritime’s OCCS system onboard Eastway vessels Atlantis A and X-Press Elbe	**Scope**: Installation and full integration of Value Maritime CO_2 Battery technology. Offload CO_2 batteries at European greenhouses for reuse of CO_2 to grow crops or flowers.	**Companies**: Value Maritime, Eastway	
		TRL: Estimated at 7- 9	**Fuel:** Fossil	**Impact:** OCCS demonstration.	

Project	Type	Objective / TRL	Scope & ship type / Fuel	Companies / Impact, outcome & challenges	Technology
		Objective: Install of Value Maritime's OCCS system onboard two Samskip container vessels.	**Scope**: Installation of the OCCS system on Samskip Innovator and Samskip Endeavour 803 TEU container ships. Capture and store CO_2 into ISO tank containers on deck. Offload the so-called CO_2 batteries in port for consumers such as greenhouses and return empty for the next voyage.	**Companies**: Value Maritime, Samskip	
		TRL: Estimated at 7- 9	**Fuel:** Fossil	**Impact:** OCCS demonstration.	
		Objective: Install of Value Maritime's OCCS system LR1 product tanker Nexus Victoria	**Scope**: Installation of the OCCS system on Nexus Victoria 75,000DWT LR1 product tanker.	**Companies**: Value Maritime, Mitsui O.S.K. Lines, Ltd. (MOL)	
		TRL: Estimated at 7- 9	**Fuel:** Fossil	**Impact:** OCCS demonstration. Estimated emissions reduction 10%, with potential scalability to 30%.	

Table 0-2 Inventory: Projects related to CO_2 value chain, potentially affecting OCCS technologies – Terminal and LCO_2 transportation.

Project	Type	Objective	Scope	Companies	Relevance
CETO – CO_2 efficient transport via ocean	Private Partnership (JIP)	Reduce risks and uncertainties related to the design, construction, and operation of a low-pressure CO_2 ship transport chain Prove the feasibility and reliability of a low-pressure CO_2 value chain for large-scale transportation of liquid CO_2	Design an LCO_2 ship with low-pressure tanks and cargo handling systems Test materials and conduct medium-scale testing and process simulations Evaluate conditioning and liquefaction Provide fundamental knowledge and experience applicable to any low-pressure CO_2 transport chain	DNV, Equinor, Gassco, Shell, TotalEnergies	CO_2 liquefaction
Stella Maris	Governmental Funding (Engineering study & Pilot Project, CLIMIT)	Evaluate the feasibility of large-scale marine CO_2 transport, offshore offloading, intermediate storage, and continuous injection into subsea saline aquifers for cost-effective CCS solutions.	Explore technical solutions for CO_2 logistics, including shuttle tankers, offshore offloading systems, and Floating Storage and Injection Units (FSIU) Assess maximum-size storage solutions Evaluate operational risks and regulatory compliance to develop a scalable CO_2 transport and storage network	Moss Maritime AS, TGE Marine Gas Engineering GmbH, Sevan SSP AS, APL Norway AS, DNV	LCO_2 transportation and disposal
CO_2next	European Union Funding (Connecting Europe Facility CEF Energy)	Explore the construction of an independent, open-access terminal for liquid CO_2 at the Maasvlakte in the Port of Rotterdam.	Potential launch by 2029 with a capacity of 5.4 Mtpa, expandable to 15 Mtpa. Key features include 2 jetties for liquid CO_2 delivery, 6 spherical tanks for temporary CO_2 storage, and connection with an offshore pipeline.	Gasunie, Vopak, TotalEnergies and Shell	LCO_2 terminal and disposal
Antwerp@C CO_2 Export Hub	European Union Funding (Connecting Europe Facility CEF Energy)	Develop open-access infrastructure for CO_2 transport, liquefaction, and loading onto ships for offshore storage	Capture CO_2 from industrial sites in the Antwerp port area and transport it through an intra-port pipeline network. Construct a shared terminal with a CO_2 liquefaction unit, buffer storage, and marine loading infrastructure for cross-border shipping. Aim for an export capacity of 2.5 Mtpa, with potential expansion to 10 Mtpa by 2030.	Air Liquide, Fluxys, Port of Antwerp-Bruges	LCO_2 terminal and disposal
Ghent Carbon Hub	European Union Funding (Connecting Europe Facility CEF Energy)	Study the Ghent Carbon Hub project, an open-access, multi-modal CO_2 storage and liquefaction terminal at North Sea Port.	Integrate a CO_2 pipeline network linking the Walloon region to the hub in Ghent. Develop open-access infrastructure with a CO_2 storage and liquefaction terminal, and a pipeline network collecting CO_2 from various emitters. Load liquefied CO_2 onto ships for permanent offshore storage. Process up to 4 million tonnes of CO_2 per year. Connect Mons and Ghent to provide export options for CO_2 emitters in Wallonia.	Fluxys Belgium, North Sea Port, ArcelorMittal Belgium	LCO_2 terminal and disposal

Project	Type	Objective	Scope	Companies	Relevance
			Final investment decision expected in 2025, with operations targeted to begin by 2027.		
Zeebrugge Multi-molecule Hub	PCI funding	Transform the Zeebrugge LNG terminal into a multi-molecule hub supporting large-scale decarbonization by integrating services for hydrogen, CO_2 transport and storage, and carbon-neutral fuels.	The project involves expanding the terminal's infrastructure to handle hydrogen, synthetic methane, and CO_2	Fluxys	LCO_2 terminal and disposal
$GOCO_2$	European Union Funding (Connecting Europe Facility CEF Energy)	To capture CO_2 emissions and transport them via pipeline to the Montoir-de-Bretagne terminal for permanent geological storage.	FEED study phase for the Grand Ouest CO_2 infrastructure	Elengy, partners committed Heidelberg Materials, Lafarge and Lhoist.	LCO_2 terminal and disposal
D'Artagnan: Dunkirk CO_2 Hub Phase I	European Union Funding (Connecting Europe Facility CEF Energy)	The D'Artagnan CO_2 Hub project aims to establish open-access infrastructure in France for CO_2 transport, liquefaction, and export from hard-to-abate industries in Dunkirk.	Phase I includes a 37 km pipeline and a CO_2 export terminal, set to operate by the end of 2027, supporting European CO_2 transport and storage initiatives.	Air liquide, Fluxys, Terminal CO_2 dunkerque, Gaz-opale, Dunkerque lng	LCO_2 terminal and disposal
ECO_2CEE	Project of Common Interest PCI	Gdansk terminal	Develop an open-access CCS concept in Lithuania and Poland. The terminal will accommodate CO_2 delivered via rail and pipelines, transporting liquid CO_2 by train to the Gdańsk terminal for temporary storage before loading onto ships for offshore storage.	Air liquide, Lafarge, Orlen	LCO_2 terminal and disposal
Coda Terminal	European Union Funding (Innovation Fund)	Reduce CO_2 transport and storage costs by creating a scalable land-based carbon mineral storage terminal in Straumsvik, Iceland. Achieve permanent CO_2 storage as carbonate minerals using Carbfix technology.	Inject captured CO_2 into basaltic rocks for permanent storage. Lower costs to 13 €/tCO_2. Manage maritime transportation with innovative low-pressure tank designs by Dan-Unity CO_2. Store 21 million tons of CO_2 over ten years. Address over half of Iceland's annual emissions and about 2.5% of the EU's required reductions by 2030. Start operation by April 1, 2026.	Carbfix, Dan-Unity CO_2	LCO_2 terminal and disposal; LCO_2 tank
$APOLLOCO_2$ project	Project of Common Interest PCI, application for Connecting	The $APOLLOCO_2$ project aims to establish large-scale CCS infrastructure in South-Eastern Europe, aggregating CO_2 from local emitters in Greece to a central liquefaction terminal. It will connect emitters to a terminal	Key infrastructure elements include CO_2 aggregation in southern Greece through 260 km of land-based and 15 km offshore pipeline, land-based and offshore liquefaction, and buffer storage	DESFA	LCO_2 terminal and disposal

Project	Type	Objective	Scope	Companies	Relevance
	Europe Facility	on Revithoussa Island and transport liquefied CO_2 by low-pressure ships to storage facilities in Prinos, Ravenna, or other EU locations.	at Revithoussa Island. The facilities will handle 5 MTPA, with potential expansion to 10 MTPA.		
Norne Carbon Storage Hub	Project of Common Interest PCI, co-funded by the European Union	CO_2 reception facilities, pipelines, and wells in Denmark, designed to and permanently store CO_2 in deep natural geological reservoirs.	Develop a large-scale CO_2 storage network in Denmark by 2030, comprising reception facilities, pipelines, and dedicated wells for transporting and injecting domestic and international CO_2 into existing natural underground reservoirs. The project aims to store over 15 million tons of CO_2 annually by the mid-2030s.	Fidelis, Ross Energy, Ramboll, Port of Aalborg, Kalundborg Havn	CO2 reception facilities
Longship	Public-Private Partnerships	Develop a full-scale CCS value chain in Norway, integrating CO_2 capture, transport, and geological storage to support industrial decarbonization	Capture CO_2 from industrial sources Transport CO_2 via ships to a terminal Inject CO_2 into the Northern Lights offshore storage site Lay the foundation for future CCS initiatives across Europe	Heidelberg Materials, Hafslund Celsio, and the Northern Lights consortium (Equinor, Shell and TotalEnergies)	LCO_2 terminal and disposal
Northern Lights		Establish large-scale, open-access CO_2 transport and storage infrastructure for Northern Europe, enabling industrial emitters to reduce their carbon footprint by storing CO_2 in deep saline aquifers.	The project transports liquefied CO_2 from capture sites to a terminal near Bergen, Norway, where it is injected into a subsea geological formation using existing offshore infrastructure.	Partnership between Equinor, Shell and TotalEnergies	LCO_2 terminal and disposal

Appendix B Suezmax cost economic analysis

■ Vessel overview

For the Suezmax vessel, the main dimensions and machinery are shown in Table 0-3.

Table 0-3 Suezmax base case vessel main dimensions and machinery.

Suezmax tanker case study – Vessel specifications	
First year in service	2025
DWT	Appr. 160,000 tons
Lightweight	Appr. 25,000 tons
Propulsion system	1 x 2-Stroke Diesel engine of abt. 13.5 MW
Electricity supply	3 x 4-stroke Diesel engines of 1.3 MW each
Heat supply	1 x composite boiler 2 x auxiliary boilers

The analysis of the vessel's voyage operating profile is shown in Figure 0-1, where the percentage of time at low speeds (below 7 knots), speeds between 7 and 14 knots and 14 knots and higher are shown along with the percentage of time vessel spends at anchorage and at operations. Vessel is considered to trade for an average round trip of 40 days, meaning appr. 9 round trips per year. Operation profile data are extracted from AIS. Vessel is assumed not to engage in Cargo Heating Operations.

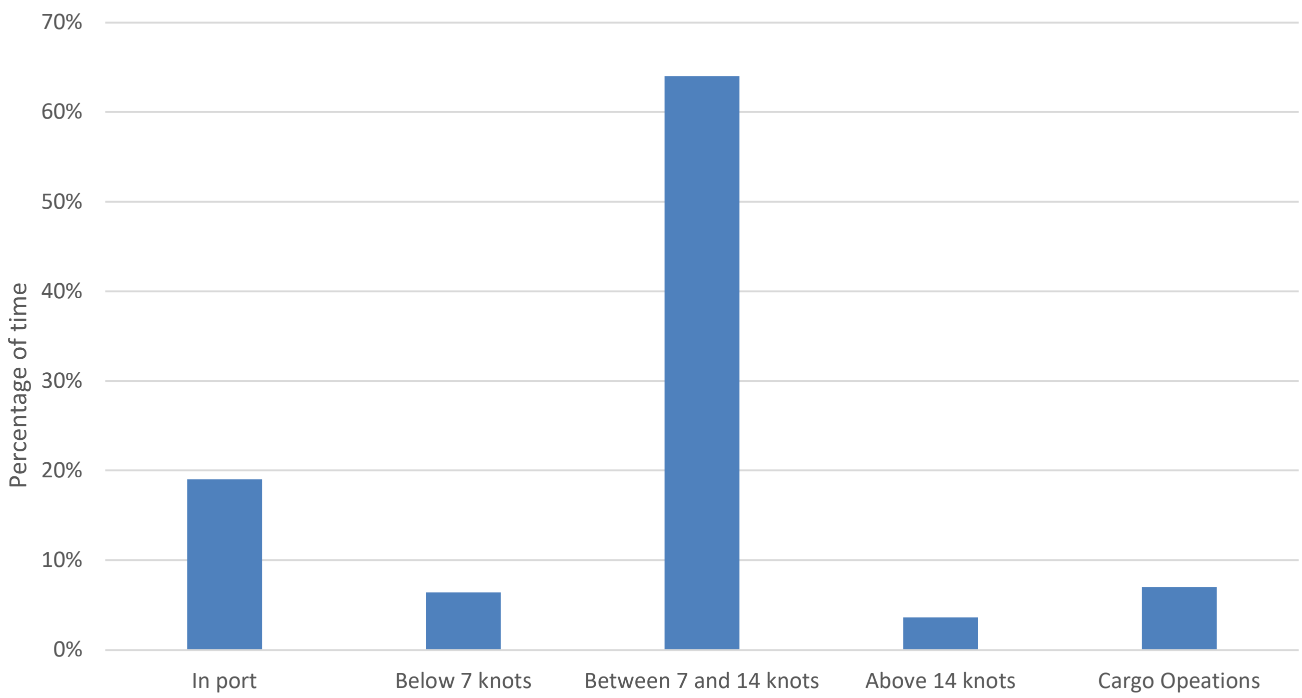

Figure 0-1 Suezmax operating profile.

- **<u>Technology selection</u>**

The Suezmax vessel's operational profile, characterized by relatively long voyage durations, sufficient onboard space, and stable engine load conditions, makes it a suitable candidate for the integration of chemical absorption systems.

Chemical absorption technology can be integrated with the vessel's existing machinery, utilizing waste heat from the engines to minimize additional energy requirements, which is an additional advantage for its selection.

A Suezmax vessel provides well suited deck space to accommodate the OCCS components and the liquid CO_2 storage tanks. The space that will be examined for installation of the OCCS (including CO_2 liquefaction plant) is behind vessel's funnel and for the LCO_2 storage tanks is the space forward of the accommodation. Same is shown in more details in the next sections of this chapter.

- **<u>CO_2 performance analysis</u>**

The OCCS technology is examined for sweeps of CO_2 capture capacity. The results from 1, 2 & 3 TPH are presented, as these present options that are reasonable in terms of LCO_2 storage and maintain the operation of the Aux Gens and boilers within manufacturer and redundancy limits (load below 90%, 1 Aux D-G on standby).

The analysis presumes the availability of a suitably sized "donkey" boiler to bridge the operational gap between the composite boiler's maximum capacity and the auxiliary boiler's minimum load. This configuration ensures that, when steam demand exceeds the composite boiler's output but remains below the auxiliary boiler's threshold, the system avoids operating the auxiliary boiler at suboptimal load conditions. This arrangement minimizes steam dumping and enhances overall thermal efficiency.
While this is expected to have a minimal impact on the NB case, as it can be incorporated into the design, this may require a design consideration for the retrofit case.

For the analysis of OCCS technology in terms of energy efficiency a state-of-the-art system is considered for both the NB and retrofit vessels with:
- solvents reducing additional heat demands for the chemical solvent regeneration (assumed at 2GJ/ton of CO_2).
- compression stage assuming energy demand at the order of 300kWh/ton of CO_2.

In the case of the NB vessel two additional considerations will take place:
- Properly sized AEECOs for the OCCS, sized to the capacity of the exhaust gas enthalpy from the Auxiliary Engines (including two exhaust gas boilers for the auxiliary generator sets)
- Installation of PTO of 1.8 MW (to cover vessel's electrical demands during sailing, including OCCS)

Table 0-4 Suezmax case - Technology Components for each configuration.

Design / Components	Aux. Engines' Economizers	PTO
Retrofit	-	-
Newbuilding with AEECOs	X	-
Newbuilding with PTO	-	X

Table 0-5 State of the art OCCS Energy requirements.

OCCS Energy Requirements	
Electric demands [kWh/ton CO_2]	300
Solvent Regeneration [GJ/ton CO_2]	2.0

Comparative analysis

Results of the analysis for the capture rate of 1, 2 and 3 TPH are shown in Figure 0-2.

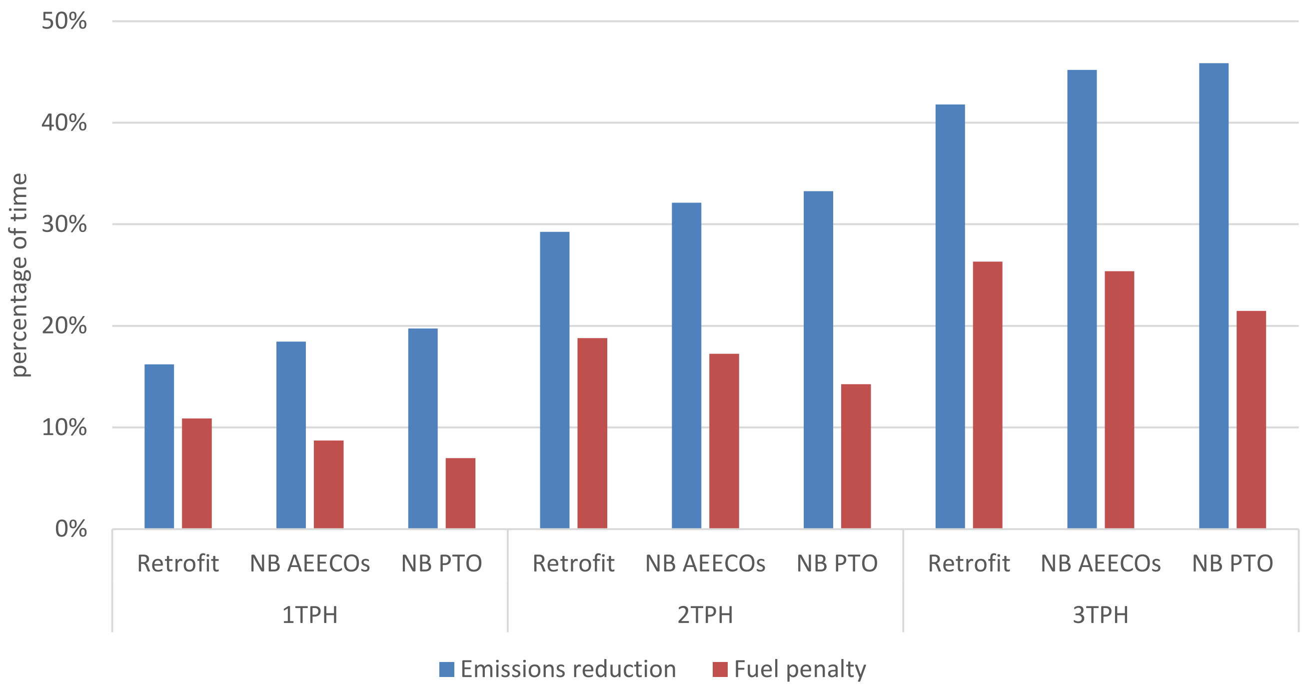

Figure 0-2 Suezmax - Emissions reduction vs Fuel penalty.

CO_2 performance

A typical round trip for the vessel has a duration of approximately 40 days, as illustrated in the voyage profile shown in Figure 0-1. Based on this operational cycle, the vessel is expected to complete around nine round voyages per year. This frequency forms the basis for evaluating the annual performance of the onboard systems, particularly in terms of fuel consumption and emissions.

The yearly assessment includes the total consumption of fuel in metric tons, the corresponding total CO_2 emissions generated, and the amount of CO_2 captured in each case. Additionally, the analysis presents the net CO_2 emissions released into the atmosphere after capture, as well as the total quantity of CO_2 abated. These metrics provide a comprehensive overview of the environmental performance of the vessel and the effectiveness of the OCCS in reducing GHG emissions.

The yearly CO_2 performance results are shown Figure 0-3.

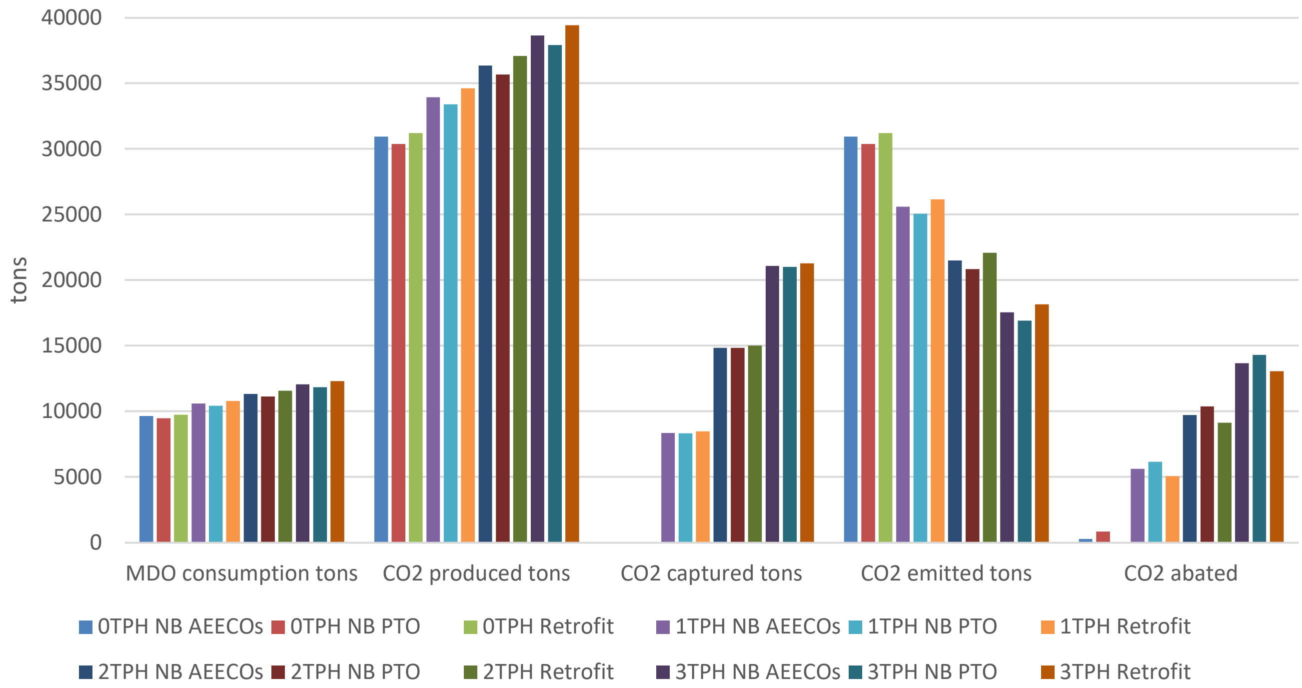

Figure 0-3 Suezmax - OCCS yearly performance.

OCCS impact on machinery performance

In this section an overview of the effect of the OCCS technology on the different machinery of the vessel (Aux. Engines and Boilers) will be presented.

Figure 0-4 illustrates the impact of the different OCCS capture rates on the utilization of key machinery components, specifically the main engine and auxiliary engines, during laden sailing at a service speed of 13 knots, which is the average speed of the vessel. As the OCCS capture rate increases from 1 TPH to 3 TPH, the load on the two auxiliary engines rises from 52% to 75%. Notably, when the PTO system is employed, the main engine and PTO can meet the additional electrical demand imposed by the OCCS system, thereby eliminating the need to engage auxiliary generators.

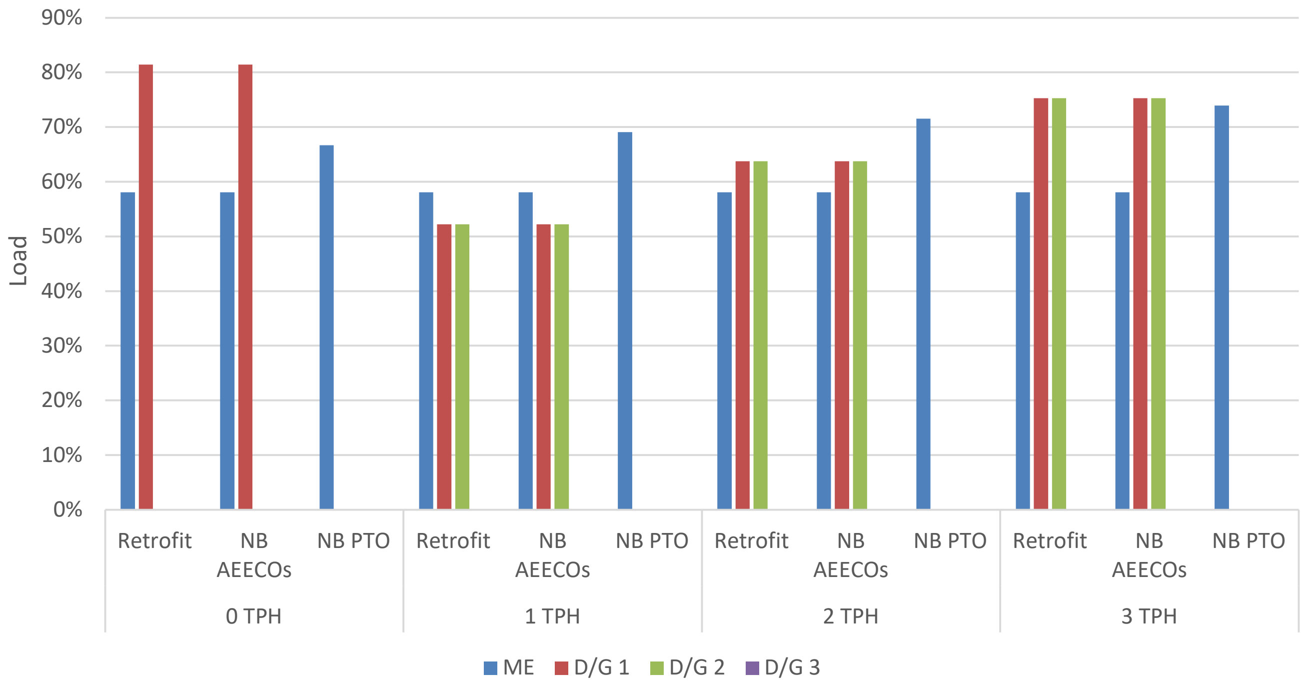

Figure 0-4 Suezmax - OCCS Impact on Main Engine and Aux. Engines at 13 knots in laden condition.

The OCCS has additional heat demands which are covered from vessel’s existing exhaust section of composite boiler and from the oil section of composite boiler, whenever the exhaust section of composite boiler capacity is not sufficient.

Figure 0-5 shows the total steam demand of the vessel including the ones of the OCCS, during laden sailing at a service speed of 13 knots. For this reason, the cases without the OCCS have been included in the graph as well.

As can be seed from the graph, regardless of the technology equipped the total steam demands remain steady for the same carbon capture rate.

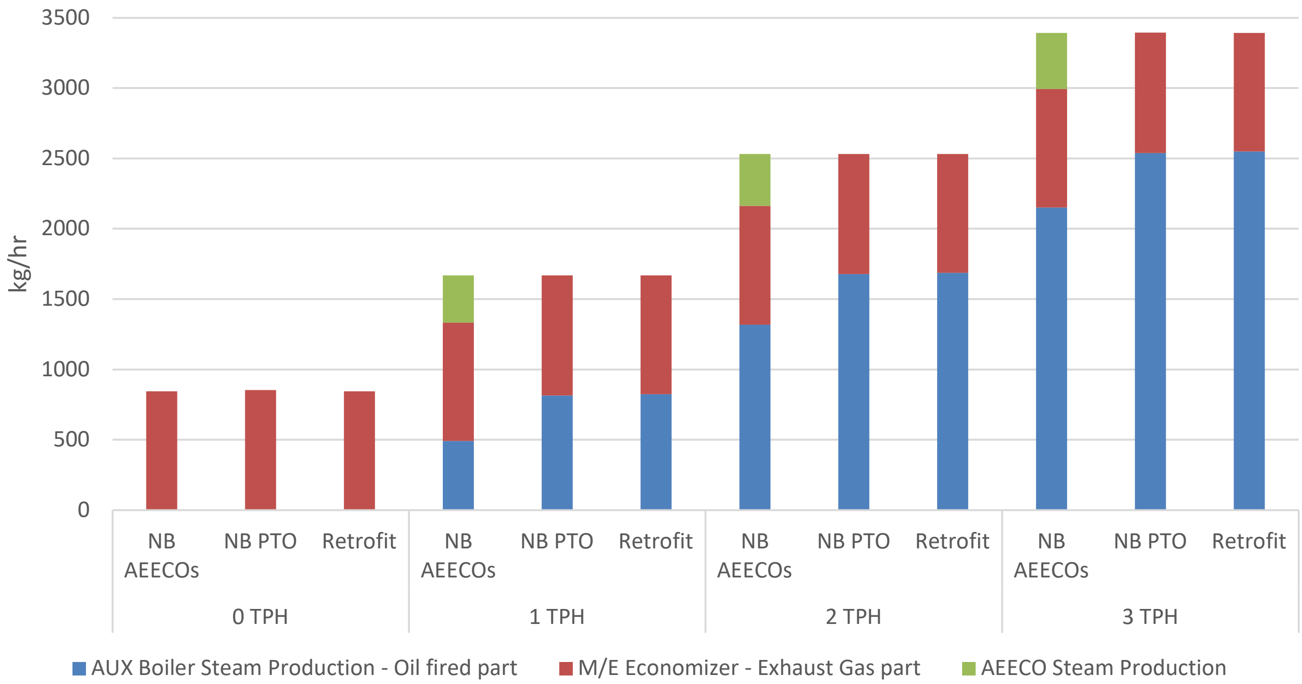

Figure 0-5 Suezmax - OCCS Impact on Aux. boiler & Economizers at 13 knots in laden condition.

- **<u>Economic impact analysis</u>**

CO_2 abatement cost

CO_2 abatement cost analysis will present the cost associated with reducing one metric ton of carbon dioxide emissions compared to the baseline scenario for each of the examined cases.

The CO_2 abatement cost assessment is conducted for both the newbuilding and the retrofit cases and evaluated under three implementation cost scenarios: low, average, and high. All financial figures are discounted to the base year 2025, with a discount rate of 8% applied (Xiaobo Luo, 2017), (Sadi Tavakoli, 2024).

The CO_2 abatement costs per tons of abated CO_2 are shown in Figure 0-6 for each of different scenarios, low, base and high. The retrofit case shows the worst performance in terms of CO_2 abatement costs compared to the optimized newbuilding cases. From the optimized newbuilding cases, the case with the PTO provides the better results.

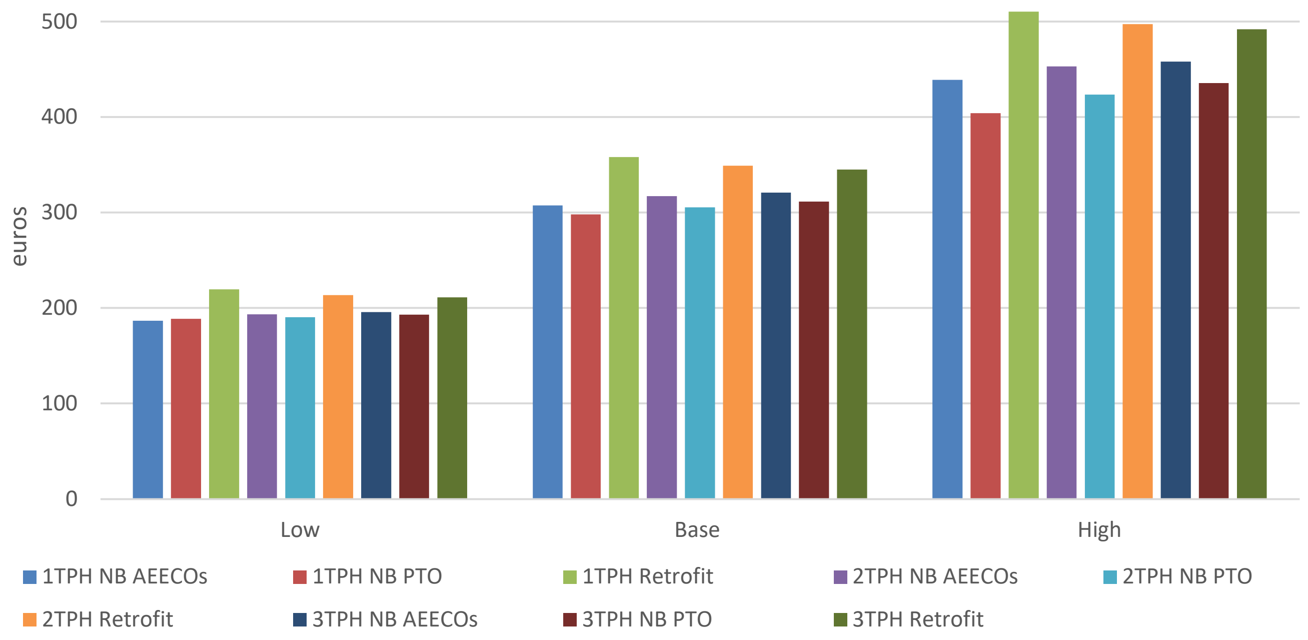

Figure 0-6 Suezmax - CO_2 abatement cost per tons CO_2 abated.

CAPEX / OPEX calculation

In this section a more detailed overview of the CAPEX costs per case is done. For CAPEX costs the following technologies are considered:

- CCS
- PTO
- AEECOs

For the PTO CAPEX an additional installation of 1,000,000 euros is considered for the Suezmax vessel.

Figure 0-7 presents the CAPEX analysis results across the various examined cases and scenarios.

The analysis indicates that the optimized newbuilding equipped with PTO exhibits the highest CAPEX, followed by the optimized newbuilding with AEECOs, while the retrofit case demonstrates the lowest CAPEX.

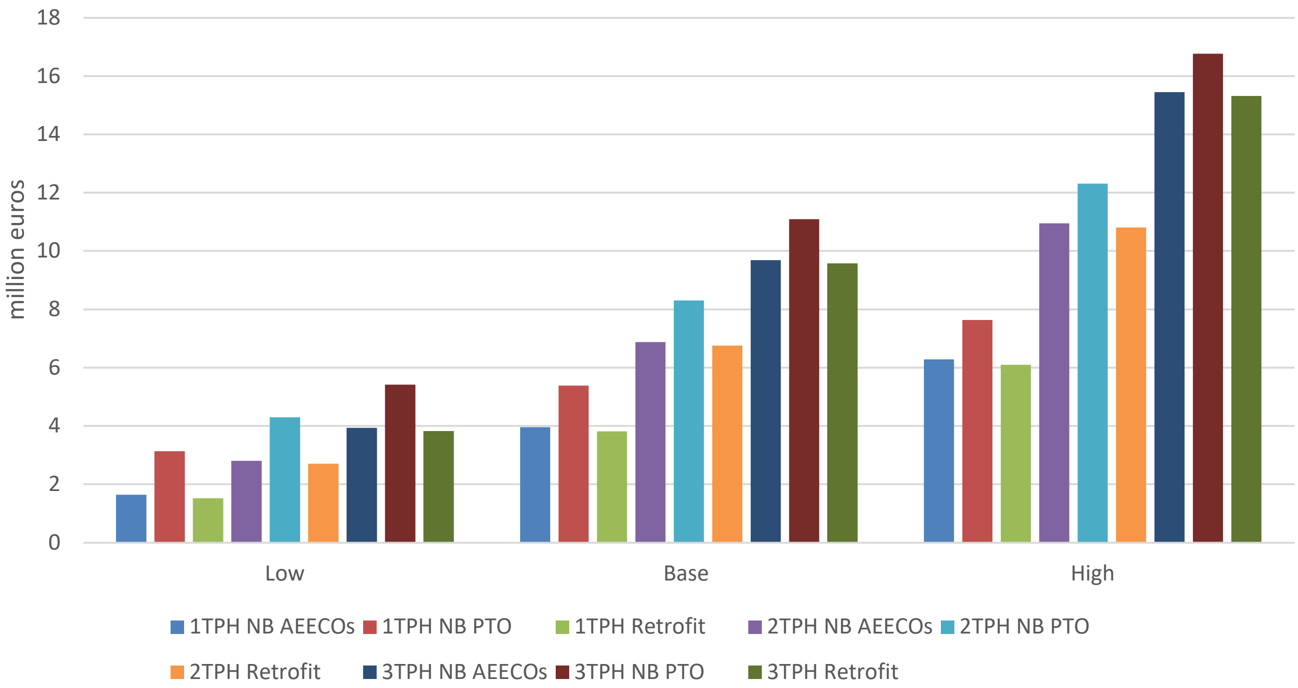

Figure 0-7 – Suezmax - CAPEX analysis.

In order to estimate the yearly fuel OPEX for the examined cases, prices are assumed as per Table 3-15. The fuel OPEX results are shown in Figure 0-8 for all examined cases. As can be seen for all the different OCCS capture rates, the case of the newbuilding design with the PTO provides the lower yearly fuel OPEX.

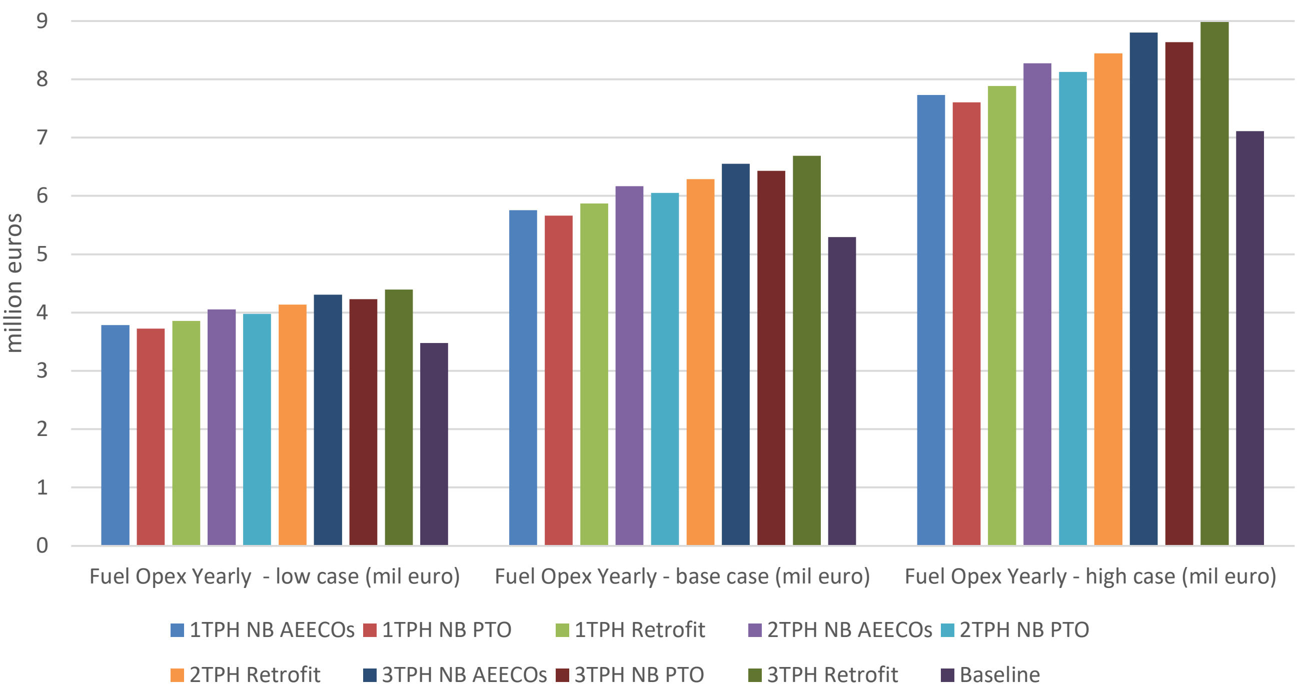

Figure 0-8 Suezmax - Yearly Fuel OPEX in mil. Euro.

Economic analysis of disposal cost

For the economic analysis of the disposal cost, the assumptions made are shown in 3.2.1. With these assumptions the disposal cost for the captured CO_2 on a yearly basis for the Suezmax vessel is shown in Figure 0-9.

As can be seen, the retrofit scenario comes with a slightly higher CO_2 disposal cost compared to the optimized newbuilding case.

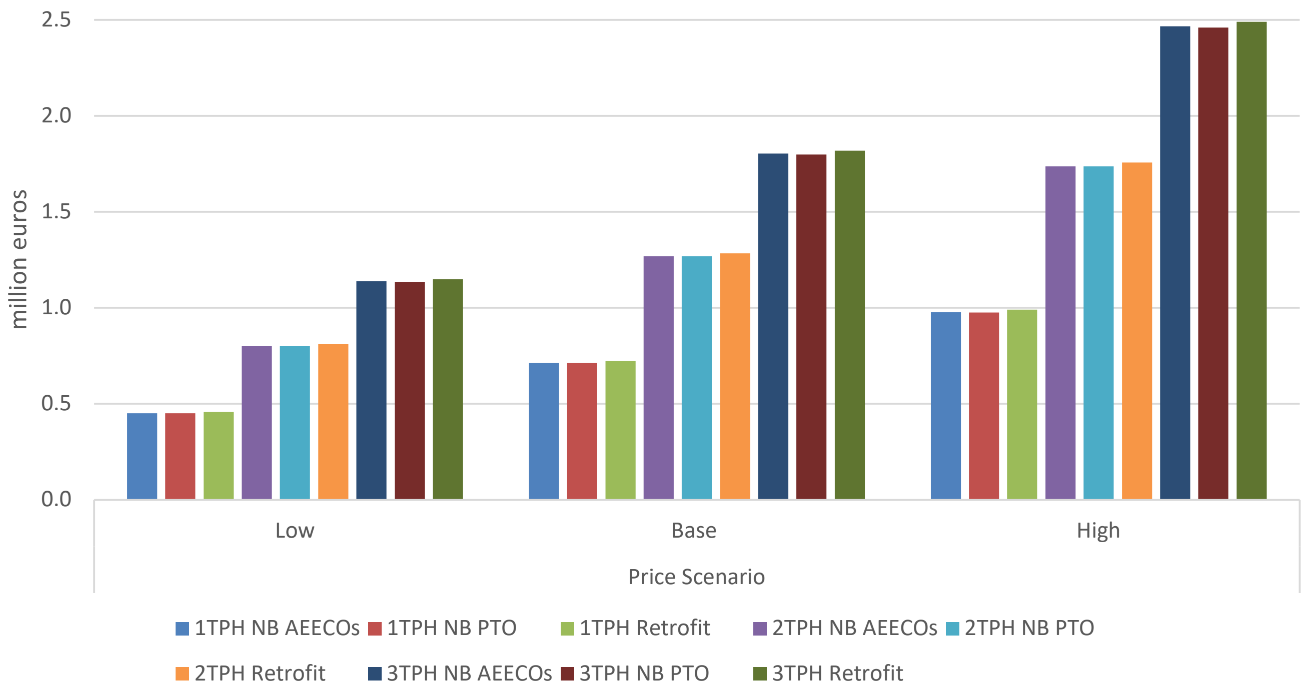

Figure 0-9 Suezmax - Yearly disposal cost of CO_2.

CO_2 abatement cost per ton of Captured CO_2 – sensitivity analysis

Following the evaluation of various cost metrics, namely CAPEX, fuel OPEX, and CO_2 disposal costs, a sensitivity analysis was conducted to assess their impact on the overall CO_2 abatement cost. This analysis, illustrated in Figure 0-10, shows the case of the OCCS system with a capture rate of 2 TPH.

The results indicate that the CO_2 disposal cost and fuel OPEX exert the most significant influence on the abatement cost. These are followed by the technology CAPEX and maintenance costs, which have a moderate impact. In contrast, the cost of solvents contributes minimally to the overall CO_2 abatement cost.

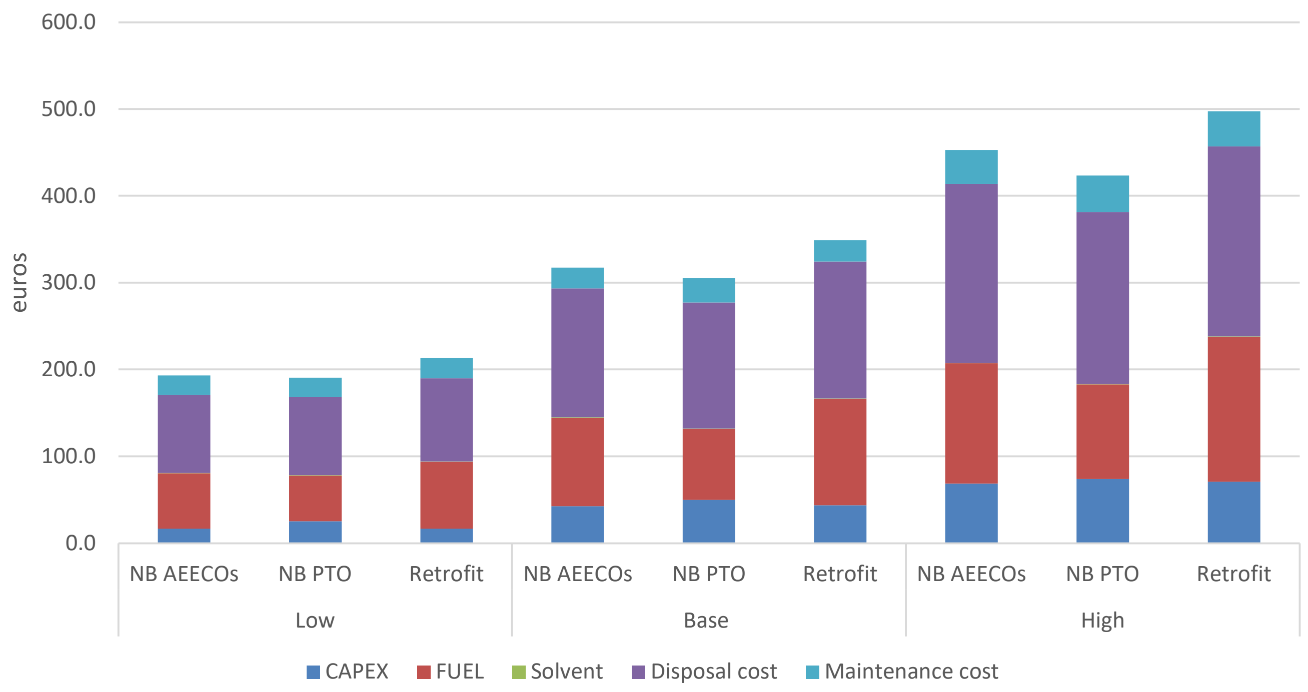

Figure 0-10 Suezmax - CO_2 abatement cost per ton CO_2 sensitivity analysis for the 2 TPH capture rate.

Port offloading and ship interface analysis

The displaced vapor results are showcased in tons, according to the different CO_2 capture rates and vessel tank sizes as shown in Figure 0-11. The required energy of the systems involved (pump, heater and cooler) is showcased separately for each vessel and CO_2 capture rates in kWh in Figure 0-12.

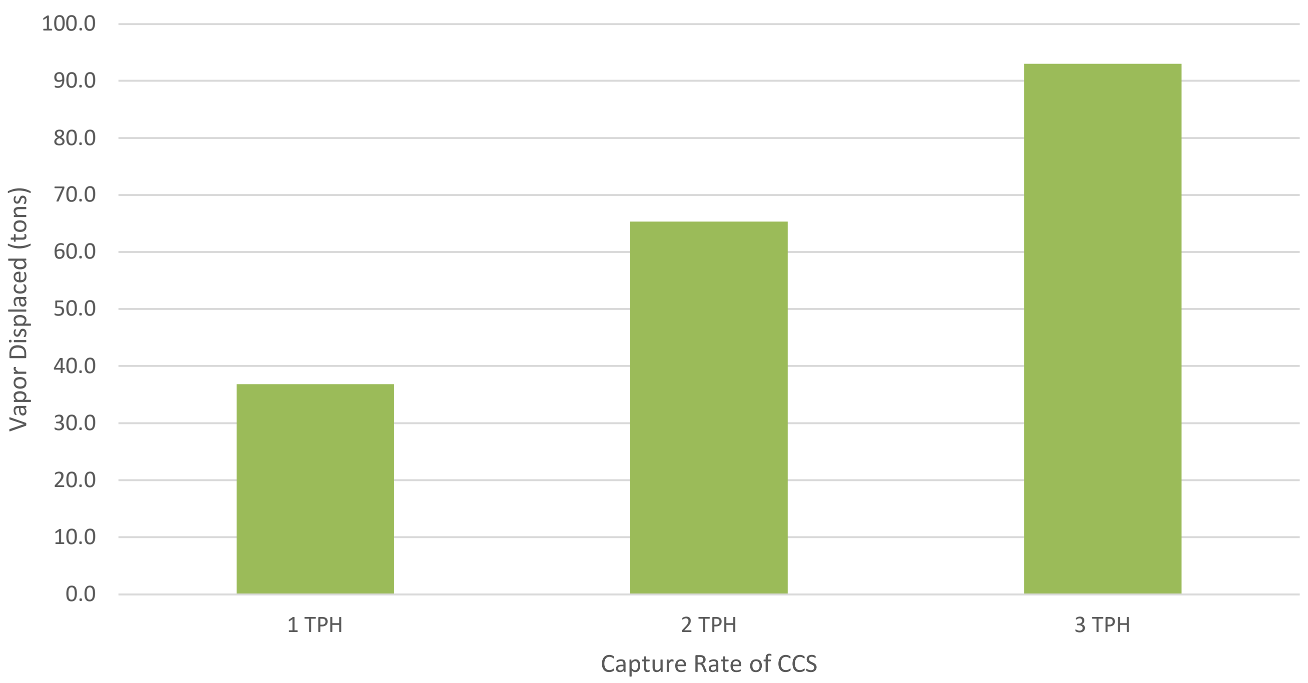

Figure 0-11 Suezmax - displaced vapor during offloading per capture rate, assuming an offloading rate of 250 m^3/hr.

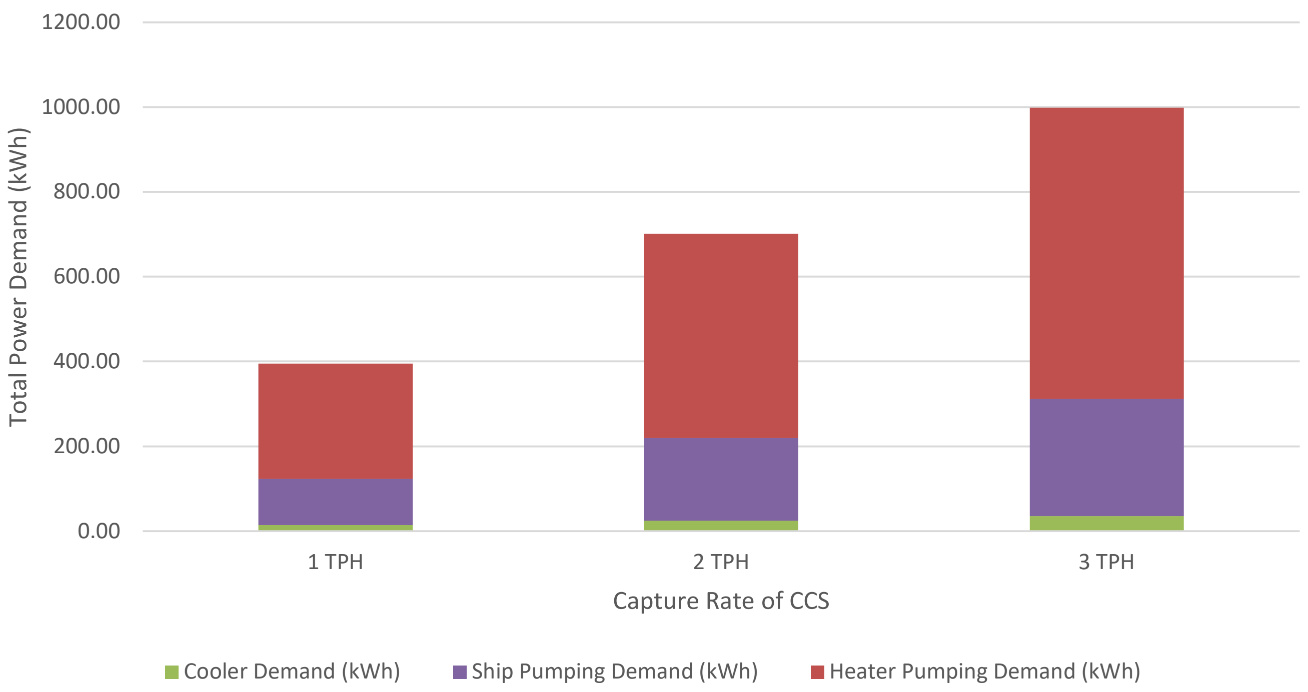

Figure 0-12 Suezmax - total required energy during offloading, assuming an offloading rate of 250 m^3/hr.

- **Technical impact analysis**

This section presents a high-level analysis of the potential impact associated with the installation of the OCCS on the vessel. The objective is to guide the reader through the key considerations and preliminary assessments required when evaluating the feasibility and implications of OCCS integration on the Suezmax tanker.

When installing an OCCS considerations related to the following items should be made:

- Absorber and regeneration stacks
- Liquefaction plant
- LCO_2 tanks
- Required space and installation location for the relevant components
- Additional weight
- Effect on vessel's structural integrity
- Effect on vessel's stability
- Piping and rerouting
- Maintenance
- Conflict with cargo operations

Conflict of cargo operations is regarded insignificant for oil tankers in general.

Additional maintenance and inspections are regarded marginal, but for the supporting structure above and below deck of the heavy LCO_2 tanks, there are new critical areas subject to inspection like for stringer heels and hopper tank knuckles.

The deck of oil tankers is also relatively strong with many bulkheads below deck which may be well suited to support the heavy deck loads. In case of retrofit, the additional girders, stiffeners and brackets and the increased thickness of existing structure is regarded moderate to small.

LCO_2 storage tanks capacity and dimensions estimation

The estimations for the required capacity of the LCO_2 tank, for an average round trip voyage profile of appr. 40 days, considering a margin of +10% (unforeseen delays/ extended cargo operations) is shown in Table 0-6. LCO_2 storage tanks are considered to be filled up to 95% of their volume. LCO_2 density is assumed at 1,110 kg/m^3. Capacity of the LCO_2 is given on an average basis per different capture rates, since the different cases (optimized newbuilding with PTO or AEECOs and retrofit) have slight differences in the captured CO_2 quantities.

Table 0-6 Suezmax - LCO_2 Storage Tanks specifications.

LCO_2 Storage Tanks specifications				
Capture rate of OCCS	CO_2 captured per 40 days+10% margin (m^3)	LCO_2 total required capacity (m^3)	Tank D x L (m) (per storage tank)	Total weight including LCO_2 (tons)
1 TPH	880	930	6 x 19	1250
2 TPH	1560	1650	7 x 22	2200
3 TPH	2210	2350	8 x 26	3000

For the Suezmax case, it is assumed that the system has two equally sized LCO_2 storage tanks, instead of one, since this arrangement will better utilize the available space onboard the Suezmax's deck.

OCCS impact on vessel space demands

LCO_2 Storage Tanks

The two LCO_2 storage tanks are fitted on the main deck, port and starboard, in front of the accommodation area as shown in Figure 0-13. This placement utilizes the available deck space efficiently and ensures easy access for maintenance and offloading.

- Newbuilding: In a newbuilding scenario, the design of the vessel can be optimized from the outset to accommodate the LCO_2 storage tanks. This allows for integration with minimal impact on the vessel's overall design.
- Retrofit: In a retrofit scenario, existing structures may need to be modified to fit the CO_2 tanks. This could involve reinforcing the deck or relocating other equipment, such as bollards or ballast tank vents and possibly foam cannons.

Since the installation location of the LCO_2 storage tanks and the OCCS are located on the deck area of the Suezmax, these areas are usually not classified as gas dangerous areas. Nevertheless, welding to deck is potentially an issue for the retrofit case.

Nevertheless, if the installation location of the OCCS or the LCO_2 storage tanks is classified as a hazardous area, additional safety measures must be implemented. This includes ensuring that all associated electrical equipment, such as sensors and instrumentation, are certified for use in explosive atmospheres (e.g., EX-certified).

To mitigate the need for hazardous area compliance, an alternative approach may involve installing the tanks above deck, outside the classified zone. However, this solution requires further structural analysis, as it introduces additional loads, up to 10% additional weight of the storage tank, and necessitates reinforcement of the supporting structure, potentially impacting the vessel's overall weight and stability.

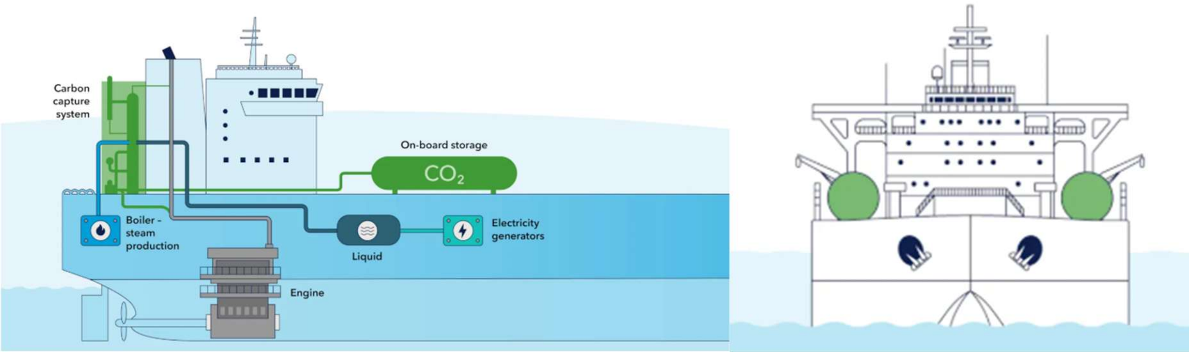

Figure 0-13 Potential location of OCCS system & LCO_2 storage tanks onboard a Suezmax vessel. Source: https://www.dnv.com/expert-story/maritime-impact/on-board-carbon-capture-and-storage-equipment-feasibility-study/ .

Carbon Capture System

The absorber and regeneration stacks can be installed right behind the vessel's funnel. This location leverages the existing structures and minimizes interference with other operations of the vessel. In terms of piping this placement will result in long additional piping.

- Newbuilding: For newbuilds, the OCCS can be integrated into the vessel's design from the beginning. This ensures optimal placement and weight distribution, enhancing the vessel's stability and operational efficiency.
- Retrofit: Retrofitting the OCCS requires advance planning to integrate it with the existing structures. This may involve additional engineering work to ensure the system does not interfere with the vessel's existing operations.

In both newbuilding and retrofit, the OCCS system will be required to be placed on dedicated strengthened supports, in order to not interfere with vessel's mooring operations.

Regarding the OCCS dimensions, for a typical 2 TPH CO_2 capture rate and as an approximation, the absorber column's hash a height of12m and a diameter of 4.5m, while the striper column has a height of 6m and a diameter of 2.2m.

Liquefaction Plant

This system is typically located in the engine room or a designated space on deck, with a potential placement being close to the OCCS capture system. Typical dimensions for the system for a capture rate of 2 TPH is similar to a 40 ft container, meaning that a space of appr. 28 – 30 m^2 should be allocated.

- Newbuilding: In a newbuilding case, the liquefaction plant can be designed into the vessel's layout, ensuring it fits seamlessly with other systems. This allows for efficient use of space and integration with the vessel's power and heat systems.
- Retrofit: Installing a liquefaction plant in an existing vessel may require some modifications, such as structural reinforcements to support the weight and vibration of the equipment.

For the liquefaction plant, given the presence of pressurized CO_2 and potential leak scenarios, the same safety requirements, such as dedicated ventilation, gas detection, and explosion-proof equipment, are expected to apply same as LCO_2 storage tanks. To comply with these standards and mitigate risks, the liquefaction plant may need to be installed in a segregated, purpose-built compartment adjacent to or outside the ER, rather than within the general machinery space.

Impact on weight

The CO_2 storage tanks are placed on either side of the vessel, ensuring balanced weight distribution. The placement of the OCCS components takes place behind the funnel. Weight distribution per component and the effect on Lightweight increase per case is shown in Table 0-7.

Table 0-7 Suezmax - OCCS weight distribution (tons).

OCCS Weight distribution in tons per examined capture rates			
	1 TPH	**2 TPH**	**3 TPH**
OCCS System weight - Structure only	230	380	515
Increase compared to baseline LWT	0.9 %	1.5 %	2.1%

Additionally, the impact on hull girder loads needs to be analysed for retrofit vessels based on stability calculations with the updated mass distribution and accordingly updated still water moments. It may be that the updated still water moments are within the design moments, and this should be confirmed. Limited consequence is expected. For a newbuilding vessel, this is already part of design envelope moments. In the context of the present study this will not be further analysed but is mentioned here for sake of completion of understanding to the reader.

The increased vertical centre of gravity is regarded marginal and may reduce the transverse dynamic accelerations in roll affecting favourably the inertia and internal cargo and ballast tank pressure loads for extreme strength and fatigue assessment, hence this is not regarded additional scope in the retrofit case.

Impact on stability

The effect of the OCCS system on vessel's stability shall be assessed to ensure compliance with acceptable limits. The evaluation must include the weight of liquids contained within the system under normal operating conditions.

- For the newbuild case, the OCCS system's weight and distribution shall be incorporated into the initial stability calculations and lightship definition. The inclining test shall reflect the vessel's final configuration, including the OCCS installation.
- For retrofit installation, the OCCS system introduces changes to the existing lightship particulars, as shown in Table 0-7. As such, a new inclining test may be required to accurately determine the updated stability characteristics and ensure continued compliance with regulatory requirements.

With the installation of the OCCS components and when the LCO_2 tanks are full, the vessel's center of gravity shifts slightly higher, and a bit aft compared to the vessel without the OCC. these changes could reduce the ship's natural balance and make it more sensitive to rolling in rough seas. Depending on the actual vessel's conditions, it may be necessary to adjust either the ship's ballast, by adding weight lower in the hull to counterbalance the higher equipment or redistribute cargo to improve balance, especially for the case of the retrofit vessel.

Impact on Cargo Capacity

As shown above, the installation of the OCCS system, including LCO_2 storage tanks, introduces a substantial increase in the vessel's lightship weight. Depending on the carbon capture rate and system configuration, the total added weight, including the stored liquefied CO_2 for a roundtrip, may range from approximately 1,200 to 3,050 metric tons. This increase is significant relative to the vessel's baseline lightweight, particularly at higher capture rates, and may directly affect the available deadweight for cargo due to draft and stability constraints.

The OCCS system components, such as compressors, piping, tanks, insulation, and structural reinforcements, contribute to this added weight and must be accounted for during the design or retrofit phase as shown in the previous sections. The resulting reduction in available deadweight impacts the vessel's capacity to carry cargo.

To mitigate these effects, operational adjustments may be necessary. This includes modifying ballast water configurations, such as reducing or redistributing ballast to maintain acceptable trim and draft conditions. Deadweight increase studies is relevant in the retrofit case with less than 0.3 m draft increase. Voyage planning must also consider the reduced cargo margin, especially on routes with strict draft limitations or where fuel efficiency is a key operational concern.

In newbuild scenarios, these impacts can be more effectively managed through integrated design solutions. Optimized ballast arrangements and structural accommodations can be implemented to offset the added weight and preserve vessel stability and cargo capacity.

- **Economic Viability**

EU ETS impact

To quantify the financial exposure of the system under the EU Emissions Trading System (EU ETS), two operational scenarios are considered based on the vessel's annual voyage distribution:

- Scenario A – Low EU Exposure:

The vessel completes 2 out of 9 annual round trips involving entry and exit from the EU (e.g., transatlantic voyages between the USA and Europe). This corresponds to 22% of total voyages being subject to EU ETS regulation.

- Scenario B – High EU Exposure:

The vessel completes 5 out of 9 annual round trips involving EU ports, representing 55% of total voyages under EU ETS coverage.

For both scenarios, carbon pricing is modelled using a base rate of €170 per ton of CO_2[88].

This comparative framework enables a clear understanding of the annual cost implications associated with varying levels of EU ETS exposure, supporting informed decision-making regarding operational strategy and emissions compliance.

The comparison of these two scenarios is made for the capture rate of 2 TPH. The analysis focuses on the the savings of EU ETS allowance, enabling a direct evaluation of the economic viability of the system under varying levels of EU ETS exposure. Results of the analysis can be seen in Table 0-8.

Table 0-8 Suezmax - EU ETS analysis for 2 TPH.

Scenario	EU ETS allowance savings in thousands of euros on a yearly basis	
	Low EU Exposure	High EU Exposure
NB PTO	173	434
NB AEECOS	171	428
RETROFIT	165	413

Scenario-Based Assessment of OCCS and Biofuels Under the IMO GFI Metric

Following section 3.3.2, the scenarios related to the OCCS potential impact on the ship's attained GFI were defined as follows:

- Scenario 1: When calculating the attained GFI the captured CO_2 is subtracted by the formula, while the ship fuel energy includes the fuel penalty. This assumption does not include the full lifecycle emissions of the procedure such as the ones arising from the transportation and permanent storage of the captured CO_2.
- Scenario 2: The attained GFI is calculated based on the WtW emission factors of the LCA guidelines, where for OCCS, the TtW factor is adjusted by the e_{OCCS} term. In this scenario the OCCS fuel penalty is omitted from the fuel energy in the attained GFI formula ship.
- Scenario 3: The attained GFI is calculated based on the WtW emission factors of the LCA guidelines, where for OCCS the TtW factor is adjusted by the e_{OCCS} term except from the OCCS energy penalty term, which is accounted in the ship fuel energy via the OCCS fuel penalty.

Figure 0-14 presents the results of a cost assessment, summarizing the annual operational expenses associated with the implementation of the OCCS solution, alongside the costs of the remedial units under the proposed GFI framework. Additionally, the alternative solution of biofuels usage, is evaluated to achieve the same attained GFI as Scenario 1 (which is estimated to be the lower value).

[88] Energy Transition Outlook 2024

The first instance of annual OPEX savings is observed in year 2028 for the case of biofuels minimum price, while for the mid-price scenario it is estimated that up to 2034 the differential OPEX does not showcase savings. For the OCCS case it is assumed that in the end of 2031 the retrofit is implemented on board, as the differential OPEX savings begin from 2032 and onwards.

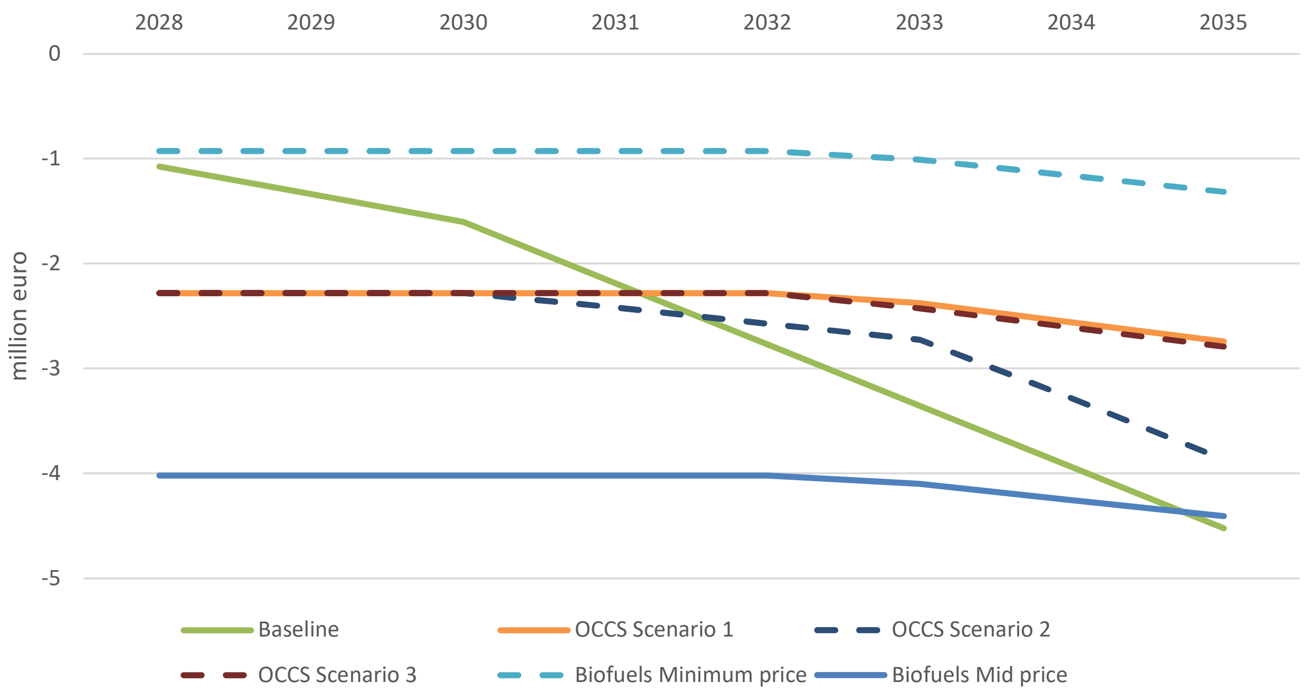

Figure 0-14. Suezmax - OCCS comparison to biofuels. Annual differential OPEX cashflows.

The following graph illustrates the attained GFI for each case scenario.

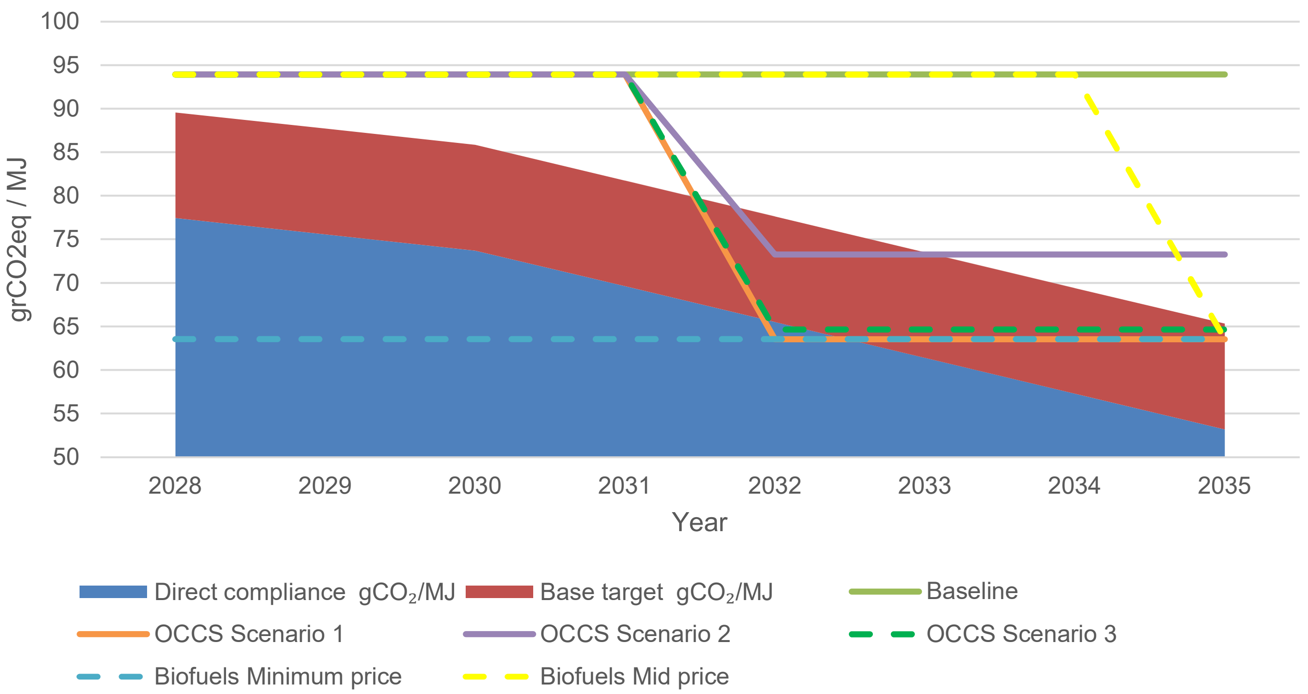

Figure 0-15. Suezmax - OCCS comparison to biofuels. Attained GFI scenario analysis trajectory.

In Figure 0-16 the discounted differential OPEX cashflows on the above analysis are accumulated for the years covering 2028-2035 (blue stack) while the red bars represent the margin of the discounted differential OPEX of OCCS and biofuels against the baseline vessel. Under this particular price scenarios the usage of biofuels, seem to be beneficial when the minimum fuel price is projected, contrary to their performance on the mid price scenario.

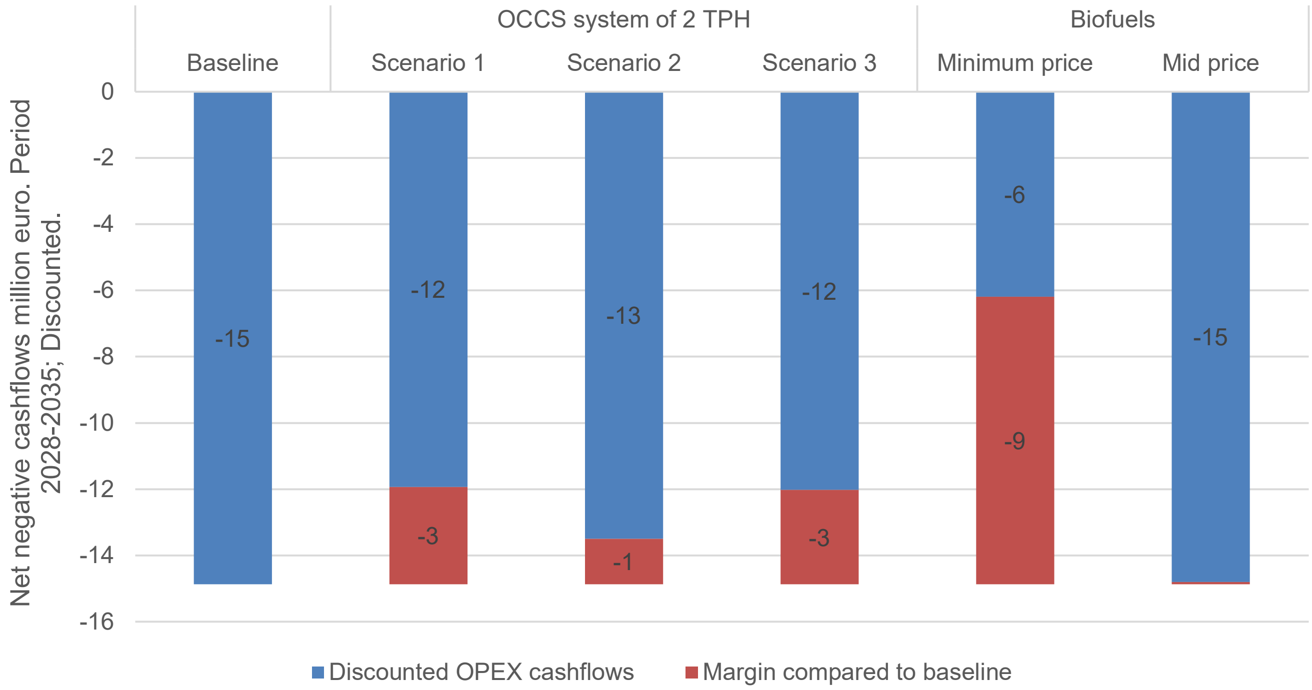

Figure 0-16. Suezmax - OCCS comparison to biofuels. Discounted Differential OPEX cashflows from 2028-2035.

Appendix C 15,000 TEU Dual Fuel LNG container cost economic analysis

■ Vessel overview

For the 15,000 TEU dual fuel LNG container vessel, the main dimensions and machinery are shown below.

Table 0-9 Container case vessel main dimensions and machinery.

15,000 TEU container case study – Vessel specifications	
First year in service	2025
DWT	Appr. 160,000 tons
Lightweight	Appr. 45,000 tons
Propulsion system	1 x 2-Stroke Dual fuel engine of abt. 45 MW
Electricity supply	4 x 4-stroke Dual fuel of abt. 4 MW each
Heat supply	1 x Auxiliary Boiler 1 x Main Engine Exhaust Gas Economizer

The operational profile of a typical 15,000 TEU container vessel is analysed below, detailing the distribution of time spent underway, at anchor, and during port operations as shown in Figure 0-17.

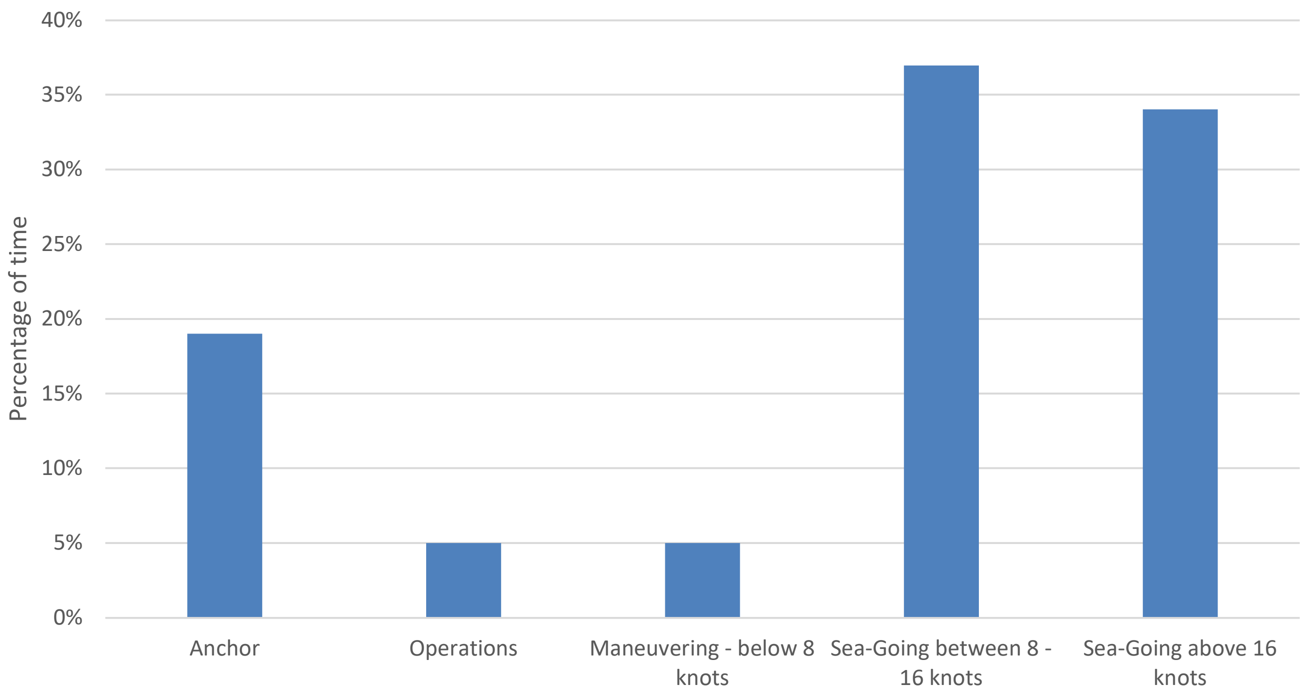

Figure 0-17 Container operating profile.

- **CO_2 performance analysis**

The OCCS technology is examined for sweeps of CO_2 capture capacity. The results from 2, 4 & 6 TPH are presented, as these present options that are reasonable in terms of LCO_2 storage and maintain the operation of the Aux Gens and boilers within manufacturer and redundancy limits (load below 90%, 1 Aux D-G on standby).

In the case of the NB vessel the installation of PTO of 8 MW (to cover vessel's electrical demands during sailing, including OCCS) has been considered in order to see the effect of the PTO in the overall system, since PTO is a relevant technology to examine for a vessels of this type (DNV, Energy Efficiency Measures and Technologies, 2025a).

In terms of AEECOs, vessel is already equipped with them, so they are already part of both examined cases.

Table 0-10 Container - Technology Components for each configuration.

Design / Components	Aux. Engines' Economizers	PTO
Retrofit	X	-
Newbuilding with PTO	X	X

Same as for the Suezmax case, the examined OCCS technology in terms of energy efficiency a state-of-the-art system is considered with specification as shown in Table 0-5

Comparative analysis

Results of the analysis for the capture rate of 2 TPH, 4 TPH and 6 TPH are shown in Figure 0-18

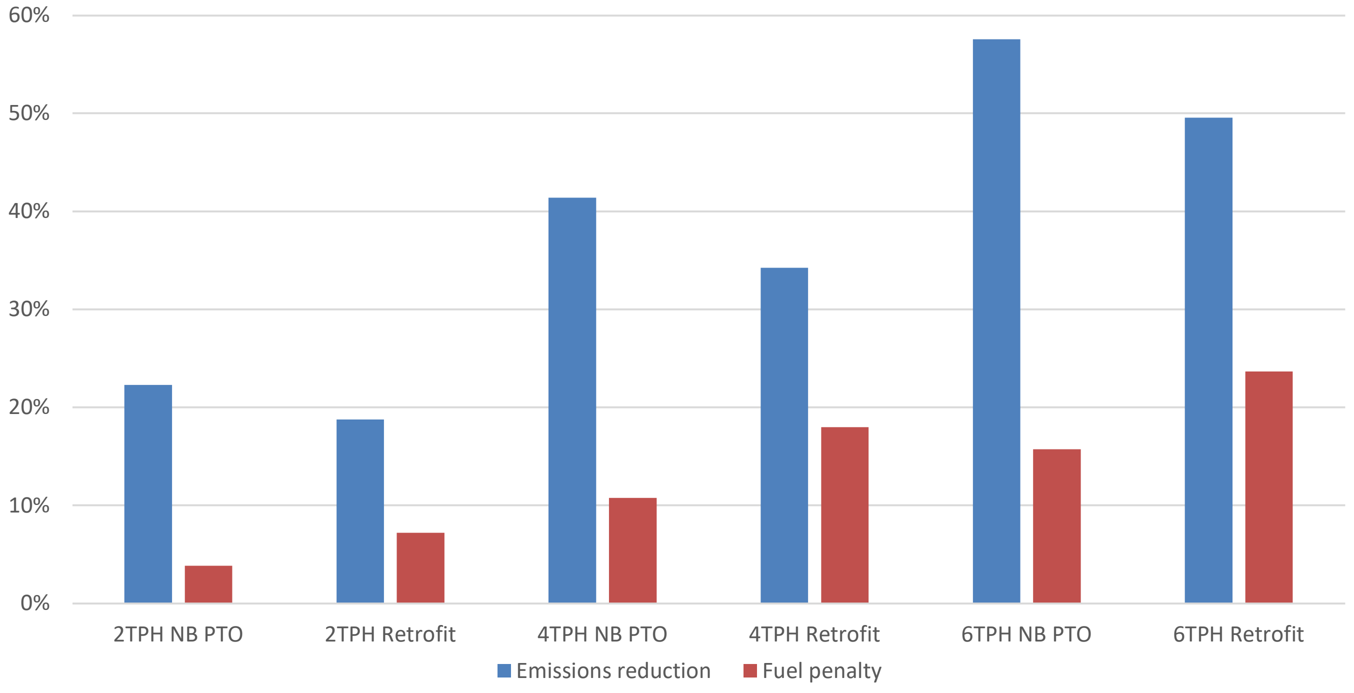

Figure 0-18 Container - Emissions reduction vs Fuel penalty.

CO_2 performance

A typical round trip for this type of vessel has a duration of approximately 70 days. Based on this operational cycle, the vessel is expected to complete around five round voyages per year. This frequency forms the basis for evaluating the annual performance of the onboard systems, particularly in terms of fuel consumption and emissions.

The yearly assessment includes the total consumption of LNG and MDO, both in metric tons, the corresponding total CO_2 emissions generated, and the amount of CO_2 captured by each case. Additionally, the analysis presents the net

CO_2 emissions released into the atmosphere after capture, as well as the total quantity of CO_2 abated. These metrics provide a comprehensive overview of the environmental performance of the vessel and the effectiveness of the OCCS in reducing GHG emissions.

The yearly CO_2 performance results are shown for the OCCS capacity of 2 TPH, 4 TPH and 6 TPH in Figure 0-19.

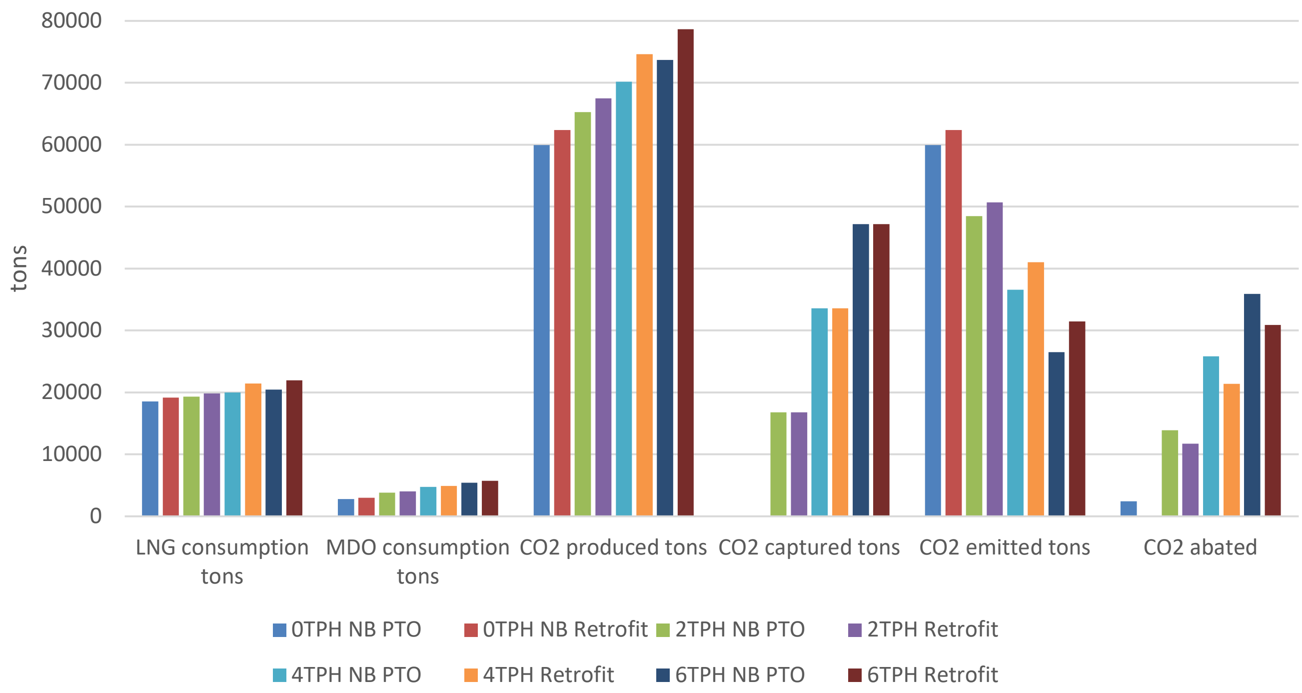

Figure 0-19 Container - OCCS yearly performance.

OCCS impact on machinery performance

In this section an overview of the effect of the OCCS technology on the different machinery of the vessel (Aux. Engines and Boilers) will be presented.

Figure 0-20 illustrates the impact of the different OCCS capture rates on the utilization of key machinery components, specifically the main engine and auxiliary engines, during laden sailing at a service speed of 18 knots, being the average speed of the vessel. For the retrofit case, as the OCCS capture rate increases from 2 TPH to 6 TPH, the load on the auxiliary engines rises from 80% to 90% and for the 4 TPH and 6 TPH capture rates 3 Aux. engines have to be utilized for a load up to 70%. In the optimized newbuilding with PTO, when the PTO system is employed, the main engine and PTO can meet the additional electrical demand imposed by the OCCS system, thereby eliminating the need to engage auxiliary generators.

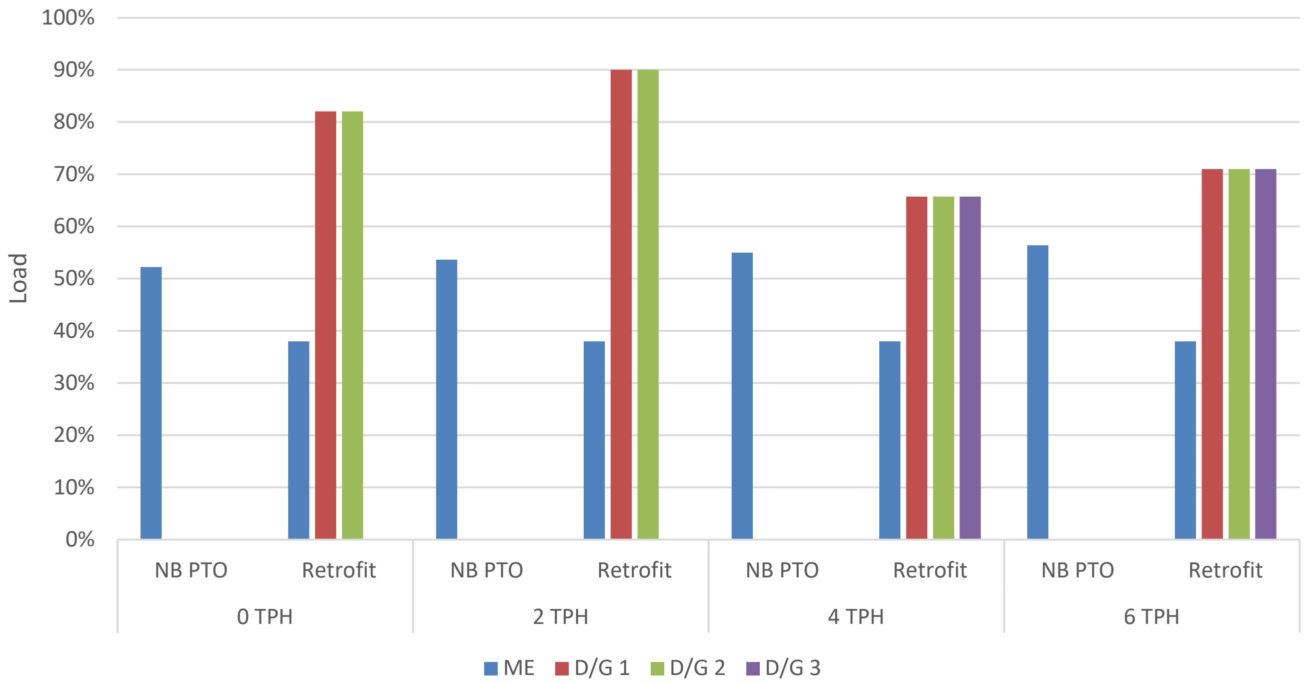

Figure 0-20 Container - OCCS Impact on Main Engine and Aux. Engines at 18 knots in laden condition.

Figure 0-21 shows the total steam demand of the vessel including the ones of the OCCS, during laden sailing at a service speed of 18 knots, being the average speed of the vessel. For this reason, the cases without the OCCS have been included in the graph as well.

As can be seed from the graph, regardless of the technology equipped the total steam demands remain steady for the same carbon capture rate.

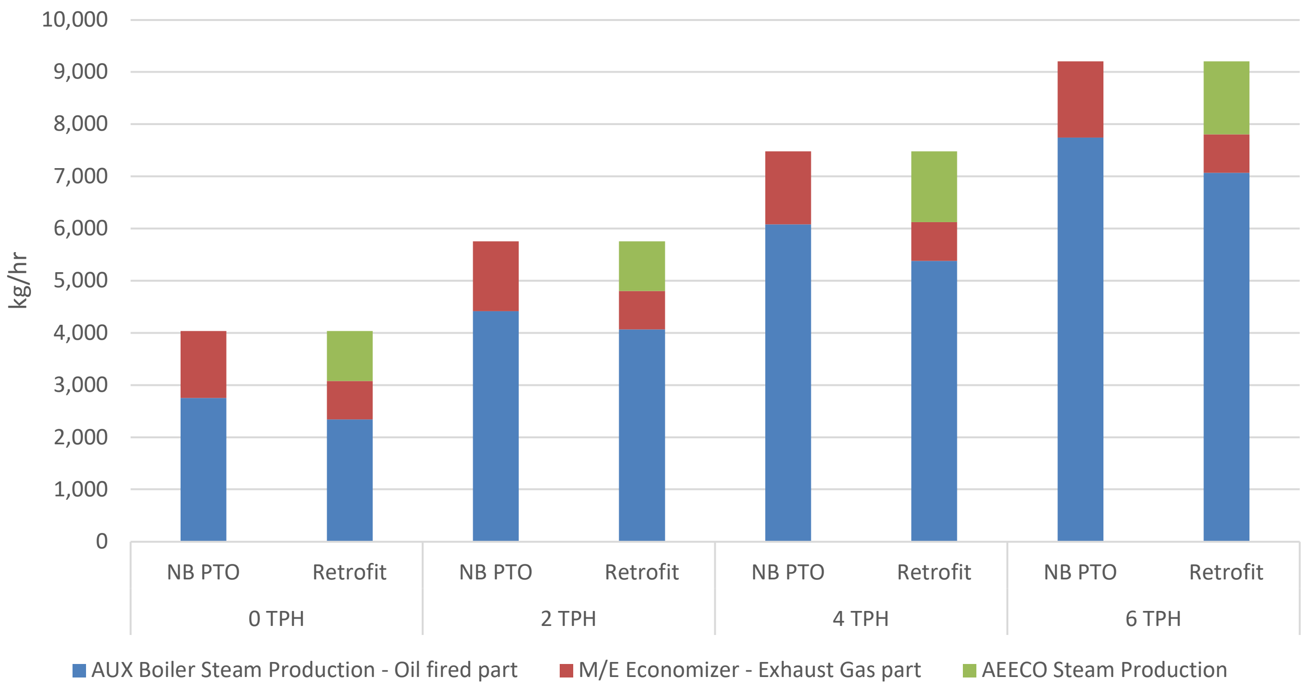

Figure 0-21 Container - OCCS Impact on Aux. boiler & Economizers at 18 knots in laden condition.

- **Economic impact analysis**

CO_2 abatement cost

CO_2 abatement cost analysis presents the cost associated with reducing one metric ton of carbon dioxide emissions compared to the baseline scenario for each of the examined cases.

The CO_2 abatement cost assessment is evaluated under three implementation cost scenarios: low, base, and high, which are detailed in Figure 0-22. As per the analysis, all financial figures are discounted to the base year 2025, with a discount rate of 8% applied (Xiaobo Luo, 2017), (Sadi Tavakoli, 2024).

Results of the CO_2 abated cost are shown in Figure 0-22. In the container case, the lowest CO_2 abated cost in each case if the optimized newbuilding with the PTO with the 6 TPH capture rate followed closely by the optimized new building with PTO with 4 TPH capture rate.

Figure 0-22 Container - CO_2 abatement cost per tons CO_2 abated.

CAPEX / OPEX calculation

In this section a more detailed overview of the CAPEX costs per case is done, CAPEX costs can be found in 3.2.1.

Figure 0-23 presents the CAPEX analysis results.

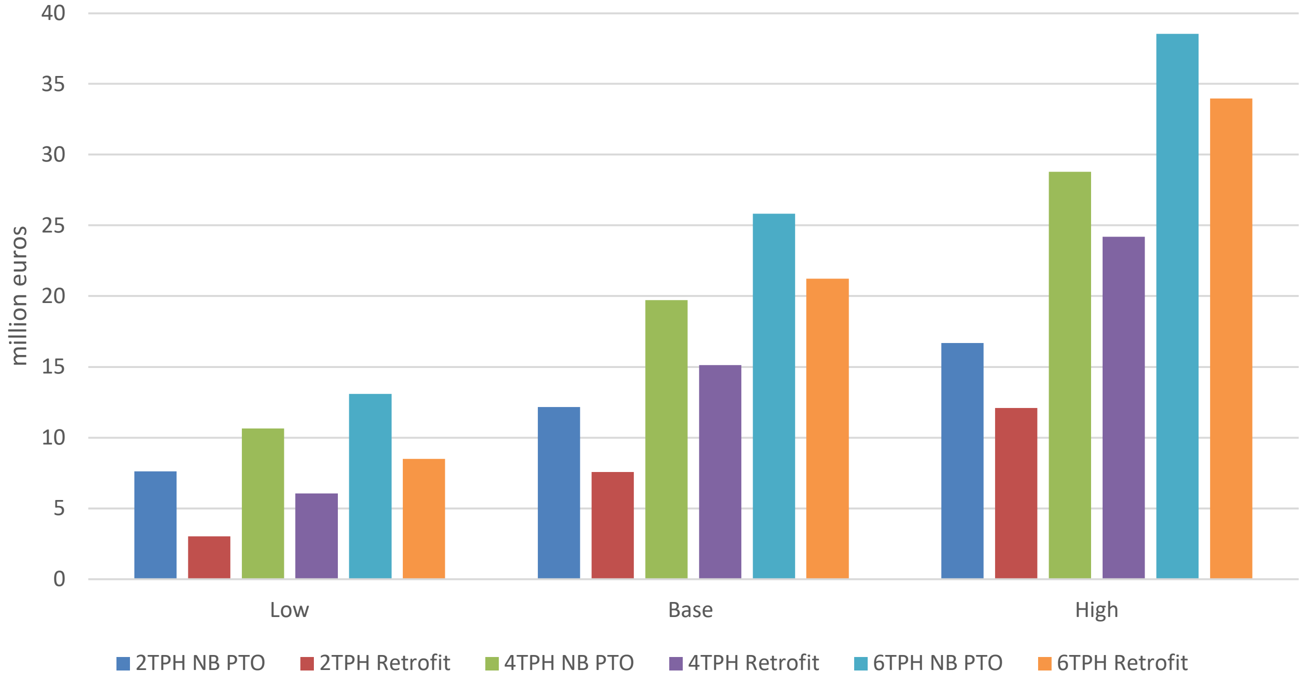

Figure 0-23 Container - CAPEX analysis.

In order to estimate the yearly fuel OPEX for the examined cases, prices are assumed as per Table 3-15. Results are shown in Figure 0-24.

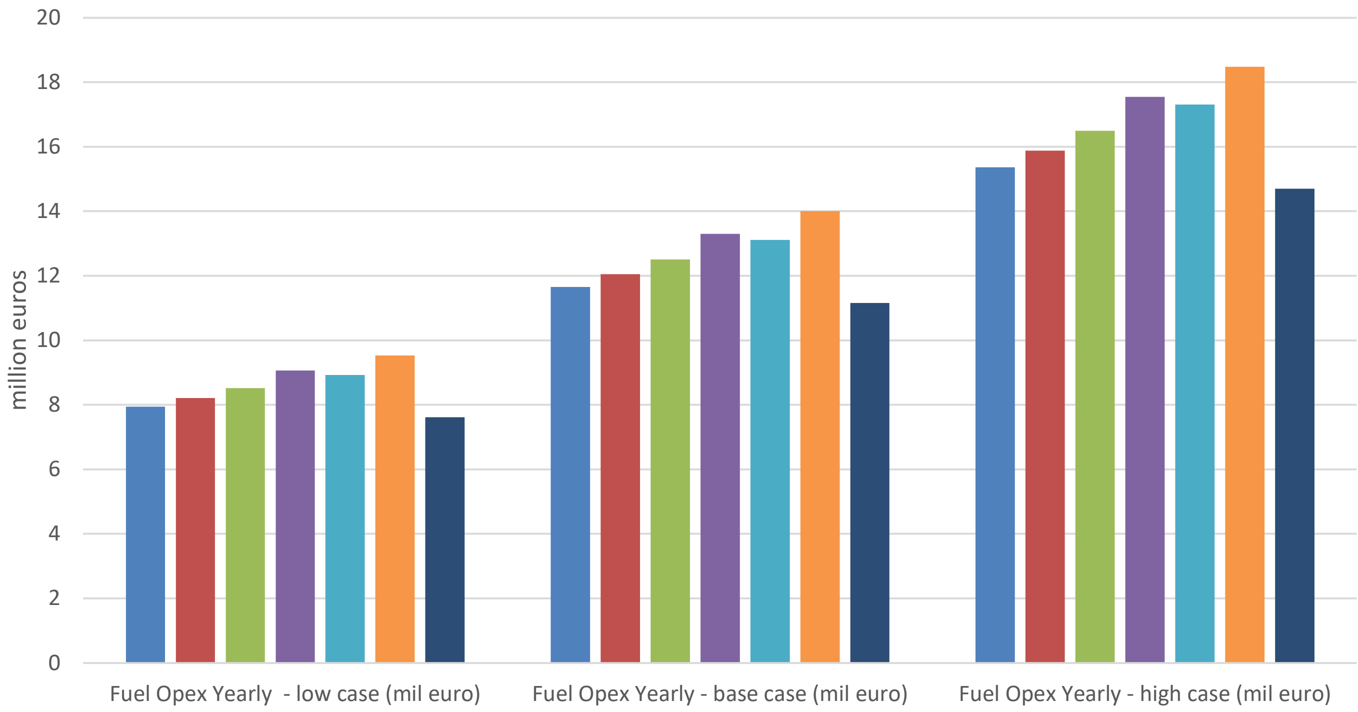

Figure 0-24 Container - Yearly Fuel OPEX in mil. Euro.

Economic analysis of disposal cost

For the economic analysis of the disposal cost, the following assumptions are as mentioned in Table 3-15, with the disposal cost for the captured CO_2 on a yearly basis for the RoPax vessel is shown in Figure 0-25.

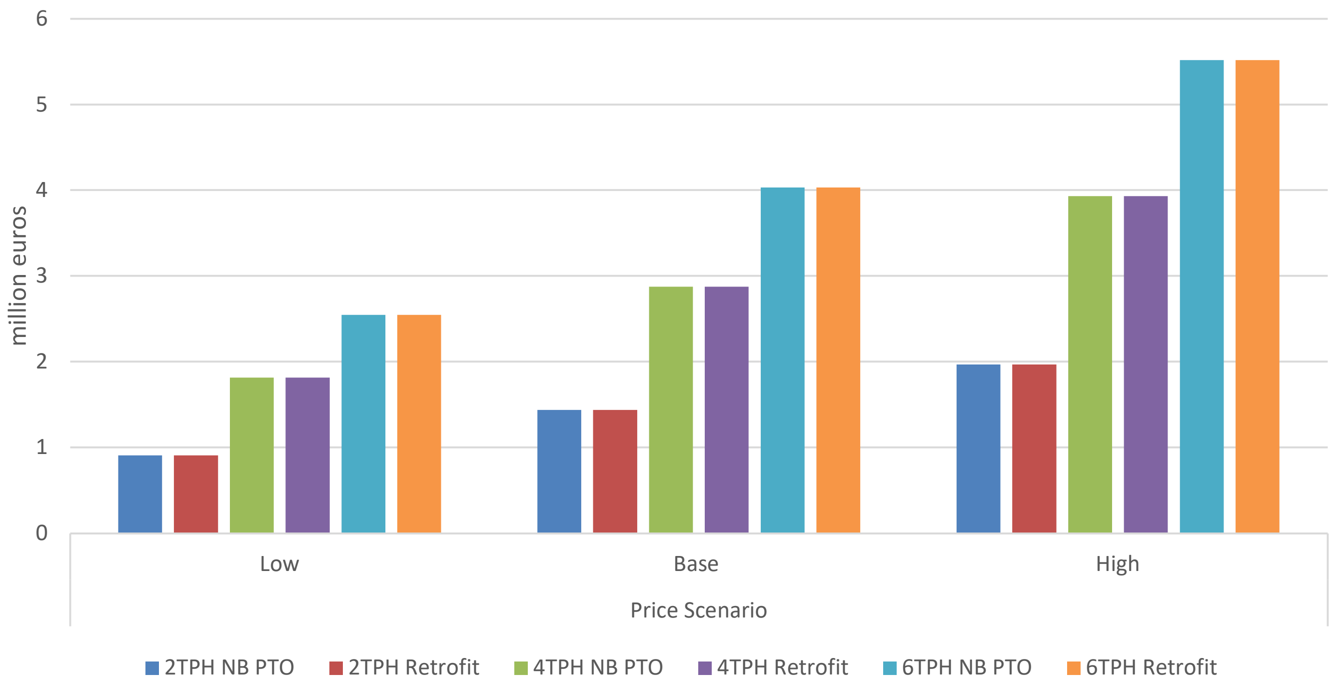

Figure 0-25 Container Yearly disposal cost of CO_2.

CO_2 abatement cost per ton of Captured CO_2 – sensitivity analysis

Following the evaluation of various cost metrics, namely CAPEX, fuel OPEX, and CO_2 disposal costs, a sensitivity analysis was conducted to assess their impact on the overall CO_2 abatement cost. This analysis, illustrated in Figure 0-26, shows the case of the OCCS system with a capture rate of 4 TPH.

The results indicate that the CO_2 disposal cost and fuel OPEX exert the most significant influence on the abatement cost. These are followed by the technology CAPEX and maintenance costs, which have a moderate impact. In contrast, the cost of solvents contributes minimally to the overall CO_2 abatement cost.

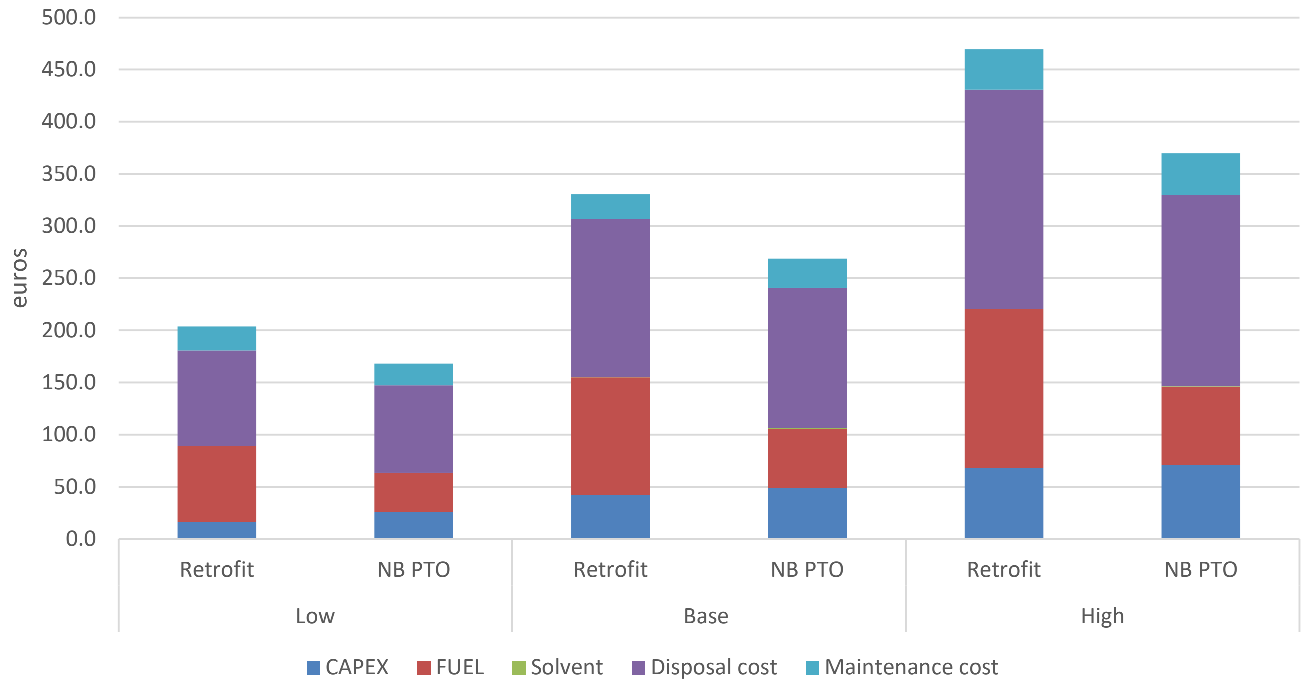

Figure 0-26 Container - CO_2 abatement cost per ton CO_2 sensitivity analysis for the 4 TPH capture rate.

Port offloading and ship interface analysis

The displaced vapor results are showcased in tons, according to the different CO_2 capture rates and vessel tank sizes as shown in Figure 0-27. The required energy of the systems involved (pump, heater and cooler) is showcased separately for each vessel and CO_2 capture rates in kWh in Figure 0-28.

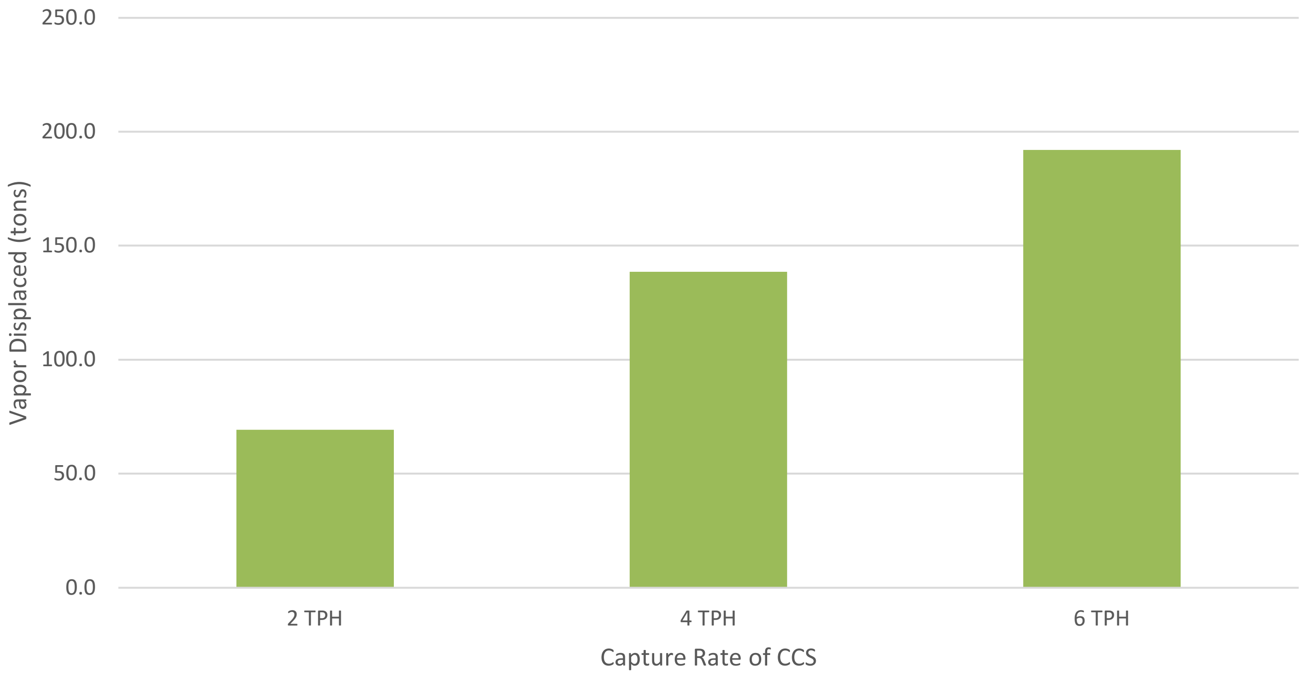

Figure 0-27 Container - displaced vapor during offloading per capture rate, assuming an offloading rate of 500m³/hr.

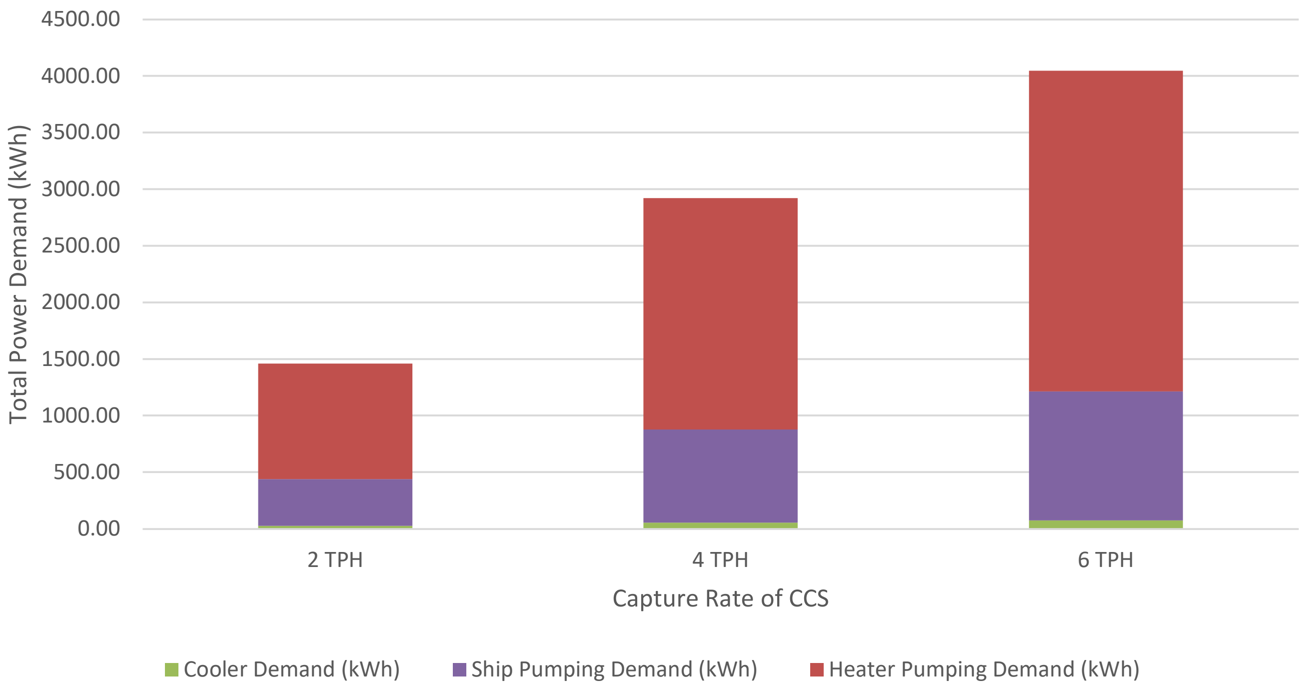

Figure 0-28 Container - total required energy during offloading, assuming an offloading rate of 500m³/hr.

- **Technical impact analysis**

For the container vessel, stability and strength have slightly higher focus, while a bigger concern is the space demand and the related container cargo loss for the retrofit case.

With the location of the LCO_2 tank conflict with cargo operations is regarded as insignificant.

LCO_2 storage tanks capacity and dimensions estimation

The container vessel is assumed to make 5 round trips per year, with each round trip lasting appr. 70 days. A container vessel has several port calls during a trip, so the offloading frequency is assumed to take place twice per round trip, in our case every 35 days. The estimations for the required capacity of the LCO_2 tank, considering a margin of +10% (unforeseen delays/ extended cargo operations) is shown in Table 0-11.

LCO_2 storage tanks are considered to be filled up to 95% of their volume. LCO_2 density is assumed at 1,110 kg/m^3. Capacity of the LCO_2 is given on an average basis per different capture rates, since the different cases (optimized newbuilding with PTO and retrofit) have slight differences in the captured CO_2 quantities.

Table 0-11 Container - LCO_2 Storage Tanks specifications.

LCO_2 Storage Tanks specifications				
Capture rate of OCCS	CO_2 captured per 35 days+10% margin (m^3)	LCO_2 total required capacity (m^3)	Tank D x L (m) (per storage tank)	Total weight including LCO_2 (tons)
2 TPH	1550	1480	9 x 28	2100
4 TPH	3100	3000	11 x 34	4160
6 TPH	4300	4150	12 x 40	5860

For the Container vessel case, it is assumed that the system has one LCO_2 storage tank.

OCCS impact on vessel space demands

LCO_2 Storage Tanks

The proposed configuration involves locating the LCO_2 storage tank within the aft cargo hold, right next to the vessel's funnel, while positioning the OCCS unit on the deck above. This arrangement is conceptually aligned with operational efficiency and spatial practicality, but it requires further assessment tailored to each vessel's design and operational profile.

- Newbuilding: In a newbuilding scenario, the design of the vessel can be optimized from the outset to accommodate the LCO_2 storage tank. This allows for integration with minimal impact on the vessel's overall design.
- Retrofit: In a retrofit scenario, existing structures will need to be modified to fit the CO_2 tank. This could involve reinforcing the cargo hold or relocating other equipment.

It is less likely that the location of the OCCS components are located in a hazardous area, as in the case of the Suezmax tanker.

Repurposing the aft cargo hold for the LCO_2 storage tank will result in a reduction of available container slots, depending on the tank's dimensions, insulation requirements, and supporting infrastructure. While this area is generally less critical for container stacking, any impact on cargo capacity must be evaluated in the context of the vessel's commercial operations. Structural reinforcement and integration of safety systems, such as venting, fire protection, and monitoring, will also be necessary to comply with applicable maritime regulations and class society standards. The size of the larger LCO_2 tank occupies a space similar to about 175 TEU and weight wise about 419 TEU, so between 1 and 3% loss in cargo capacity for the retrofit case.

It is important to note that this configuration is presented as a conceptual guideline. The feasibility, safety, and operational implications of such an installation must be assessed on a case-by-case basis. Each vessel owner should conduct a detailed engineering study to evaluate structural compatibility, cargo impact, regulatory compliance, and integration with existing systems. Collaboration with classification societies and technology providers is essential to ensure that the final design meets all technical and safety requirements.

Carbon Capture System

The absorber and regeneration stacks can be installed right behind the vessel's funnel on the deck above the cargo hold which will accommodate the LCO_2 storage tank.

- Newbuilding: For newbuilds, the OCCS can be integrated into the vessel's design from the beginning. This ensures optimal placement and weight distribution, enhancing the vessel's stability and operational efficiency.
- Retrofit: Retrofitting the OCCS requires advance planning to integrate it with the existing structures. This may involve additional engineering work to ensure the system does not interfere with the vessel's existing operations.

Liquefaction Plant

This system is typically located in the engine room or a designated space on deck, with a potential placement being close to the OCCS capture system.

- Newbuilding: In a newbuilding case, the liquefaction plant can be designed into the vessel's layout, ensuring it fits seamlessly with other systems. This allows for efficient use of space and integration with the vessel's power and heat systems.
- Retrofit: Installing a liquefaction plant in an existing vessel may require some modifications, such as structural reinforcements to support the weight and vibration of the equipment.

Impact on weight

The LCO_2 storage tank is placed centric to ensure balanced weight distribution. The placement of the OCCS components takes place behind the funnel. Weight distribution per component and the effect on Lightweight increase per case is shown in Table 0-12.

Table 0-12 Container - OCCS weight distribution (tons).

OCCS Weight distribution in tons per examined capture rates			
	2 TPH	**4 TPH**	**6 TPH**
OCCS System weight - Structure only	330	620	885
Increase compared to baseline LWT	0.7%	1.4%	2.0%

Additionally, the impact on hull girder loads needs to be analysed for retrofit vessels based on stability calculations with the updated mass distribution. The design maximum and minimum hogging moments for container vessels may be exceeded with low probability, hence the change of the still water bending moment curve as a consequence of the additional weights is expected to have small consequence in practise, and the existing design moments may be kept as limitation in the loading computer for the arrangement of the containers on each voyage. However, the loading computer will have to be updated to account for the new lightweight mass distribution. For a newbuilding vessel, the additional weights is already part of design with envelope moments. In the context of the present study this will not be further analysed but is mentioned here for sake of completion of understanding to the reader.
The cargo securing manual will not be influenced when the LCO_2 tank is within the cargo hold for the retrofit case.

Impact on stability

The effect of installing the OCCS on the container vessel's stability must be carefully assessed to ensure compliance with acceptable limits. This evaluation should include the weight of all liquids contained within the system under normal operating conditions, such as absorbents, solvents, and liquefied CO_2. The vertical and longitudinal distribution of these weights can influence the vessel's centre of gravity and overall stability characteristics. It may change the metacentric height value, GM, in the order of 0.5 m when the storage tanks are full but is very much dependent on the vessel's actual loading condition and exactly where the storage tanks are located. This change in GM is less significant on such larger container vessels, known to have quite good stability, but uneven distribution may have to be handled by the heeling tank during transit. This weight will also have to be included in the loading computer calculations as updated lightweight distribution for the fixed part of the mass and as separate cargo loads based on the filling level of the storage tanks. With the flexibility of placing containers it is expected to be limited consequence on stability in practise and the original stability requirements may be kept. Hence, the weights will be important to include, but the consequence is expected small to insignificant in practise for the retrofit case as each voyage needs careful stability assessment anyway.

For newbuild container vessels, the weight and placement of the OCCS components, including the OCCS unit and the LCO_2 storage tank located in the aft cargo hold right behind the funnel, should be incorporated into the initial stability calculations and lightship definition. The inclining test must reflect the vessel's final configuration, inclusive of the OCCS installation, to ensure regulatory compliance from the outset.

Impact on Cargo Capacity

As shown Table 0-12, the installation of the OCCS system, including LCO_2 storage tanks, introduces a substantial increase in the vessel's lightship weight. Depending on the carbon capture rate and system configuration, the total added weight, including the stored liquefied CO_2, may range from approximately 2100 to 5900 metric tons. This increase is significant relative to the vessel's baseline lightweight, particularly at higher capture rates, and may directly affect the available deadweight for cargo due to draft and stability constraints.

The OCCS system includes components such as compressors, absorber and stripper columns, liquefaction units, and the LCO_2 tank, which in this proposed configuration is installed in the aft cargo hold beneath the funnel. This location, while operationally efficient, results in the loss of container slots in that section of the vessel. Depending on the tank's dimensions and insulation requirements, the installation may displace several TEU slots, reducing the vessel's overall cargo throughput. Additionally, the added weight shifts the vessel's centre of gravity slightly higher and aft, which may influence trim and stability margins.

These changes can impact the vessel's ability to carry its full complement of containers, particularly on routes with strict draft limitations or where fuel efficiency is a key concern. To mitigate these effects, vessel operators may need to adjust ballast configurations or redistribute container loads to maintain acceptable trim and stability. Voyage planning must also account for the reduced cargo margin, especially in high-capacity or draft-restricted ports. The increased weight may be counteracted by deadweight increase calculations, so the 3% loss in container capacity may be reduced to about 1% loss in container capacity as earlier mentioned for the larger LCO_2 tank. This may have marginal impact also because container ships are often not achieving 100% utilisation with regard to container capacity.

For newbuild container vessels, these impacts can be addressed more effectively through integrated design solutions. Structural accommodations and optimized ballast arrangements can be incorporated from the outset to offset the added weight and preserve container capacity. In retrofit scenarios, however, a detailed engineering assessment is essential to evaluate the trade-offs and ensure continued compliance with regulatory requirements and commercial viability.

- **Economic viability**

EU ETS impact

To quantify the financial exposure of the system under the EU Emissions Trading System (EU ETS), two operational scenarios are considered based on the vessel's annual voyage distribution:

- Scenario A – Low EU Exposure:

The vessel spends approximately 20% of its annual operating time in voyages from and to EU territorial waters and ports. This includes occasional calls to EU ports (e.g., one out of five voyages involving EU stops), resulting in limited exposure to EU ETS regulation.

- Scenario B – High EU Exposure:

The vessel spends around 60% of its annual operating time in voyages starting or ending in EU jurisdiction. This results in substantial coverage under the EU ETS, with a majority of emissions subject to regulation.

For both scenarios, carbon pricing is modelled using a base rate of €170 per ton of CO_2[89].

This comparative framework enables a clear understanding of the cost implications associated with varying levels of EU ETS exposure, supporting informed decision-making regarding operational strategy and emissions compliance.

The comparison of these two scenarios is made for the capture rate of 4 tons of CO_2 per hour. The analysis focuses on the savings of EU ETS allowance, enabling a direct evaluation of the economic viability of the system under varying levels of EU ETS exposure. Results of the analysis can be seen in Table 0-13.

Table 0-13 Container - EU ETS analysis for 4 TPH.

Scenario	EU ETS allowance savings in thousands of euros on a yearly basis	
	Low EU Exposure	High EU Exposure
NB PTO	388	1,163
RETROFIT	331	992

Scenario-Based Assessment of OCCS and Bio-LNG Under the IMO GFI Metric

Following section 3.3.2, the scenarios related to the OCCS potential impact on the ship's attained GFI were defined as follows:

- Scenario 1: When calculating the attained GFI[90] the captured CO_2 is subtracted by the formula, while the ship fuel energy includes the fuel penalty. This assumption does not include the full lifecycle emissions of the procedure such as the ones arising from the transportation and permanent storage of the captured CO_2.
- Scenario 2: The attained GFI is calculated based on the WtW emission factors of the LCA guidelines, where for OCCS, the TtW factor is adjusted by the e_{OCCS} term. In this scenario the OCCS fuel penalty is omitted from the fuel energy in the attained GFI formula ship.
- Scenario 3: The attained GFI is calculated based on the WtW emission factors of the LCA guidelines, where for OCCS the TtW factor is adjusted by the e_{OCCS} term except from the OCCS energy penalty term, which is accounted in the ship fuel energy via the OCCS fuel penalty.

Figure 0-29 presents the results of a cost assessment, summarizing the annual operational expenses associated with the implementation of the OCCS solution, alongside the costs of the remedial units under the proposed GFI framework. Additionally, the alternative solution of bio-LNG usage, is evaluated to achieve the same attained GFI as Scenario 3 (which is estimated to be the lower value).

The first instance of annual OPEX savings is observed in year 2031 for the case of bio-LNG minimum price, while for the mid-price scenario it is estimated that up to 2035 the differential OPEX does not showcase savings. For the OCCS case it is assumed that in the end of 2032 the retrofit is implemented on board, as the differential OPEX savings begin from 2033 and onwards.

[89] Energy Transition Outlook 2024

[90] $GFI_{attained} = \frac{\sum_{j=1}^{J} EI_j \times Energy_j}{Energy_{total}}$, attained GFI formula based on IMO Circular Letter No. 5005 (Draft revised MARPOL Annex VI).

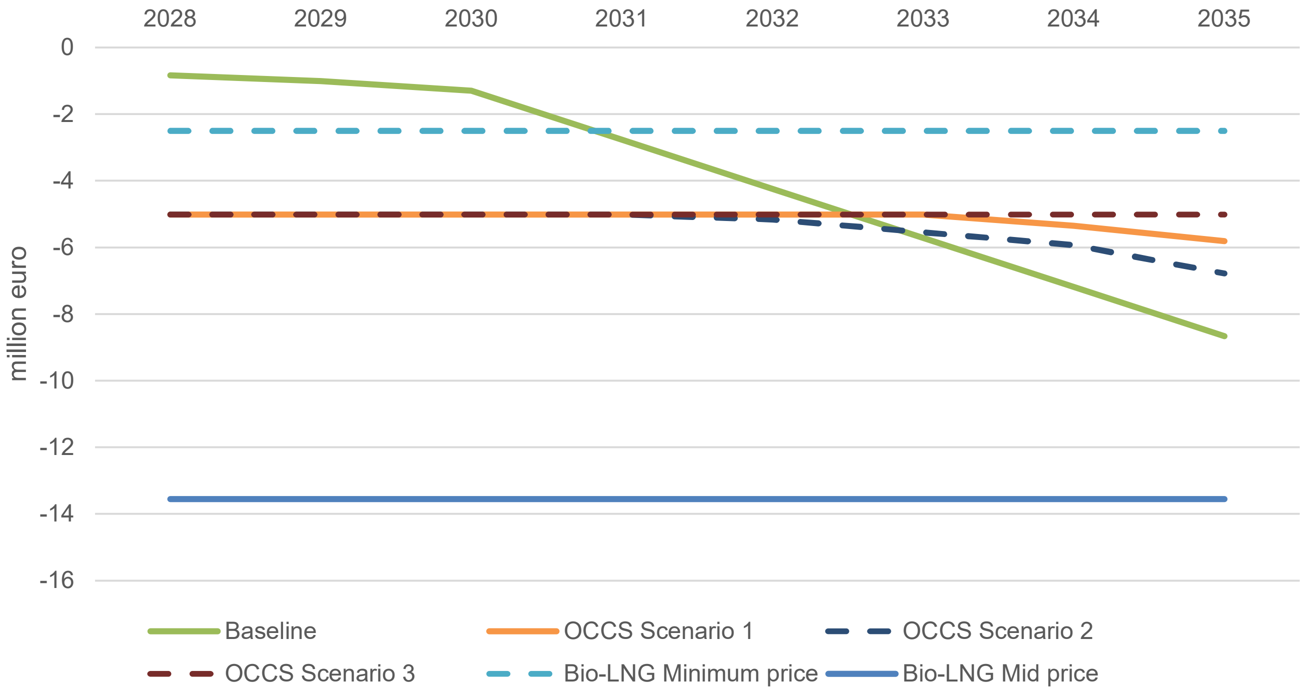

Figure 0-29. Container - OCCS comparison to biofuels. Annual differential OPEX cashflows.

The following graph illustrates the attained GFI for each case scenario.

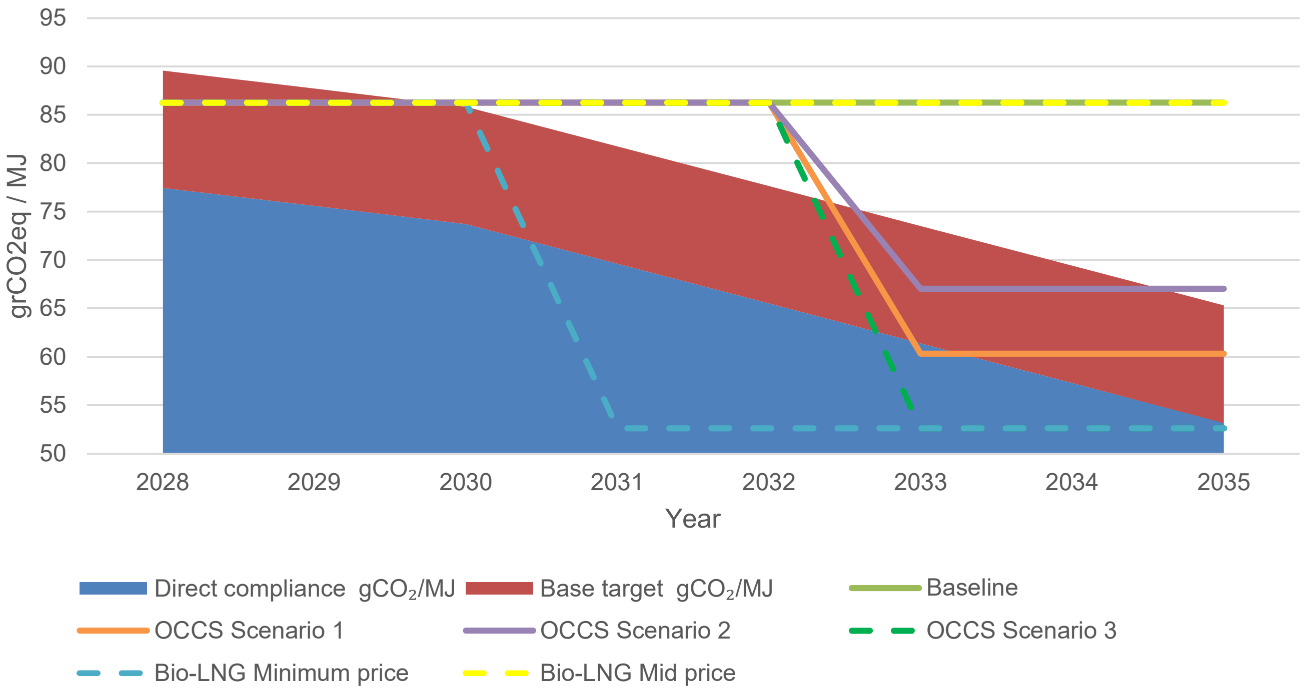

Figure 0-30 Container - OCCS comparison to bio-LNG. Attained GFI scenario analysis trajectory.

In Figure 0-31 the discounted differential OPEX cashflows on the above analysis are accumulated for the years covering 2028-2035 (blue stack) while the red bars represent the margin of the discounted differential OPEX of OCCS and bio-LNG against the baseline vessel. Under this particular price scenarios the usage of bio-LNG, seems to be beneficial when the minimum fuel price is projected, contrary to the mid price scenario.

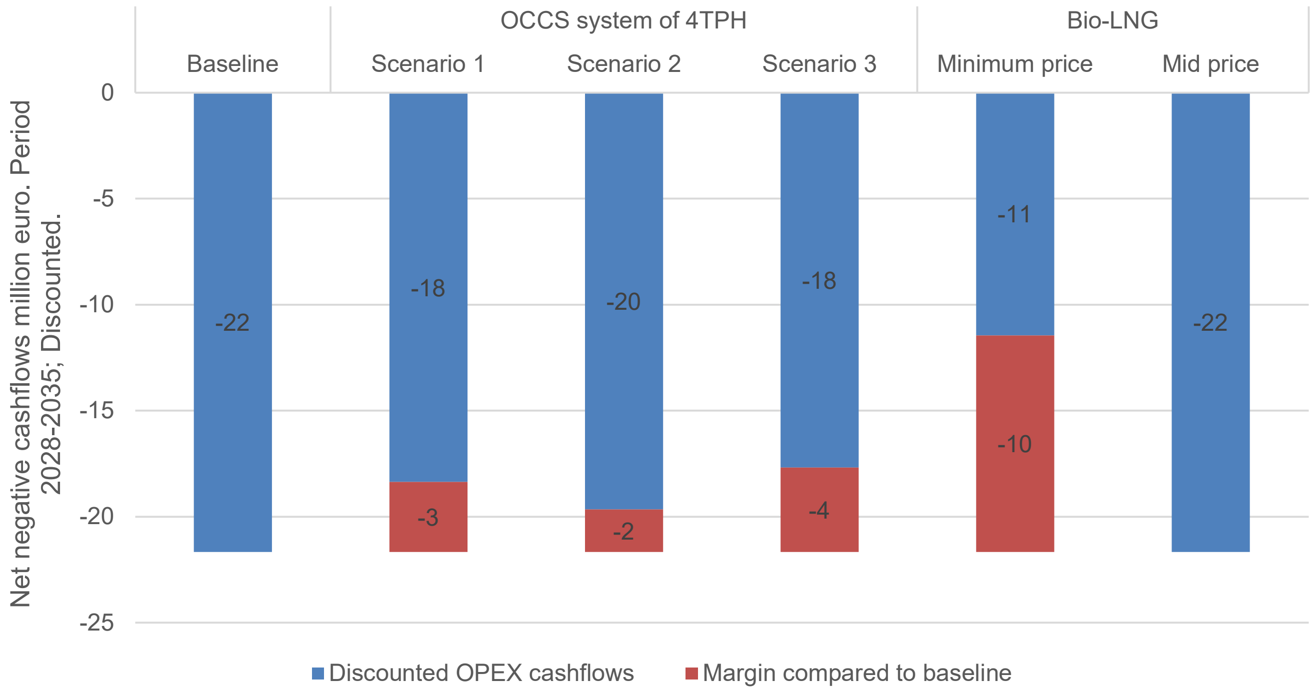

Figure 0-31. Container - OCCS comparison to bio-LNG. Discounted Differential OPEX cashflows from 2028-2035.

Appendix D Ro-Pax cost economic analysis

■ Vessel overview

For the Ro-Pax vessel, the main dimensions and machinery are shown below. During its port calls, the vessel is supplied with electrical power by means of a shore-side electricity supply (High Voltage External Connection).

Table 0-14 RoPax case vessel main dimensions and machinery.

Ro-Pax case study – Vessel specifications	
First year in service	2025
DWT	Appr. 1,700 tons
Lightweight	Appr. 4,000 tons
Propulsion system	2 x 4-Stroke Diesel engine of abt. 3.2 MW each
Electricity supply	4 x 4-stroke D-G of abt. 560 kW each (sea-going) Shore connection
Heat supply	Oil fired Aux. Boiler

The vessel operates on a short-distance route between neighbouring ports. Its schedule involves several frequent, brief intraday coastal transits, the number of which depends on the season of the year. These transits are followed by extended periods moored at its primary terminal, where it remains docked for several hours during nighttime. During these layovers, the vessel connects to a shore-side electrical supply system, which allows it to shut down its auxiliary engines and draw energy from the local grid. This setup significantly reduces local emissions, noise, and fuel consumption while docked, aligning with environmental regulations and sustainability goals. The shore power connection ensures that essential onboard systems, such as lighting, ventilation, and communications, remain fully operational without relying on fossil fuels.

The vessel's auxiliary boiler remains in operation throughout the majority of the day to maintain the temperature of the fuel oil storage, settling, and service tanks. This function, however, is assumed by the main engine economiser when the vessel is underway.

Figure 0-32 presents the vessel's operational profile over the course of a full calendar year, derived from AIS data. The analysis indicates that the vessel remains moored at port for more than half the time. The remaining operational time is distributed between port manoeuvring activities and sea-going transit, with the latter typically conducted at an average speed of approximately 16 knots.

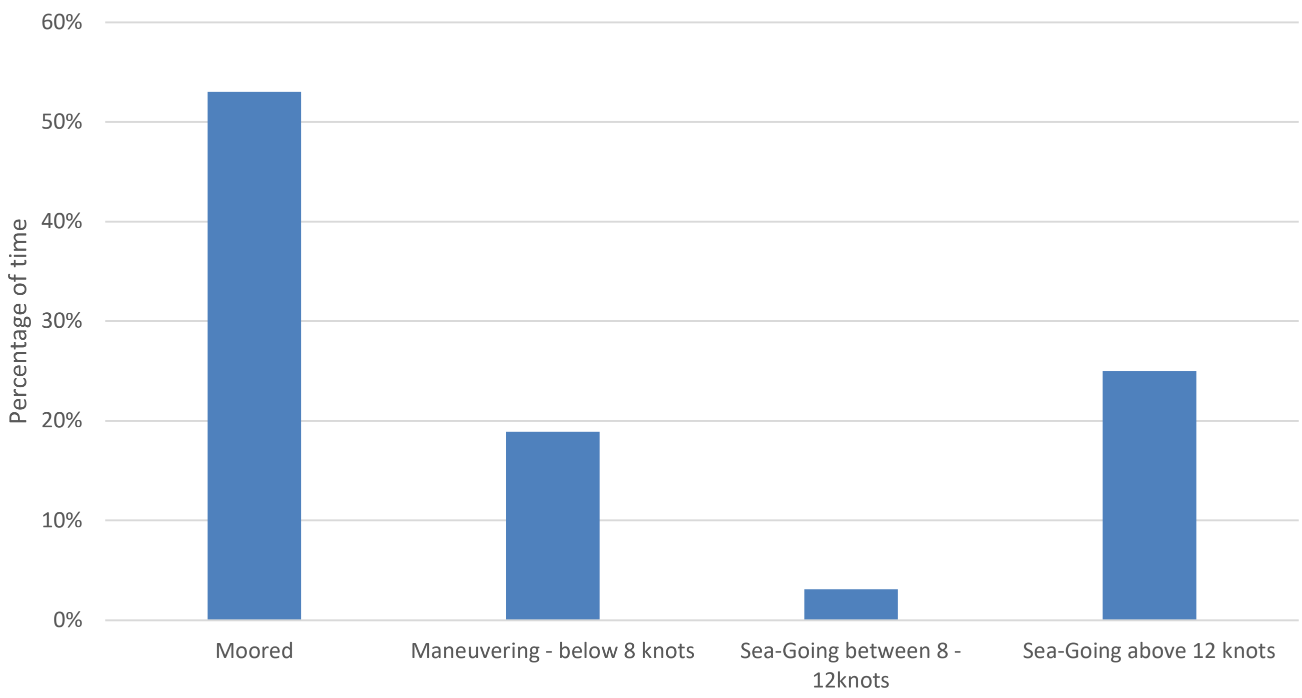

Figure 0-32 RoPax operating profile.

- **CO_2 performance analysis**

The OCCS technology is examined for sweeps of CO_2 capture capacity. The results from 0.25, 0.50, 0.75 & 1.00 TPH are presented, as these present options that are reasonable in terms of LCO_2 storage and maintain the operation of the Auxiliary Gensets and boilers within manufacturer and redundancy limits (load below 90%, 1 Aux. Diesel Generator on standby).

For the case of RoPax vessels with similar operational profiles to the one examined, it is considered that the presence of a shaft generator may not be as beneficial due to the limited time spent at sea-going. Furthermore, as per (DNV, Energy Efficiency Measures and Technologies, 2025a), the installation of exhaust-gas boilers on auxiliary engines is less likely to be beneficial for vessels that exhibit extensive use of shore power. This is expected to be more prevalent in the upcoming years as a result of REGULATION (EU) 2023/1804, which details the Targets for shore-side electricity supply in maritime ports, by requiring that Member States ensure a minimum shore-side electricity supply for seagoing container ships and seagoing passenger ships is provided in TEN-T maritime ports by 31 December 2029.

Therefore, for the case of the RO-PAX vessel the retrofit scenario will be examined with the OCCS technology in terms of energy efficiency a state-of-the-art system is considered with specification shown in Table 0-5.

For all years after 1st January 2030, vessel is considered to use shore connection during her port stay, each being approximately 12 hours in duration, meaning that all vessel’s systems including OCCS are not operated during port stay. The only system operating during vessel’s port stay is assumed to be the Aux. boiler which covers vessel’s steam demands.

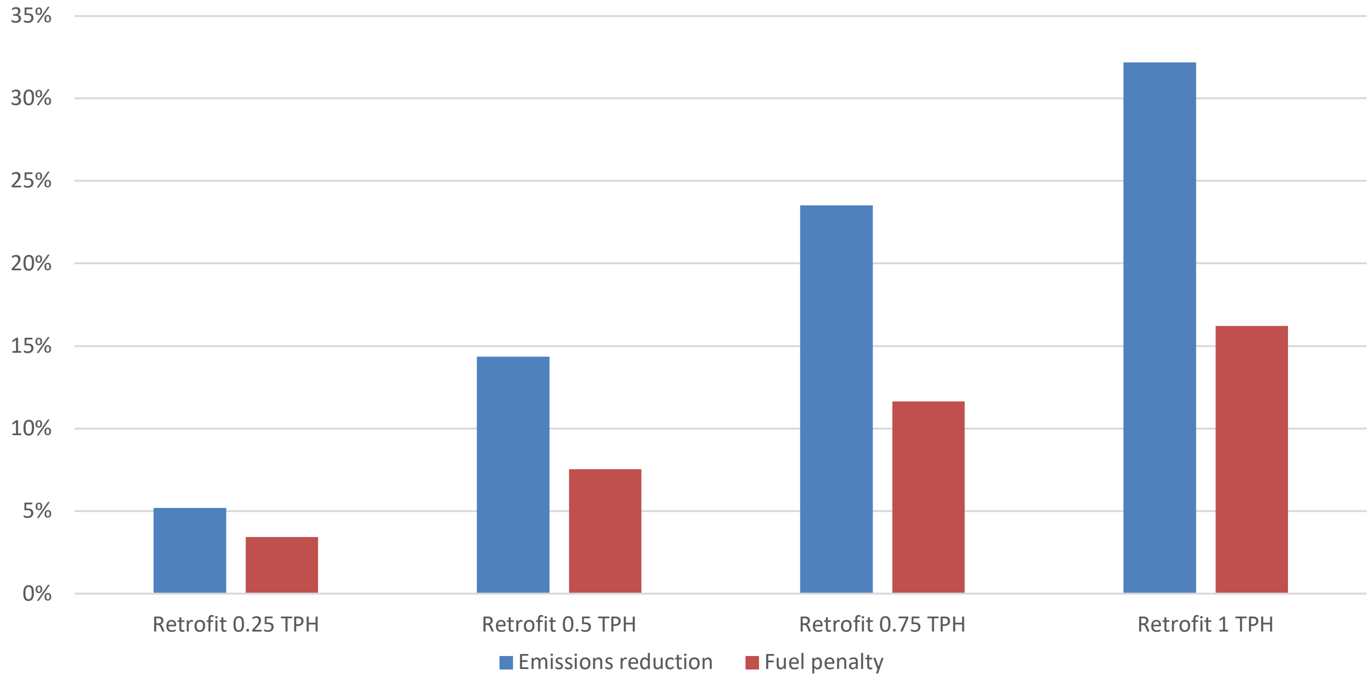

Figure 0-33 RoPax - Emissions reduction vs Fuel penalty.

CO_2 performance

Based on the operational profile provided, the vessel engages in several coastal round-trips per day, while remains moored at port during the night. The yearly assessment includes the total consumption of fuel in metric tons, the corresponding total CO_2 emissions generated, and the amount of CO_2 captured by each case. Additionally, the analysis presents the net CO_2 emissions released into the atmosphere after capture, as well as the total quantity of CO_2 abated. These metrics provide a comprehensive overview of the environmental performance of the vessel and the effectiveness of the OCCS in reducing GHG emissions.

The yearly CO_2 performance results are shown for the OCCS capacity of 0.25, 0.50, 0.75 & 1.00 TPH in Figure 0-34.

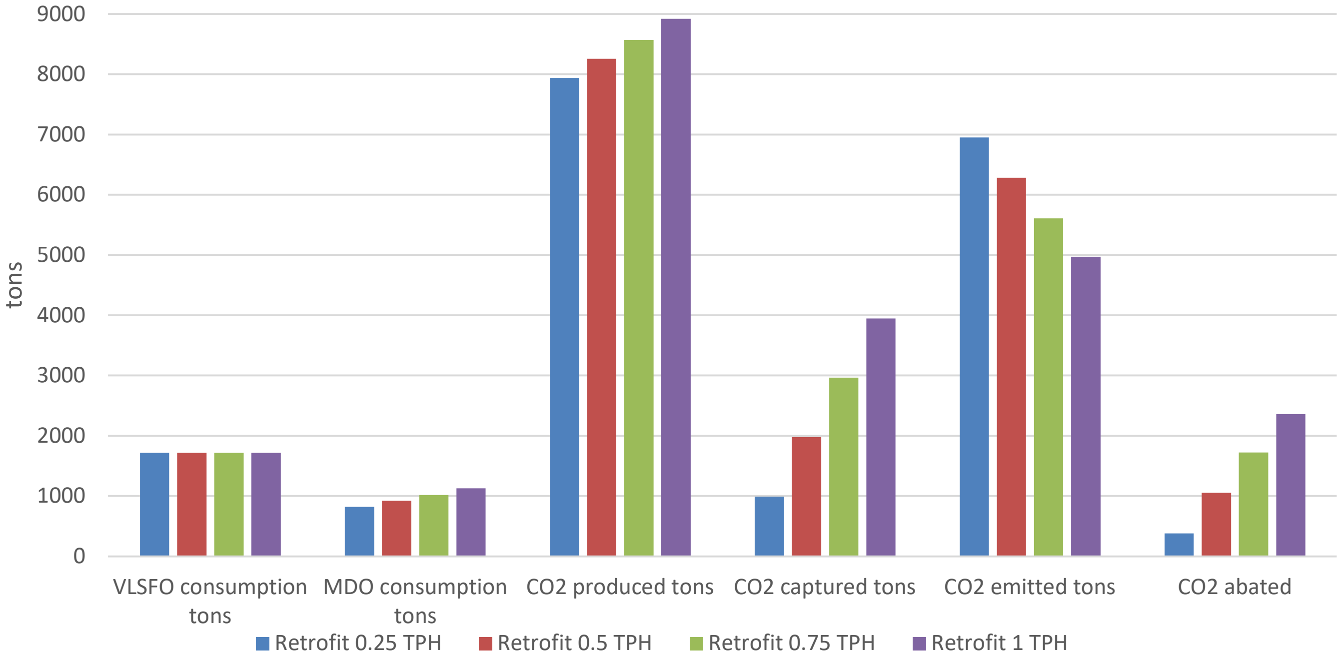

Figure 0-34 RoPax - OCCS yearly performance.

OCCS impact on machinery performance

In this section an overview of the effect of the OCCS technology on the different machinery of the vessel (Aux. Engines and Boilers) will be presented.

Figure 0-35 illustrates the impact of the different OCCS capture rates on the utilization of key machinery components, specifically the main engine and auxiliary engines, during laden sailing at a service speed of 15 knots, which is the average speed of the vessel. As the OCCS capture rate increases from 0.25 TPH to 1 TPH, the load on the two auxiliary engines rises from 47% to 70% utilization. Main Engine load remains steady for all OCCS capture rates, since no PTO has been installed in the RoPax case.

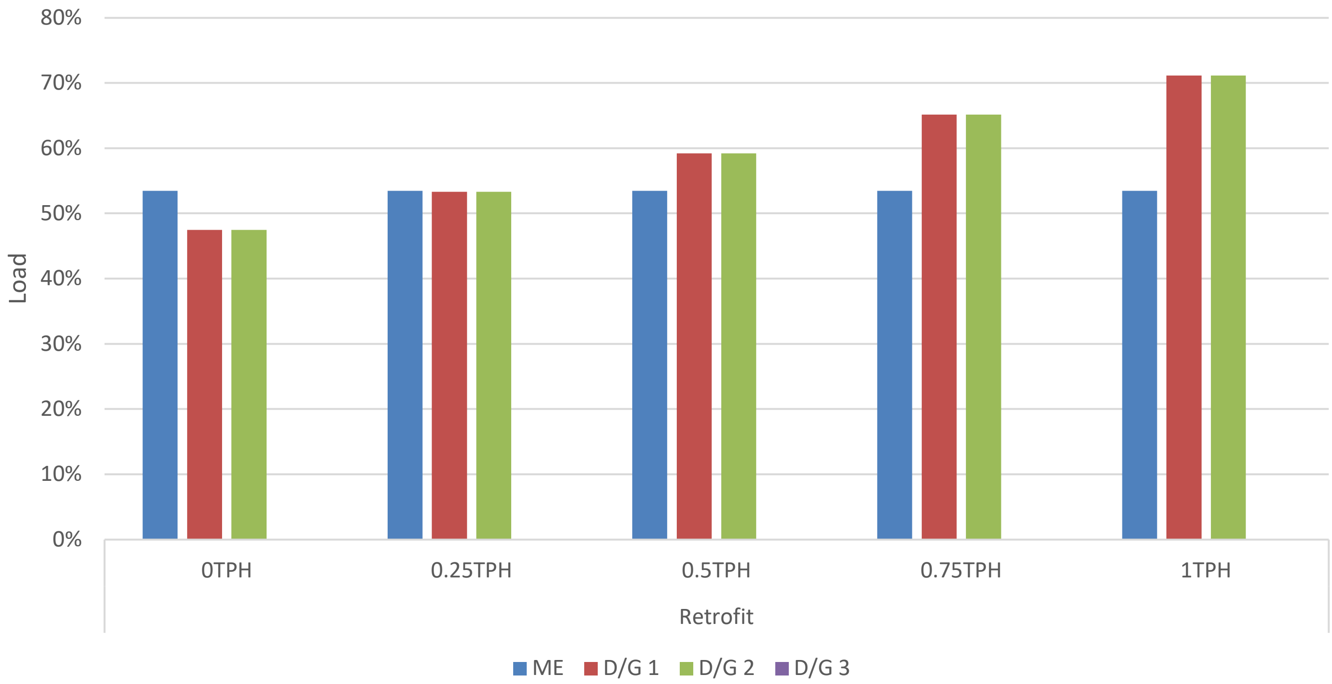

Figure 0-35 RoPax - OCCS Impact on Main Engine and Aux. Engines at 15 knots in laden condition.

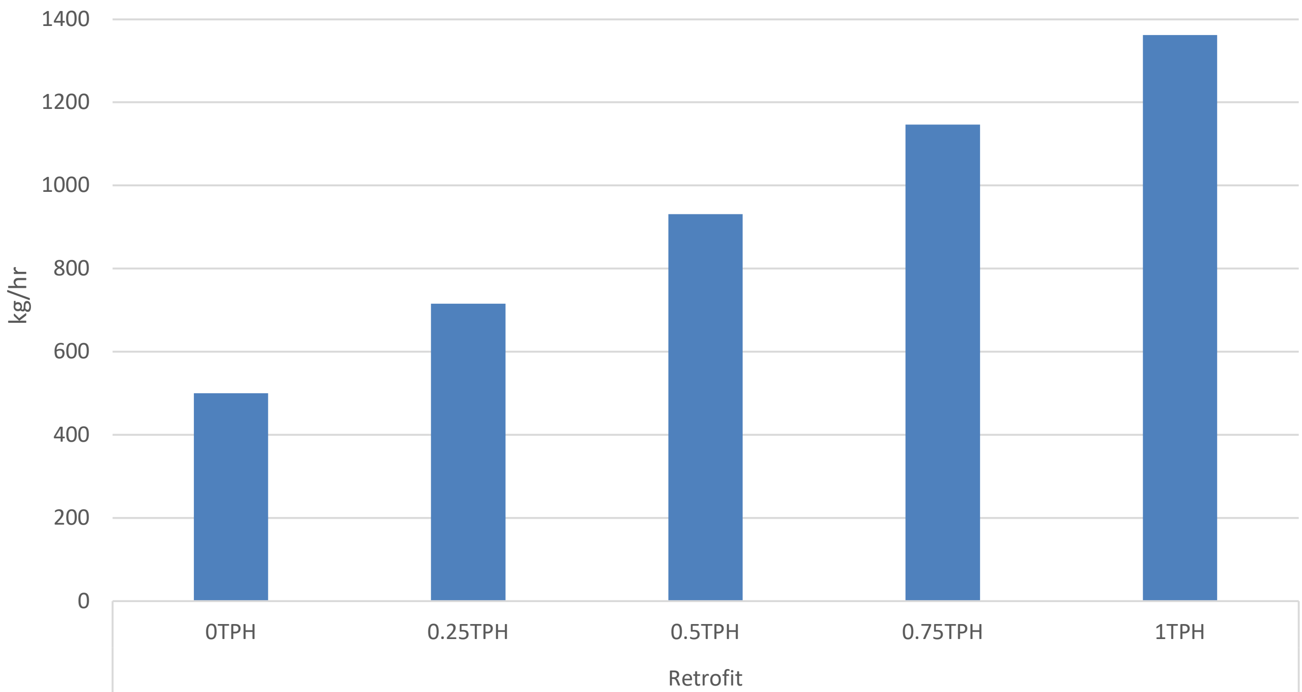

Figure 0-36 RoPax case - total steam production per roundtrip including OCCS heat demand.

- **Economic impact analysis**

CO_2 abatement cost

CO_2 abatement cost analysis will present the cost associated with reducing one metric ton of carbon dioxide emissions compared to the baseline scenario for each of the examined cases.

The CO_2 abatement cost assessment is evaluated under three implementation cost scenarios: low, base, and high. all financial figures are discounted to the base year 2025, with a discount rate of 8% applied (Xiaobo Luo, 2017), (Sadi Tavakoli, 2024).

Results of the CO_2 abated cost are shown in Figure 0-37.

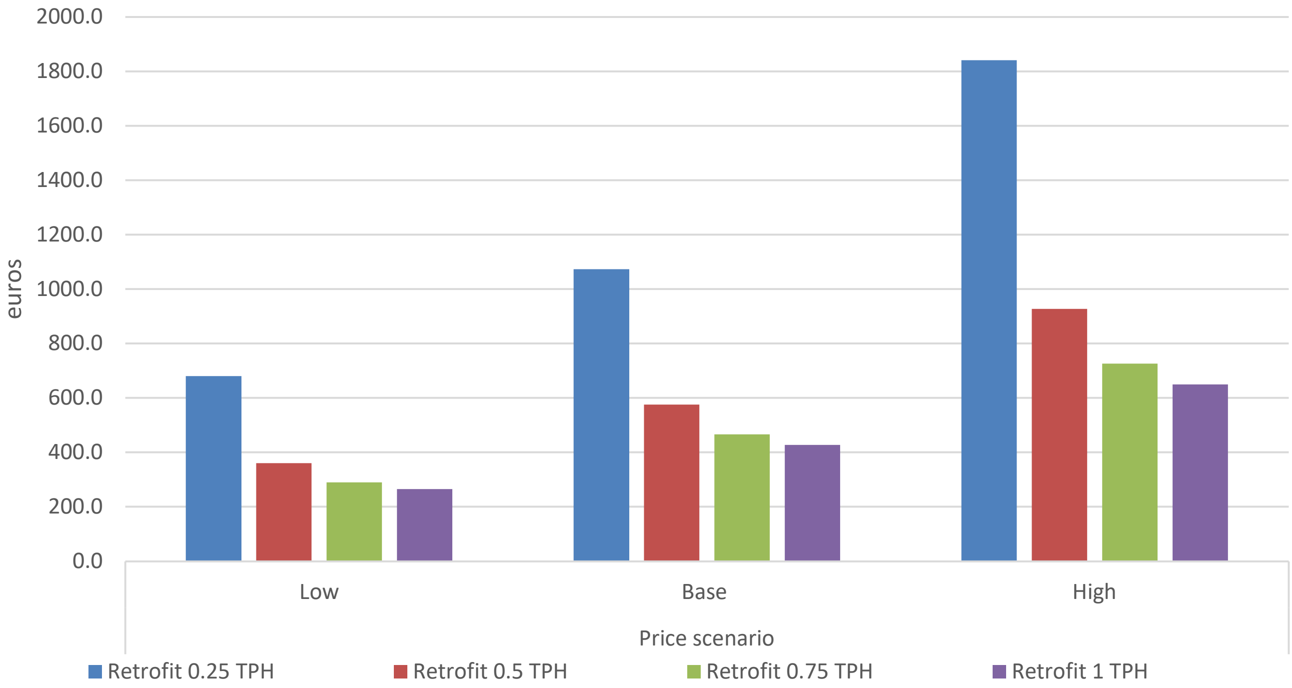

Figure 0-37 RoPax - CO_2 abatement cost per tons CO_2 abated.

CAPEX / OPEX calculation

In this section a more detailed overview of the CAPEX costs per case is done. For CAPEX costs the OCCS technology is considered since PTO and AEECOs were not beneficial/optimal for the RoPax case

Figure 0-38 presents the CAPEX analysis results.

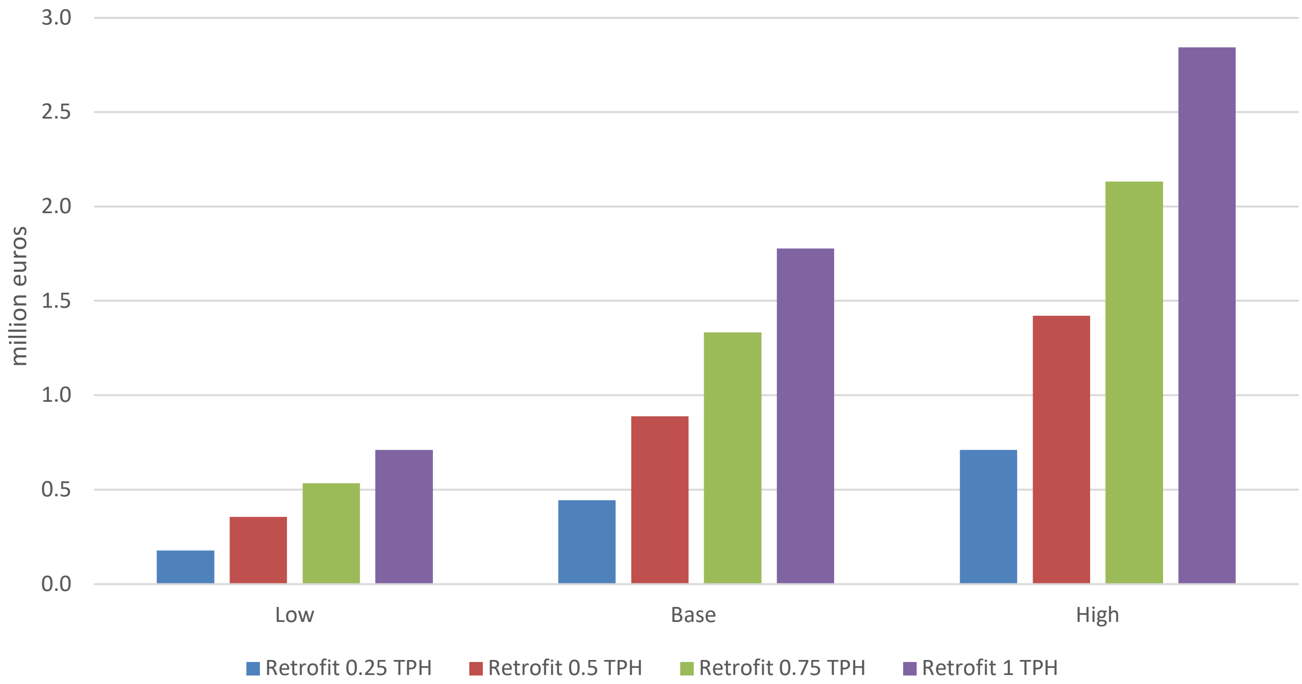

Figure 0-38 RoPax - CAPEX analysis.

In order to estimate the yearly fuel OPEX for the examined cases, prices are assumed as per Table 3-15. The OPEX fuel results are shown in Figure 0-39 for all cases examined and for the 3 different price scenarios. As mentioned in the introduction for the RoPax vessel, after 1st January 2030, vessel is considered to use shore connection while at port, with the cost of shore connection undertaken from vessel owner. The cost for kWh is considered to be between 0.10 €/kWh and 0.20 €/kWh.

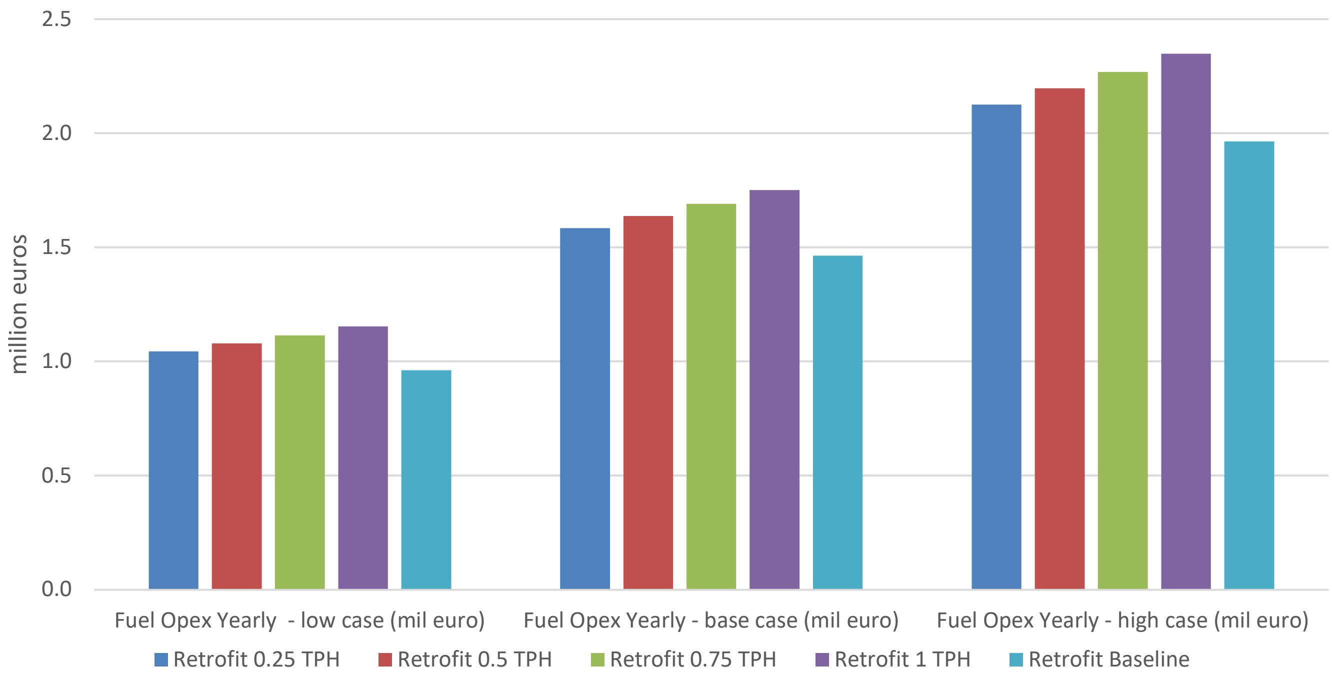

Figure 0-39 RoPax - Yearly Fuel OPEX in mil. Euro.

Economic analysis of disposal cost

The disposal cost for the captured CO_2 on a yearly basis for the RoPax vessel is shown in Figure 0-40.

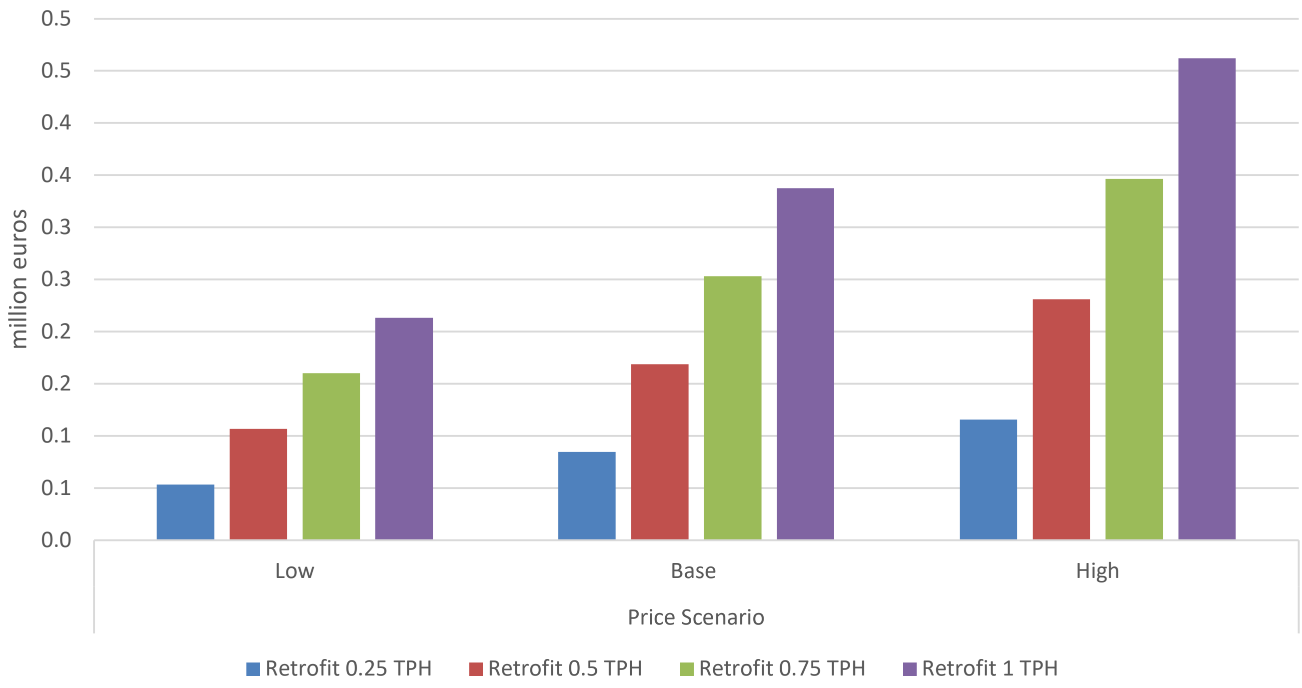

Figure 0-40 RoPax - Yearly disposal cost of CO_2.

CO_2 abatement cost per ton of Captured CO_2 – sensitivity analysis

Following the evaluation of various cost metrics, namely CAPEX, fuel OPEX, and CO_2 disposal costs, a sensitivity analysis was conducted to assess their impact on the overall CO_2 abatement cost. This analysis shows the case of the OCCS system with a capture rate of 1.0 TPH.

The results indicate that the CO_2 disposal cost and fuel OPEX exert the most significant influence on the abatement cost. These are followed by the technology CAPEX and maintenance costs, which have a moderate impact. In contrast, the cost of solvents contributes minimally to the overall CO_2 abatement cost.

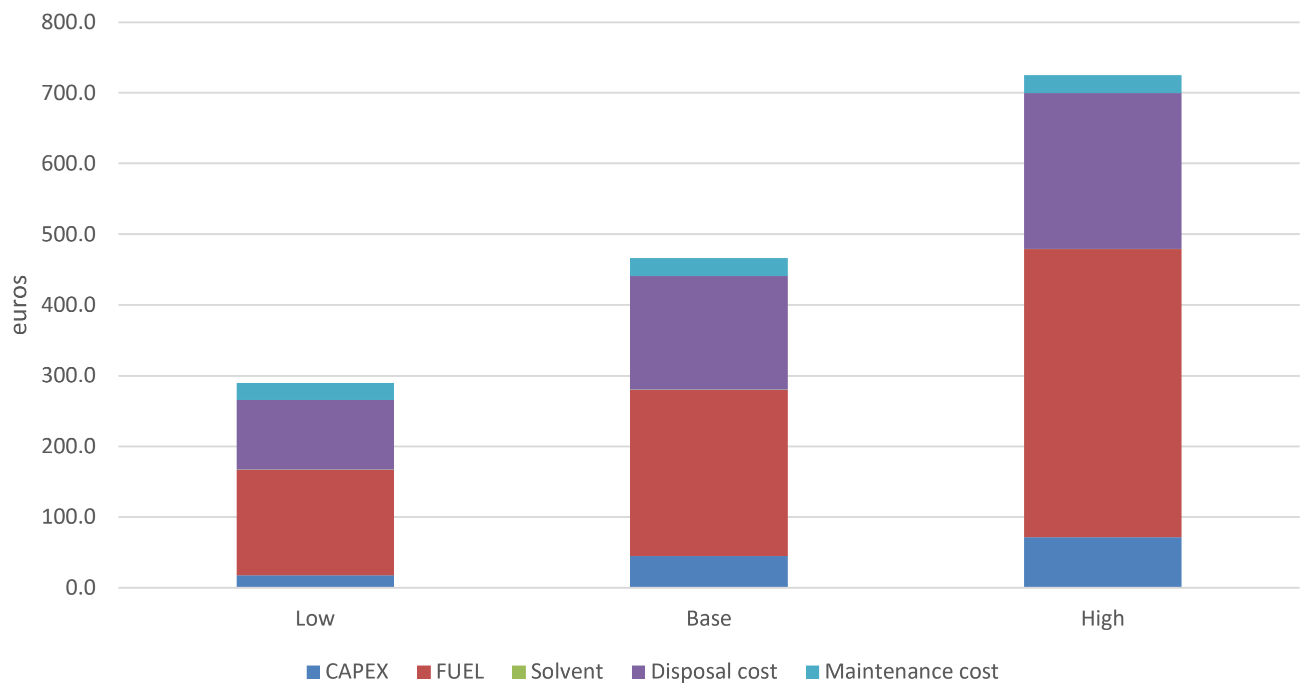

Figure 0-41 RoPax - CO_2 abatement cost per ton CO_2 sensitivity analysis for the 1.0 TPH capture rate.

Port offloading and ship interface analysis

The displaced vapor results are showcased in tons, according to the different CO_2 capture rates and vessel tank sizes as shown in Figure 0-42. The required energy of the systems involved (pump, heater and cooler) is showcased separately for each vessel and CO_2 capture rates in kWh in Figure 0-43.

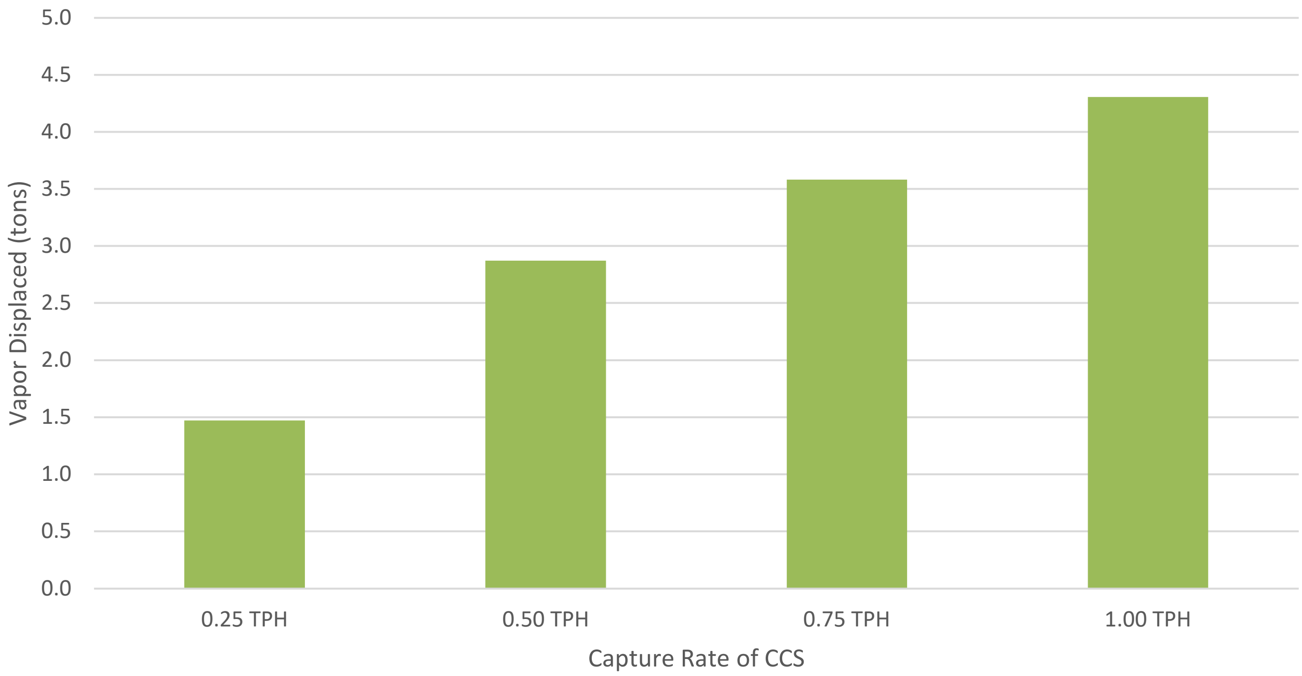

Figure 0-42 RoPax - displaced vapor during offloading per capture rate, assuming an offloading rate of 50 m^3/hr.

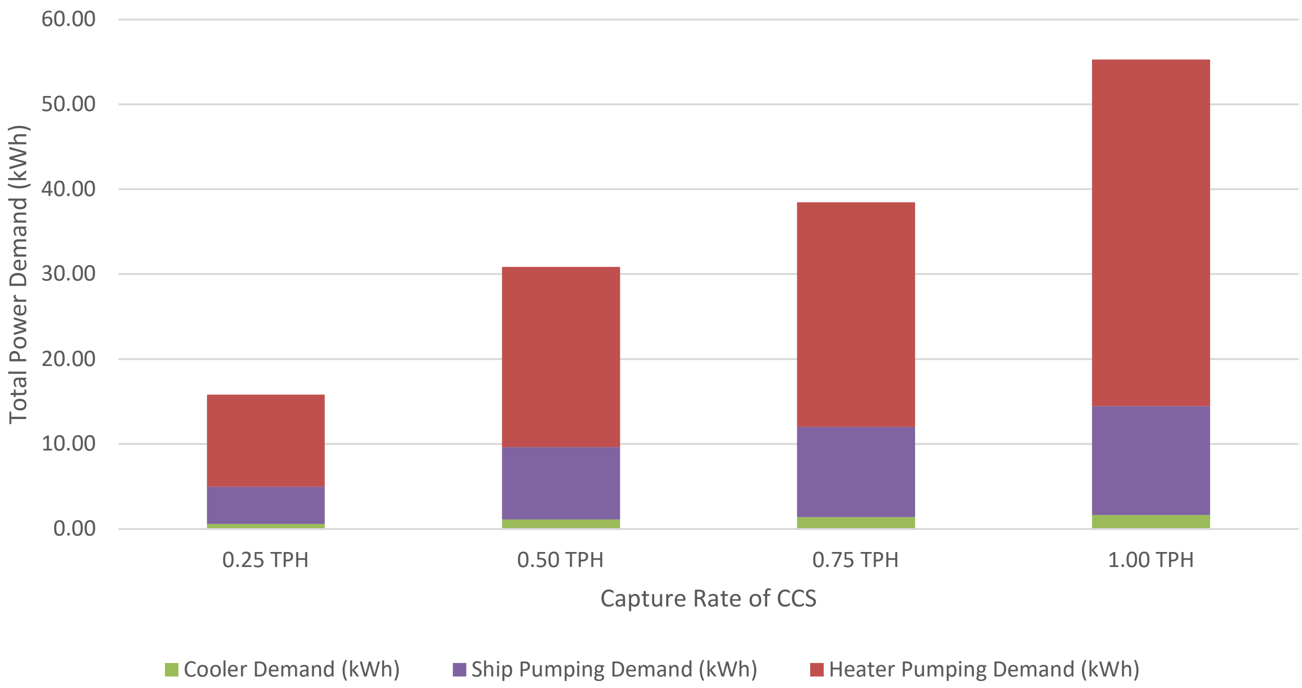

Figure 0-43 RoPax - total required energy during offloading, assuming an offloading rate of 50 m^3/hr.

- **Technical impact analysis**

This section presents a high-level analysis of the potential impact associated with the installation of the OCCS on the vessel. The objective is to guide the reader through the key considerations and preliminary assessments required when evaluating the feasibility and implications of OCCS integration. In contradiction to container ships and oil tankers the two key concerns are deck strength when heavy tanks are placed on top deck, and stability is also a main concern. Cargo loss is also a relevant topic from a commercial perspective. These are however very much dependent on the capacity of the LCO_2 tanks.

LCO_2 storage tanks capacity and dimensions estimation

The estimations for the required capacity of the LCO_2 tank is based on the specificities of the operating profile of the vessel. It is assumed that any LCO_2 captured during the sailing of the vessel shall be discharged every 15 days, while vessel is at port, so as not to interfere with its daily trade. The fact that LCO_2 will be discharged every 15 days also leads to relatively smaller LCO_2 tanks and weight, when compared to vessels that engage in deep sea voyages. LCO_2 storage tanks are considered to be filled up to 95% of their volume, while LCO_2 density is assumed to be equal to 1,110 kg/m^3.

Table 0-15 RoPax - LCO_2 Storage Tanks specifications.

LCO_2 Storage Tanks specifications				
Capture rate of OCCS	CO_2 captured per 15 days+10% margin (m3)	LCO_2 total required capacity (m^3)	Tank D x L (m) (per storage tank)	Total weight including LCO_2 (tons)
0.25 TPH	39	50	2 x 7	98
0.50 TPH	73	80	2 x 8	152
0.75 TPH	91	100	3 x 9	189
1.00 TPH	109	120	3 x 9	223

OCCS impact on vessel space demands

LCO_2 Storage Tanks

The two LCO_2 storage tanks are fitted on vessel's upper most deck port and starboard, in front of the funnel. This placement utilizes the available space on this deck efficiently and ensures easy access for maintenance and offloading. Since the RoPax case looks into a retrofit scenario, a potential reinforcing of the deck may be required.

The installation location of the LCO_2 storage tanks is likely not classified as a hazardous area.

Carbon Capture System

The absorber and regeneration stacks can be installed between the vessel's funnel and the LCO_2 storage tanks. This location leverages the existing structures and minimizes interference with other operations of the vessel. In terms of piping this placement will result in long additional piping.

Retrofitting for OCCS requires advance planning to integrate it with the existing structures. This may involve additional engineering work to ensure the system does not interfere with the vessel's existing operations.

Liquefaction Plant

This system is typically located in the engine room or a designated space on deck, with a potential placement being close to the OCCS capture system. Typical dimensions for the system for a capture would require a space of appr. 28 – 30 m^2 to be allocated.

In the case of the RoPax vessel, the installation of the liquefaction plant will take place in an existing vessel and therefore may require some modifications, such as structural reinforcements to support the weight and vibration of the equipment.

Impact on weight

The CO_2 storage tanks are placed symmetrically on the vessel, to ensure a balanced weight distribution along the roll axis. The placement of the OCCS components is behind the funnel. Weight distribution per component and the effect on Lightweight increase per case is shown in Table 0-16.

Table 0-16 RoPax - OCCS weight distribution (tons).

OCCS Weight distribution in tons per examined capture rates				
	0.25 TPH	0.50 TPH	0.75 TPH	1.00 TPH
OCCS System weight - Structure only	54	68	84	98
Increase compared to baseline LWT	1.3%	1.7%	2.1%	2.5%

The impact on hull girder loads is regarded insignificant, and for ro-ro vessels it is more the transverse loads that are the main concern and not necessarily the longitudinal hull girder loads, which is more of a concern for a pure passenger vessel. The additional weights should in any case be included in loading manual for both stability calculations and still water bending moment distribution. The hull girder strength margin for this vessel size is however considered as significant, so not being an issue even for the retrofit case.

The local deck structure intended to support the heavy tanks is, however, regarded as weak, and moderate to substantial additional strengthening is regarded necessary to support the heavy deck loads even for the smallest LCO_2 tanks. This could include additional pillar arrangement. Because of the additional heavy tanks on the top deck, racking assessment is regarded necessary for this ship type, as the transverse accelerations with heavy weights on top deck may significantly increase the racking moment. This implies that the frame system also needs to be assessed. However, how the racking moment is taken up by the framing system depends very much on the specific vessel design and number of racking bulkheads and may be quite much better on a Ro-Pax vessel than on a purer Ro-Ro vessel. The additional steel weight may consequently be moderate and may be a significant part of the total structural weight of the OCCS.

Impact on stability

The effect of the OCCS system on vessel's stability shall be assessed to ensure compliance with acceptable limits. The evaluation must include the weight of liquids contained within the system under normal operating conditions. .

The OCCS integration on a RoPax vessel, including the capture unit, liquefaction plant, and LCO_2 storage tanks, has direct implications for vessel stability. Installing these components on the uppermost deck, while operationally convenient, raises the vessel's VCG. This results in a reduced metacentric height (GM), which can negatively affect initial stability, increase roll motions and therefore reducing the vessel's ability to recover from heeling in rough sea conditions. It may change the metacentric height value, GM, in the order of 0.6 m when the storage tanks are full but is very much dependent on the vessel's design and exact location of the storage tanks and the other OCCS units. This change in GM is considerable on a vessel type known to have stability focus and may be in the order of the lower acceptable threshold of the GM value.

Alternatively, placing the LCO_2 tanks within the vehicles decks offers stability benefits by lowering the VCG and improving the righting arm characteristics. However, this configuration introduces safety concerns due to the proximity of passengers and crew to enclosed spaces that may be classified as hazardous zones. The presence of pressurized CO_2 in such areas requires enhanced ventilation, gas detection systems, and EX-certified equipment, which may offset the stability advantages with increased complexity and cost.

In both scenarios, structural reinforcement may be necessary to support the added weight and dynamic loads. While a detailed hydrostatic analysis is beyond the scope of this study, the impact on vessel stability must be acknowledged as a key factor in the technoeconomic evaluation of OCCS retrofitting. The benefit is that there are normally some reserves on the stability for the retrofit case which may be sufficient without significant consequence especially for the case of the smaller LCO_2 tanks.

For the liquefaction plant, given the presence of pressurized CO_2 and potential leak scenarios, the same safety requirements, such as dedicated ventilation, gas detection, and explosion-proof equipment, are expected to apply. To comply with these standards and mitigate risks, the liquefaction plant may need to be installed in a segregated, purpose-built compartment adjacent to or outside the ER, rather than within the general machinery space.

Impact on Transporting Capacity

The OCCS installation on a RoPax vessel, including the capture unit, liquefaction plant, and LCO_2 storage tanks, can significantly affect the vessel's cargo carrying capacity, both in terms of available volume and deadweight.

If the LCO_2 storage tanks are placed within the cargo hold, they will occupy physical space that would otherwise be used for vehicles or freight. Even with LCO_2 tanks on deck, deadweight increase studies in the retrofit case may be relevant to avoid loss in cargo capacity. The larger LCO_2 tank may be comparable to 100 cars. This directly reduces the vessel's commercial payload capacity and may impact route profitability, especially on high-demand lines. Additionally, the presence of CCS infrastructure in cargo areas may interfere with loading and unloading operations, requiring reconfiguration of access routes or the establishment of safety zones, further limiting usable space.

Even when the CCS system is installed on the uppermost deck, preserving cargo volume, the added mass of the system consumes part of the vessel's deadweight allowance, potentially affecting the total weight the vessel can safely carry, including cargo, fuel, provisions, passengers, and equipment. The CCS system, depending on its scale, may reduce the margin available for cargo and other payloads, potentially requiring adjustments to fuel loads or limiting freight intake.

This trade-off is particularly relevant for RoPax vessels, which rely on a balance between passenger services and freight revenue. The impact on operational flexibility, route economics, and regulatory compliance should be considered alongside the environmental benefits of CCS integration.

- **Economic Viability**

For the RoPax vessel, the financial exposure under the EU Emissions Trading System (EU ETS) is assessed based on its intra-EU operational profile. Two scenarios are considered to reflect different levels of regulatory coverage:

- Scenario A – Low EU Exposure:

The vessel operates predominantly on intra-EU routes connecting mainland ports, with approximately 70% of its annual operating time within regulated zones.

- Scenario B – High EU Exposure:

The vessel operates solely on intra-EU routes, with 100% of its annual operating time within regulated zones.

It should be noted that, for vessels operating primarily on routes serving EU islands with populations below 200,000 inhabitants, in accordance with EU ETS provisions, emissions from such voyages are exempt from regulation, resulting in minimal financial exposure.

Carbon pricing is modelled at €170 per ton of CO_2, and the analysis is based on a capture rate of 1 TPH. The focus is placed on the potential savings in EU ETS allowance costs, providing a clear view of the economic viability of OCCS deployment for RoPax vessels under varying regulatory conditions. Detailed results are presented in Table 0-17.

Table 0-17 RoPax - EU ETS analysis for 1 TPH.

Scenario	EU ETS allowance savings in thousands of euros on a yearly basis	
	Low EU Exposure	High EU Exposure
1 TPH Retrofit	434	620

Appendix E LNGC cost economic analysis

■ Vessel overview

For the LNGC vessel, the main dimensions and machinery are shown below.

Table 0-18 LNGC case vessel main dimensions and machinery.

LNGC case study – Vessel specifications	
First year in service	2025
DWT	Appr. 90,000 tons
Lightweight	Appr. 35,000 tons
Propulsion system	2 x 2-Stroke Dual fuel engine of abt. 12.5 MW each
Electricity supply	2 x 4-stroke Dual Fuel engines of 3 MW each 2 x 4-stroke Dual fuel engines of 4.5 MW each
Heat supply	2 x auxiliary boilers 1 x Main Engine Exhaust Gas Economizer

The operational profile of a typical 174,000 m^3 LNGC is analysed below, detailing the distribution of time spent underway, at anchor, and during port operations as shown in Figure 0-44. Results are aggregated for laden and ballast voyages

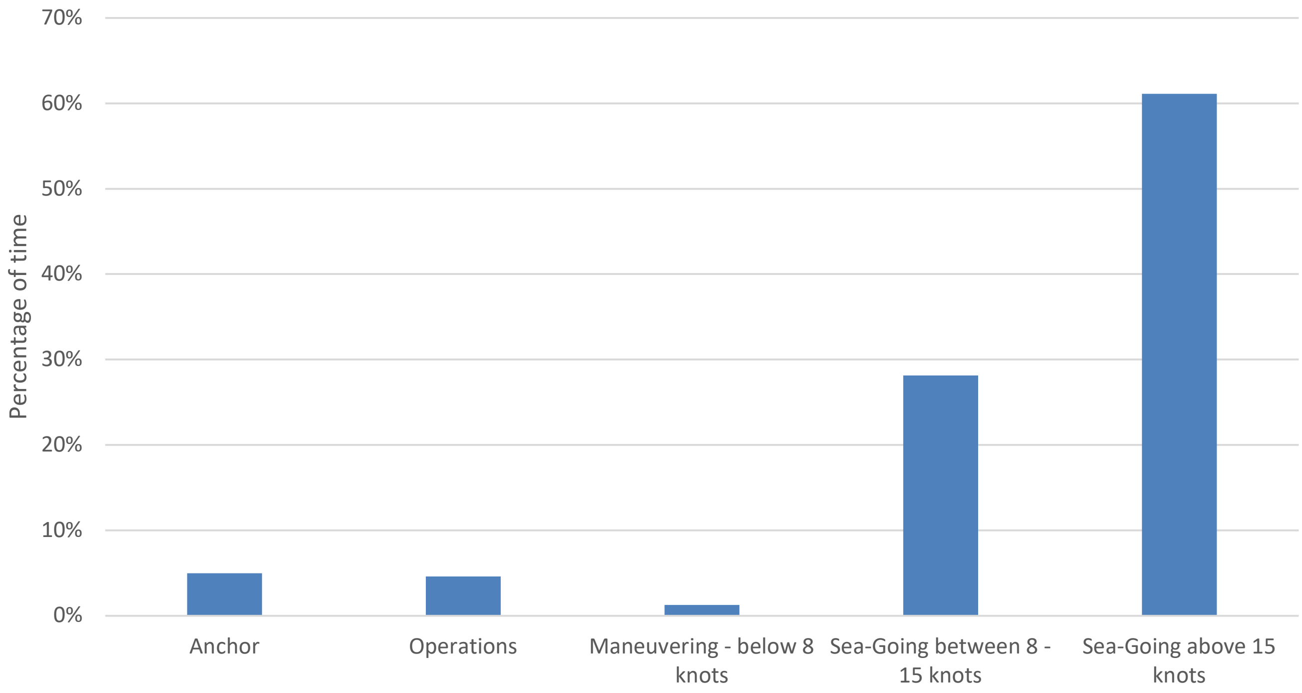

Figure 0-44 LNGC operating profile.

- **CO_2 performance analysis**

The OCCS technology is examined for sweeps of CO_2 capture capacity. The results from 1, 2 & 3 TPH are presented, as these present options that are reasonable in terms of LCO_2 storage and maintain the operation of the Aux Gens and boilers within manufacturer and redundancy limits (load below 90%, 1 Aux D-G on standby).

Same as rest of the cases, in the case of the NB vessel two additional considerations will take place:

- Properly sized AEECOs for the OCCS, sized to the capacity of the exhaust gas enthalpy from the Auxiliary Engines (including two exhaust gas boilers for the auxiliary generator sets)
- Installation of two units of PTO of 2 MW each (to cover vessel's electrical demands during sailing, including OCCS)

Table 0-19 LNGC - Technology Components for each configuration.

Design / Components	Aux. Engines' Economizers	PTO
Retrofit	-	-
Newbuilding with PTO	-	X
Newbuilding with AEECOs	X	-

Same as for the Suezmax case, the examined OCCS technology in terms of energy efficiency a state-of-the-art system is considered with specification as shown in Table 0-5

Comparative analysis

Results of the analysis for the capture rate of 1 TPH, 2 TPH and 3 TPH are shown in Figure 0-45

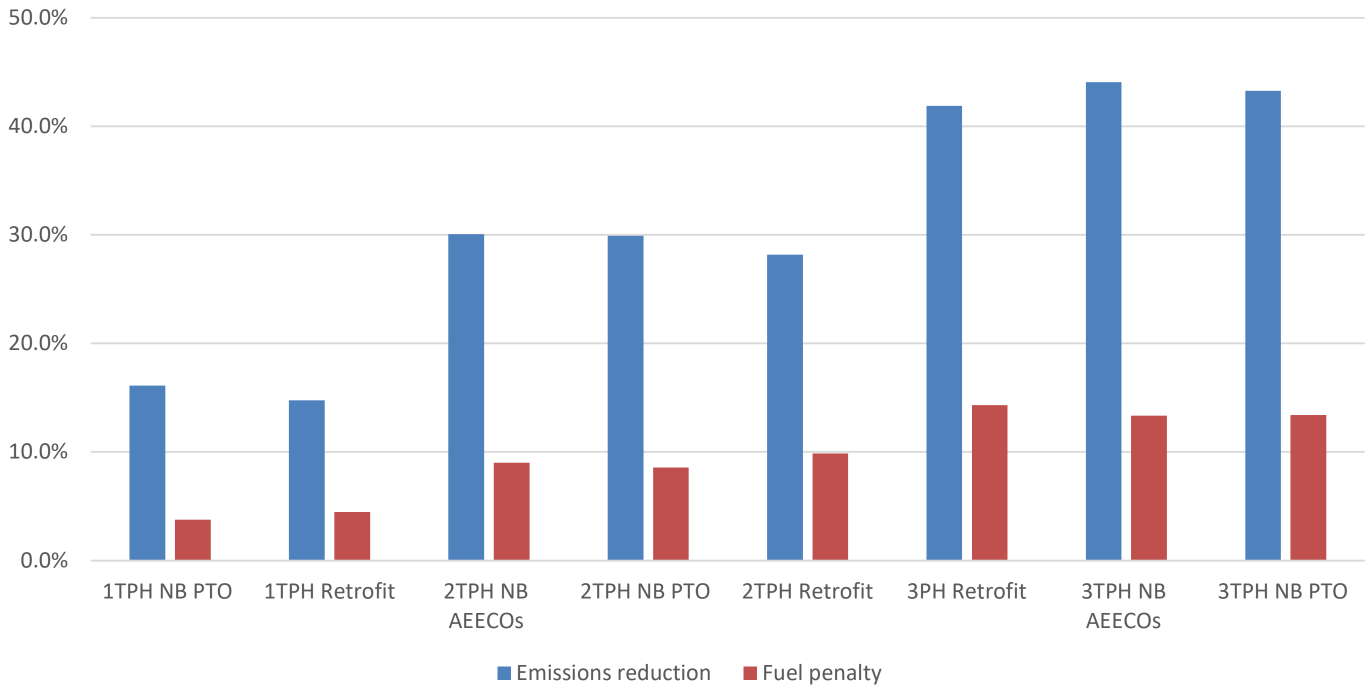

Figure 0-45 LNGC - Emissions reduction vs Fuel penalty.

CO_2 performance

A typical round trip for this type of vessel has a duration of approximately 40 days[91]. Based on this operational cycle, the vessel is expected to complete around nine round voyages per year. This frequency forms the basis for evaluating the annual performance of the onboard systems, particularly in terms of fuel consumption and emissions.

The yearly assessment includes the total consumption of LNG, MDO and HFO, both in metric tons, the corresponding total CO_2 emissions generated, and the amount of CO_2 captured by each case. Additionally, the analysis presents the net CO_2 emissions released into the atmosphere after capture, as well as the total quantity of CO_2 abated. These metrics provide a comprehensive overview of the environmental performance of the vessel and the effectiveness of the OCCS in reducing GHG emissions.

The yearly CO_2 performance results are shown for the OCCS capacity of 1 TPH, 2 TPH and 3 TPH in Figure 0-46.

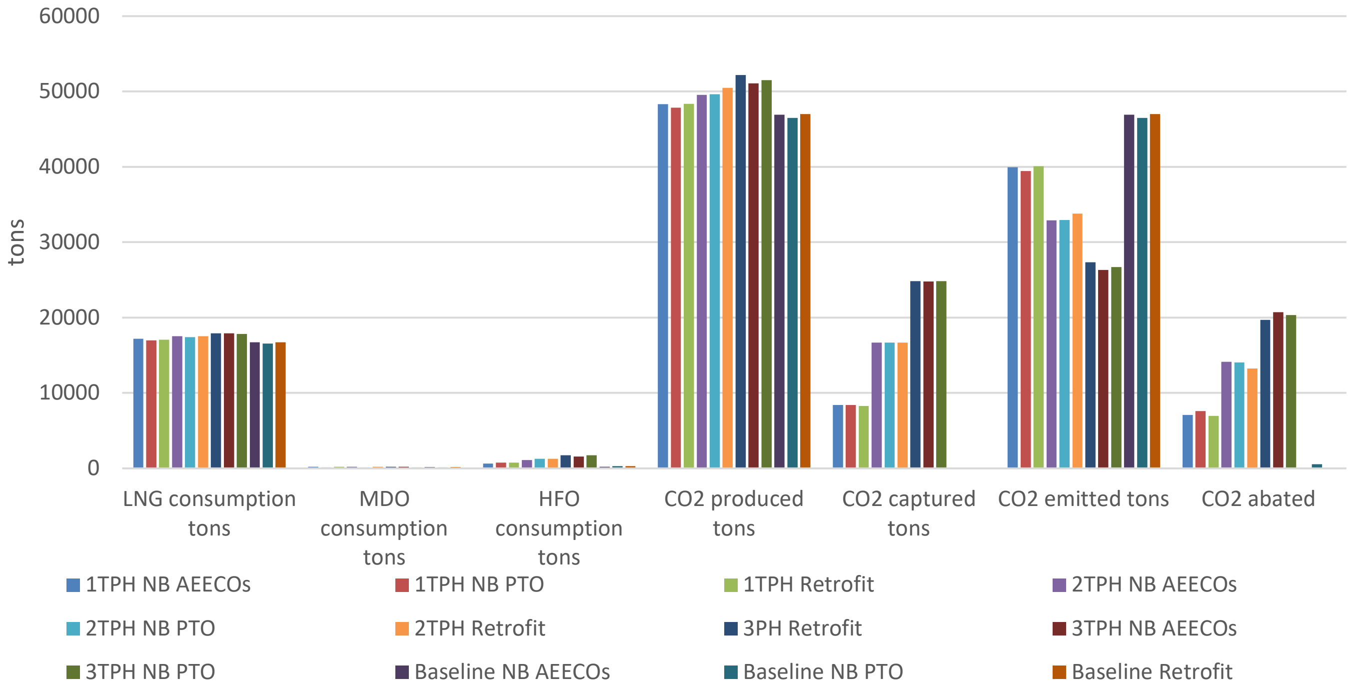

Figure 0-46 LNGC - OCCS yearly performance.

OCCS impact on machinery performance

In this section an overview of the effect of the OCCS technology on the different machinery of the vessel (Aux. Engines and Boilers) will be presented.

Figure 0-47 illustrates the impact of the different OCCS capture rates on the utilization of key machinery components, specifically the main engine and auxiliary engines, during laden sailing at a service speed of 16 knots, which is the average speed of the vessel. For the retrofit case and NB AEECOs, as the OCCS capture rate increases from 1 TPH to 3 TPH, the load on the auxiliary engines rises from 60% to appr. 80%. In the optimized newbuilding with PTO, when the PTO system is employed, the main engine and PTO can meet the additional electrical demand imposed by the OCCS system, thereby eliminating the need to engage auxiliary generators.

[91] Expanded Panama Canal reduces travel time for shipments of U.S. LNG to Asian markets - U.S. Energy Information Administration (EIA)

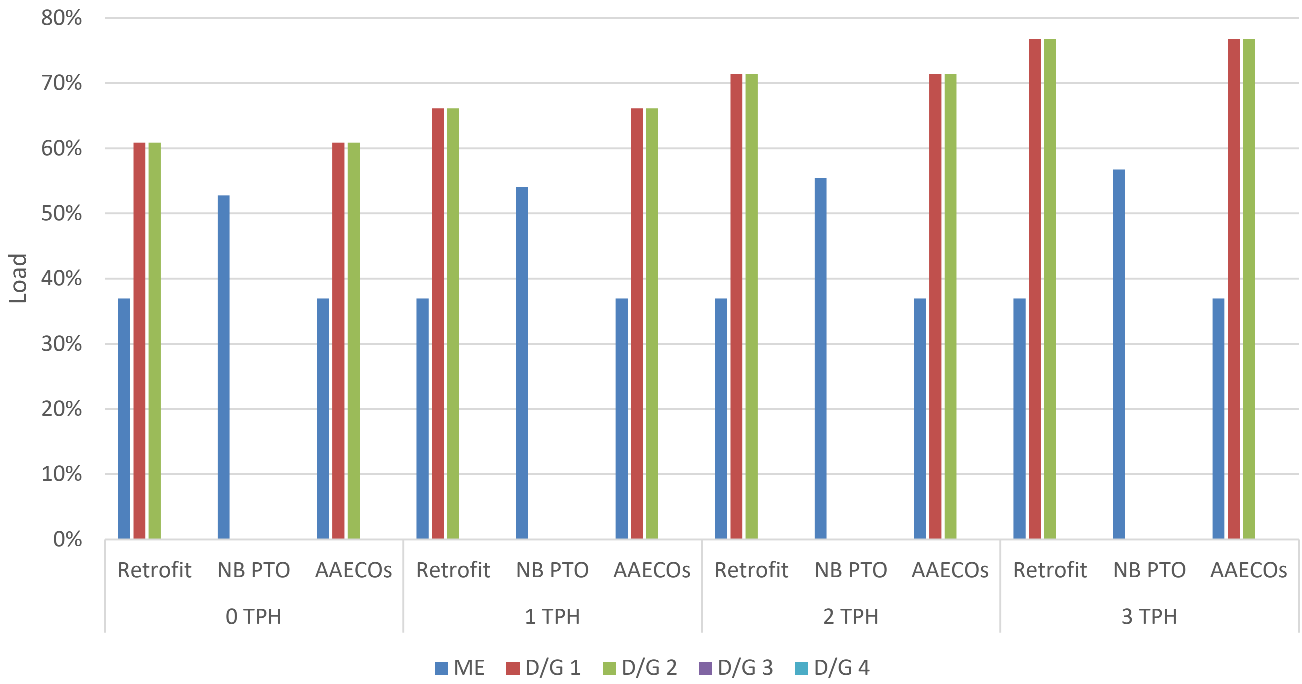

Figure 0-47 LNGC - OCCS Impact on Main Engine and Aux. Engines at 16 knots in laden condition.

Figure 0-48 LNGC - OCCS Impact on Aux. boiler & Economizers at 16 knots in laden conditionshows the total steam demand of the vessel including the ones of the OCCS, during laden sailing at a service speed of 16 knots. For this reason, the cases without the OCCS have been included in the graph as well.

As can be seed from the graph, regardless of the technology equipped the total steam demands remain steady for the same carbon capture rate.

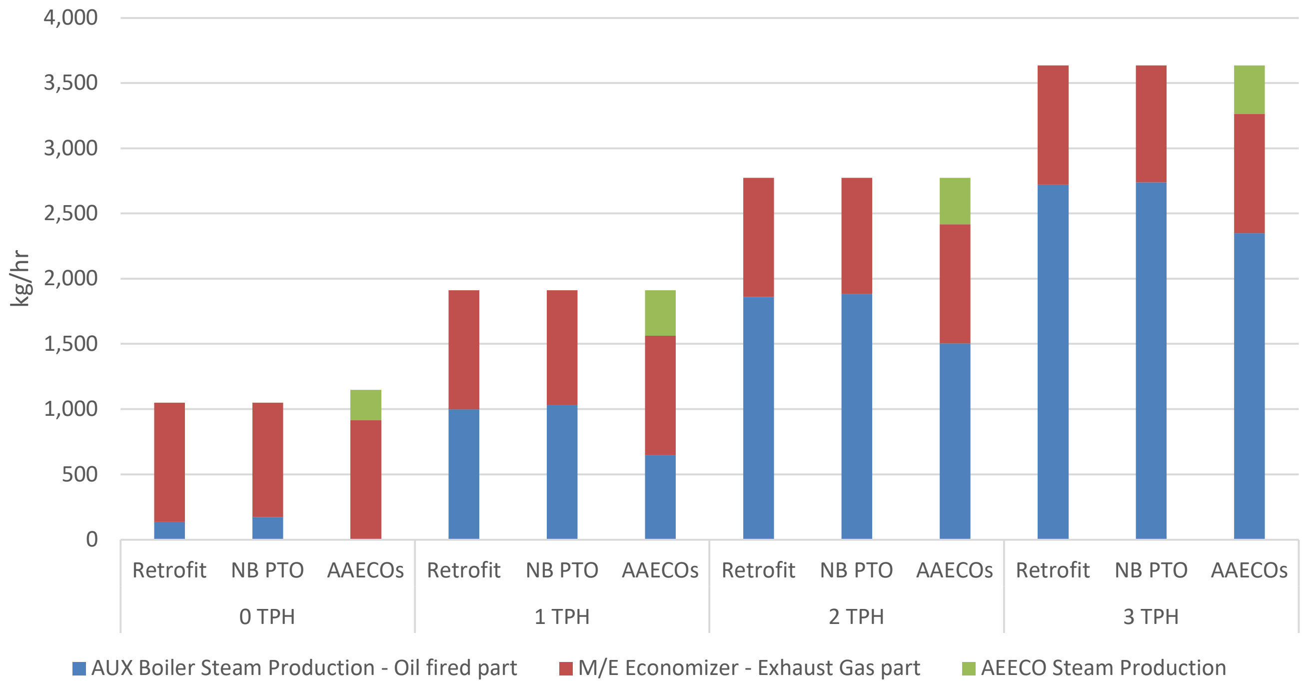

Figure 0-48 LNGC - OCCS Impact on Aux. boiler & Economizers at 16 knots in laden condition.

- **Economic impact analysis**

CO_2 abatement cost

Same as previous cases, results of the CO_2 abated cost are shown in Figure 0-49. The lowest CO_2 abated cost in each case is the optimized newbuilding with the AEECOs.

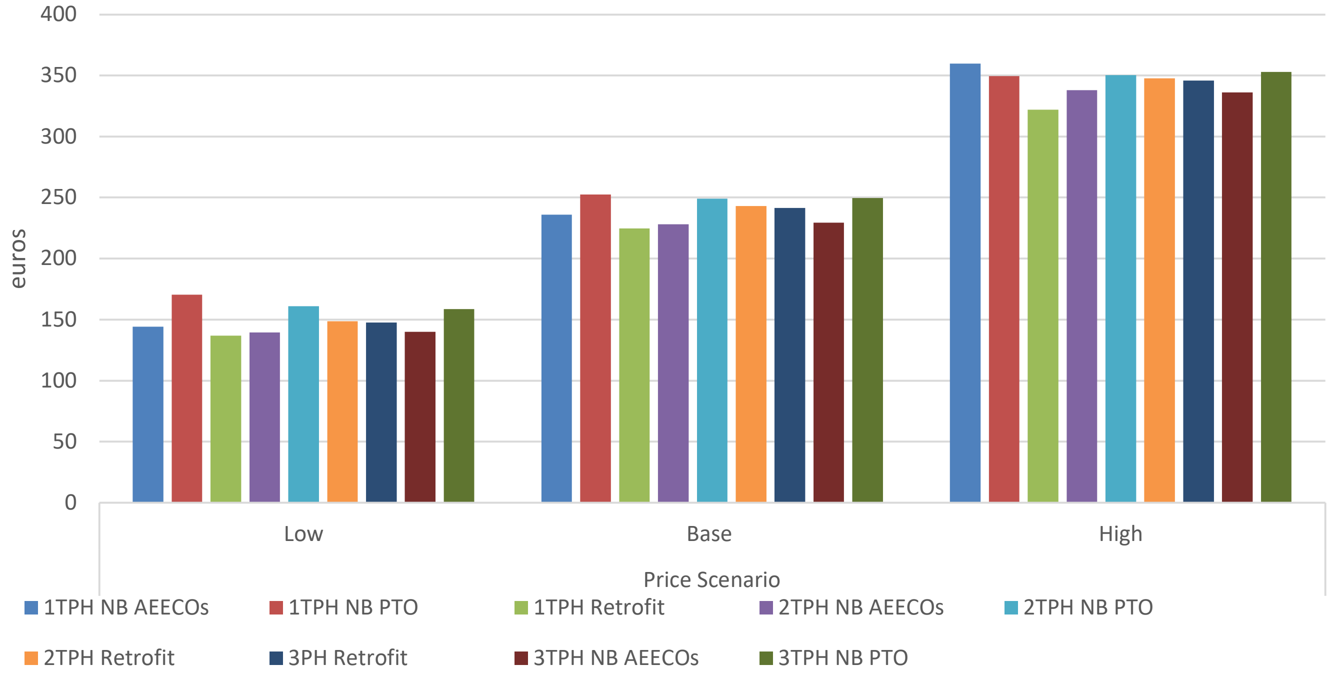

Figure 0-49 LNGC - CO_2 abatement cost per tons CO_2 abated.

CAPEX / OPEX calculation

In this section a more detailed overview of the CAPEX costs per case is done, CAPEX costs can be found in 3.2.1.

Figure 0-50 presents the CAPEX analysis results.

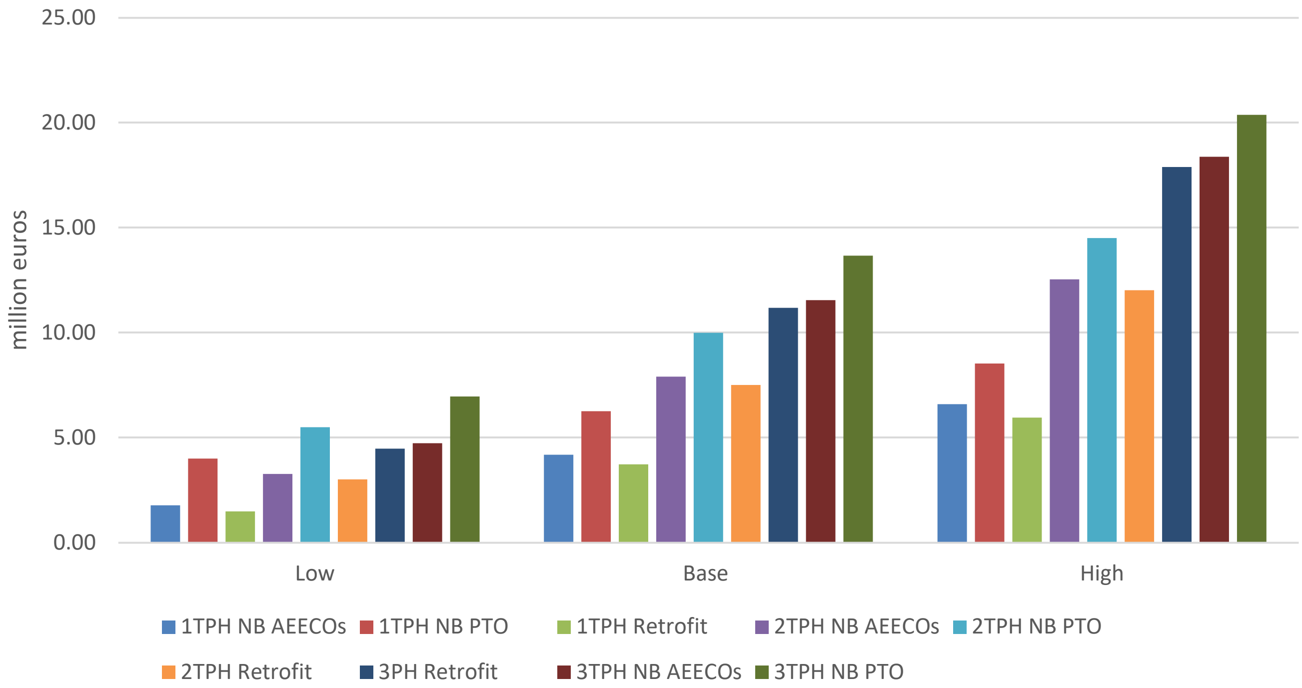

Figure 0-50 LNGC - CAPEX analysis.

In order to estimate the yearly fuel OPEX for the examined cases, different fuel costs for LNG and MDO are considered as shown in Table 3-15. Results are shown in Figure 0-51.

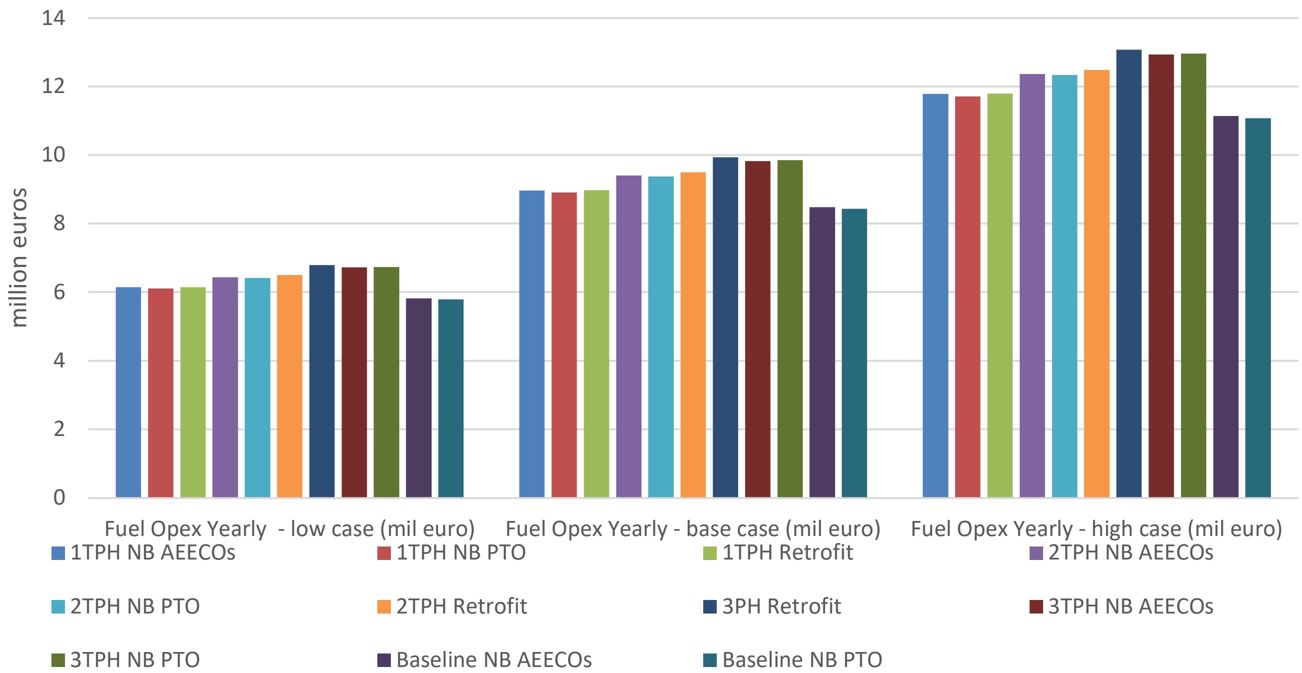

Figure 0-51 LNGC - Yearly Fuel OPEX in mil. Euro.

Economic analysis of disposal cost

For the economic analysis of the disposal cost, the following assumptions are as mentioned in Table 3-15, with the disposal cost for the captured CO_2 on a yearly basis for the LNGC vessel shown in Figure 0-52.

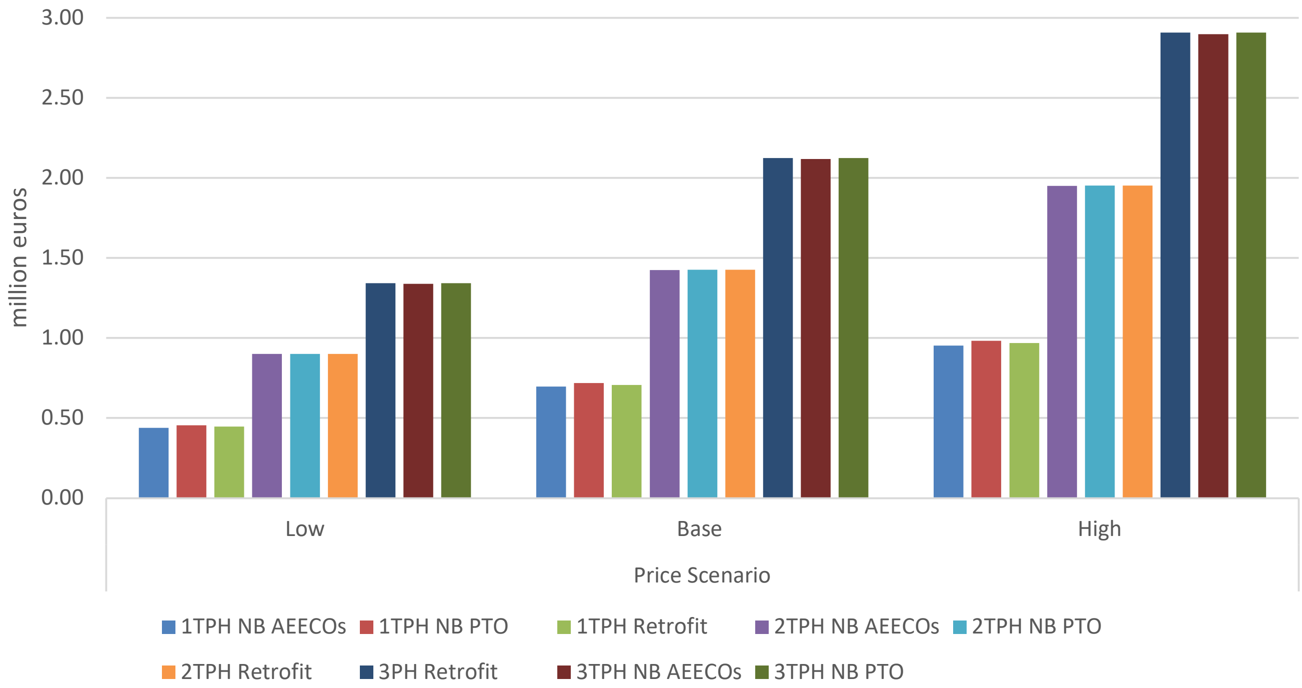

Figure 0-52 LNGC Yearly disposal cost of CO_2.

CO_2 abatement cost per ton of Captured CO_2 – sensitivity analysis

Following the evaluation of various cost metrics, namely CAPEX, fuel OPEX, and CO_2 disposal costs, a sensitivity analysis was conducted to assess their impact on the overall CO_2 abatement cost. This analysis, illustrated in Figure 0-53, shows the case with the OCCS system with a capture rate of 3 TPH.

The results indicate that the CO_2 disposal cost and fuel OPEX exert the most significant influence on the abatement cost. These are followed by the technology CAPEX and maintenance costs, which have a moderate impact. In contrast, the cost of solvents contributes minimally to the overall CO_2 abatement cost.

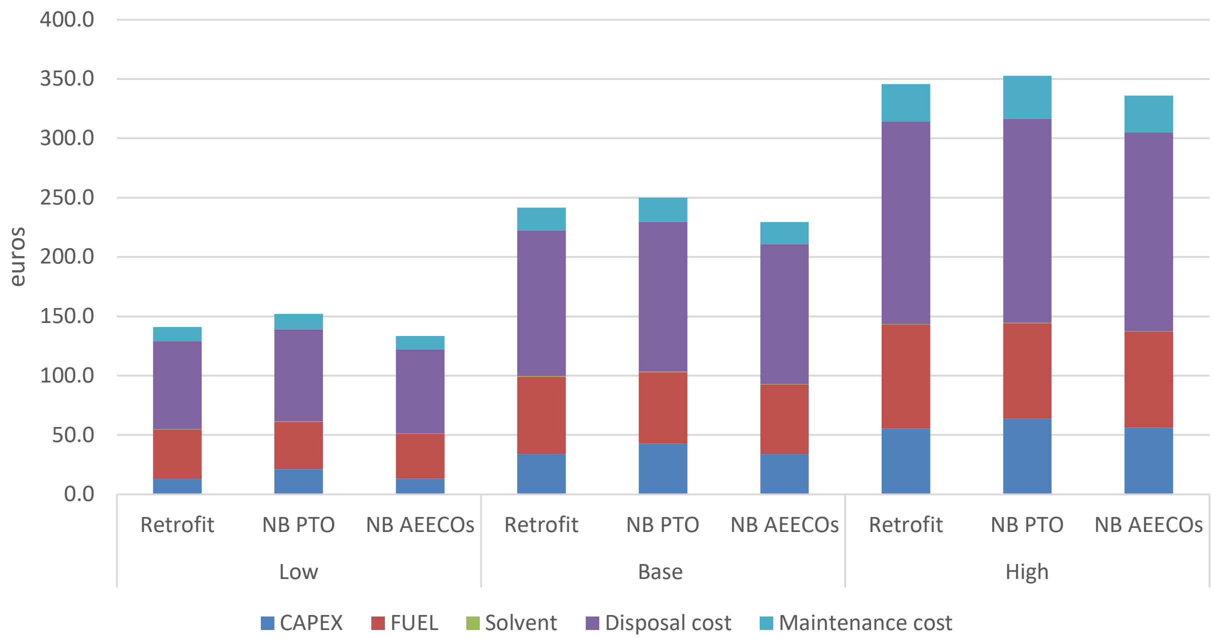

Figure 0-53 LNGC - CO_2 abatement cost per ton CO_2 sensitivity analysis for the 3 TPH capture rate.

Port offloading and ship interface analysis

The displaced vapor results are showcased in tons, according to the different CO_2 capture rates and vessel tank sizes as shown in Figure 0-54. The required energy of the systems involved (pump, heater and cooler) is showcased separately for each vessel and CO_2 capture rates in kWh in Figure 0-55.

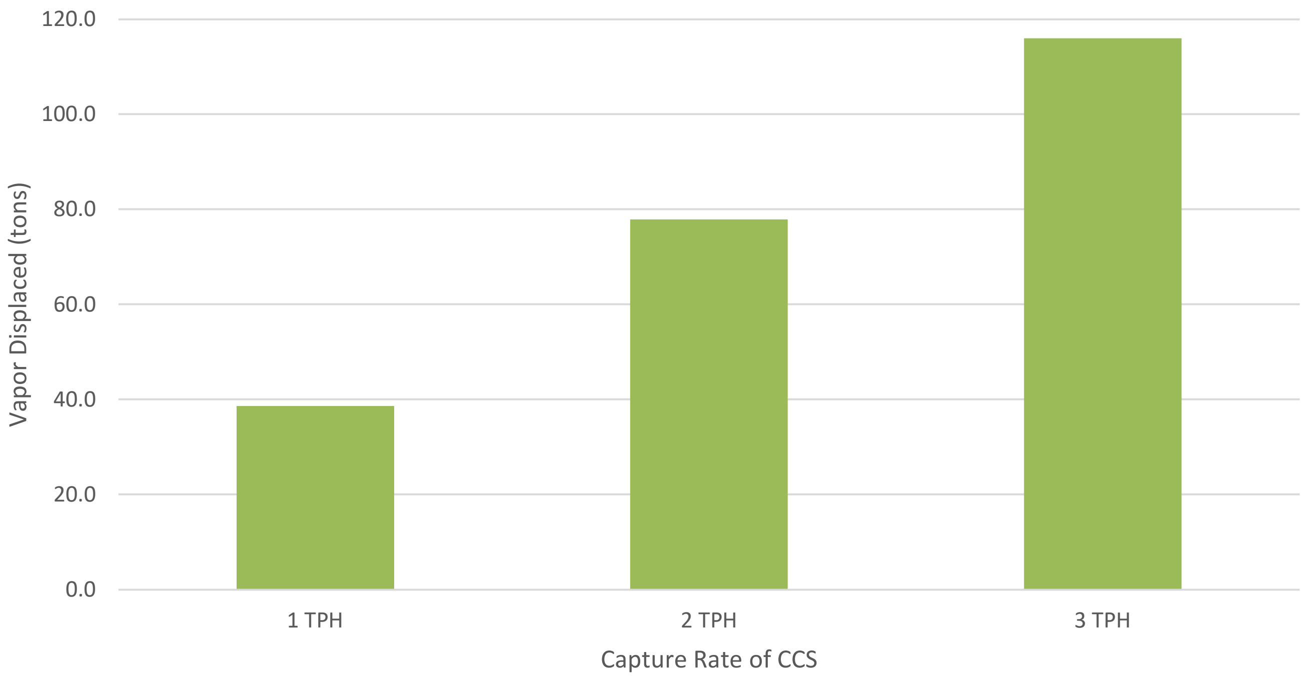

Figure 0-54 LNGC - displaced vapor during offloading per capture rate, assuming an offloading rate of 500 m3/hr.

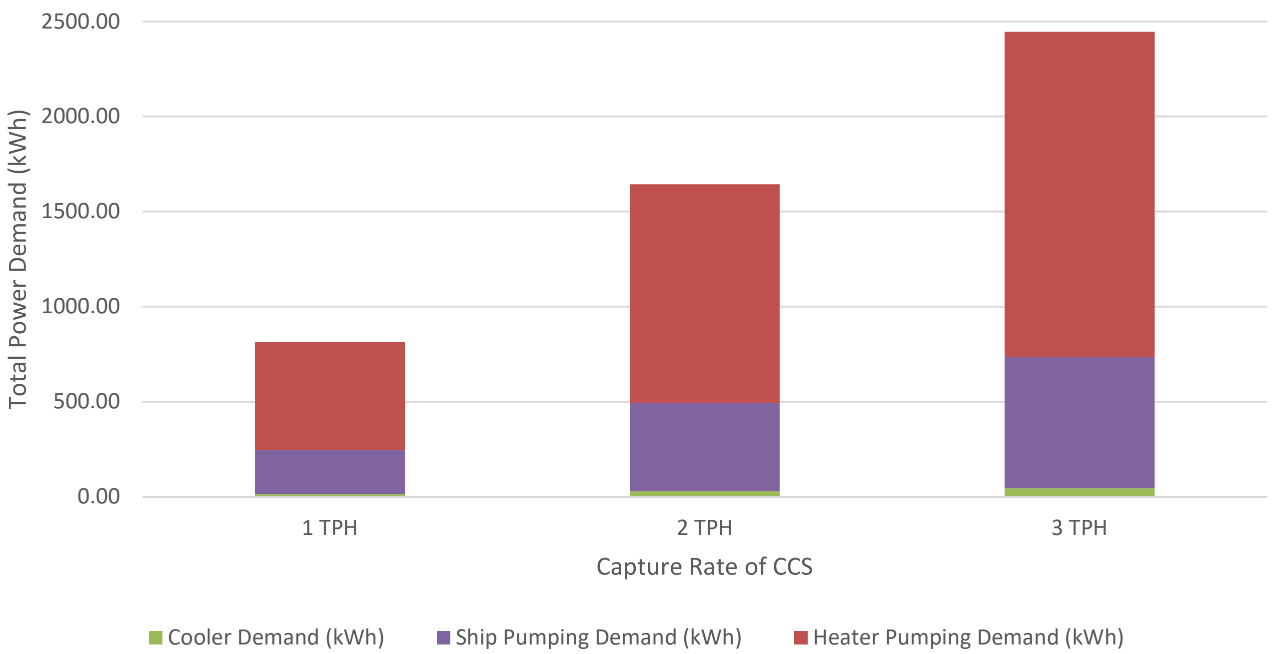

Figure 0-55 LNGC - total required energy during offloading, assuming an offloading rate of 500 m^3/hr.

- **Technical impact analysis**

LCO_2 storage tanks capacity and dimensions estimation

The LNGC vessel is assumed to make 9 round trips per year, with each round trip lasting appr. 40 days. The offloading frequency is assumed to take place once per round trip. The estimations for the required capacity of the LCO_2 tank, considering a margin of +10% (unforeseen delays/ extended cargo operations) is shown in Table 0-20.

LCO_2 storage tanks are considered to be filled up to 95% of their volume. LCO_2 density is assumed at 1,110 kg/m^3. Capacity of the LCO_2 is given on an average basis per different capture rates, since the different cases (optimized newbuilding with PTO and retrofit) have slight differences in the captured CO_2 quantities.

Table 0-20 LNGC - LCO_2 Storage Tanks specifications

LCO_2 Storage Tanks specifications				
Capture rate of OCCS	CO_2 captured per 40 days+10% margin (m^3)	LCO_2 total required capacity (m^3)	Tank D x L (m) (per storage tank)	Total weight including LCO_2 (tons)
1 TPH	870	920	5x16	1300
2 TPH	1750	1850	6x18	2500
3 TPH	2600	2750	7x21	3600

For the LNGC vessel case, it is assumed that the system has four LCO_2 storage tank.

OCCS impact on vessel space demands

LCO_2 Storage Tanks

The proposed configuration involves locating the four LCO_2 storage tanks on the main deck. This arrangement follows the findings and proposal of a previous conducted study for an LNGC[92].

- Newbuilding: In a newbuilding scenario, the design of the vessel can be optimized from the outset to accommodate the LCO_2 storage tank. This allows for integration with minimal impact on the vessel's overall design.
- Retrofit: In a retrofit scenario, existing structures will need to be modified to fit the CO_2 tank. This could involve reinforcing the hull and potentially a raised superstructure or relocating other equipment.

Since the installation location of the LCO_2 storage tanks and the OCCS are located on the deck area of the LNGC, these areas are usually not classified as gas dangerous areas for LNG carriers. Nevertheless, welding to deck is potentially an issue for the retrofit case.

It is important to note that this configuration is presented as a conceptual guideline. The feasibility, safety, and operational implications of such an installation must be assessed on a case-by-case basis. Each vessel owner should conduct a detailed engineering study to evaluate structural compatibility, cargo impact, regulatory compliance, and integration with existing systems. Collaboration with classification societies and technology providers is essential to ensure that the final design meets all technical and safety requirements.

Carbon Capture System

The absorber and regeneration stacks can be installed on the deck aft the accommodation area

- Newbuilding: For LNGC newbuilds, the OCCS can be incorporated into the vessel’s design from the outset. This allows for optimal integration with the gas handling systems and ensures proper placement and weight distribution, contributing to vessel stability and operational efficiency.

[92] Investigating Carbon Capture and Storage for an LNG carrier

- Retrofit: Retrofitting an OCCS on an existing LNGC requires careful planning to accommodate the system within the vessel's existing layout, particularly around the cargo containment and gas processing areas. Additional engineering may be needed to avoid interference with cryogenic systems and maintain safety and performance standards.

Liquefaction Plant

The liqufecation plant could be placed amidships and forward of the compressor room.

- Newbuilding: In the case of an LNGC newbuild, the liquefaction plant can be integrated into the vessel's design from the beginning. This enables seamless alignment with the cargo containment and gas processing systems, while optimizing space utilization and integration with the vessel's power and heat recovery systems.
- Retrofit: Installing a liquefaction plant on an existing LNGC may require structural modifications, including reinforcements to support the equipment's weight and vibration. Careful planning is essential to ensure compatibility with existing cryogenic systems and to maintain safety and operational efficiency.

- **Impact on weight**

Weight distribution per component and the effect on Lightweight increase per case is shown in Table 0-21.

Table 0-21 LNGC - OCCS weight distribution (tons).

OCCS Weight distribution in tons per examined capture rates			
	1 TPH	**2 TPH**	**3 TPH**
OCCS System weight - Structure only	280	440	620
Increase compared to baseline LWT	0.9%	1.4%	2.0%

Additionally, the impact on hull girder loads must be assessed for retrofit LNG carriers, based on updated stability calculations reflecting the revised mass distribution. While the design maximum and minimum hogging and sagging moments for LNGCs are typically conservative, the changes in the still water bending moment curve due to the added weight of the OCCS and liquefaction systems are expected to have limited practical impact. Therefore, the existing design moment limits may remain valid for the vessel's loading computer, which is used to check each loading condition. However, the loading computer must be updated to reflect the new lightweight mass distribution and ensure accurate longitudinal strength assessments. For newbuild LNGCs, these additional weights are already considered within the design envelope moments. This topic is not further analysed in the present study but is included here for completeness and to support the reader's understanding.

Impact on stability

The effect of installing the OCCS on the LNG carrier's stability must be carefully assessed to ensure compliance with regulatory limits. This evaluation should include the weight of all liquids contained within the system under normal operating conditions, such as absorbents, solvents, and liquefied CO_2. The vertical and longitudinal distribution of these weights can influence the vessel's centre of gravity and overall stability characteristics. It may change the metacentric height value, GM, in the order of 0.5 m when the storage tanks are full and for cargo condition, but it depends on the actual loading condition. In ballast condition this change is considered relatively small, while in cargo condition the change can be significant.

These changes must be reflected in the loading computer through an updated lightweight distribution model for the fixed masses and with the storage tanks with mass dependent on the filling level. Given the fixed nature of LNG cargo containment and limited flexibility in weight redistribution, the impact on overall stability is expected to be manageable, provided each voyage undergoes a thorough stability assessment.

For newbuild LNG carriers, the weight and placement of OCCS components should be incorporated into the initial stability calculations and lightship definition. The inclining test must reflect the vessel's final configuration, inclusive of the OCCS installation, to ensure compliance with classification and statutory requirements from the outset.

Impact on Cargo Capacity

The installation of the OCCS system, including LCO_2 storage tanks, results in an increase in the vessel's lightship weight. Depending on the carbon capture rate and system configuration, the total added weight, including the stored liquefied CO_2, may range from approximately 1,400 to 3,900 metric tons. This increase is significant relative to the vessel's baseline lightweight, particularly at higher capture rates, and may directly affect the available deadweight for cargo due to draft and stability constraints.

The OCCS system introduces additional weight, potentially influencing the vessel's trim and stability margins. These changes may affect the vessel's ability to carry its full LNG cargo capacity, especially on routes with strict draft limitations or where fuel efficiency is critical. Reducing the LNG tanks filling level below 70% during transit is however not acceptable from a sloshing damage point of view. To mitigate these effects, operators may need to adjust ballast configurations or optimize voyage planning to maintain acceptable trim and stability. The increased weight may be partially offset by deadweight increase calculations, and the overall impact on cargo capacity is expected to be marginal and so is the additional fuel consumption related to additional wet surface because of increased draft.

For newbuild LNG carriers, these impacts can be addressed more effectively through integrated design solutions. Structural accommodations and optimized ballast arrangements can be incorporated from the outset to offset the added weight and preserve cargo capacity. In retrofit scenarios, however, a detailed engineering assessment is essential to evaluate trade-offs and ensure continued compliance with regulatory requirements and operational performance.

- **Economic viability**

EU ETS impact

To quantify the financial exposure of the system under the EU Emissions Trading System (EU ETS), two operational scenarios are considered based on the vessel's annual voyage distribution:

- Scenario A – Low EU Exposure:

The vessel spends approximately 20% of its annual operating time on trips starting/ending in non-EU to EU ports. This includes occasional calls to EU ports (e.g., one out of five voyages involving EU stops), resulting in limited exposure to EU ETS regulation.

- Scenario B – High EU Exposure:

The vessel spends around 80% of its annual operating time on trips starting/ending in non-EU to EU ports. This results in substantial coverage under the EU ETS, with a majority of emissions subject to regulation.

For both scenarios, carbon pricing is modelled using a base rate of €170 per ton of CO_2[93].

This comparative framework enables a clear understanding of the cost implications associated with varying levels of EU ETS exposure, supporting informed decision-making regarding operational strategy and emissions compliance.

The comparison of these two scenarios is made for the capture rate of 3 tons of CO_2 per hour. The analysis focuses on the savings of EU ETS allowance, enabling a direct evaluation of the economic viability of the system under varying levels of EU ETS exposure. Results of the analysis can be seen in Table 0-22.

[93] Energy Transition Outlook 2024

Table 0-22 LNGC - EU ETS analysis for 3 TPH.

Scenario	EU ETS allowance savings in thousands of euros on a yearly basis	
	Low EU Exposure	High EU Exposure
NB PTO	276	1,103
NB AEECOs	277	1,107
RETROFIT	271	1,086

Scenario-Based Assessment of OCCS and Bio-LNG Under the IMO GFI Metric

Following section 3.3.2, the scenarios related to the OCCS potential impact on the ship's attained GFI were defined as follows:

- Scenario 1: When calculating the attained GFI[94] the captured CO_2 is subtracted by the formula, while the ship fuel energy includes the fuel penalty. This assumption does not include the full lifecycle emissions of the procedure such as the ones arising from the transportation and permanent storage of the captured CO_2.
- Scenario 2: The attained GFI is calculated based on the WtW emission factors of the LCA guidelines, where for OCCS, the TtW factor is adjusted by the e_{OCCS} term. In this scenario the OCCS fuel penalty is omitted from the fuel energy in the attained GFI formula ship.
- Scenario 3: The attained GFI is calculated based on the WtW emission factors of the LCA guidelines, where for OCCS the TtW factor is adjusted by the e_{OCCS} term except from the OCCS energy penalty term, which is accounted in the ship fuel energy via the OCCS fuel penalty.

Figure 0-56 presents the results of a cost assessment, summarizing the annual operational expenses associated with the implementation of the OCCS solution, alongside the costs of the remedial units under the proposed GFI framework. Additionally, the alternative solution of bio-LNG usage, is evaluated to achieve the same attained GFI as Scenario 1 (which is estimated to be the lower value).

The first instance of annual OPEX savings is observed in year 2030 for the case of bio-LNG minimum price, while for the mid-price scenario it is estimated that up to 2035 the differential OPEX does not showcase savings. For the OCCS case it is assumed that in the end of 2031 the retrofit is implemented on board, as the differential OPEX savings begin from 2032 and onwards.

94 $GFI_{attained} = \frac{\sum_{j=1}^{J} EI_j \times Energy_j}{Energy_{total}}$, attained GFI formula based on IMO Circular Letter No. 5005 (Draft revised MARPOL Annex VI).

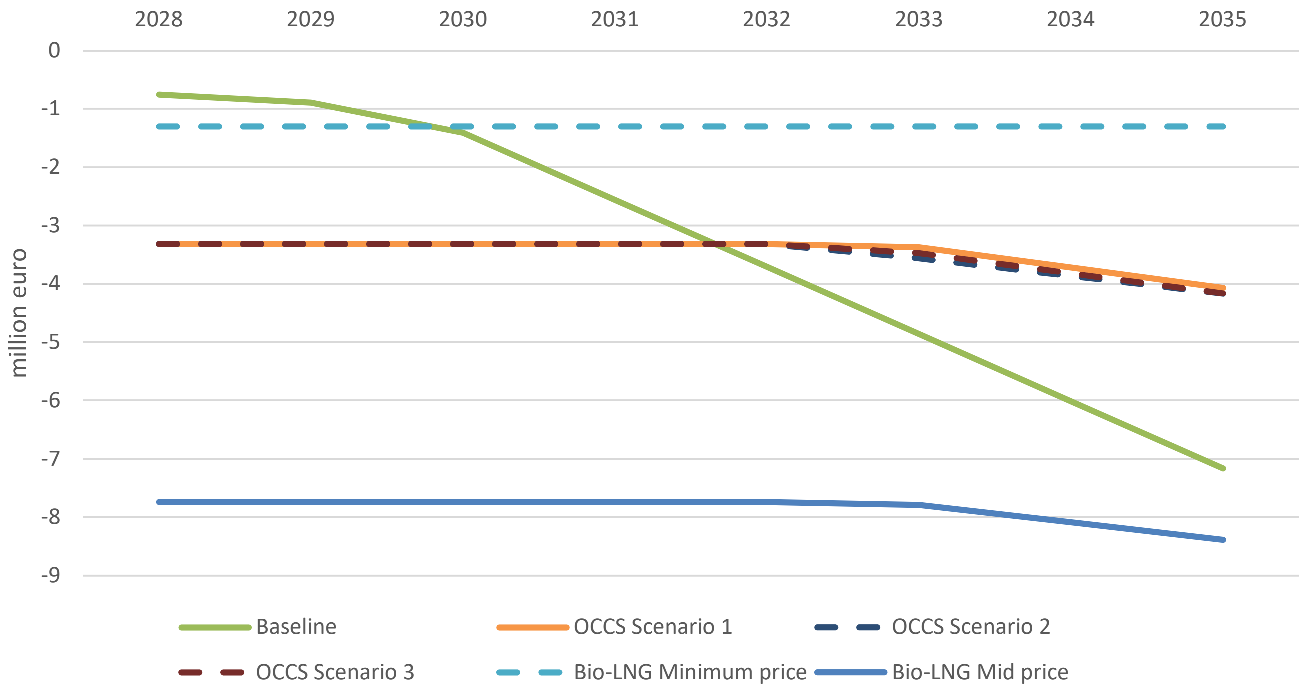

Figure 0-56. LNGC - OCCS comparison to biofuels. Annual differential OPEX cashflows.

Figure 0-57 illustrates the attained GFI for each case scenario.

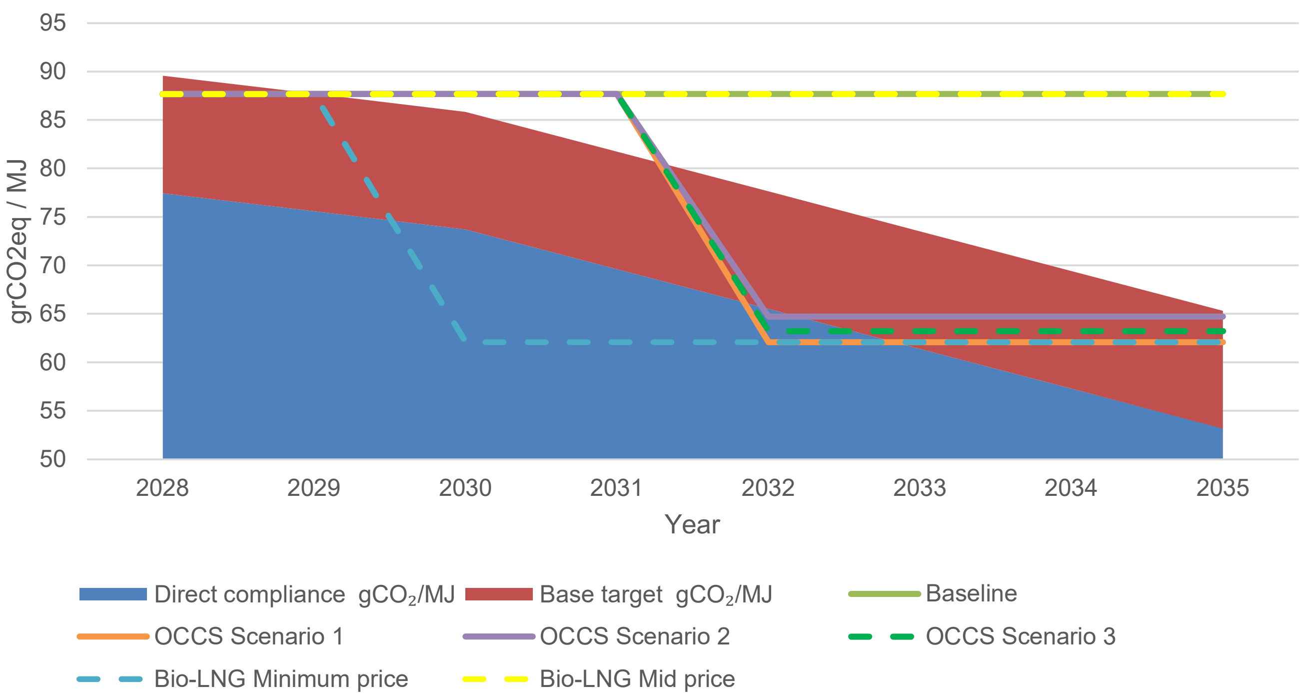

Figure 0-57 LNGC - OCCS comparison to bio-LNG. Attained GFI scenario analysis trajectory.

In Figure 0-58 the discounted differential OPEX cashflows on the above analysis are accumulated for the years covering 2028-2035 (blue stack) while the red bars represent the margin of the discounted differential OPEX of OCCS and bio-LNG against the baseline vessel. Under this particular price scenarios, the usage of bio-LNG, seem to be beneficial when the minimum fuel price is projected, contrary to the mid-price scenario.

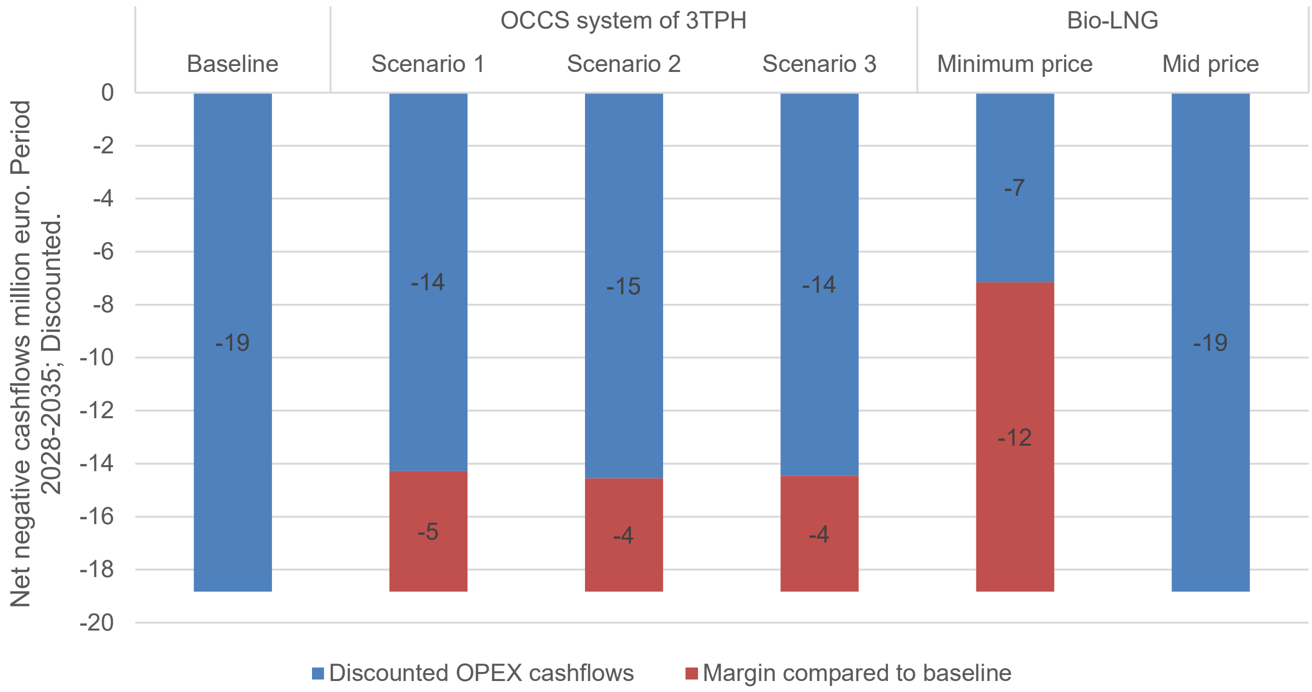

Figure 0-58. LNGC - OCCS comparison to bio-LNG. Discounted Differential OPEX cashflows from 2028-2035.

Appendix F 1,700 TEU Feeder container cost economic analysis

- **Vessel overview**

For the 1,700 TEU container feeder vessel, the main dimensions and machinery are shown below.

Table 0-23 Feeder container case vessel main dimensions and machinery.

1,700 TEU container feeder case study – Vessel specifications	
First year in service	2025
DWT	Appr. 25,000 tons
Lightweight	Appr. 8,500 tons
Propulsion system	1 x 2-Stroke Diesel engine of abt. 11.0 MW
Electricity supply	3 x 4-stroke Diesel engines of 1.5 MW each
Heat supply	1 x auxiliary boiler 1 x Main Engine Exhaust Gas Economizer

The operational profile of a typical feeder container vessel is analysed below, detailing the distribution of time spent underway, at anchor, and during port operations as shown in Figure 0-59. Results are aggregated for laden and ballast voyages

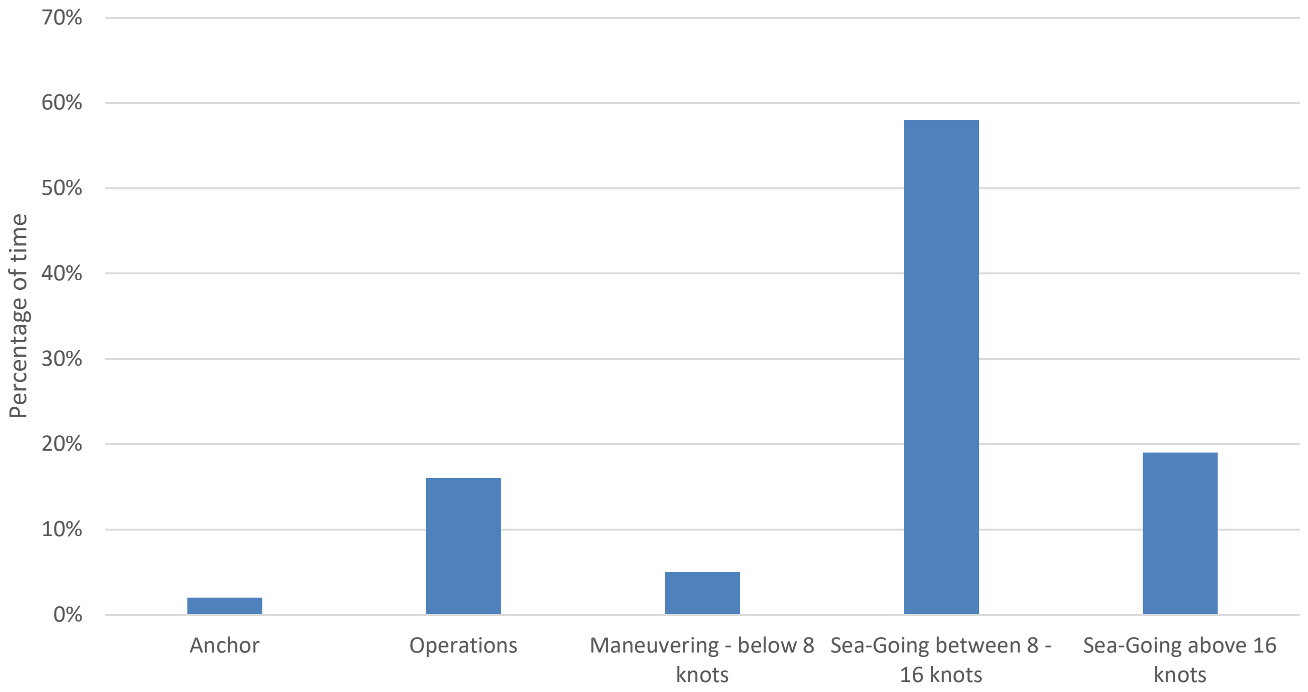

Figure 0-59 Feeder container operating profile.

- **CO_2 performance analysis**

The OCCS technology is examined for sweeps of CO_2 capture capacity. The results from 0.5 & 1 TPH are presented, as these present options that are reasonable in terms of LCO_2 storage and maintain the operation of the Aux Gens and boilers within manufacturer and redundancy limits (load below 90%, 1 Aux D-G on standby). It should be noted here for a capture rate of 1.5 TPH and above all 3 Aux. D-G were engaged in the onboard electric production, highlighting the need for upgrading the existing Aux. D-G to ones of higher power or installing a fourth one. This is not examined in the present study.

Same as rest of the cases, in the case of the NB vessel two additional considerations will take place:

- Properly sized AEECOs for the OCCS, sized to the capacity of the exhaust gas enthalpy from the Auxiliary Engines (including two exhaust gas boilers for the auxiliary generator sets).
- Installation of PTO of 1.4 MW.

Table 0-24 Feeder container - Technology Components for each configuration.

Design / Components	Aux. Engines' Economizers	PTO
Retrofit	-	-
Newbuilding with PTO	-	X
Newbuilding with AEECOs	X	-

Same as for the Suezmax case, the examined OCCS technology in terms of energy efficiency a state-of-the-art system is considered with specification as shown in Table 0-5

Comparative analysis

Results of the analysis for the capture rate of 0.5 TPH and 1 TPH are shown in Figure 0-60.

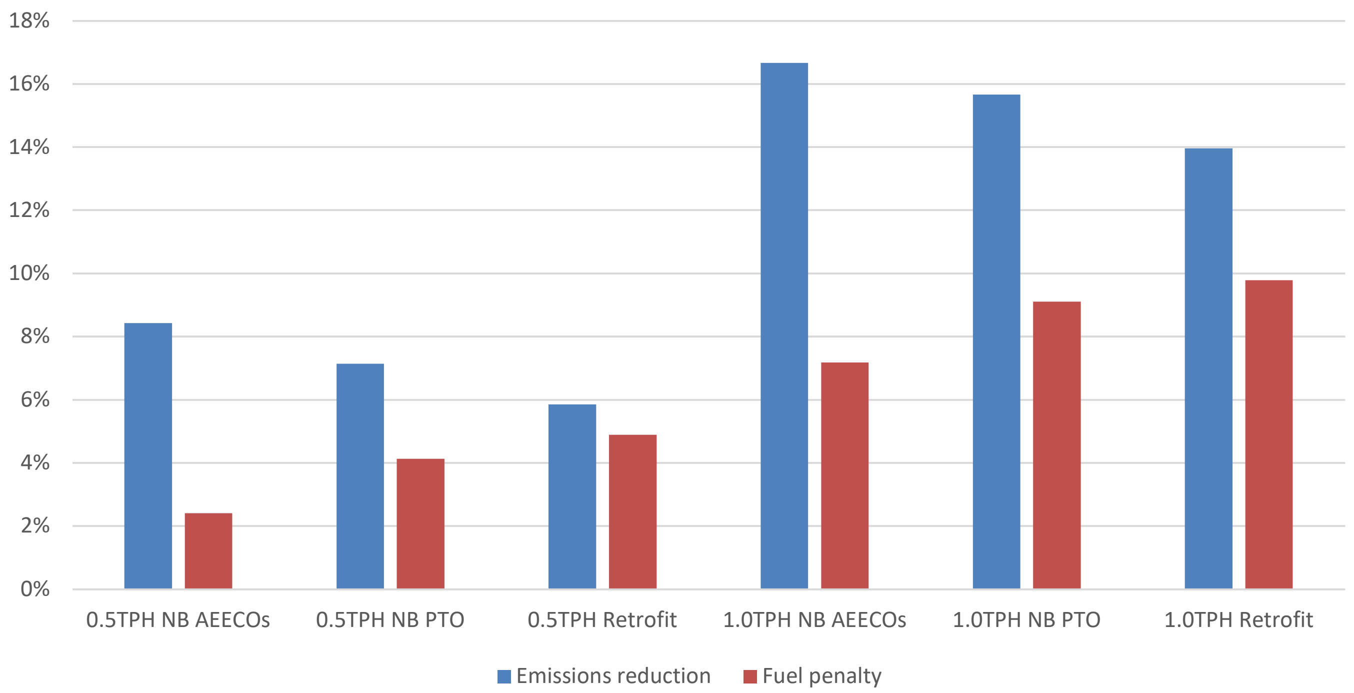

Figure 0-60 Feeder Container - Emissions reduction vs Fuel penalty.

CO_2 performance

A typical round trip for this type of vessel has a duration of approximately 15 days. Based on this operational cycle, the vessel is expected to complete around 24 round voyages per year. This frequency forms the basis for evaluating the annual performance of the onboard systems, particularly in terms of fuel consumption and emissions.

The yearly assessment includes the total consumption of fuel in metric tons, the corresponding total CO_2 emissions generated, and the amount of CO_2 captured by each case. Additionally, the analysis presents the net CO_2 emissions released into the atmosphere after capture, as well as the total quantity of CO_2 abated. These metrics provide a comprehensive overview of the environmental performance of the vessel and the effectiveness of the OCCS in reducing GHG emissions.

The yearly CO_2 performance results are shown for the OCCS capacity of 0.5 TPH and 1 TPH in Figure 0-61.

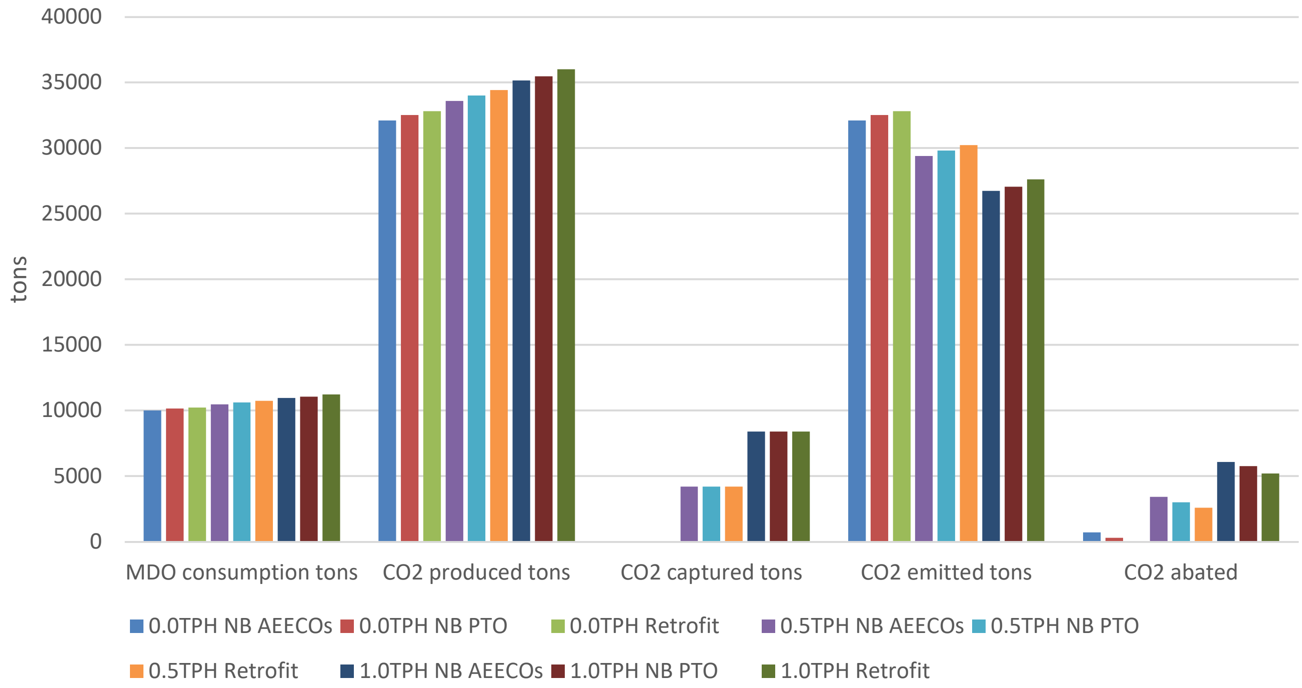

Figure 0-61 Feeder container - OCCS yearly performance.

OCCS impact on machinery performance

In this section an overview of the effect of the OCCS technology on the different machinery of the vessel (Aux. Engines and Boilers) will be presented.

Figure 0-62 illustrates the impact of the different OCCS capture rates on the utilization of key machinery components, specifically the main engine and auxiliary engines, during laden sailing at a speed of 16 knots, being the average speed for this vessel. For the retrofit case and NB AEECOs, as the OCCS capture rate increases from 0.5 TPH to 1 TPH, the load on the auxiliary engines rises from 75% to appr. 85%. In the optimized newbuilding with PTO, when the PTO system is employed, the main engine and PTO can meet the additional electrical demand imposed by the OCCS system, engaging one additional auxiliary generator.

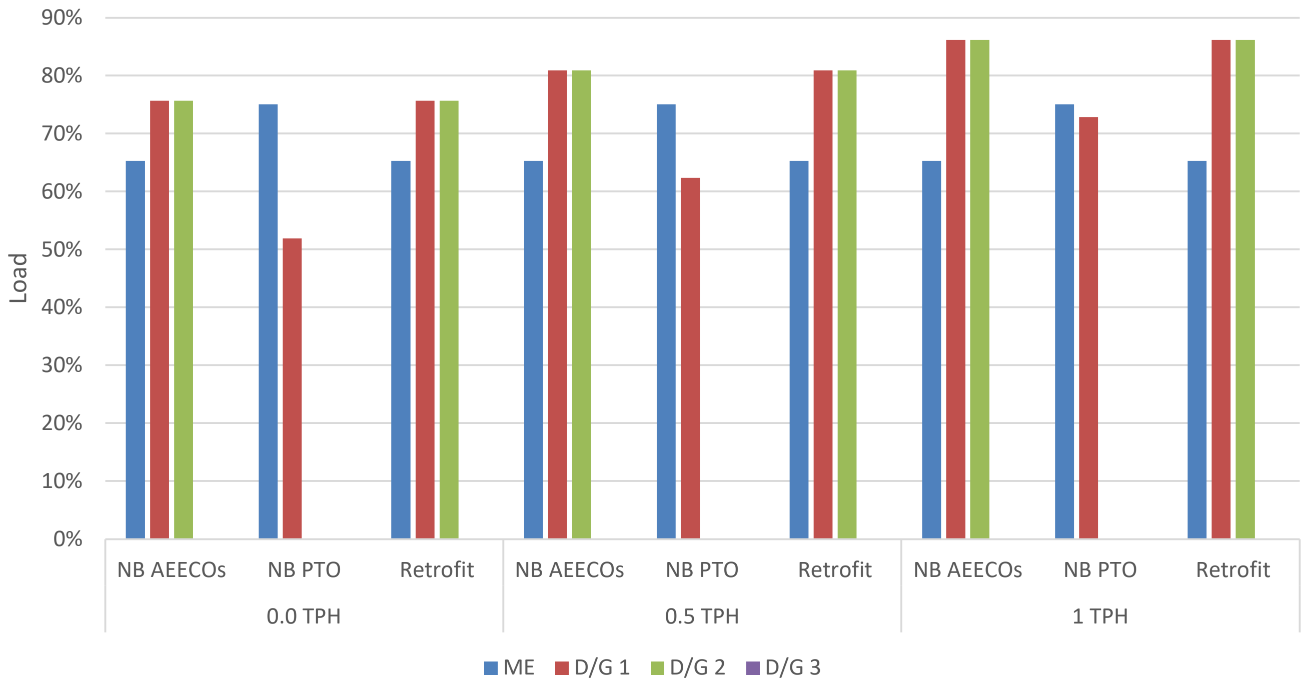

Figure 0-62 Feeder container - OCCS Impact on Main Engine and Aux. Engines at 16 knots in laden condition.

Figure 0-63 shows the total steam demand of the vessel including the ones of the OCCS, during laden sailing at a service speed of 16 knots. For this reason, the cases without the OCCS have been included in the graph as well.

As can be seed from the graph, regardless of the technology equipped the total steam demands remain steady for the same carbon capture rate.

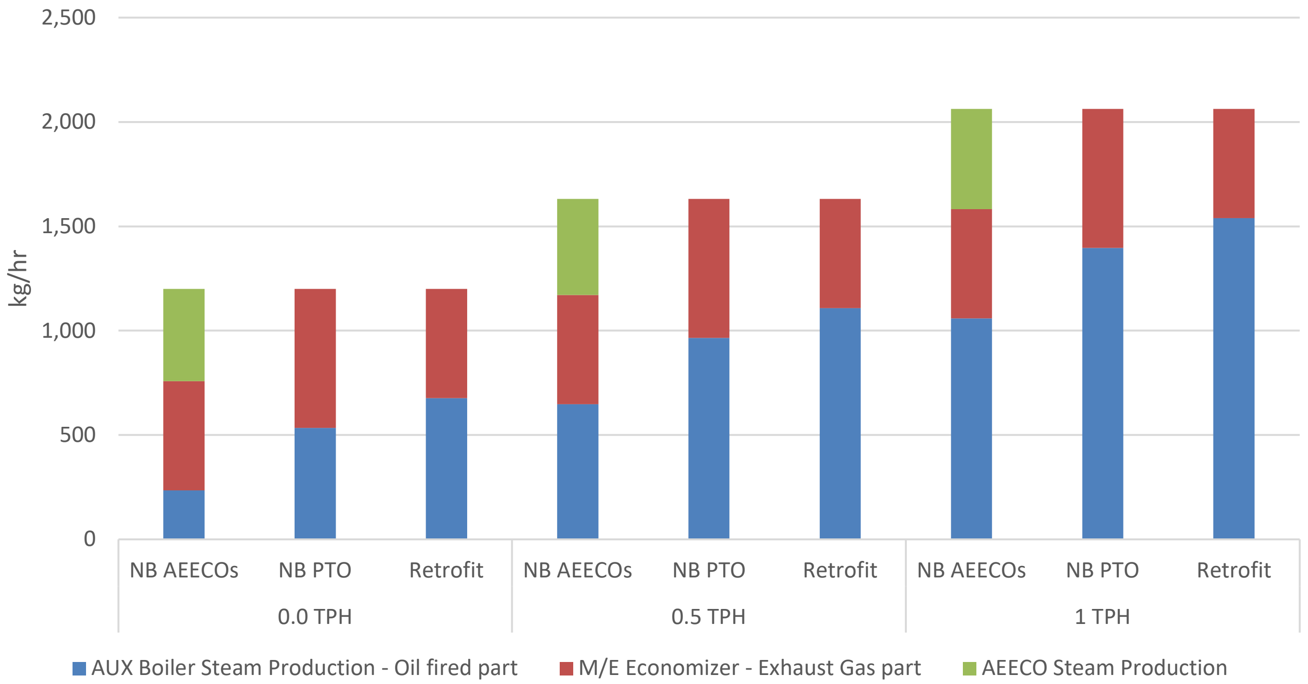

Figure 0-63 Feeder container - OCCS Impact on Aux. boiler & Economizers at 16 knots in laden condition.

■ Economic impact analysis

CO_2 abatement cost

Same as previous cases, results of the CO_2 abated cost are shown in Figure 0-64. The lowest CO_2 abated cost in each case is the optimized newbuilding with the AEECOs.

Figure 0-64 Feeder container - CO_2 abatement cost per tons CO_2 abated.

CAPEX / OPEX calculation

In this section a more detailed overview of the CAPEX costs per case is done, CAPEX costs can be found in 3.2.1.

Figure 0-65 presents the CAPEX analysis results.

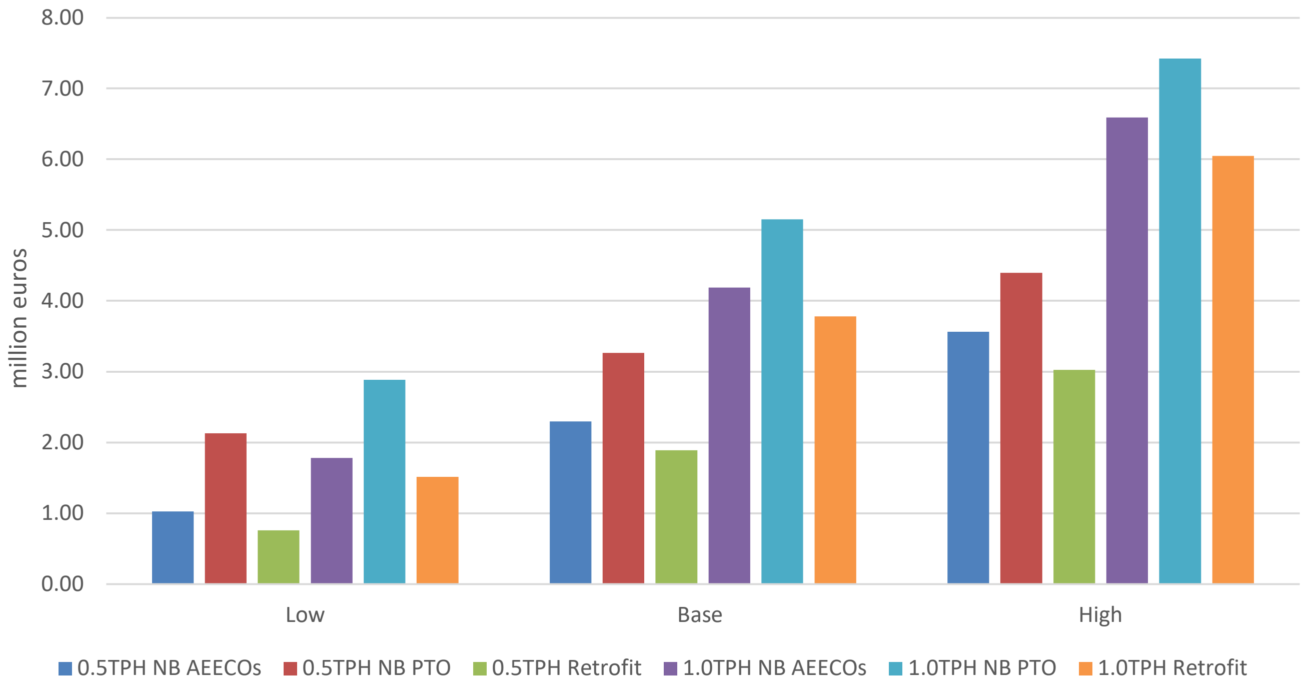

Figure 0-65 Feeder container - CAPEX analysis.

In order to estimate the yearly fuel OPEX for the examined cases, the costs are considered as shown in Table 3-15. Results are shown in Figure 0-66.

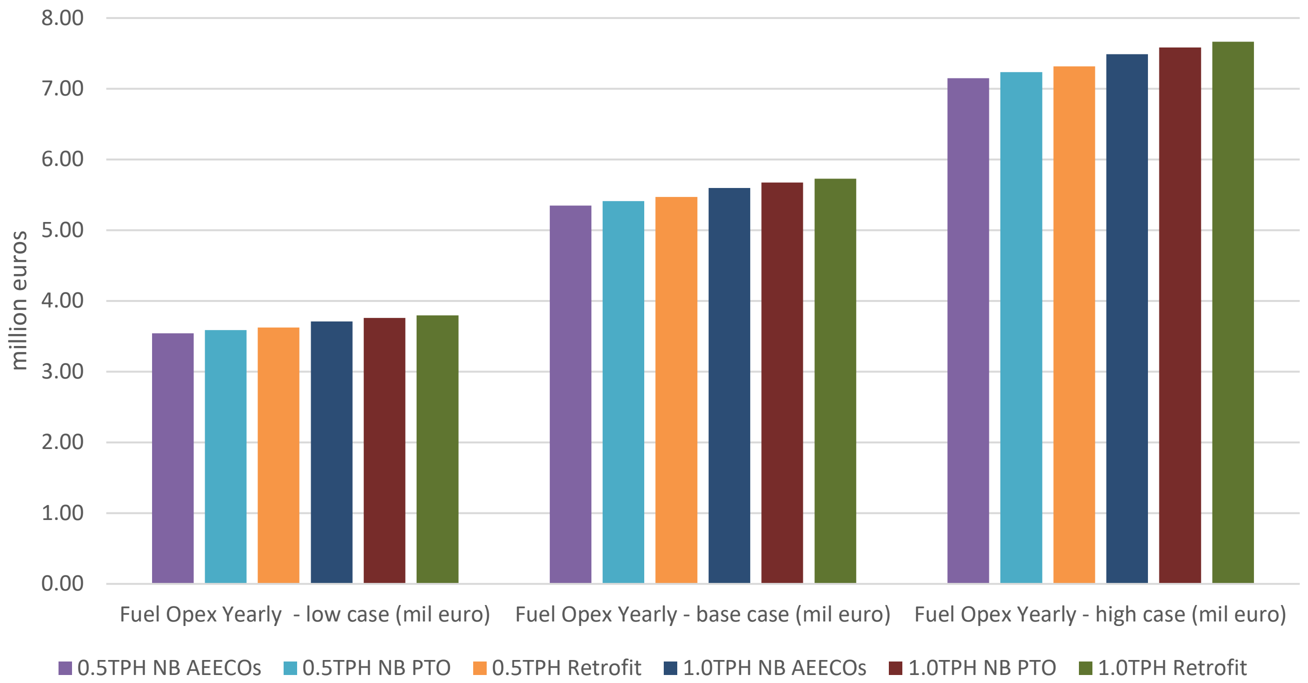

Figure 0-66 Feeder container - Yearly Fuel OPEX in mil. Euro.

Economic analysis of disposal cost

For the economic analysis of the disposal cost, the following assumptions are as mentioned in Table 3-15, with the disposal cost for the captured CO_2 on a yearly basis for the feeder container vessel shown in Figure 0-67.

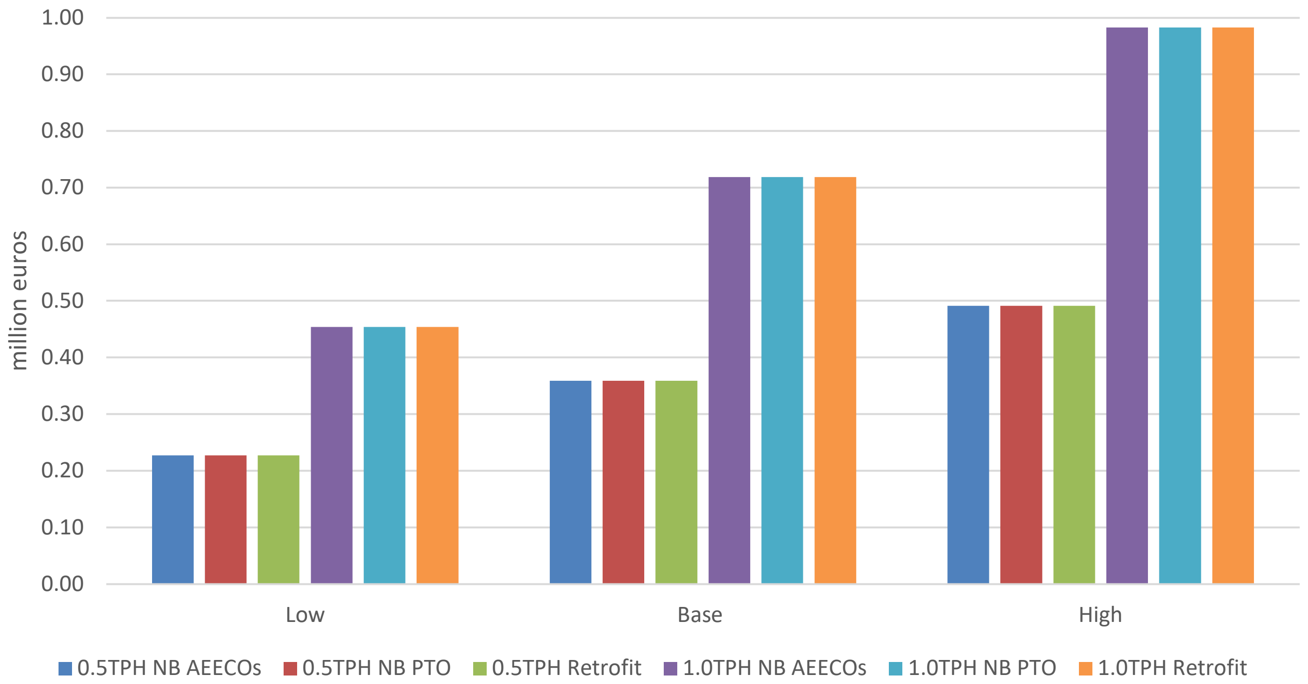

Figure 0-67 Feeder container - Yearly disposal cost of CO_2.

CO_2 abatement cost per ton of Captured CO_2 – sensitivity analysis

Following the evaluation of various cost metrics, namely CAPEX, fuel OPEX, and CO_2 disposal costs, a sensitivity analysis was conducted to assess their impact on the overall CO_2 abatement cost. This analysis, illustrated in Figure 0-68, shows the case with the OCCS system with a capture rate of 1 TPH.

The results indicate that the CO_2 disposal cost and fuel OPEX exert the most significant influence on the abatement cost. These are followed by the technology CAPEX and maintenance costs, which have a moderate impact. In contrast, the cost of solvents contributes minimally to the overall CO_2 abatement cost.

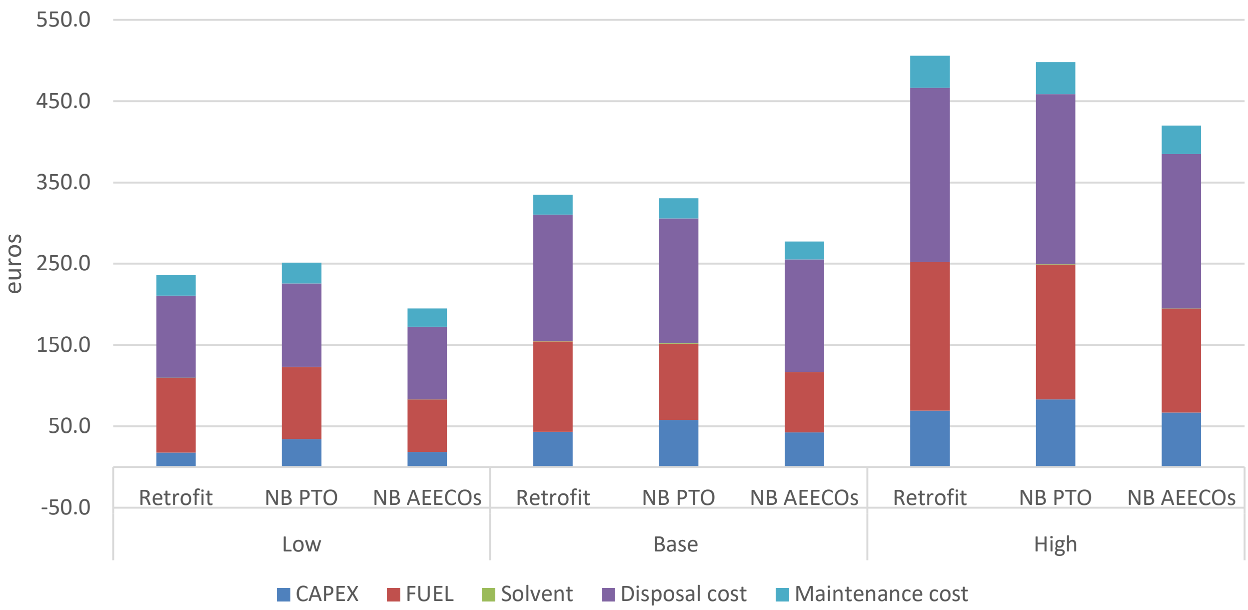

Figure 0-68 Feeder Container - CO_2 abatement cost per ton CO_2 sensitivity analysis for the 1 TPH capture rate.

Port offloading and ship interface analysis

The displaced vapor results are showcased in tons, according to the different CO_2 capture rates and vessel tank sizes as shown in Figure 0-69. The required energy of the systems involved (pump, heater and cooler) is showcased separately for each vessel and CO_2 capture rates in kWh in Figure 0-70.

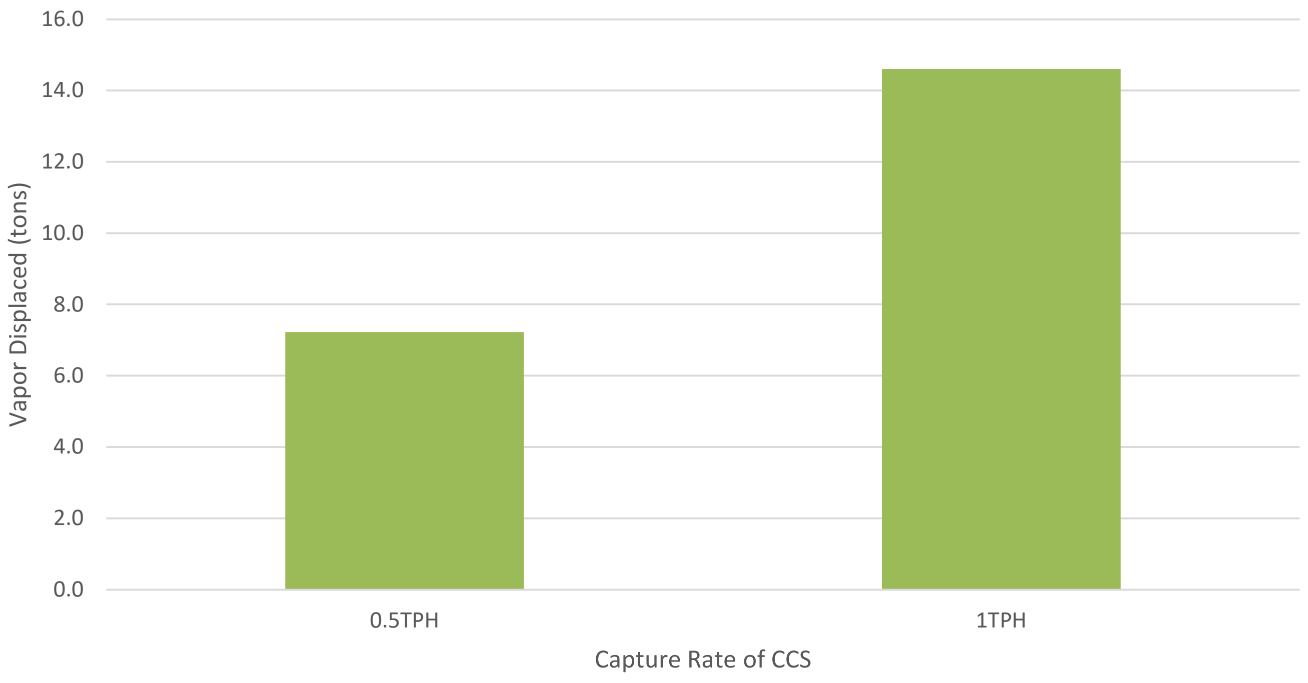

Figure 0-69 Feeder container - displaced vapor during offloading per capture rate, assuming an offloading rate of 100 m3/hr.

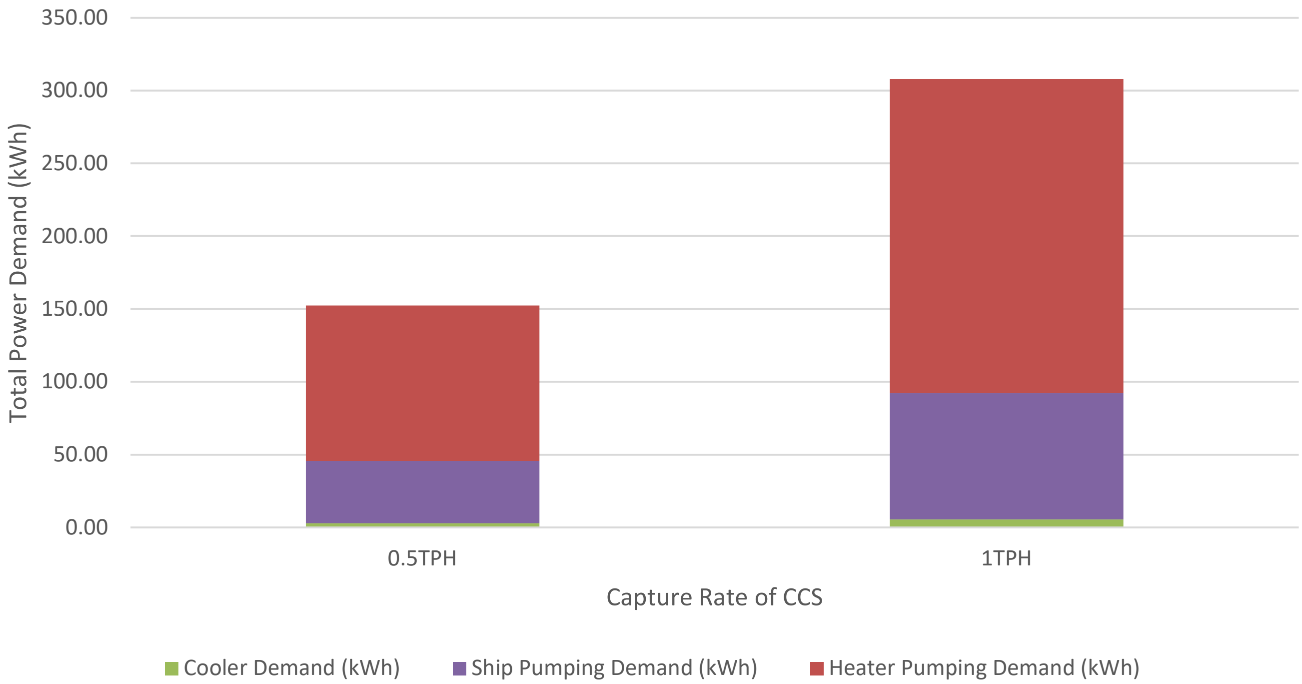

Figure 0-70 Feeder Container - total required energy during offloading, assuming an offloading rate of 100 m3/hr.

■ <u>**Technical impact analysis**</u>

For the feeder container vessel, stability and strength have slightly higher focus, while a bigger concern is the space demand and the related container cargo loss for the retrofit case.

With the location of the LCO_2 tank conflict with cargo operations is regarded as insignificant.

LCO_2 storage tanks capacity and dimensions estimation

The feeder container vessel is assumed to make 24 round trips per year, with each round trip lasting appr. 15 days. The offloading frequency is assumed to take place once per round trip. The estimations for the required capacity of the LCO_2 tank, considering a margin of +10% (unforeseen delays/ extended cargo operations) is shown in Table 0-25.

LCO_2 storage tanks are considered to be filled up to 95% of their volume. LCO_2 density is assumed at 1,110 kg/m^3. Capacity of the LCO_2 is given on an average basis per different capture rates, since the different cases (optimized newbuilding with PTO and retrofit) have slight differences in the captured CO_2 quantities.

Table 0-25 Feeder container - LCO_2 Storage Tanks specifications.

LCO_2 Storage Tanks specifications				
Capture rate of OCCS	CO_2 captured per 15 days+10% margin (m^3)	LCO_2 total required capacity (m^3)	Tank D x L (m) (per storage tank)	Total weight including LCO_2 (tons)
0.5TPH	165	180	5x15	300
1TPH	330	350	5x17	520

For the Feeder Container vessel case, it is assumed that the system has one LCO_2 storage tank.

OCCS impact on vessel space demands

LCO_2 Storage Tanks

For the feeder container, the proposed configuration involves locating the LCO_2 storage tank within the aft cargo hold, right next to the engine room, while positioning the OCCS unit on the deck above. This arrangement is conceptually aligned with operational efficiency and spatial practicality, but it requires further assessment tailored to each vessel's design and operational profile.

- Newbuilding: In a newbuilding scenario, the design of the vessel can be optimized from the outset to accommodate the LCO_2 storage tank. This allows for integration with minimal impact on the vessel's overall design.
- Retrofit: In a retrofit scenario, existing structures will need to be modified to fit the CO_2 tank. This could involve reinforcing the cargo hold or relocating other equipment.

Same as for the 15,000 TEU container vessel, it is less likely that the location of the OCCS components are located in a hazardous area.

Repurposing the aft cargo hold for the LCO_2 storage tank will result in a reduction of available container slots, depending on the tank's dimensions, insulation requirements, and supporting infrastructure. While this area is generally less critical for container stacking, any impact on cargo capacity must be evaluated in the context of the vessel's commercial operations. Structural reinforcement and integration of safety systems, such as venting, fire protection, and monitoring, will also be necessary to comply with applicable maritime regulations and class society standards.

It is important to note that this configuration is presented as a conceptual guideline. The feasibility, safety, and operational implications of such an installation must be assessed on a case-by-case basis. Each vessel owner should conduct a detailed engineering study to evaluate structural compatibility, cargo impact, regulatory compliance, and integration with existing systems. Collaboration with classification societies and technology providers is essential to ensure that the final design meets all technical and safety requirements.

Carbon Capture System

The absorber and regeneration stacks can be installed on the deck above the cargo hold which will accommodate the LCO_2 storage tank.

- Newbuilding: For newbuilds, the OCCS can be integrated into the vessel's design from the beginning. This ensures optimal placement and weight distribution, enhancing the vessel's stability and operational efficiency.
- Retrofit: Retrofitting the OCCS requires advance planning to integrate it with the existing structures. This may involve additional engineering work to ensure the system does not interfere with the vessel's existing operations.

Liquefaction Plant

This system is typically located in the engine room or a designated space on deck, with a potential placement being close to the OCCS capture system.

- Newbuilding: In a newbuilding case, the liquefaction plant can be designed into the vessel's layout, ensuring it fits seamlessly with other systems. This allows for efficient use of space and integration with the vessel's power and heat systems.
- Retrofit: Installing a liquefaction plant in an existing vessel may require some modifications, such as structural reinforcements to support the weight and vibration of the equipment.

Impact on weight

The LCO_2 storage tank is placed centric to ensure balanced weight distribution. The placement of the OCCS components takes place behind the funnel. Weight distribution per component and the effect on Lightweight increase per case is shown in Table 0-26.

Table 0-26 Feeder container - OCCS weight distribution (tons).

OCCS Weight distribution in tons per examined capture rates		
	0.5 TPH	**1 TPH**
OCCS System weight - Structure only	110	140
Increase compared to baseline LWT	1.3%	1.6%

Same as the 15,000 TEU container, the impact on hull girder loads needs to be analysed for retrofit vessels based on stability calculations with the updated mass distribution. The additional weights are unfavourable located contributing to an increased hogging moment. However, the design maximum and minimum hogging moments for container vessels may be exceeded with low probability, hence the change of the still water bending moment curve as a consequence of the additional weights is expected to have small consequence in practise, and the existing design moments may be kept as a limitation in the loading computer for the arrangement of the containers on each voyage. However, the loading computer will have to be updated to account for the new lightweight mass distribution. For a newbuilding vessel, the additional weights is already part of design with envelope moments. In the context of the present study this will not be further analysed but is mentioned here for sake of completion of understanding to the reader.
The cargo securing manual will not be influenced when the LCO_2 tank is within the cargo hold for the retrofit case.

Impact on stability

The effect of installing the OCCS on the container vessel's stability must be carefully assessed to ensure compliance with acceptable limits. This evaluation should include the weight of all liquids contained within the system under normal operating conditions, such as absorbents, solvents, and liquefied CO_2. The vertical and longitudinal distribution of these weights can influence the vessel's centre of gravity and overall stability characteristics. In the extreme case it may change the metacentric height value, GM, in the order of 0.3 m but is very much dependent on the vessel's actual loading condition. This value is however significant for a vessel type and size known to have stability issues. This will also have to be included in the loading computer calculations as updated lightweight distribution. With the flexibility of placing containers, it is expected to be limited consequence on stability in practise and the original stability requirements may be kept. Hence, the weights will be important to include, but the consequence is expected small to insignificant in practise for the retrofit case as each voyage needs careful stability assessment anyway.

For newbuild container vessels, the weight and placement of the OCCS components, including the OCCS unit and the LCO_2 storage tank located in the aft cargo hold, should be incorporated into the initial stability calculations and lightship definition. The inclining test must reflect the vessel's final configuration, inclusive of the OCCS installation, to ensure regulatory compliance from the outset.

Impact on Cargo Capacity

The OCCS system's proposed configuration is installed in the area of the aft cargo hold. This location, while operationally efficient, results in the loss of container slots in that section of the vessel. Depending on the tank's dimensions and insulation requirements, the installation may displace several TEU slots, reducing the vessel's overall cargo throughput. Additionally, the added weight shifts the vessel's centre of gravity slightly higher and aft, which may influence trim and stability margins.

These changes can impact the vessel's ability to carry its full complement of containers, particularly on routes with strict draft limitations or where fuel efficiency is a key concern. To mitigate these effects, vessel operators may need to adjust ballast configurations or redistribute container loads to maintain acceptable trim and stability. Voyage planning must also account for the reduced cargo margin, especially in high-capacity or draft-restricted ports. The increased weight may be counteracted by deadweight increase calculations. This may have marginal impact also because container ships are often not achieving 100% utilisation with regard to container capacity.

For newbuild container vessels, these impacts can be addressed more effectively through integrated design solutions. Structural accommodations and optimized ballast arrangements can be incorporated from the outset to offset the added weight and preserve container capacity. In retrofit scenarios, however, a detailed engineering assessment is essential to evaluate the trade-offs and ensure continued compliance with regulatory requirements and commercial viability.

- **Economic viability**

EU ETS impact

To quantify the financial exposure of the system under the EU Emissions Trading System (EU ETS), the feeder container vessel is assumed to be 100% of time within EU voyages.

Carbon pricing is modelled using a base rate of €170 per ton of CO_2[95].

This comparative framework enables a clear understanding of the cost implications associated with potential EU ETS exposure, supporting informed decision-making regarding operational strategy and emissions compliance.

The scenarios are made for the capture rate of 1 ton of CO_2 per hour. The analysis focuses on the savings of EU ETS allowances, enabling a direct evaluation of the economic viability of the system under varying configurations of OCCS system integration. Results of the analysis can be seen in Table 0-27.

Table 0-27 Feeder container - EU ETS analysis for 1 TPH.

Scenario	EU ETS allowance savings in thousands of euros on a yearly basis	
	Low EU Exposure	High EU Exposure
NB PTO	-	920
NB AEECOs	-	901
Retrofit	-	877

Scenario-Based Assessment of OCCS and Biofuels Under the IMO GFI Metric

Following section 3.3.2, the scenarios related to the OCCS potential impact on the ship's attained GFI were defined as follows:

- Scenario 1: When calculating the attained GFI the captured CO_2 is subtracted by the formula, while the ship fuel energy includes the fuel penalty. This assumption does not include the full lifecycle emissions of the procedure such as the ones arising from the transportation and permanent storage of the captured CO_2.
- Scenario 2: The attained GFI is calculated based on the WtW emission factors of the LCA guidelines, where for OCCS, the TtW factor is adjusted by the e_{OCCS} term. In this scenario the OCCS fuel penalty is omitted from the fuel energy in the attained GFI formula ship.
- Scenario 3: The attained GFI is calculated based on the WtW emission factors of the LCA guidelines, where for OCCS the TtW factor is adjusted by the e_{OCCS} term except from the OCCS energy penalty term, which is accounted in the ship fuel energy via the OCCS fuel penalty.

Figure 0-14 presents the results of a cost assessment, summarizing the annual operational expenses associated with the implementation of the OCCS solution, alongside the costs of the remedial units under the proposed GFI framework. Additionally, the alternative solution of biofuels usage, is evaluated to achieve the same attained GFI as Scenario 1 (which is estimated to be the lower value).

The first instance of annual OPEX savings is observed in year 2028 for the case of biofuels minimum price, while for the mid-price scenario it is estimated that unitl to 2031 the differential OPEX does not showcase savings. For the

[95] Energy Transition Outlook 2024

OCCS case it is assumed that in the period of 2029-2030 (depending in the scenario) the retrofit is implemented on board, as the differential OPEX savings begin from 2030 and onwards.

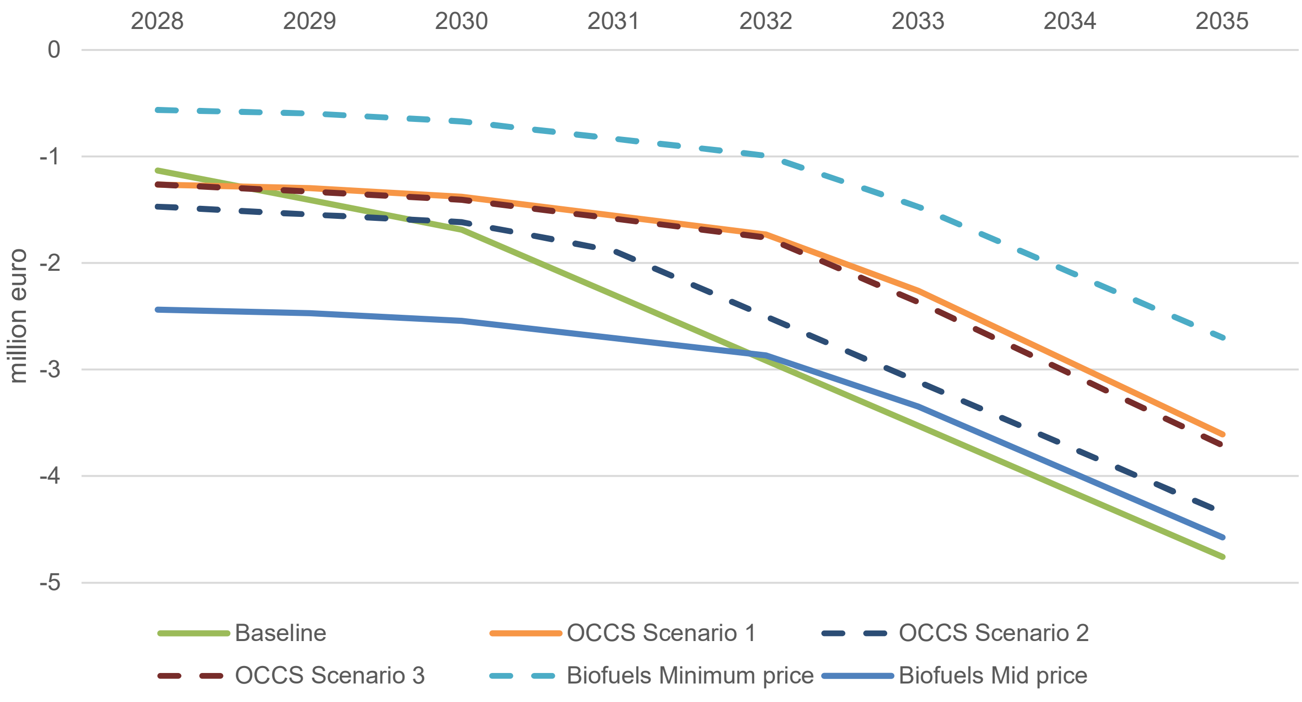

Figure 0-71. Feeder container - OCCS comparison to biofuels. Annual differential OPEX cashflows.

The following graph illustrates the attained GFI for each case scenario.

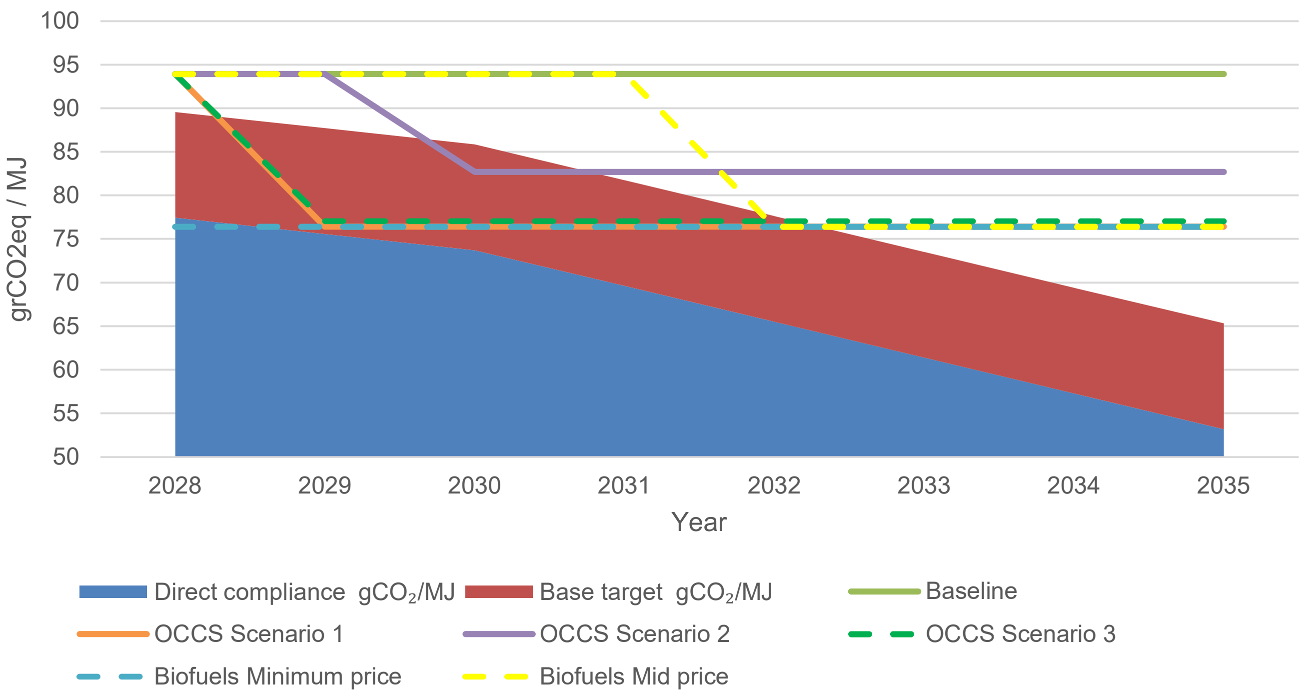

Figure 0-72. Feeder container - OCCS comparison to biofuels. Attained GFI scenario analysis trajectory.

In Figure 0-16 the discounted differential OPEX cashflows on the above analysis are accumulated for the years covering 2028-2035 (blue stack) while the red bars represent the margin of the discounted differential OPEX of OCCS and biofuels against the baseline vessel. Under this particular price scenarios the usage of biofuels, seem to be beneficial when the minimum fuel price is projected, contrary to their performance on the mid price scenario.

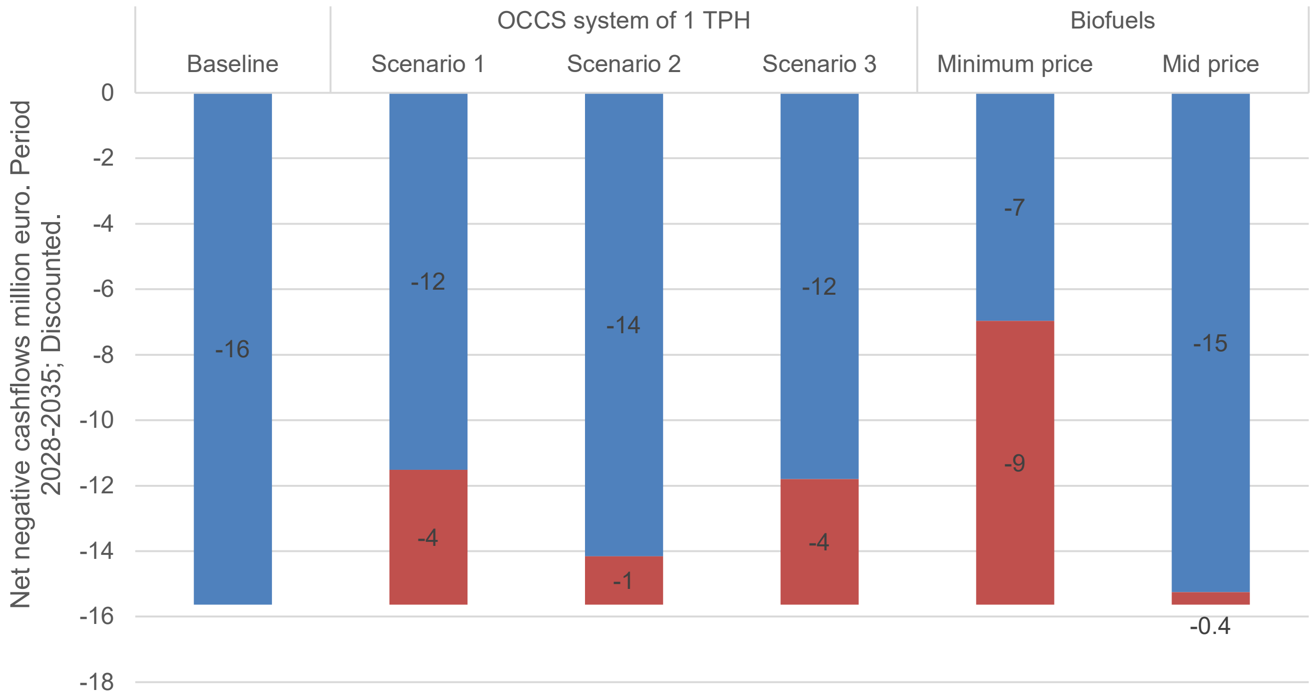

Figure 0-73. Feeder container - OCCS comparison to biofuels. Discounted Differential OPEX cashflows from 2028-2035.

Appendix G MR Tanker cost economic analysis

■ **Vessel overview**

For the MR tanker vessel, the main dimensions and machinery are shown below.

Table 0-28 MR tanker case vessel main dimensions and machinery.

MR tanker case study – Vessel specifications	
First year in service	2025
DWT	Appr. 40,000 tons
Lightweight	Appr. 8,500 tons
Propulsion system	1 x 2-Stroke Diesel engine of abt. 7.5 MW
Electricity supply	3 x 4-stroke Diesel engines of 1.0 MW each
Heat supply	1 x auxiliary boiler 1 x Main Engine Exhaust Gas Economizer

The operational profile of a typical MR tanker vessel is analysed below, detailing the distribution of time spent underway, at anchor, and during port operations as shown in Figure 0-74. Results are aggregated for laden and ballast voyages

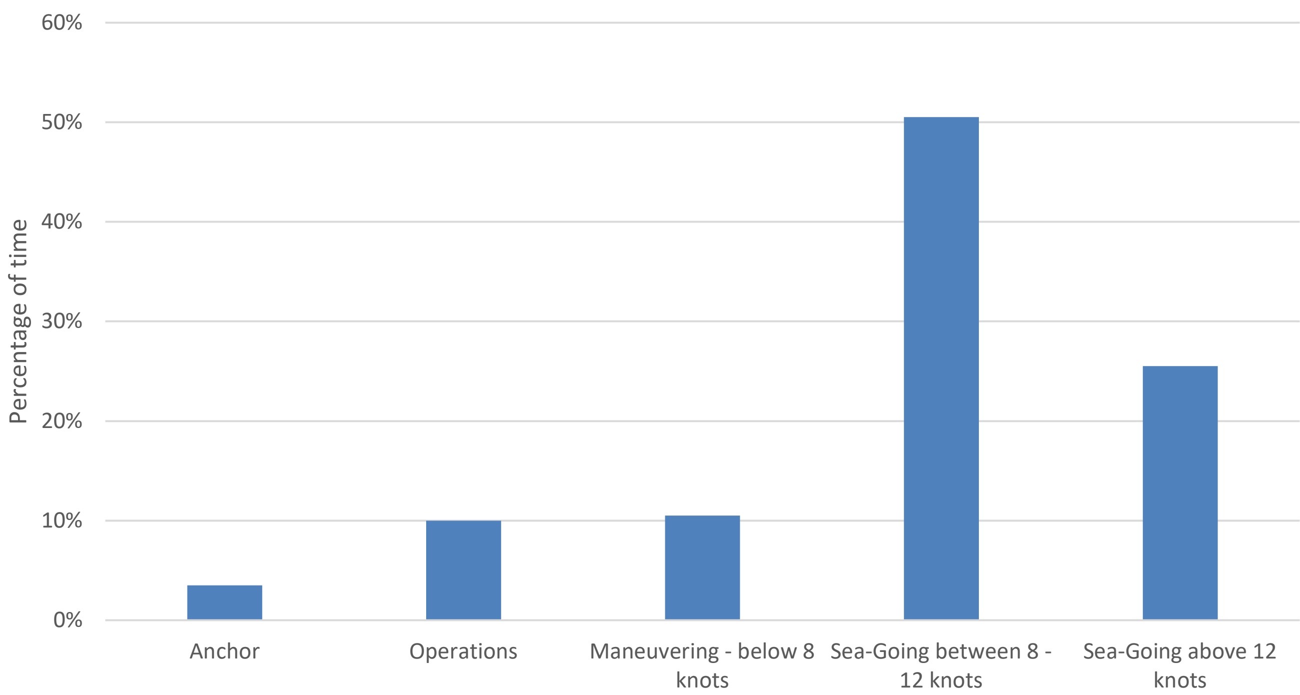

Figure 0-74 MR tanker operating profile.

■ **CO_2 performance analysis**

The OCCS technology is examined for sweeps of CO_2 capture capacity. The results from 0.5 &1 TPH are presented, as these present options that are reasonable in terms of LCO_2 storage and maintain the operation of the Aux Gens and boilers within manufacturer and redundancy limits (load below 90%, 1 Aux D-G on standby).

Same as rest of the cases, in the case of the NB vessel two additional considerations will take place:

- Properly sized AEECOs for the OCCS, sized to the capacity of the exhaust gas enthalpy from the Auxiliary Engines (including two exhaust gas boilers for the auxiliary generator sets)
- Installation of PTO of 0.9 MW

Table 0-29 MR tanker - Technology Components for each configuration.

Design / Components	Aux. Engines' Economizers	PTO
Retrofit	-	-
Newbuilding with PTO	-	X
Newbuilding with AEECOs	X	-

Same as for the Suezmax case, the examined OCCS technology in terms of energy efficiency a state-of-the-art system is considered with specification as shown in Table 0-5

Comparative analysis

Results of the analysis for the capture rate of 0.5 TPH and 1 TPH are shown in Figure 0-75

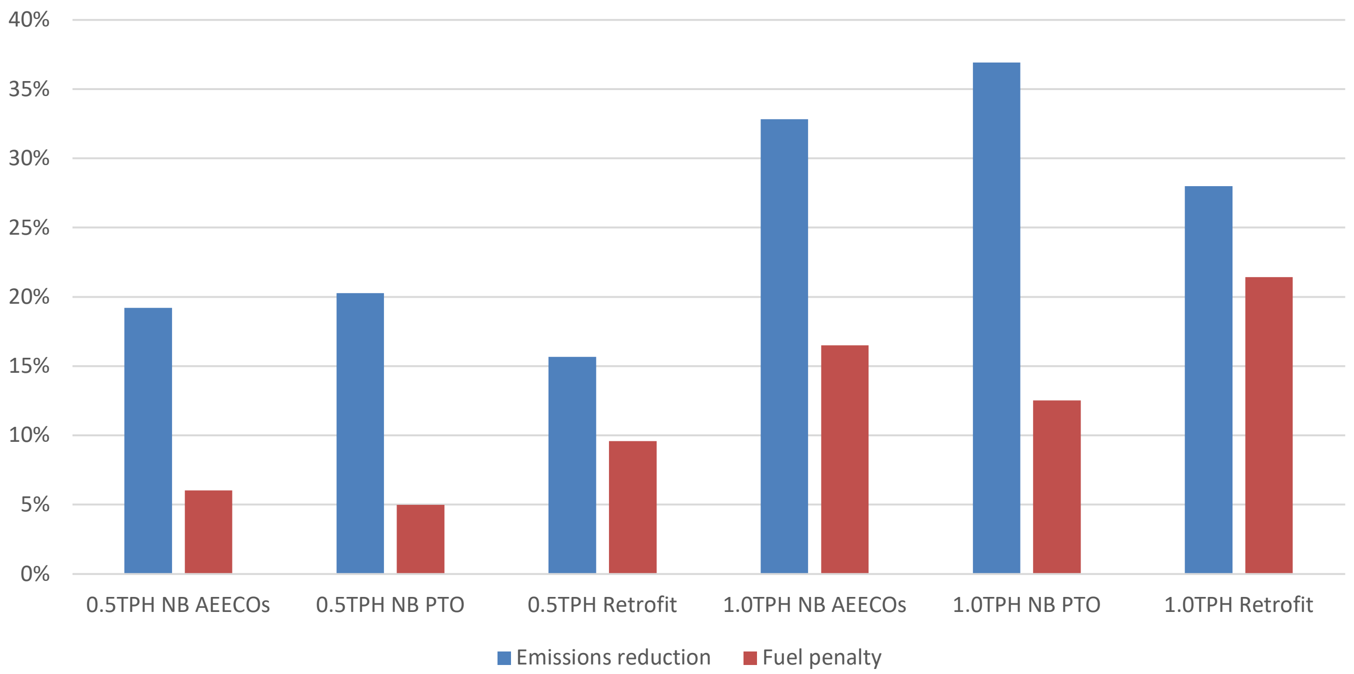

Figure 0-75 MR tanker - Emissions reduction vs Fuel penalty.

CO_2 performance

A typical round trip for this type of vessel has a duration of approximately 15 days. Based on this operational cycle, the vessel is expected to complete around 24 round voyages per year. This frequency forms the basis for evaluating the annual performance of the onboard systems, particularly in terms of fuel consumption and emissions.

The yearly assessment includes the total consumption of fuel in metric tons, the corresponding total CO_2 emissions generated, and the amount of CO_2 captured by each case. Additionally, the analysis presents the net CO_2 emissions released into the atmosphere after capture, as well as the total quantity of CO_2 abated. These metrics provide a comprehensive overview of the environmental performance of the vessel and the effectiveness of the OCCS in reducing GHG emissions.

The yearly CO_2 performance results are shown for the OCCS capacity of 0.5 TPH, 1 TPH & 1TPH in Figure 0-76.

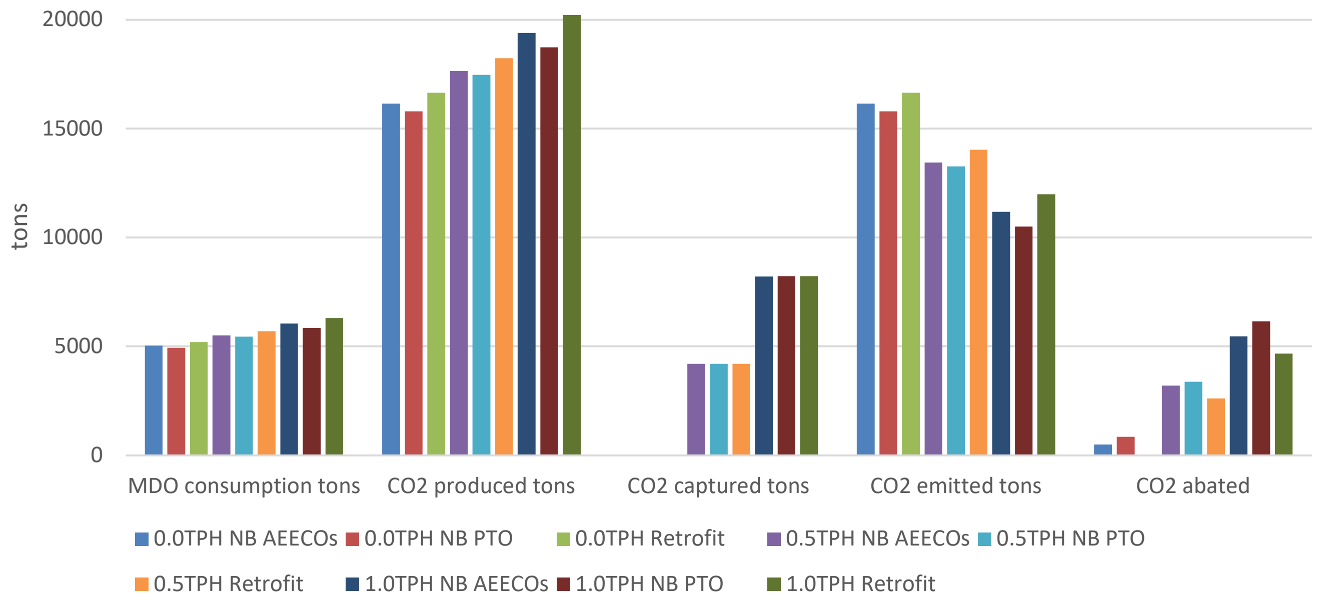

Figure 0-76 MR tanker - OCCS yearly performance.

OCCS impact on machinery performance

In this section an overview of the effect of the OCCS technology on the different machinery of the vessel (Aux. Engines and Boilers) will be presented.

Figure 0-77 illustrates the impact of the different OCCS capture rates on the utilization of key machinery components, specifically the main engine and auxiliary engines, during laden sailing at a service speed of 12 knots, which is the average speed of the vessel. For the retrofit case and NB AEECOs, as the OCCS capture rate increases from 0.5 TPH to 1.5 TPH, the load on the auxiliary engines rises from 65% to appr. 80%. In the optimized newbuilding with PTO, when the PTO system is employed, the main engine and PTO can meet the additional electrical demand imposed by the OCCS system, engaging one additional auxiliary generator.

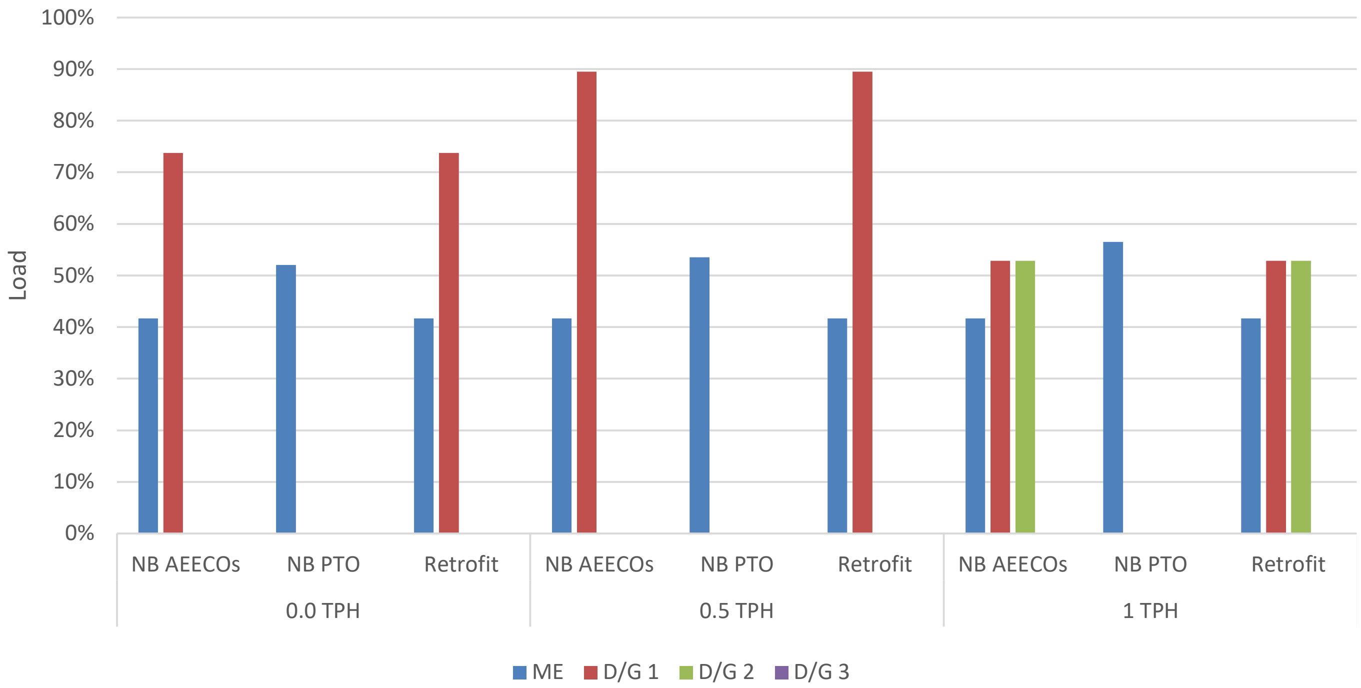

Figure 0-77 MR tanker - OCCS Impact on Main Engine and Aux. Engines at 12 knots in laden condition.

Figure 0-78 shows the OCCS steam demand coverage from the Aux. boiler and the Main Engine and Aux. Engines economizers, during laden sailing at a service speed of 12 knots.

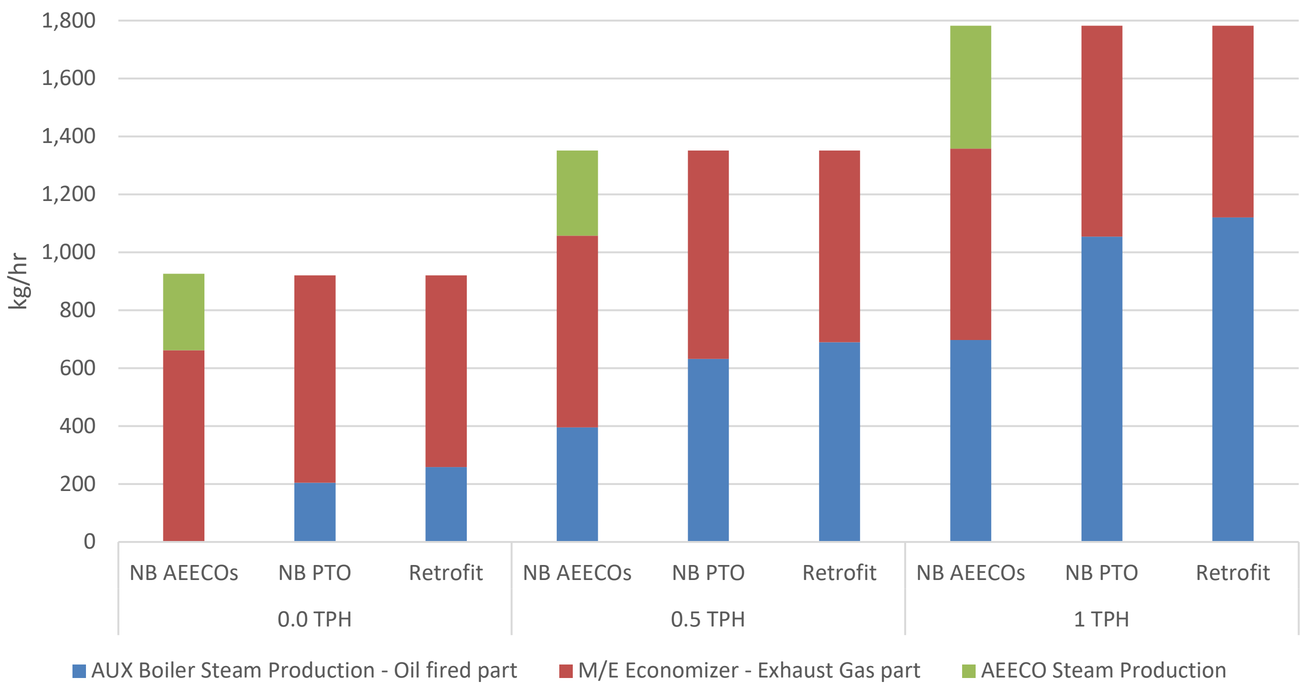

Figure 0-78 MR tanker - OCCS Impact on Aux. boiler & Economizers at 12 knots in laden condition.

- **<u>Economic impact analysis</u>**

CO_2 abatement cost

Same as previous cases, results of the CO_2 abated cost are shown in Figure 0-79. The lowest CO_2 abated cost in each case is the optimized newbuilding with the PTO.

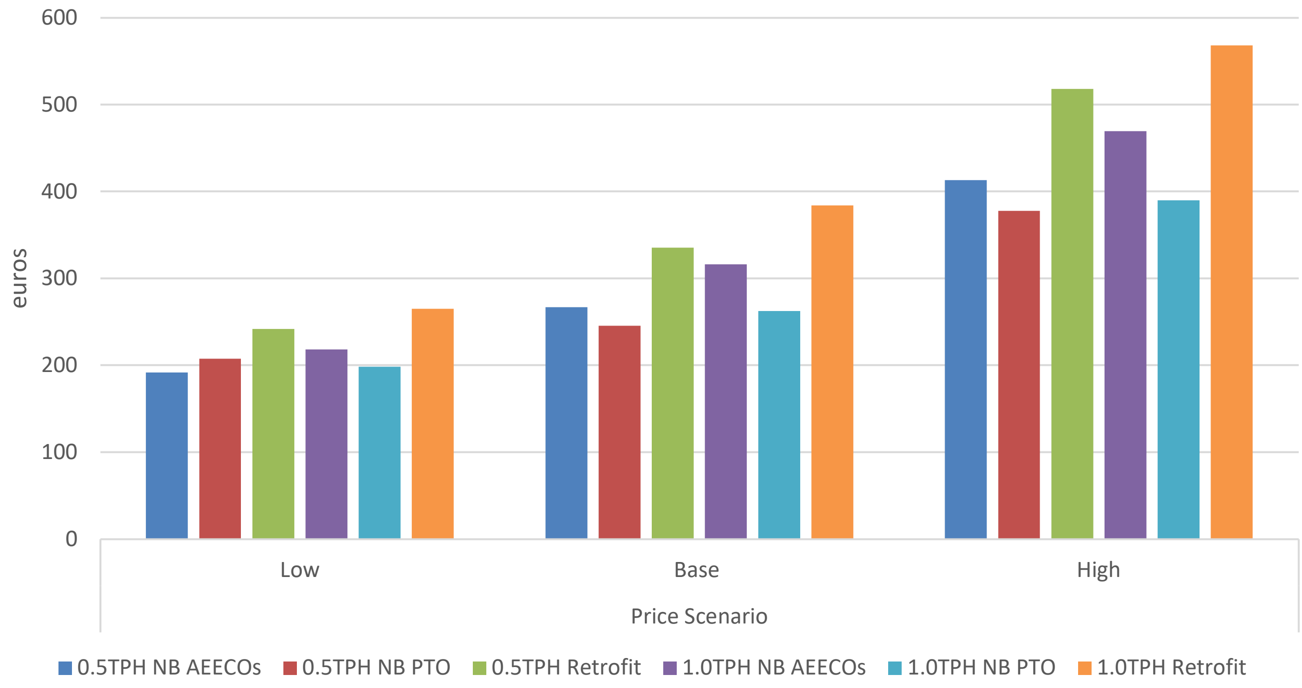

Figure 0-79 MR tanker - CO_2 abatement cost per tons CO_2 abated.

CAPEX / OPEX calculation

In this section a more detailed overview of the CAPEX costs per case is done, CAPEX costs can be found in 3.2.1.

Figure 0-80 presents the CAPEX analysis results.

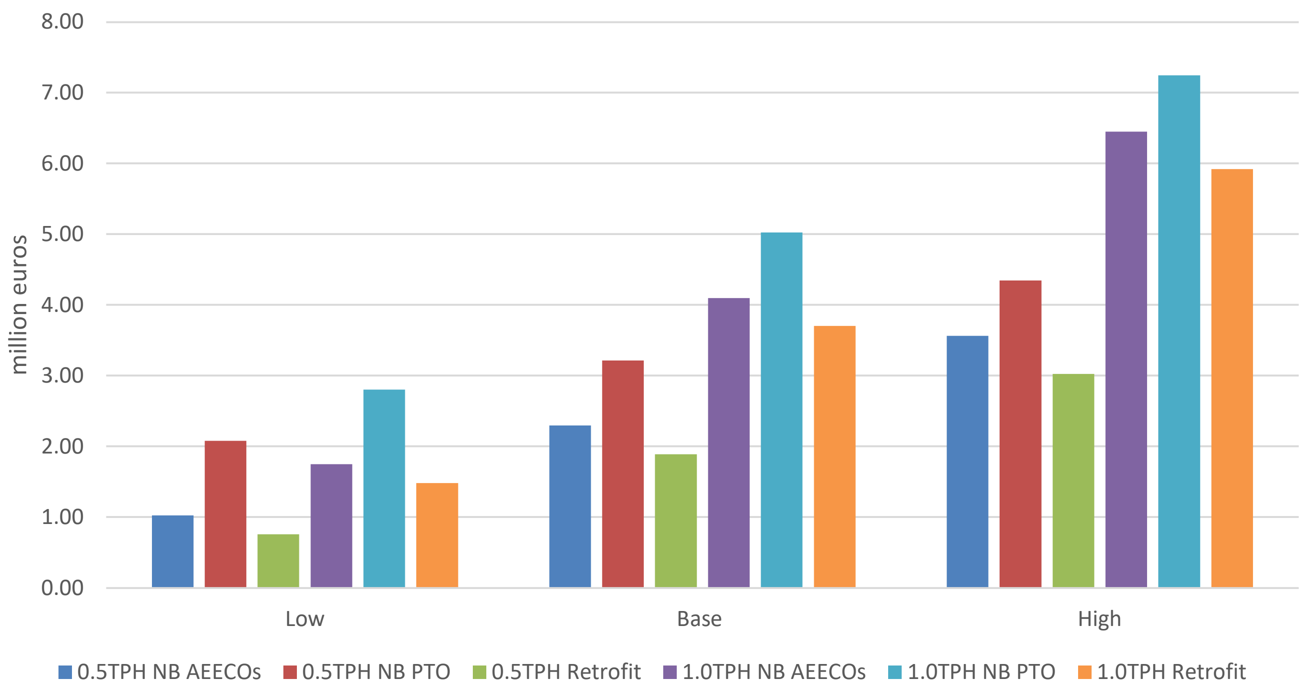

Figure 0-80 MR tanker - CAPEX analysis.

In order to estimate the yearly fuel OPEX for the examined cases, the costs are considered as shown in Table 3-15. Results are shown in Figure 0-81.

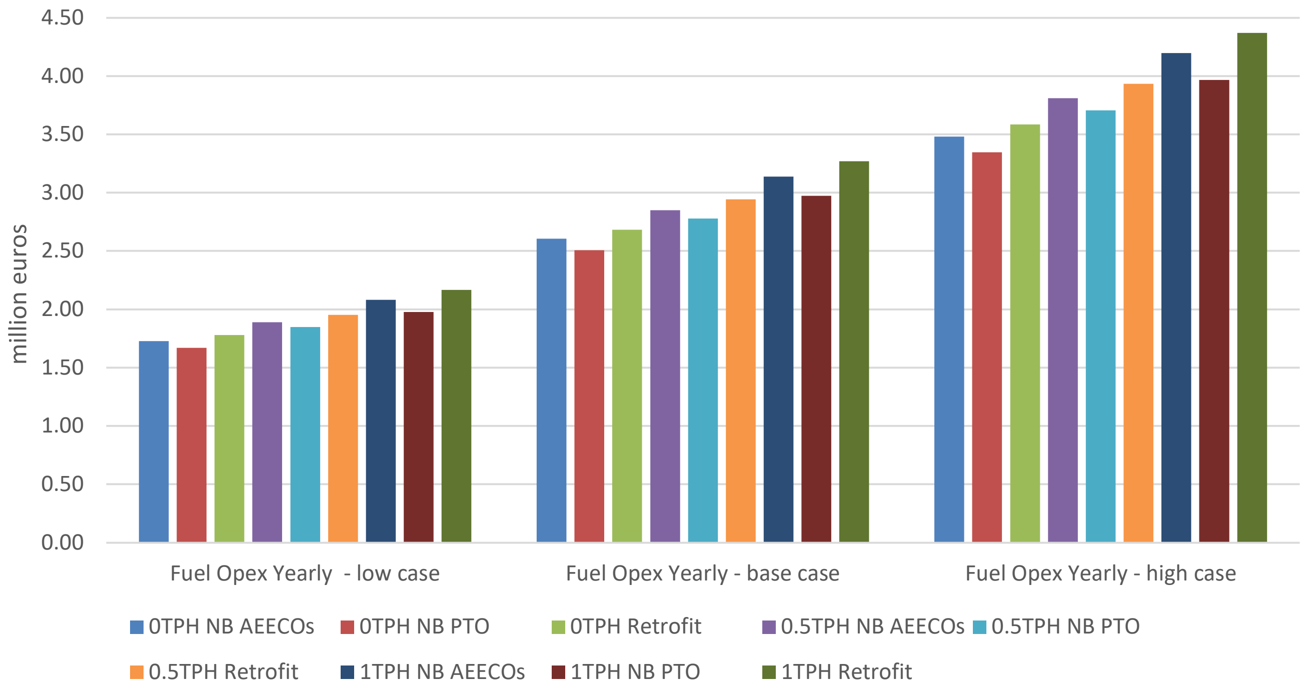

Figure 0-81 MR tanker - Yearly Fuel OPEX in mil. Euro.

Economic analysis of disposal cost

For the economic analysis of the disposal cost, the following assumptions are as mentioned in Table 3-15, with the disposal cost for the captured CO_2 on a yearly basis for the LNGC vessel shown in Figure 0-82.

Figure 0-82 MR tanker - Yearly disposal cost of CO_2.

CO_2 abatement cost per ton of Captured CO_2 – sensitivity analysis

Following the evaluation of various cost metrics, namely CAPEX, fuel OPEX, and CO_2 disposal costs, a sensitivity analysis was conducted to assess their impact on the overall CO_2 abatement cost. This analysis, illustrated in Figure 0-83, shows the case with the OCCS system with a capture rate of 1 TPH.

The results indicate that the CO_2 disposal cost and fuel OPEX exert the most significant influence on the abatement cost. These are followed by the technology CAPEX and maintenance costs, which have a moderate impact. In contrast, the cost of solvents contributes minimally to the overall CO_2 abatement cost.

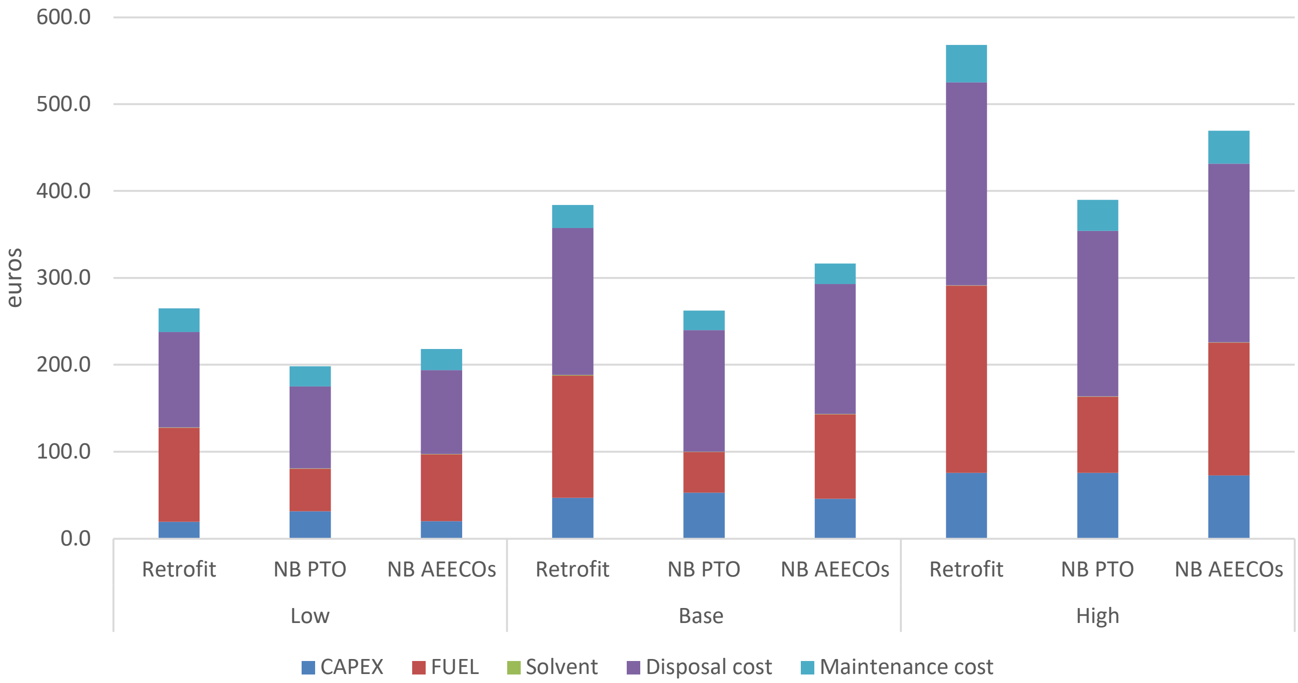

Figure 0-83 MR tanker - CO_2 abatement cost per ton CO_2 sensitivity analysis for the 1 TPH capture rate.

Port offloading and ship interface analysis

The displaced vapor results are showcased in tons, according to the different CO_2 capture rates and vessel tank sizes as shown in Figure 0-84. The required energy of the systems involved (pump, heater and cooler) is showcased separately for each vessel and CO_2 capture rates in kWh in Figure 0-85.

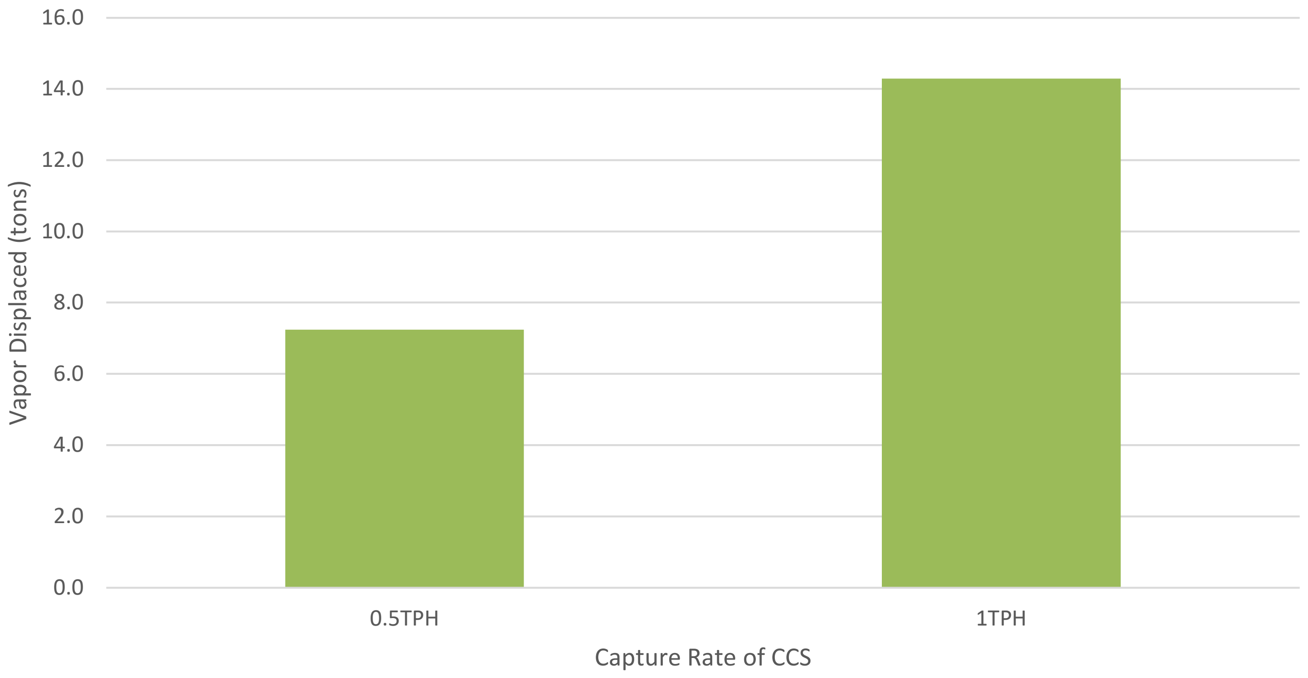

Figure 0-84 MR tanker - displaced vapor during offloading per capture rate, assuming an offloading rate of 100 m^3/hr.

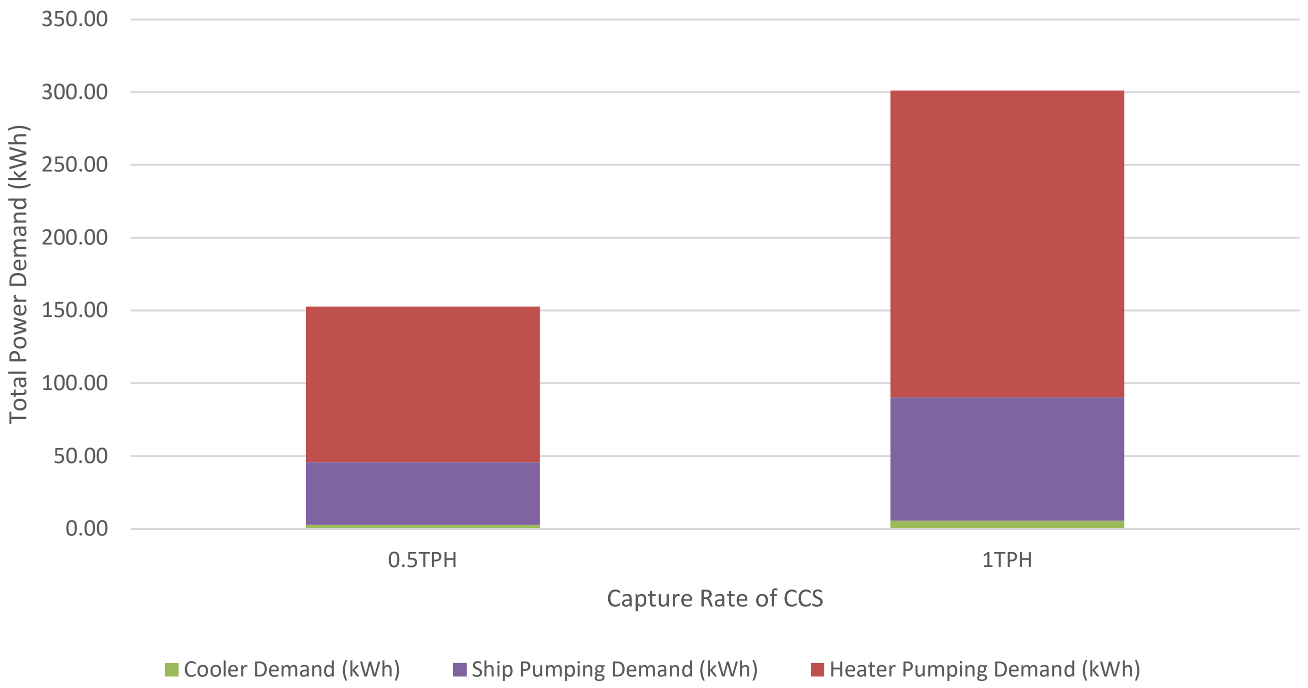

Figure 0-85 MR tanker - total required energy during offloading, assuming an offloading rate of 100 m^3/hr.

- **Technical impact analysis**

Same as for Suezmax case, the deck of MR tankers is also relatively strong with many bulkheads below deck which may be well suited to support the heavy deck loads. In case of retrofit, the additional girders, stiffeners and brackets and the increased thickness of existing structure is regarded moderate to small. The location of the LCO_2 tank conflict with cargo operations is regarded as insignificant.

LCO_2 storage tanks capacity and dimensions estimation

The MR tanker is assumed to make 24 round trips per year, with each round trip lasting appr. 15 days. The offloading frequency is assumed to take place once per round trip. The estimations for the required capacity of the LCO_2 tank, considering a margin of +10% (unforeseen delays/ extended cargo operations) is shown in Table 0-30.

LCO_2 storage tank is considered to be filled up to 95% of their volume. LCO_2 density is assumed at 1,110 kg/m^3. Capacity of the LCO_2 is given on an average basis per different capture rates, since the different cases (optimized newbuilding with PTO and retrofit) have slight differences in the captured CO_2 quantities.

Table 0-30 MR tanker - LCO_2 Storage Tanks specifications.

LCO_2 Storage Tanks specifications				
Capture rate of OCCS	CO_2 captured per 15 days+10% margin (m^3)	LCO_2 total required capacity (m^3)	Tank D x L (m) (per storage tank)	Total weight including LCO_2 (tons)
0.5TPH	165	180	4x14	290
1.0TPH	323	340	5x17	510

For the MR tanker case, it is assumed that the system has one LCO_2 storage tank.

OCCS impact on vessel space demands

LCO_2 Storage Tanks

For the MR tanker, the proposed configuration involves locating the LCO_2 storage tank on the main deck in front of the accommodation area[96].

- Newbuilding: In a newbuilding scenario, the design of the vessel can be optimized from the outset to accommodate the LCO_2 storage tank. This allows for integration with minimal impact on the vessel's overall design.
- Retrofit: In a retrofit scenario, existing structures will need to be modified to fit the CO_2 tank. This could involve reinforcing the deck or relocating other equipment, such as bollards or ballast tank vents and possibly foam cannons.

Since the installation location of the LCO_2 storage tanks and the OCCS are located on the deck area of the MR tanker, these areas are usually not classified as gas dangerous areas. Nevertheless, welding to deck is potentially an issue for the retrofit case.

Nevertheless, if the installation location of the OCCS or the LCO_2 storage tanks is classified as a hazardous area, additional safety measures must be implemented. This includes ensuring that all associated electrical equipment, such as sensors and instrumentation, are certified for use in explosive atmospheres (e.g., EX-certified).

To mitigate the need for hazardous area compliance, an alternative approach may involve installing the tanks above deck, outside the classified zone. However, this solution requires further structural analysis, as it introduces additional loads, up to 10% additional weight of the storage tank, and necessitates reinforcement of the supporting structure, potentially impacting the vessel’s overall weight and stability.

It is important to note that this configuration is presented as a conceptual guideline. The feasibility, safety, and operational implications of such an installation must be assessed on a case-by-case basis. Each vessel owner should conduct a detailed engineering study to evaluate structural compatibility, cargo impact, regulatory compliance, and integration with existing systems. Collaboration with classification societies and technology providers is essential to ensure that the final design meets all technical and safety requirements.

[96] What would an Onboard Carbon Capture and Storage (OCCS) system look like on the Stena Impero? - GCMD

Carbon Capture System

The absorber and regeneration stacks can be installed right behind the vessel's funnel. This location leverages the existing structures and minimizes interference with other operations of the vessel. In terms of piping this placement will result in long additional piping.

- Newbuilding: For newbuilds, the OCCS can be integrated into the vessel's design from the beginning. This ensures optimal placement and weight distribution, enhancing the vessel's stability and operational efficiency.
- Retrofit: Retrofitting the OCCS requires advance planning to integrate it with the existing structures. This may involve additional engineering work to ensure the system does not interfere with the vessel's existing operations.

In both newbuilding and retrofit, the OCCS system will be required to be placed on dedicated strengthened supports, in order to not interfere with vessel's mooring operations.

Liquefaction Plant

Same as the carbon capture system, the liquefaction plant can be installed right behind the vessel's funnel.

- Newbuilding: In a newbuilding case, the liquefaction plant can be designed into the vessel's layout, ensuring it fits seamlessly with other systems. This allows for efficient use of space and integration with the vessel's power and heat systems.
- Retrofit: Installing a liquefaction plant in an existing vessel may require some modifications, such as structural reinforcements to support the weight and vibration of the equipment.

For the liquefaction plant, given the presence of pressurized CO_2 and potential leak scenarios, the same safety requirements, such as dedicated ventilation, gas detection, and explosion-proof equipment, are expected to apply same as LCO_2 storage tanks. To comply with these standards and mitigate risks, the liquefaction plant may need to be installed in a segregated, purpose-built compartment adjacent to or outside the ER, rather than within the general machinery space.

Impact on weight

The LCO_2 storage tank is placed centric to ensure balanced weight distribution. The placement of the OCCS components takes place behind the funnel. Weight distribution per component and the effect on Lightweight increase per case is shown in Table 0-31.

Table 0-31 MR tanker - OCCS weight distribution (tons).

MR tanker case - OCCS Weight distribution in tons per examined capture rates		
Capture rate	**0.5 TPH**	**1 TPH**
OCCS System weight - Structure only	100	140
Increase compared to baseline LWT	1.1%	1.6%

Same as the Suezmax case, the impact on hull girder loads needs to be analysed for retrofit vessels based on stability calculations with the updated mass distribution and accordingly updated still water moments. It may be that the updated still water moments are within the design moments, and this should be confirmed. Limited consequence is expected. For a newbuilding vessel, this is already part of design envelope moments. In the context of the present study this will not be further analysed but is mentioned here for sake of completion of understanding to the reader.

The increased vertical centre of gravity is regarded marginal and may reduce the transverse dynamic accelerations in roll affecting favourably the inertia and internal cargo and ballast tank pressure loads for extreme strength and fatigue assessment, hence this is not regarded additional scope in the retrofit case.

Impact on stability

The effect of the OCCS system on vessel's stability shall be assessed to ensure compliance with acceptable limits. The evaluation must include the weight of liquids contained within the system under normal operating conditions. In the extreme case it may change the metacentric height value, GM, in the order of 0.2 m in full load condition and in ballast condition possibly up to the double. The stability is however good in ballast condition, so it is mainly affecting stability in full load condition.

- For the newbuild case, the OCCS system's weight and distribution shall be incorporated into the initial stability calculations and lightship definition. The inclining test shall reflect the vessel's final configuration, including the OCCS installation.
- For retrofit installation, a new inclining test may be required to accurately determine the updated stability characteristics and ensure continued compliance with regulatory requirements.

With the installation of the OCCS components and when the LCO_2 tank is full, the vessel's center of gravity shifts slightly higher, and a bit aft compared to the vessel without the OCC. these changes could reduce the ship's natural balance and make it more sensitive to rolling in rough seas. Depending on the actual vessel's conditions, it may be necessary to adjust either the ship's ballast, by adding weight lower in the hull to counterbalance the higher equipment or redistribute cargo to improve balance, especially for the case of the retrofit vessel.

Impact on Cargo Capacity

The installation of the OCCS system, including LCO_2 storage tanks, introduces a substantial increase in the vessel's lightship weight. This increase is significant relative to the vessel's baseline lightweight, particularly at higher capture rates, and may directly affect the available deadweight for cargo due to draft and stability constraints.

The OCCS system components, such as compressors, piping, tanks, insulation, and structural reinforcements, contribute to this added weight and must be accounted for during the design or retrofit phase as shown in the previous sections. The resulting reduction in available deadweight impacts the vessel's capacity to carry cargo.

To mitigate these effects, operational adjustments may be necessary. This includes modifying ballast water configurations, such as reducing or redistributing ballast to maintain acceptable trim and draft conditions. Deadweight increase studies is relevant in the retrofit case with less than 0.3 m draft increase. Voyage planning must also consider the reduced cargo margin, especially on routes with strict draft limitations or where fuel efficiency is a key operational concern.

In newbuild scenarios, these impacts can be more effectively managed through integrated design solutions. Optimized ballast arrangements and structural accommodations can be implemented to offset the added weight and preserve vessel stability and cargo capacity.

- **Economic viability**

EU ETS impact

To quantify the financial exposure of the system under the EU Emissions Trading System (EU ETS), two operational scenarios are considered based on the vessel's annual voyage distribution:

- Scenario A – Low EU Exposure:

The vessel spends approximately 50% of its annual operating time in voyages into or out of the EU/EEA. This includes occasional calls to EU ports (e.g., one out of five voyages involving EU stops), resulting in limited exposure to EU ETS regulation compared to the following Scenario B.

- Scenario B – High EU Exposure:

The vessel spends around 100% of its annual operating time within EU/EEA. This results in substantial coverage under the EU ETS, with all the emissions subject to the regulation.

For both scenarios, carbon pricing is modelled using a base rate of €170 per ton of CO_2[97].

[97] Energy Transition Outlook 2024

This comparative framework enables a clear understanding of the cost implications associated with varying levels of EU ETS exposure, supporting informed decision-making regarding operational strategy and emissions compliance.

The comparison of these two scenarios is made for the capture rate of 1 ton of CO_2 per hour. The analysis focuses on the savings of EU ETS allowance, enabling a direct evaluation of the economic viability of the system under varying levels of EU ETS exposure. Results of the analysis can be seen in Table 0-32.

Table 0-32 MR Tanker - EU ETS analysis for 1 TPH.

Scenario	EU ETS allowance savings in thousands of euros on a yearly basis	
	Low EU Exposure	High EU Exposure
NB PTO	198	893
NB AEECOs	187	837
RETROFIT	170	783

Scenario-Based Assessment of OCCS and Biofuels Under the IMO GFI Metric

Following section 3.3.2, the scenarios related to the OCCS potential impact on the ship's attained GFI were defined as follows:

- Scenario 1: When calculating the attained GFI the captured CO_2 is subtracted by the formula, while the ship fuel energy includes the fuel penalty. This assumption does not include the full lifecycle emissions of the procedure such as the ones arising from the transportation and permanent storage of the captured CO_2.
- Scenario 2: The attained GFI is calculated based on the WtW emission factors of the LCA guidelines, where for OCCS, the TtW factor is adjusted by the e_{OCCS} term. In this scenario the OCCS fuel penalty is omitted from the fuel energy in the attained GFI formula ship.
- Scenario 3: The attained GFI is calculated based on the WtW emission factors of the LCA guidelines, where for OCCS the TtW factor is adjusted by the e_{OCCS} term except from the OCCS energy penalty term, which is accounted in the ship fuel energy via the OCCS fuel penalty.

Figure 0-14 presents the results of a cost assessment, summarizing the annual operational expenses associated with the implementation of the OCCS solution, alongside the costs of the remedial units under the proposed GFI framework. Additionally, the alternative solution of biofuels usage, is evaluated to achieve the same attained GFI as Scenario 1 (which is estimated to be the lower value).

The first instance of annual OPEX savings is observed in year 2028 for the case of biofuels minimum price, while for the mid-price scenario it is estimated that up to 2034 the differential OPEX does not showcase savings. For the OCCS case it is assumed that in the end of 2031 the retrofit is implemented on board, as the differential OPEX savings begin from 2032 and onwards.

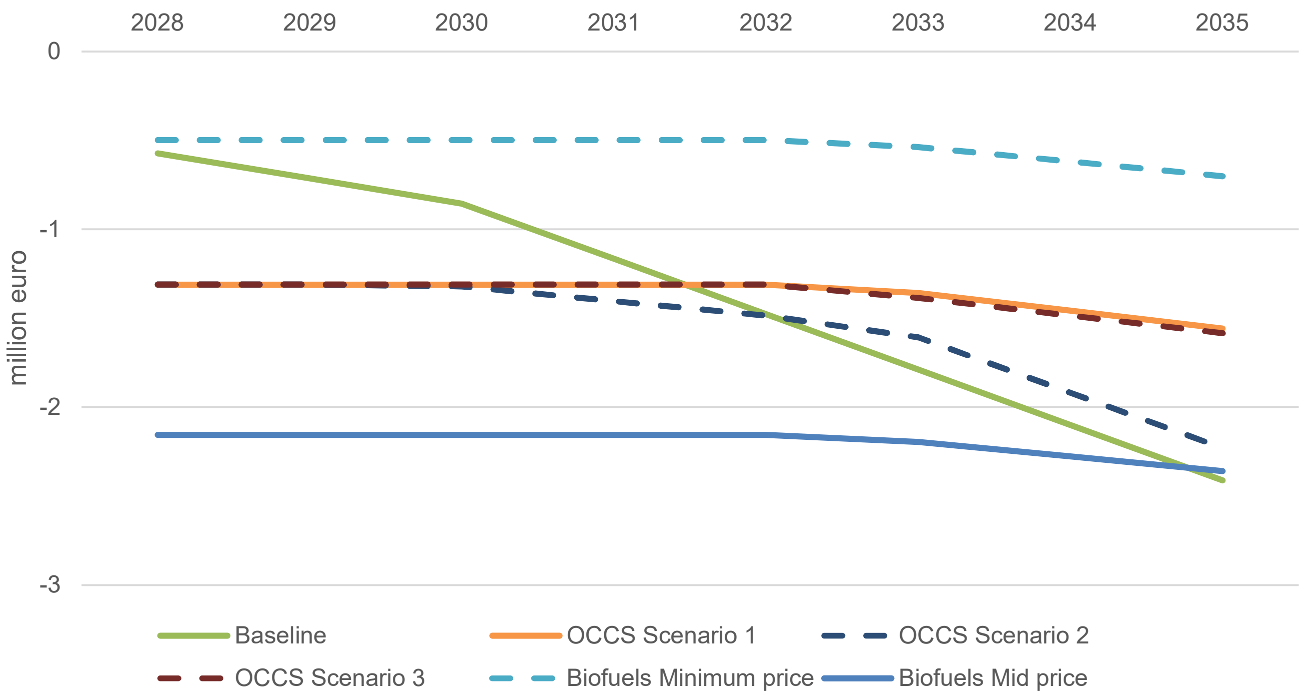

Figure 0-86. MR Tanker - OCCS comparison to biofuels. Annual differential OPEX cashflows.

The following graph illustrates the attained GFI for each case scenario.

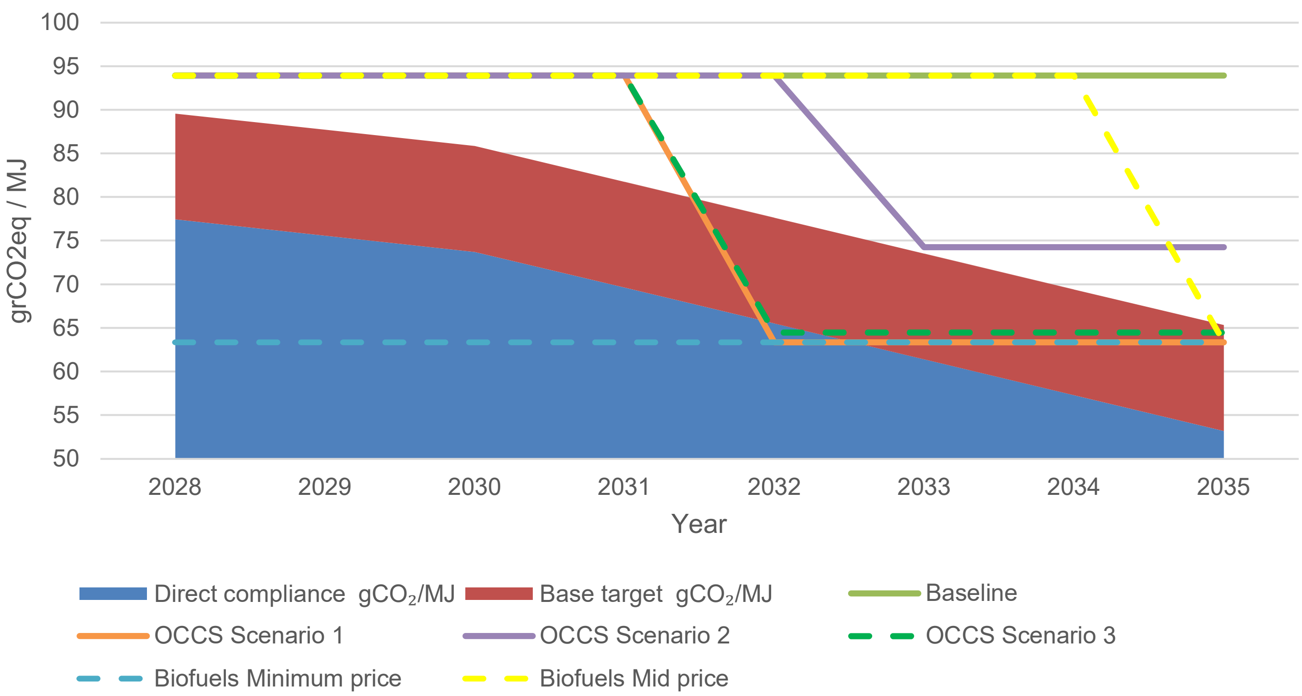

Figure 0-87. MR Tanker - OCCS comparison to biofuels. Attained GFI scenario analysis trajectory.

In Figure 0-16 the discounted differential OPEX cashflows on the above analysis are accumulated for the years covering 2028-2035 (blue stack) while the red bars represent the margin of the discounted differential OPEX of OCCS and biofuels against the baseline vessel. Under this price scenarios the usage of biofuels, seems to be beneficial when the minimum fuel price is projected, contrary to their performance on the mid price scenario.

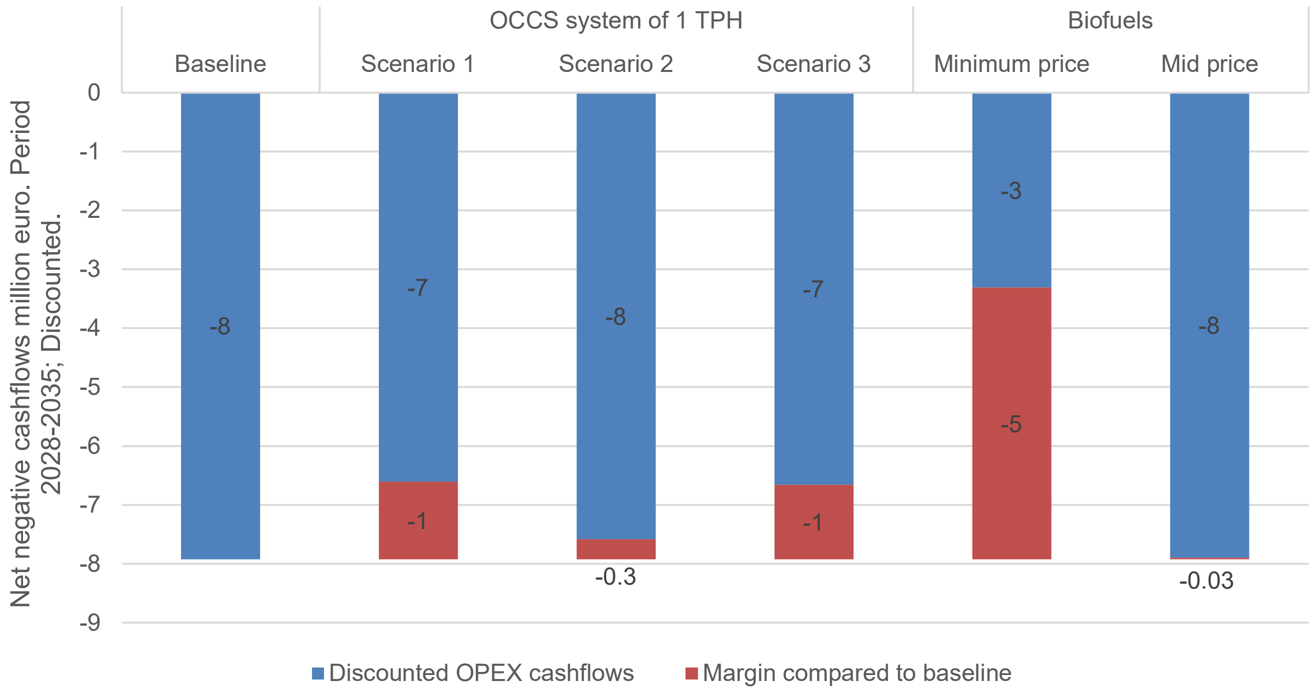

Figure 0-88. MR Tanker - OCCS comparison to biofuels. Discounted Differential OPEX cashflows from 2028-2035.

Appendix H Suezmax and MR tanker HAZID/HAZOP log – chemical absorption OCCS

Table 0-33 HAZID/HAZOP log for Suezmax & MR tanker vessel – chemical absorption OCCS

ID	Guideword	Major cause	Subsequent causes	Potential consequences	Existing or planned safety measures	F 1	Sp 1	Sa 1	Se 1	R 1	Proposed additional safety measures (recommendations)
Node 1.1:	**Design: Pre-treatment stage**										
1.1.1	Leakages	Leaking of exhaust stream	- Wear and tear of valves or flanges - Piping rupture -Material degradation or failure - Corrosion (water source for the pre-treatment stage) -Improper assembly or installation	- Leaks lead to asphyxiation - Relase of harmful gases (e.g. CO_2, NO_x , SO_x)	- Proper installation procedures - Pre-treatment of CO_2 - Temperature monitoring	2	2	3	3	M	RC1: For vessels with scrubber installed, the proper water handling in the scrubber should be considered and analyzed
1.1.2		Leaking of chemicals	-No chemical use for pre-treatment			1	1	1	1	L	
1.1.3		Leakage of effluents or working media (condensation of flue gas, other)	-Leakage in the water treatment system - High acidity NaOH leakage - In case of U type scrubbers - valves may maloperate	- Leak of water back to the engine	- Redundant piping or bypass systems	2	2	2	2	L	RC 2: For vessels with scrubber installed, control/monitoring of the level water of the scrubber (U - Type)
1.1.4	High temperature	Heated pipes and containers (tanks)	-Hot flue gas from exhaust	- Burns to personnel - Thermal cracking/stress of nearby	- Exhaust gas bypass - Temperature monitoring - Thermal	2	2	1	2	L	RC 3: Warning signs and restricted access in the high

ID	Guideword	Major cause	Subsequent causes	Potential consequences	Existing or planned safety measures	F 1	Sp 1	Sa 1	Se 1	R 1	Proposed additional safety measures (recommendations)
				components - Fire hazard	insulation of hot surfaces						temperature designated areas
1.1.5		Flue gas exceeding design temperature at inlet	-Hot flue gas from exhaust	- Damage to heat exchangers or scrubbers - System shutdown or failure	- Exhaust gas bypass - Temperature monitoring	2	1	1	3	M	
1.1.6	Loss of system	Pre-treatment stage failure	- Control failure	- Disruption of carbon capture process - Increased emissions - Potential damage to downstream equipment	-Safety shutdown of system (continuous operation not required) -System bypass	2	1	3	3	M	
Node 1.2:	**Design: Capture system - Absorber**										
1.2.1	Leakages	Leaking of exhaust stream at valves or flanges in the absorber module and pumps	-Assembly errors -Material failure -Carry over of acidic compounds from pre-treatment stage in the absorber	-Release of harmful gases -Health hazards -Environmental pollution -Component failure cracks -Degradation of amines	-Exhaust blower damper -Exhaust forced draft fan	2	3	2	2	M	RC 4: Corrosive-resistant materials (high grade steel)
1.2.2		Leaking of chemicals at valves flanges of the absorber module and pumps	-Assembly errors -Material failure	-Chemical burns - harmful not lethal -Toxic exposure - harmful not lethal	-Upgraded type of material of pipeline	2	3	2	2	M	
1.2.3		Carryover of wash water and chemicals at	-Increased solvent flow -Inefficient	-Environmental contamination -Personnel exposure	-Efficient demister operation (part of basic design)	2	3	2	2	M	

ID	Guideword	Major cause	Subsequent causes	Potential consequences	Existing or planned safety measures	F 1	Sp 1	Sa 1	Se 1	R 1	Proposed additional safety measures (recommendations)
		absorber exhaust gas outlet	operation of demister		-Extra washing stage after the absorber stage (part of basic design)						
1.2.4	Pressure drop	Exhaust gas pressure drop	-Clogging in the packing bed reactors -Fan failure -Overfilling of solvent	- System inefficiency - potential damage to equipment	-System bypass mode	2	1	2	2	L	
1.2.5	High temperature	Loss of exhaust gas cooling stage	-Low water flow in pre-treatment stage -Loss of pre-treatment stage	-Overheating -Potential equipment stage -System shutdown	-System bypass mode	3	2	3	2	M	
1.2.6	Performance degradation	Chemical performance accelerating degradation	-Aging -Gas impurities -Loss of chemical pre-mixing system -Part-load performance -Circulating pumps failure -Excessive gas flow due to oversize of exhaust gas fan	-Reduced capture efficiency - Increased emissions	-Monitoring and proper maintenance of chemicals	3	1	2	2	M	RC 5: Proper quality of chemicals used
1.2.7	Loss of system	Absorber stage failure	-Control failure	-Carbon capture process disruption -Potential damage to downstream equipment	-Safety shutdown of system (continuous operation not currently required) -System bypass	2	1	2	2	L	

ID	Guideword	Major cause	Subsequent causes	Potential consequences	Existing or planned safety measures	F 1	Sp 1	Sa 1	Se 1	R 1	Proposed additional safety measures (recommendations)
Node 1.3:	**Design: Capture system - Regenerator column**										
1.3.1	Leakages	Solvent and chemicals leakage	-Pump malfunction -Clogging -Overflow of solvent from regeneration column -Valves or flanges leakage -Leakage of amine into the steam loop	-Exposure of the personnel	-Low liquid to gas ratio volumetric flow, lower compared to Sulphur Scrubbers -Level and system monitoring in place -Periodic testing and preventive maintenance of system -Control valve to the atmosphere -PSV (pressure relief valve) valve on the stripper	2	3	2	2	M	RC 6: Proper sizing of the compressor RC 7: Leakage detectors in the drip trays and where leakages are more likely to occur (e.g. under pumps) RC 8: Chemical sensor in the steam RC 9: Measurement of the difference of the pressure of the two streams
1.3.2		Leakage of pure CO_2	-Errors in the assembly of the system -Wear and tear -Mechanical failure	-Asphyxiation -Toxicity	-Gas detection system in place and closing of valves -Proper installation location	2	3	2	2	M	RC 10: Ensuring proper assembly and use of durable materials RC 11: Establish procedures for regular inspection and maintenance of components
1.3.3	High pressure	Excessive CO_2 gas	-Improper size/malfunction	-Release of pure CO_2, posing health	-PSV (pressure relief valve) on	2	3	2	3	M	RC 6: Proper sizing of the compressor

ID	Guideword	Major cause	Subsequent causes	Potential consequences	Existing or planned safety measures	F 1	Sp 1	Sa 1	Se 1	R 1	Proposed additional safety measures (recommendations)
			of the compressor	hazards and environmental risks.	the stripper -Control valve to the atmosphere						
1.3.4	High temperature (160-180 deg Celsius)	Reboiler control loss	- Marginal operation - Reboiler duty drop - Chemical performance degradation	-High temperature (due to low flow) -Thermal stress -Potential damage	-High temperature alarms for reboiler -Existing safeguards on pressure relief on High Pressure Heat Exchanger	2	1	2	2	L	RC 12: Control of steam pressure
1.3.5	Performance degradation	CO_2 separation performance degradation	- Marginal operation - Reboiler duty drop - Chemical performance degradation	-CO_2 separation performance -Reduced capture efficiency	-Before gas CO_2 compressor there is a CO_2 detection system	2	1	2	2	L	
1.3.6	Loss of system	Stripper stage failure	-Control failure	-Failure of the stripper stage -Disruption of the entire capture process	-Safety shutdown of system (continuous operation not currently required) -System bypass	2	1	2	3	M	
Node 1.4:	**Design: Gas Piping**										
1.4.1	Leakages	Release of pure CO_2	-Release of CO_2 straight out of the system boundaries	-Health hazards to crew -Environmental pollution	-Regular inspection and maintenance -Leakage detection of CO_2	3	3	2	3	M	RC 4: Corrosive-resistant materials (high grade steel)

ID	Guideword	Major cause	Subsequent causes	Potential consequences	Existing or planned safety measures	F 1	Sp 1	Sa 1	Se 1	R 1	Proposed additional safety measures (recommendations)
1.4.2			Improper routing of pipes	System inefficiency or failure	-Regular inspection and maintenance -Leakage detection of CO_2	2	1	2	2	L	RC 13: Detailed analysis during NB or retrofitting of the system RC 4: Corrosive-resistant materials (high grade steel)
1.4.3	Pressure drop	Excessive pressure drop in gas pipes	-No or miscalculation of pressure drop	System inefficiency or failure	-Proper design of exhaust booster fan	2	1	2	2	L	RC 14:Detailed calculations of pressure drop of gas routing
Node 1.5:	**Design: Liquefaction Plant**										
1.5.1	Leakages	CO_2 gas leakages in the liquefaction plant	- Valve, flange leaks - Material failure or incompatibility - Mechanical failure	-Release of CO_2 -Health hazards to crew -Environmental pollution	-Piping rated to working pressure with safety margin -Piping hydrostatic tests -Thermal Relief Valve in piping lines for the liquid phase (as per IGC code) - Life saving appliances	2	3	2	3	M	RC 15:CO_2 gas & liquid management plan as worst case scenario RC 16: Dispersion analysis based on the worst case scenario (max CO_2 flow)
1.5.2		Leakage of flammable refrigerant	- Valve, flange leaks - Pressure or thermal stress - Static electricity - Material incompatibility - Impurity effect / corrosion	-Fire or explosion risk -Health hazards to crew -Environmental pollution	-Gas detection in the deckhouse -Regular inspection and maintenance -Use of compatible materials	2	3	3	3	M	RC 17: Safety ventilations requirements to ensure proper air exchange in compartments as per IGF code.

ID	Guideword	Major cause	Subsequent causes	Potential consequences	Existing or planned safety measures	F 1	Sp 1	Sa 1	Se 1	R 1	Proposed additional safety measures (recommendations)
			- Loss of performance at purification stage		- Gas detection in the deck house						
1.5.3	Performance degradation	Clogging	-Dry ice formation in the liquid lines -Solidification of hydrates -Methane traces	-Reduced system efficiency -Potential damage to equipment -Pressure increase	- Regular cleaning and maintenance - Proper cleaning/removal of debris during installation -Pressure monitoring -Proper ESD philosophy	3	1	2	2	M	RC 18: Use of anti-clogging agents
1.5.4	Fire	Use of flammable refrigerants (e.g., ethylene)	Same as 1.5.2			2	3	3	3	M	
1.5.5	Loss of system	Liquefaction plant failure	-Human error -Extreme weather conditions -Equipment malfunction -Control system errors	-System shutdown -Increase emissions -Potential damage to equipment	-Bypass of the system - ESD philosophy in place	2	1	2	2	L	RC 19: Pressure could be controlled in the stripper, making the need to bypass the absorber column not necessary -RC 36: Crew to undertake relevant training and be familiarized with procedures for human error prevention around the OCCS system installed onboard

ID	Guideword	Major cause	Subsequent causes	Potential consequences	Existing or planned safety measures	F 1	Sp 1	Sa 1	Se 1	R 1	Proposed additional safety measures (recommendations)
1.5.6	Less CO_2	Less CO_2 in the incoming stream	Carriage of water	-Reduced efficiency of the system -Malfunction/Damage of the liquefaction unit	-Cooling of CO_2 stream -Humidity/dew point sensors -Pressure monitoring -ESD philosophy	1	1	2	2	L	
1.5.7	Leakages	Piping downstream the liquefaction plant	Material cracking , pipe Ductile fracture Material defection construction	-Asphyxiation -Skin exposure	-Proper materials -Gas detectors -PPE gas detection portable	2	3	2	2	M	RC 7: Leakage detectors in the drip trays and where leakages are more likely to occur RC 20: Welded connections, flange connections to be equipped with spill protection RC 21: NDT requirements - leak test requirements RC 22: Stress and fatigue analysis for subcooled liquid flows RC 16: Dispersion analysis based on the worst case scenario (max CO_2 flow)
Node 1.6:	**Design: Storage**										
1.6.1	Leakages	Release of pure CO_2	-Release of CO_2 straight out of the tank -Leakages in flanges or valves	-Release of CO_2 into the environment -Health hazards -Loss of emissions	-Gas detectors -PSV systems - Two PRVs per tank - System to work as intended	3	3	2	3	M	RC 23: Regulatory framework uncertainty in IGF and IGC in LCO_2 tank system (to be further studied)

ID	Guideword	Major cause	Subsequent causes	Potential consequences	Existing or planned safety measures	F 1	Sp 1	Sa 1	Se 1	R 1	Proposed additional safety measures (recommendations)
				reduction performance - Material brittleness due to localized cooling	with two PRVs with no ice formation (to be proved)						
1.6.2	Loss of containment	Corrosion	-Improper sizing of materials	-Static electricity -The release may develop into a cloud formation	regular monitoring and maintenance purification of CO_2 stream	2	2	3	3	M	RC 4: Corrosive-resistant materials (high grade steel)
1.6.3		Cracks	Excessive loads	-Static electricity -The release may develop into a cloud formation	-Tank sadle fatigue analysis	1	2	3	3	L	
1.6.4		High pressure	-Excessive vapor phase in the tank -Loss of refrigeration	-Static electricity -The release may develop into a cloud formation	-Pressure relief system -Holding time of Type C tanks	2	2	3	3	M	RC 37: To examine redundancy options of the BOG management system (associated with containment system type and capacity, complexity, positioning of the tank and pressure regime low pressure). It should be noted that the continuous operation of the system is not a requirement
1.6.5	Low pressure	Valve failure	PRV stucks open	Dry ice formation	-Low pressure alarm with shut down -Pressure monitoring	1	2	2	3	L	

ID	Guideword	Major cause	Subsequent causes	Potential consequences	Existing or planned safety measures	F 1	Sp 1	Sa 1	Se 1	R 1	Proposed additional safety measures (recommendations)
1.6.6	Level	LCO_2 storage tanks overfilling	-Uncontrolled operation of liquefaction plant	-The release may develop into a cloud formation	-Level sensors (with sufficient redundancy) -Shut down system activation -Holding time calculation for tanks	2	2	3	3	M	RC 24: Operational optimization of the system RC 25: Voyage planning to take into consideration the amount of LCO_2 to be stored during the voyage and until the next LCO_2 offloading
Node 1.7:	**Design: General layout**										
1.7.1	Stability	Lack of stability and seakeeping ability of installation onboard	-Positioning of systems -Ship motions	Capsizing or loss of vessel stability	-Stability calculations -Ballast adjustments	2	2	4	3	M	
1.7.2	Leakages	Gas leaks to ventilation systems or confined spaces to neighbouring compartments	-Point is covered above	Health hazards to crew, potential explosions	Adequate separation and isolation of systems gas detection systems	2	2	2	2	L	
1.7.3	Weight	Additional weight of OCCS components and storage tanks	- Improper weight distribution onboard vessel - Impact on trading / cargo carrying capacity	-Impact on trading (potential deadweight reduction) - Structural stress, reduced fuel efficiency	-Weight distribution analysis -Structural reinforcement	2	1	4	3	M	
Node 2:	**Operation: Voyage**										
2.1	Exhaust gas high hazardous components	Acid gas HC, Methane MEA leaks leaving the absorber	Covered by Nodes 1.1.1 (pre-treatment stage), 1.2.1 (absorber leakages), 1.2.6 (performance degradation / gas impurities)							M	

ID	Guideword	Major cause	Subsequent causes	Potential consequences	Existing or planned safety measures	F 1	Sp 1	Sa 1	Se 1	R 1	Proposed additional safety measures (recommendations)
2.2	Chemicals	Leaks from chemical treatment components	Covered by Nodes 1.2.1 (absorber leakages)							M	
2.3	Leakages	Release of pure CO_2	Covered by Nodes 1.4.1 (releases of CO_2 gas) & Nodes 1.5.7 (releases of CO_2 liquid)							M	
2.4	Pure CO_2 Containment	Mechanical Damage	Covered by Nodes 1.6.2 (Containment loss due to corrosion) & Nodes 1.6.3 (Containment loss due to high pressure) & Nodes 1.6.4 (Containment loss due to external factors)							M	
2.5		Environmental Exposure								M	
2.6		System failures								M	
2.7		Fire or explosion								M	
2.8		- Ambient or low temperature conditions - Potentially High Pressure								M	
2.9		Corrosion								M	
2.10	Contamination of CO_2	Solvent Degradation	Covered by Nodes 1.2.2 & 1.5.6							M	
2.11		Incomplete Gas Separation								M	
2.12		Contaminated Feed Gas								M	
2.13		Carryover of Solvent Droplets								M	
2.14	High Pressure	LCO_2 Storage tanks overpressure	-Sloshing	Storage tank damage	-Location of the tank to be considered at design stage -Additional forces to be considered at tank supports -Finite element analysis for the tank	2	1	3	2	M	RC 26: Structure and fatigue analysis to take sloshing effect into consideration

ID	Guideword	Major cause	Subsequent causes	Potential consequences	Existing or planned safety measures	F 1	Sp 1	Sa 1	Se 1	R 1	Proposed additional safety measures (recommendations)
2.15		LCO_2 storage tanks overfilling	Covered in 1.6.6							M	
2.16	High temperature	Low flow Reboiler	Covered in 1.1.4, 1.1.5, 1.2.5, 1.3.3							M	
2.17	Loss of system	Backpressure in CO_2 capture system	Covered in 1.1.6, 1.2.7, 1.3.6, 1.5.5							M	
2.18		Blackout, total loss of power								M	
2.19	Level	LCO_2 storage tanks overfilling	-Uncontrolled operation of liquefaction plant	-The release may develop into a cloud formation	-Level sensors (with sufficient redundancy) -Shut down system activation -Holding time calculation for tanks	2	2	3	3	M	RC 24: Operational optimization of the system RC 25: Voyage planning to take into consideration the amount of LCO_2 to be stored during the voyage and until the next LCO_2 offloading
Node 3:	**Carbon off-loading process as standalone procedure**										
3A	**Cooling of hoses / lines (GCO_2 cooled)**										
3A.1	No flow	-Improper timing of the valves -Malfunction of gas valves at LCO_2 tank onboard (not allowing piston effect)	-Malfunction of equipment -Valve malfunction -Depressurized conditions on the liquid to gas interface inside the tank	-Prolonged or not proper cooldown procedure	-ESD link in place	2	1	2	1	L	RC 27: ESD philosophy to account for this phenomenon

ID	Guideword	Major cause	Subsequent causes	Potential consequences	Existing or planned safety measures	F 1	Sp 1	Sa 1	Se 1	R 1	Proposed additional safety measures (recommendations)
3A.2	Pressure less	-Depressurization	- Improper connections	-Prolonged or not proper cooldown procedure -CO_2 cloud formation	-Ensure pressure within the lines -ESD philosophy -ESD link in place	2	1	2	1	L	
3B	**Offloading**										
3B.1	No flow - liquid	-Leaks -LCO_2 pumps -Malfunction of gas valves at LCO_2 tank onboard (not allowing piston effect)	-Hose or transfer arm damage -Misconnections in the hose flanges -Pumps malfunction -No pressure differential	- Disruption of offloading process - Tank remaining with low CO_2 level - potential evaporation of remaining CO_2 BOG in tank - high pressure	-Emergency discharging procedures -Valve limit switch alarm	2	1	2	2	L	RC 28: Use of strainers in the manifolds RC 27: ESD philosophy to account for this phenomenon
3B.2	No flow - vapor	No vapor return from receiving facility during offloading	Failure of receiving facility equipment V/v malfunction	Tank pressure cannot be properly controlled	- Allow operation with free flow within accepted pressure limits - pressurization of the tank with inert gas in the initial stage of the offloading - vaporizer use in case of vapour return is not available - vapour return connected with receiving facility	3	1	2		M	- RC 27: ESD philosophy to account for this phenomenon RC 29: To prevent the return of contaminated vapor from the barge, the onboard LCO_2 tank will be pressurized. The liquefaction system should be operated to maintain the required tank pressure and ensure vapor containment.

ID	Guideword	Major cause	Subsequent causes	Potential consequences	Existing or planned safety measures	F 1	Sp 1	Sa 1	Se 1	R 1	Proposed additional safety measures (recommendations)
3B.3	Pressure less	Lower pressure in LCO_2 tank during offloading, down to critical pressure levels	-Excessive vapor removal from LCO_2 tank -Ambient temperature drop -Valve malfunction - Rapid Depressurization -Incorrect tank level measurement -Rupture of the hose	-Potential critical temperature in tank -Potential to exceed minimum design temperature of tank -Tank damage -Cloud formation at low levels close to the rupture	-ESD link in place -Depending on steel material (low grade): water curtain; drip trays; - ESD to be activated -SIGGTO guidelines for safe STS process operation; Safety corridors at port side -Vapor line connection to be connected and transferring vapor CO_2 during offloading	2	1	3	3	M	RC 30: Low pressure alarm and if the pressure in the LCO_2 falls down to 0.5 bar above triple point shut-down/ESD RC 31: CCTV at the manifolds for monitoring RC 32: Guarantee of the vapour return conditions of high purity at land side
3B.4		Fail in vapor return line	As per node 3B.2							M	
3B.5		Clogging	As per node 3B.1							M	
3B.6	Flow reverse	-Backflow of LCO_2 to tank	-Improper condition in receiving tank, or equipment malfunction from receiving facility -Non-return Valve malfunction	Damage to piping (low pressure at manifolds)	-Non-return valve in the discharge system -Pressure differential could not allow for this to occur -Difference in the height	1	2	3	3	L	

ID	Guideword	Major cause	Subsequent causes	Potential consequences	Existing or planned safety measures	F 1	Sp 1	Sa 1	Se 1	R 1	Proposed additional safety measures (recommendations)
					between LCO_2 tank and manifolds						
3B.7		- pressure less (see above)	As per node 3B.3							M	
3B.8	High pressure	Excessive Pressure in LCO_2 tank	-Malfunction of cooling system -Fire	Also covered in Node 1	-Firefighting equipment in place -Spray cooling system inside of the LCO_2 storage tank	2	2	3	3	M	RC 33: Water spray system should be provided for the LCO_2 tank if there is combustible cargo for the vessel in question
3B.9	Level	-Overfilling of receiving tank-->leaks	Not further examined, as it is more relevant to shore side							L	
Node 3C:	**Drain/Purging of lines**	-Depressurization	-Improper/inefficient draining (lack of passive/active systems for draining; lack of sufficient heating to vaporize the remaining LCO_2) of LCO_2 back to the tank -Improper purging of CO_2 from the manifolds flange	-Remaining liquid in lines Exposure of the personnel to CO_2	-Need for extra pumps along the process -PSVs for safe return to tank of the remaining LCO_2 - Follow normal procedures for Liquefied gas transfers	2	3	2	2	M	
		-Static electricity	-Creation of static electricity in the hose due tohigh		-No high velocity (not further	1	1	1	1	L	

ID	Guideword	Major cause	Subsequent causes	Potential consequences	Existing or planned safety measures	F 1	Sp 1	Sa 1	Se 1	R 1	Proposed additional safety measures (recommendations)
			velocity friction between liquid and hose		examined) -Bonding						
Node 4:	**Off-loading simultaneous to (Ship to ship)**										
4.1	SIMOPS - Cargo discharge operation	-Human error -Terminal restrictions for SIMOPS (depending on the ship type)	-Limited personnel -Commercial risks	-Operational disruption -Accident	- Risk assessment / SIMOPS analysis -SIGTTO requirements	2	3	2	2	M	RC 34: Safety zones; limitations of operation boundaries (no other processes encroach to the areas of LCO_2 discharge)
Node 5:	**Gas-freeing**										
5.1	Improper/inefficient dT/dt temperature	Human error Improper valve position	-Wrong flows	-Cracks -Thermal stress in tank	-Automated valve control	1	2	3	2	L	- RC 35:Operation manual to cover this and be available during the procedure -RC 36: Crew to undertake relevant training and be familiarized with procedures for human error prevention around the OCCS system installed onboard
5.2	High pressure	Clogging	-Not probable							L	
5.3	Low flow	Ineffective piston effect Improper measurement	-Insufficient density differential; Viscosity effect -Potential delays / emissions in the case of dilution	-Exposure to hazardous environment	-CO_2 sensors as PPE -Oxygen sensors before maintenance works (as per	2	2	2	2	L	- RC 35:Operation manual to cover this and be available during the procedure

ID	Guideword	Major cause	Subsequent causes	Potential consequences	Existing or planned safety measures	F 1	Sp 1	Sa 1	Se 1	R 1	Proposed additional safety measures (recommendations)
					normal gas free process)						
5.4	Remaining heel	-Inefficient heating process -Not respecting the negative suction for the pumps	- Presence of liquid that has not vented -Damage to the pumps (cavitation)	-Process delays	-Level sensors / temperatures (H,M,L) transmitters (pump column/Class requirement)	2	1	2	1	L	- RC 35:Operation manual to cover this and be available during the procedure
Node 6:	**Lay up/idle**										
6.1	Gas CO_2 Leaks	Improper isolation or securing of Containment system	-Valve malfunction -Human error -Incomplete procedures	-Environmental impact -Health hazard	-Gas freeing should take place (in case of cold lay up)	2	1	2	2	L	
6.2	LCO_2 leaks	Improper isolation or securing of Containment system	Covered in 6.1							L	
6.3	Chemical leaks	Prolonged exposure to marine environment	Covered in 1.2.2							M	

Appendix I RoPax and Feeder Container HAZID/HAZOP log – mineralization OCCS

Table 0-34 HAZID/HAZOP log for RoPAX and feeder container vessel – mineralization OCCS

ID	Guideword	Major cause	Subsequent causes	Potential consequences	Existing or planned safety measures	F 1	Sc 1	Se 1	Ss 1	R 1	Proposed additional safety measures (recommendations)
Node 1.1:	**Design: Absorber**										
1.1.1	Leakages	Leaking of exhaust stream	- Wear & tear of valves / flanges - Rupture of piping or bellows - Exhaust gas backpressure - Material failure - Improper assembly - Thermal expansion due to exhaust gas temp	- Exhaust gas leaking into cargo areas/engine casing - Blocking of the exhaust from the engine - stopping of engine - High Temperature due to exhaust leak - Asphyxiation (CO_2, NOx, SOx)	- Proper design (adequate design of piping system) and installation procedures - Regular inspection/maintenance of valves/flanges - Temperature sensors, with fail to safe - Pressure sensors, which triggers opening of valve from OCCS to open to funnel (fail to safe) - Exhaust gas fan is stopped -> exhaust bypasses OCCS system - Cooling of exhaust gas (relevant to the inlet of the fan)	2	2	3	3	M	RC1: Proper water handling/monitoring in scrubber (wet type) R2: Existence of inspection hatches

ID	Guideword	Major cause	Subsequent causes	Potential consequences	Existing or planned safety measures	F 1	Sc 1	Se 1	Ss 1	R 1	Proposed additional safety measures (recommendations)
1.1.2		Leaking of liquid solution (wet type only)	- Assembly errors -Material failure - Clogging leading to liquid solution overflow - Resonance vibration, fatigue cracking, erosion	- Exposure to chemicals causing toxicity (severity depends on the chemical agent used) - Operational inefficiency of the system - Liquid flowing to other decks (in case of ferry: exposure of passengers to working fluids, in case of feeder container accumulation of liquids in the cargo holds) - Possible cracks on connections/flanges	- Compatibility of materials with chemical agents - Leak detection in drip trays below tank connections and components - Leak detection alarms - Level sensors (fail to safe) - Regular Inspections as part of the plan - Use of PPE depending on the chemical agents used (DNV rules: PPE required based on MSDS) - Eyewash and showers - Sensor monitoring during testing (like VIBR class notation. mm/s below thresholds)	2	2	3	3	M	
1.1.3		Leakage of effluents or working media (dosing system of wet type)	- Clogging of dosing mechanism - Valve maloperation - Equipment malfunction - Control logic faults - Human error	- System operational inefficiency - Exposure of passengers/crew to working fluids - Corrosion	- pH monitoring - Control logic covering the differential in levels of the system - Regular inspections	2	2	2	3	M	RC3: Leak detection under components and piping (high-high bilge)

ID	Guideword	Major cause	Subsequent causes	Potential consequences	Existing or planned safety measures	F 1	Sc 1	Se 1	Ss 1	R 1	Proposed additional safety measures (recommendations)
1.1.4	High temperature	Heated pipes and containers (tanks)	- Hot flue gas from exhaust - Fire hazard (into the absorber in case of dry type) - Exposure to the hot flue gas - Auto ignition of material under specific conditions - Melting of materials (e.g. when Economizer is not working)	- Burns to personnel - Potential Loss of equipment	- Existence of temperature sensors/monitoring/ alarms - Warning signs prior the entry into hazardous areas - Cooling of the exhaust gas - Use of insulating materials - Existence of exhaust gas by-pass	2	2	2	2	L	
1.1.5		Flue gas exceeding design temperature at inlet	- Continuous operation of engine at high loads - Failure of Economizers - Soot fire	Covered in 1.1.4	- Partially covered in 1.1.4, with additional measures: - Regular cleaning of the soot blowers - Monitoring of flow and back pressure of the exhaust gas - Soot removal as part of the design	2	2	2	2	L	RC4: Proper consideration during the design in case of absence of Exhaust Gas Economizer
1.1.6	Loss of system	Pre-treatment stage failure	covered in the above nodes	covered in the above nodes	covered in the above nodes					M	
1.1.7		Fire from external reason	Fire in the absorber in case of flammable material	Loss of equipment/burns	Positioning at design stage - securing of component					M	
Node 1.2:	**Design: Liquid Medium Treatment Unit (Wet Type)**										

ID	Guideword	Major cause	Subsequent causes	Potential consequences	Existing or planned safety measures	F 1	Sc 1	Se 1	Ss 1	R 1	Proposed additional safety measures (recommendations)
1.2.1	Leakage	Effluent leaks - Seal or gasket failure on pumps or piping.	- Corrosion (SOx components, CO_2) - Possible over-pressure in lines due to valve misoperation or blockage - Mechanical damage to pipes and components - Ship vibrations & motions - Improper reassembly after maintenance	- Unwanted agents exposure to personnel/passengers (chemical exposure) - Contamination of onboard areas - When the leakage is on hot surfaces, the liquid medium can turn into poisonous gases - Performance degradation	- Corrosion resistance materials - Shield hot surfaces where leakages might occur - Leak detection in drip trays - Warning sign into hazardous areas	3	2	3	3	M	RC3: Leak detection under components and piping (high-high bilge) RC5: Separated location of the components
1.2.2	Performance degradation	Incorrect separation - Malfunction of solid-liquid separation equipment.	- Clogging - Incorrect dosing - Sensor failure	- Loss of system - Mechanical damage to the pump - Overflow - flooding of the treatment unit	- Preventive Maintenance of separators and cleaning schedules - Monitoring of flow	2	2	2	2	L	RC6 Redundancy monitoring of the dosing equipment
1.2.3		Pump failure or clogging due to solids	- Inadequate filtration before pump - Wear of the pump components	Mechanical damage to pump	- Control as per design conditions of the sediment tank - Pressure sensors installed before and after filters - Monitoring of pump condition - Proper training and procedures of dosing (human factor - crew)	2	2	2	2	L	RC7: Examine the need for component redundancy

ID	Guideword	Major cause	Subsequent causes	Potential consequences	Existing or planned safety measures	F 1	Sc 1	Se 1	Ss 1	R 1	Proposed additional safety measures (recommendations)
1.2.4	Corrosion	Aggressive chemical environment (OH^- ions).	- Incompatible materials: structural failure - Lack of flushing	- Unwanted agents exposure to personnel/passengers (chemical exposure) - Accumulation of the unwanted ions	- Proper control and flushing procedures of dosing - High non-corrosive quality material	2	2	3	3	M	
1.2.5	Loss of system	Complete failure of treatment unit.	- External factor (e.g. outage) - Clogging - Mechanical failure - Human error	- Performance degradation - Potential non compliance	- ESD of the system in place - Fail to safe logic	2	3	2	3	M	RC7 Examine the need for component redundancy
Node 1.3:	**Design: Dosing System for CaO and Hydroxides (wet type)**										
1.3.1	Performance	Incorrect dosing	Human error	- Overdosing -> corrosion - Underdosing -> poor performance	- Dosing control with fail safe - Monitoring the capture rate of the absorber (gas analysing pre & post) - PH monitoring	2	1	2	2	L	
Node 1.4:	**Design: Gas Piping**										

ID	Guideword	Major cause	Subsequent causes	Potential consequences	Existing or planned safety measures	F 1	Sc 1	Se 1	Ss 1	R 1	Proposed additional safety measures (recommendations)
1.4.1	Leakages	Release of CO_2 from the material	- Improper temperatures - Operations at conditions above normal (concentration, pressure, temperature)	- Dissociation of CO_2 from the sediment -> presence of CO_2 in the cargo area (ferry case) / cargo hold (feeder container) - Asphyxiation - Compliance risk	- Gas detection and alarms - Dedicated venting system with pressure relief valves - Temperature control - Quality of tank containers	2	2	3	3	M	RC8: Maintenance and inspection per analysed number of operations
Node 1.5:	**Design: Onboard Storage**										
1.5.1	Leakages	Dust generation during transfer	- Poor dust suppression systems in place - Dust up the funnel -> dust going into the atmosphere - Ship motion (potential contribution) - Improper loading of the absorber in the holding container - Uncontrolled filling process	- Respiratory hazards - Dust accumulation in machinery places / holds - Dust explosion - Environmental contamination	- Control of the transfer process - Maintain airborne dust well below the lower explosive limit (LEL) - Exhaust gas stream post treatment equipment (e.g. cyclons) - A-TEX requirements for the equipment	3	2	2	3	M	RC9: Optimized container removal in terms of logistic RC10: Keep all transfer and dosing operations fully enclosed
1.5.2	Level	Overfilling	- covered partially in node 1.5.1 - Lack of level monitoring systems	- covered partially in node 1.5.1 - Loss of integrity of the storage equipment	- covered partially in node 1.5.1 - Existence of proper filling procedures	1	2	2	2	L	

ID	Guideword	Major cause	Subsequent causes	Potential consequences	Existing or planned safety measures	F 1	Sc 1	Se 1	Ss 1	R 1	Proposed additional safety measures (recommendations)
1.5.3	Performance	Moisture ingress causing hardening or lump formation (mainly for dry scrubbers)	Moisture coming from exhaust or pretreatment stage	Reduced performance	- Accumulation of significant quantities of water are not expected	1	1	1	1	L	
1.5.4	Layout	Accessibility issues for maintenance and cleaning	Poor layout of design storage compartments	- Risk of injury - Hindrance of cleaning / inspection of the system	- Design of adequate space / clear access	2	1	1	2	L	RC11: Adequate platform/space for storage (unhindered operations)
Node 1.6:	**Design: General layout**										
1.6.1	Stability	Lack of stability and seakeeping ability of installation onboard	- Wrong position of the systems - Ship motions	- Increased accelerations - Loss of system/stability	- System position and stability analysis - All fixed weights included in the loading computer	2	3	3	3	M	RC12: New analysis/position of down flooding points taking into consideration the OCCS components/layout
1.6.2	Leakages	Dust or caustic mist ingress to ventilation systems or confined spaces to neighbouring compartments	covered from above nodes	covered from above nodes	covered from above nodes					M	
1.6.3	Leakages	Release of CO_2	covered from above nodes	covered from above nodes	covered from above nodes					M	

ID	Guideword	Major cause	Subsequent causes	Potential consequences	Existing or planned safety measures	F 1	Sc 1	Se 1	Ss 1	R 1	Proposed additional safety measures (recommendations)
1.6.4	Weight	Additional weight of OCC components and storage tanks	Covered by Node 1.6.1	Covered by Node 1.6.1	Covered by Node 1.6.1					M	RC12: New analysis/position of down flooding points taking into consideration the OCCS components/layout
Node 2:	**Operation: Voyage**										
2.1	Exhaust gas high hazardous components	Acid gas	Covered by Nodes 1.1.1 & 1.1.4	Covered by Nodes 1.1.1 & 1.1.4	Covered by Nodes 1.1.1 & 1.1.4					M	RC1: Proper water handling/monitoring in scrubber (wet type) R2: Existence of inspection hatches
2.2	Leakages	Leaks from chemical treatment components	Covered by Node 1.2.1	Covered by Node 1.2.1	Covered by Node 1.2.1					M	RC3: Leak detection under components and piping (high-high bilge) RC5: Separated location of the components
2.3	Contamination of CO_2	Contaminated Feed Gas	- Engine malfunction - Low quality fuel - high sulfur/metal content	- Non - compliance - Impact on mineralization quality	- Fuel quality monitoring/sampling - Proper design philosophy of the system - ESD system philosophy in place	2	2	2	2	L	

ID	Guideword	Major cause	Subsequent causes	Potential consequences	Existing or planned safety measures	F 1	Sc 1	Se 1	Ss 1	R 1	Proposed additional safety measures (recommendations)
2.4	Overflow	Slurry overflow due to ship motion	Covered by Nodes 1.5.1 & 1.5.2	Covered by Nodes 1.5.1 & 1.5.2	Covered by Nodes 1.5.1 & 1.5.2					M	RC9: Optimized container removal in terms of logistic RC10: Keep all transfer and dosing operations fully enclosed
2.5	Dust exposure	During lime or carbonate handling	Covered by Nodes1.5.1	Covered by Nodes1.5.1	Covered by Nodes1.5.1					M	RC9: Optimized container removal in terms of logistic RC10: Keep all transfer and dosing operations fully enclosed
2.6	Ventilation failure	In chemical / storage areas	Fan or duct failure	Accumulation of unwanted chemicals	- CO_2 detectors - Design of storage tanks to consider the chemical agent	2	2	2	2	L	
2.7	Incorrect dosing	Hydroxides during voyage	Covered by Nodes 1.2.2 & 1.3.1	Covered by Nodes 1.2.2 & 1.3.1	Covered by Nodes 1.2.2 & 1.3.1					L	RC6 Redundancy monitoring of the dosing equipment
2.8	Loss of system	Blackout, total loss of power	Covered by Nodes 1.1.6 & 1.2.5	Covered by Nodes 1.1.6 & 1.2.5	Covered by Nodes 1.1.6 & 1.2.5					M	RC7 Examine the need for component redundancy
2.9		Backpressure in CO_2 capture system	Covered by Nodes 1.1.6 & 1.2.5	Covered by Nodes 1.1.6 & 1.2.5	Covered by Nodes 1.1.6 & 1.2.5					M	RC7 Examine the need for component redundancy
Node 3:	**Mineral off-loading process as standalone procedure**										

ID	Guideword	Major cause	Subsequent causes	Potential consequences	Existing or planned safety measures	F 1	Sc 1	Se 1	Ss 1	R 1	Proposed additional safety measures (recommendations)
3.1	Level	Overfilling of receiving tank	Poor monitoring of the process	Damage to equipment	- Process monitoring - Checklists/alarms present - Emergency response plans - Tank level monitoring	2	2	2	2	L	
3.2	Dust generation	During unloading of dry carbonate solids	Covered by Node 1.5.1	Covered by Node 1.5.1	Covered by Node 1.5.1					M	RC9: Optimized container removal in terms of logistic RC10: Keep all transfer and dosing operations fully enclosed
3.3	Mechanical failure	Transfer equipment breakdown	Lack of maintenance / monitoring of the storage containers	- Spillage - Asset loss - Non-compliance risk	- Frequent monitoring/maintenance checks of the storage containers - Double containment securing of CO_2 product	1	2	2	2	L	
3.4	Spillage	During transfer of solids	-Misalignment of hoses/pipes - Human error	- Spillover/contamination - Damage to asset	- Proper alignment checks - Crew training - Offloading procedure - Risk free connection of dedicated CCS containers - no extra requirements	1	1	1	1	L	
3.5	Confined space	Hazards during compartment entry	Covered by Node 1.5.4	Covered by Node 1.5.4	Covered by Node 1.5.4					L	

ID	Guideword	Major cause	Subsequent causes	Potential consequences	Existing or planned safety measures	F 1	Sc 1	Se 1	Ss 1	R 1	Proposed additional safety measures (recommendations)
Node 4:	**Off-loading simultaneous to (Ship to shore)**										
4.1	SIMOPS - Cargo discharge operation	Improper SIMOPS	- Insufficient personnel - Lack of communication	Safety incident between passenger and trailers with CO_2 by products	- SIMOPS plan in place - Proper crew allocation with clear roles	2	3	2	2	M	RC 13: Safety zones; limitations of operation boundaries (no other processes encroach to the areas of mineralized CO_2 discharge)
Node 5:	**Lay up/idle**										
5.1	Leaks	Prolonged exposure to marine environment	not a credible risk - high temperatures needed	not a credible risk - high temperatures needed	not a credible risk - high temperatures needed					L	

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