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Research article

Techno-economic and environmental assessment of Onboard Carbon Capture for maritime net-zero compliance

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ABSTRACT

The shipping sector faces mounting pressure to align with the International Maritime Organization's (IMO) revised greenhouse gas (GHG) strategy targeting net-zero emissions by 2050. Although zero- and near-zero (ZnZ) emission fuels may offer long-term solutions, their large-scale deployment is constrained by cost, infrastructure, efficacy and safety concerns. Onboard Carbon Capture and Storage (OCCS) systems may provide a transitional approach, and this study assesses the techno-economic and environmental feasibility of across four container vessel types powered by Marine Diesel Oil (MDO), liquefied natural gas (LNG), and methanol. Two OCC technologies—chemical absorption using monoethanolamine (MEA) and cryogenic separation—are evaluated in terms of energy demand, space requirements, lifecycle GHG emissions, and economic performance under the IMO's Net-Zero Framework. Results show that MEA-based systems offer the highest GHG reduction potential (up to 41.5 % for MDO) but at the cost of increased fuel consumption (15–30 %) and cargo capacity penalties (~10 %). Cryogenic systems enhance safety but are more energy-intensive due to reliance on auxiliary power. OCC-equipped vessels can meet IMO GHG intensity targets through 2035, particularly when combined with biofuels, and provide up to a 2.2-fold cost advantage over purchasing Remedial Units (RUs). Although not a permanent solution, OCC offers a practical bridge toward maritime decarbonisation. Deployment requires policy support, port and geostorage infrastructure, and further innovation in capture technologies and waste heat integration.

1. Introduction

Shipping is recognised as the most energy efficient mode of transport relative to its contribution towards global trade; however, it currently contributes to 2.9 % of global greenhouse gas (GHG) emissions (IMO, 2018). In response, the International Maritime Organization (IMO) has committed to achieving net-zero emissions from international shipping by around 2050 (IMO, 2023). The IMO's Revised GHG Strategy (2023) highlights the critical need for the adoption of ZnZ emission technologies as a central pillar of this decarbonisation pathway (Vakili et al., 2025a).

To accelerate the deployment of ZnZ technologies within the shipping industry, the IMO, during its 83rd session of the Marine Environment Protection Committee (MEPC 83), adopted the design of a comprehensive Net-Zero Framework. This framework forms the cornerstone of the IMO's midterm measures for reducing GHG emissions, with the Global Fuel Standard (GFS) as its central component. The GFS establishes progressively stringent limits on the GHG fuel intensity (GFI) of fuels, aiming to steadily reduce emissions over time (ABS, 2025) (See Table 1).

The regulation introduces a dual-tier compliance structure: the "Base Target," which provides a more flexible compliance pathway allowing ships to gradually adapt, and the "Direct Compliance Target," which sets more ambitious limits aligned with the IMO's net-zero trajectory (IMO, 2025). Vessels that fail to meet these GFI thresholds are required to purchase Remedial Units (RUs)—compliance credits designed to compensate for excess emissions, as outlined in IMO's draft implementation guidelines—whereas ships that exceed the standard can generate Surplus Units (SUs) that may be traded to offset the non-compliance of other vessels within the global fleet (DNV, 2025a).

The penalties for shipowners are directly linked to the GFI of the fuel used. Non-compliance with the Direct Compliance Target results in a

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Table 1
IMO's GFI reduction targets and emissions pathway (2028–2040).

	GFI Reduction factor compared to 93.3 gCO_2eq/MJ		GFI (g CO_2eq/MJ)	
Year	Direct	Base	Direct	Basic
2028	17.0 %	4.0 %	77.4	89.6
2029	19.0 %	6.0 %	75.6	87.7
2030	21.0 %	8.0 %	73.7	85.8
2031	25.4 %	12.4 %	69.6	81.7
2032	29.8 %	16.8 %	65.5	77.6
2033	34.2 %	21.2 %	61.4	73.5
2034	38.6 %	25.6 %	57.3	69.4
2035	43.0 %	30.0 %	53.2	65.3
2040	65.0 %	65.0 %	32.7	32.7

Tier 1 deficit, which can be offset by acquiring Tier 1 RUs priced at $ 100 per tonne of CO_2 eq. If a vessel fails to meet the Base Target, it incurs both a Tier 1 and a Tier 2 deficit. The Tier 2 deficit must be covered by Tier 2 RUs, priced at $ 380 per tonne of CO_2 eq, in addition to the Tier 1 RUs. Alternatively, compliance may be achieved by utilizing SUs generated by vessels operating below the Direct Compliance Target (DNV, 2025b) (See Fig. 1).[1]

To achieve zero-emission shipping, it is essential to enhance energy efficiency, implement advanced exhaust treatment systems, and adopt ZnZ emission technologies, including the use of alternative fuels. Among these, ZnZ fuels will eventually play a central role in achieving long-term emission reduction targets. However, their widespread deployment is constrained by an array of challenges including maritime industry indecision, limited production capacities, high costs, lack of sustainable infrastructure, doubtful energy and CO_2 reduction efficacies, logistic complexities, safety and regulatory concerns, and the need for specialised crew training (ICS, 2024; Vakili et al., 2025a). Consequently, the substantial contribution of ZnZ fuels to decarbonisation is not anticipated until after 2040 (Vakili et al., 2025b). Improvements in energy efficiency—though important—are predicted to deliver only relatively modest gains, accounting for 7 %–16 % of GHG reductions by 2030 and rising to 32 % by 2050, including measures such as speed reduction (DNV, 2023a).

While carbon capture and storage (CCS) technologies are being developed to mitigate land-based emissions (Al Baroudi et al., 2021), their application onboard ships have recently attracted significant interest. As of September 2024, carbon capture scrubbers had been installed on only 28 vessels (Offshore Energy, 2025), highlighting the growing consideration of OCC as a viable interim solution. OCC offers a promising means to reduce GHG emissions while maintaining the use of conventional fuels, thus enabling compliance with increasingly stringent environmental regulations (DNV, 2024). However, the large-scale adoption of OCC technologies depends on several critical factors, including their technological maturity, economic feasibility, trends in alternative fuel pricing, the evolution of carbon pricing, and the broader regulatory framework for zero-emission shipping (Zanobetti et al., 2024).

Considering gaps persist in cross-comparing the techno-economic–environmental performance of alternative OCC technologies across diverse fuel types and vessel categories, the present study assesses the technical, economic, and environmental feasibility of OCC systems in maritime applications. The novelty of this research lies in its comparative analysis of two distinct carbon capture technologies—cryogenic absorption and chemical absorption—applied to three fuel scenarios: Marine Diesel Oil (MDO), liquefied natural gas (LNG), and methanol. The analysis considers four container vessel types, with variations in installed engine power, cargo capacity, and voyage duration. In addition to quantifying the associated energy and space penalties for each case, this multifaceted approach represents a significant improvement on previous studies, which have typically focused on a single capture technology, fuel type, or vessel category.

Furthermore, this study conducts a Lifecycle Analysis (LCA) analysis for the OCC systems based on the feasibility of installing an OCC system on the case-study vessels. GHG emissions savings are evaluated against a baseline of heavy fuel oil (HFO) emissions, quantified at 93.3 g CO_2 eq/MJ, consistent with the GFI of fossil fuels in 2008 on a well-to-wake (WtW) basis, as defined by the 83rd session of the Marine Environment Protection Committee (MEPC) in April 2025. Finally, the cost of captured CO_2 and the penalties under the IMO's net-zero framework—evaluated through LCA results—offer a robust economic assessment of the carbon capture technologies examined.

2. Onboard carbon capture and storage

Onboard Carbon Capture applies post-combustion carbon capture processes to marine exhaust gases, with the captured CO_2 stored onboard for subsequent offloading at ports for geological sequestration or utilisation (Lee et al., 2021). Technology offers both short-to mid-term and long-term decarbonisation potential. In the short to mid-term, OCC can substantially reduce the emission intensity of conventional-fuel vessels and serve as an effective bridging measure towards compliance with forthcoming emission regulations. In the long term, the captured CO_2 can be reused as a feedstock for synthesising ZnZ emission fuels, contributing to the establishment of a circular carbon economy (Vakili et al., 2025c).

Early investigations into the maritime deployment of OCC technologies primarily focused on adapting post-combustion capture systems from stationary industrial settings to shipboard environments (Feenstra et al., 2019; Zincir, 2020). More recent studies have transitioned towards integrated techno-economic and environmental assessments, exploring the trade-offs between energy penalties, system efficiency, and lifecycle emissions under realistic operational conditions (Zanobetti et al., 2024). Comparative analyses of capture mechanisms—including chemical absorption, cryogenic separation, membrane-based processes, and solid sorbent systems—indicate that amine-based chemical absorption currently exhibits the highest Technology Readiness Level (TRL 7–8) for maritime applications, owing to its proven industrial maturity, established supply chain, and adaptability to low-pressure exhaust environments (DNV, 2024; Thiedemann and Wark, 2025). In contrast, cryogenic carbon capture technologies, with TRLs between 5 and 6, are increasingly recognised for their operational safety advantages, absence of hazardous solvents, and lower corrosion risk, although these benefits are offset by higher electrical energy demands and auxiliary power requirements (García-Mariaca and Llera-Sastresa, 2021).

Safety and operability considerations have consequently become central to evaluating the feasibility of OCC systems at sea. The degradation and corrosive properties of amine-based solvents, alongside potential toxicity risks, introduce significant operational and occupational safety challenges that necessitate continuous monitoring and closed-loop solvent regeneration (ABS, 2023). Conversely, cryogenic systems mitigate chemical hazards but introduce cryogenic safety risks associated with material brittleness at ultra-low temperatures and the need for advanced insulation, venting, and pressure-relief mechanisms (Font-Palma et al., 2021). Moreover, the performance of OCC systems has been shown to depend strongly on exhaust gas composition, waste-heat availability, and spatial integration constraints, all of which vary substantially across vessel typologies, propulsion configurations, and operational profiles (Damartzis et al., 2022; Lee et al., 2021). These insights underscore that the successful implementation of OCC requires not only technological optimiSation but also a system-based

[1] At MEPC 83, additional measures were approved, including the introduction of a new fuel standard for ships and a global greenhouse gas pricing mechanism. However, the adoption of the IMO Net Zero Framework was postponed for one year following the Extraordinary Session of the Committee held in October 2025.

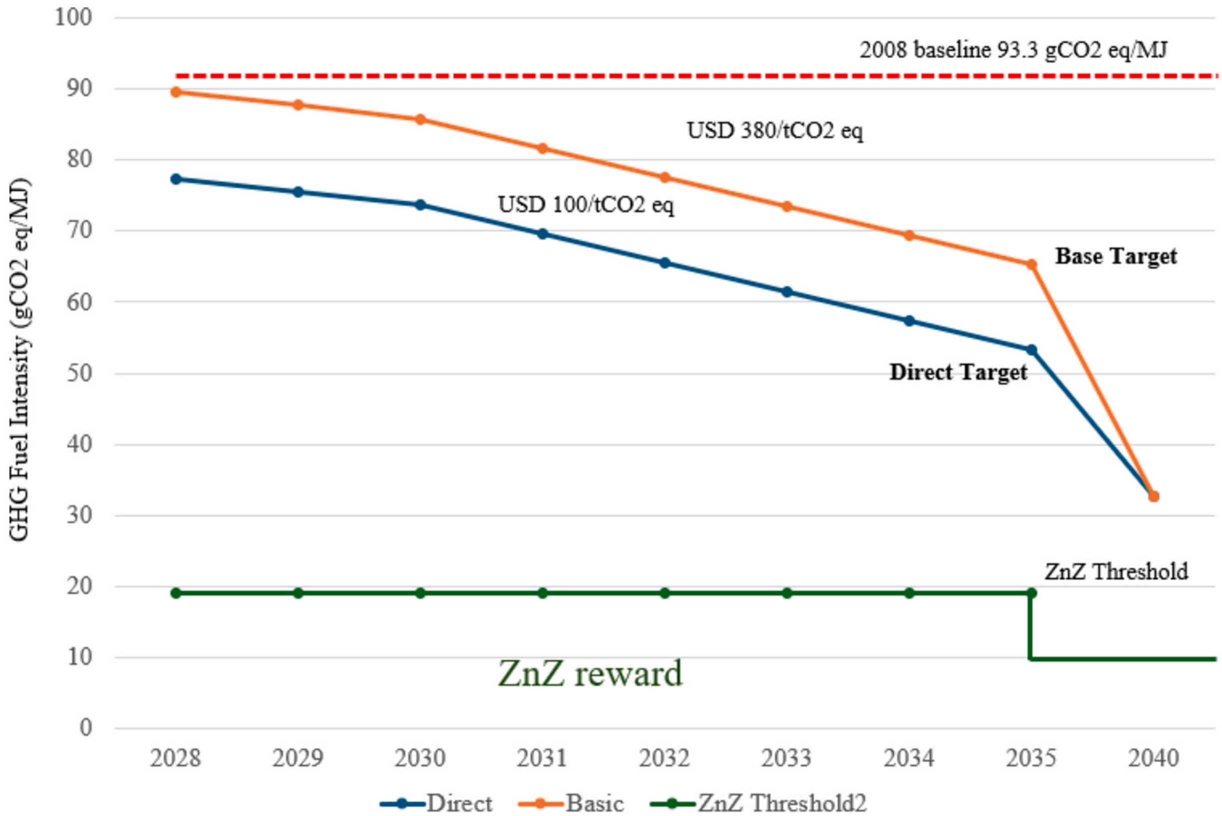

Fig. 1. Imo net-zero framework and GHG fuel intensity reduction pathways (2028–2040).

understanding of ship design, safety management, and energy integration within the broader maritime decarbonisation framework.

Building on these operational and safety considerations, recent research has increasingly focused on quantifying the environmental and emissions mitigation potential of OCC systems across different ship types and fuel scenarios. Studies have highlighted the significant potential of OCC systems in reducing GHG emissions from fossil fuel-powered shipping (Dubey and Arora, 2022). According to DNV (2024), emission reductions of up to 50 % are achievable when accounting for typical onboard energy penalties and CO_2 capture efficiencies and has the potential exists to reach 90 % (Tavakoli et al., 2024), zero emissions, and even net-negative if is combined with a 30 % share of renewable fuels and achieves a 70 % CO_2 capture rate (DNV, 2023b).

Although OCC may have strong environmental potential (Feenstra et al., 2019; Zincir, 2020), the regulatory framework, technical feasibility and overall sustainability in maritime applications remain under development and require further optimisation. The absence of a clear regulatory framework regarding the creditability of captured emissions creates considerable commercial uncertainty for shipowners and investors (Risso et al., 2023).

Meanwhile, the viability of OCC deployment is shaped by several vessel-specific factors, including ship size, operational profile, trading routes, available machinery capacity for heat and power generation, and the physical space needed for system integration (DNV, 2024). Beyond these, technical challenges persist—most notably the energy penalty associated with operating the capture system, the complexity of installation, the requirements for onboard CO_2 storage, and the logistics of offloading the captured carbon ashore (Ahmed et al., 2025). To overcome the barriers, key trade-offs emerge between achieving high CO_2 capture rates and managing the increased fuel consumption and operational costs resulting from the system's energy demands (DNV, 2024). Evaluating this trade-off necessitates consideration of several interdependent variables, including the capital and operational costs of OCC, the carbon price under the IMO's GHG pricing mechanisms, and the market cost of ZnZ fuels (Vakili et al., 2025c). In addition, the logistics of transporting captured CO_2 from ships to permanent storage sites can be complex. This process requires specialised equipment, infrastructure, and adherence to strict safety and environmental regulations to ensure the secure and effective storage of CO_2 (Al Baroudi et al., 2021), with one notable operational challenge being the handling of CO_2 impurities. Based on the current IMO discussions, shipboard OCC may not always deliver the final high purity CO_2 required by pipelines and storage sites, and additional purification at reception facilities may be necessary depending on the technology and onboard conditioning processes.

2.1. Post combustion capture methods

The most relevant approach for conventional marine energy systems is post-combustion capture, which separates carbon dioxide from exhaust gases after combustion. Various post-combustion techniques include chemical absorption, membrane separation, and cryogenic separation (Dooley et al., 2021; Wang et al., 2017). Due to their prominence in OCC applications, this study focuses on chemical absorption and cryogenic separation. Membrane-based absorption and other technologies are excluded from consideration due to their lower technology readiness levels (Khalilpour et al., 2015; Thiedemann and Wark, 2025).

Chemical absorption with amine solvents is one of the most advanced options, with a long history of use in onshore applications (DNV, 2024; Lawal et al., 2010). The technology is well-suited for OCC applications, given its high TRL and its demonstrated potential to effectively capture CO_2 from low-pressure exhaust streams with low CO_2 concentrations containing various impurities (DNV, 2024). During chemical absorption, exhaust gases are scrubbed by a liquid solution,

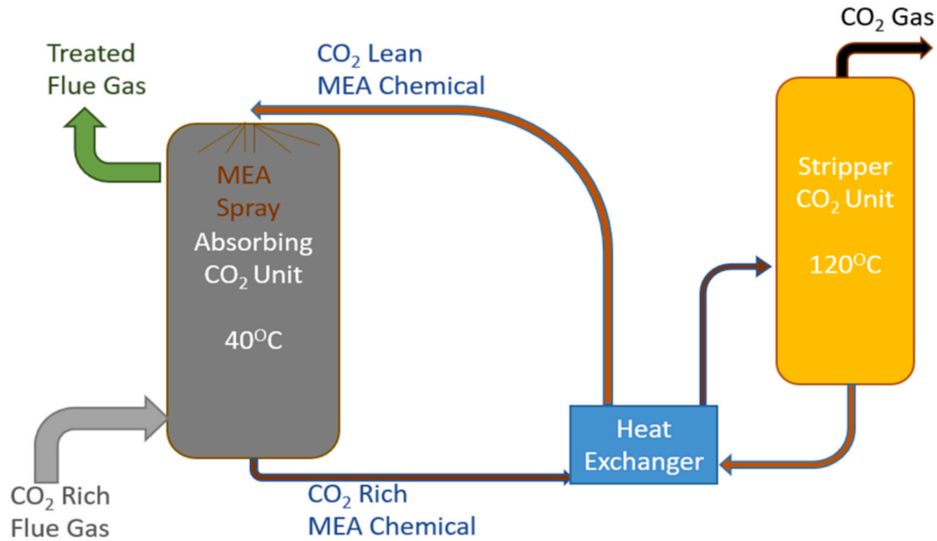

Fig. 2. System layout of Chemical Absorption Installation: A chemical, most commonly an amine-based solvent (typically MEA), is utilised to capture CO_2 by spraying on exhaust gases. The pregnant solvent is subsequently subjected to high temperatures in a "stripper" unit to release the CO_2 that is then liquified and stored (Wang et al., 2017).

typically containing amines,[2] to selectively absorb CO_2. The clean gas exits the system, while the CO_2-rich solution is either recirculated or regenerated—an energy-intensive step requiring 3–4 GJ/t CO_2 for conventional solvents or 2–2.5 GJ/t CO_2 for newer solvents (Damartzis et al., 2022). Captured CO_2 is treated and stored onboard as compressed gas, liquid, or solid, depending on the technology, until offloading (DNV, 2024) (See Fig. 2).

Published case studies, along with manufacturers' claims, indicate that carbon capturing capabilities can reach an effectiveness of up to 90 % of exhaust CO_2 (Einbu et al., 2022; MMC Maersk Mc-Kinney Møller Center for Zero Carbon Shipping, 2022). This makes capturing technologies appealing to ship owners and managers as an approach to complying with stricter emissions regulations. However, it is important to appreciate the impacts of OCC processes have in terms of additional energy demands and the reduced cargo carrying capacity of vessels (ABS, 2023). The techno-economic viability of chemical absorption systems is highly dependent on solvent type, space requirements, and process configuration (Feenstra et al., 2019; Ros et al., 2022). From both environmental and IMO regulatory perspectives, chemical systems have emerged as the most effective short-term solution for decarbonising shipping, offering the potential to improve the Energy Efficiency Design Index (EEDI) and the Energy Efficiency Existing Ship Index (EEXI) by up to 50 % when approximately 70 % of onboard CO_2 emissions are captured (Lee et al., 2021). This technology imposes minimal impact on ship volume (around 4 %) and incurs low capture costs (Negri et al., 2022). Integrating auxiliary equipment, such as gas turbines and electric heat pumps, can further improve CO_2 abatement by at least 5 % while maintaining capture costs of approximately €160/tonne of CO_2 (Luo and Wang, 2017; Visonà et al., 2024). Additionally, system optimisation to accommodate varying engine loads can significantly reduce both costs and space requirements (Oh et al., 2024). Recent OCC designs reduce energy demand and spatial footprint through advanced heat integration and modular compact units, while the adoption of solid sorbents and non-amine absorbents mitigates the use of hazardous solvents onboard (Ahmed et al., 2025).

Meanwhile, cryogenic carbon capture is an alternative promising technology to mitigate CO_2 emissions. The associated cost of OCC using cryogenic separation is claimed to be up to 70 % lower than that of conventional CO_2 absorption processes (PMW Technology, 2019). This reduction is contingent on factors such as the availability and cost of onboard utilities, as well as the quantity and composition of the exhaust gases treated (Willson et al., 2019). In the cryogenic separation, the exhaust gas stream is cooled until CO_2 condenses and then freezes (gaseous to liquid and then solid phase), thereby separating it from other gas constituents, such as nitrogen and oxygen, which require much lower temperatures to solidify (Font-Palma et al., 2021). Impurities, including water, separate out at higher temperatures before CO_2. This process results in a CO_2 product of high purity, typically reaching up to 99.9 %, depending on the feed gas composition and process configuration (Baxter et al., 2019). Phase separation can be achieved through centrifuges but requires electrical power for both the cooling and compression units (See Fig. 3).

3. Methodology

To estimate the amount of energy required, interpreted as an additional energy penalty, to capture the emitted carbon dioxide from the exhaust, all case studies are examined through a time-domain-based model of operation, coded in Python, which follows a bottom-up approach that assesses the energy requirement to propel each vessel, and the subsequent consumption and emission for each fuel selected. The same model includes the capture, conversion of state (to liquid or solid), and storage processes of the carbon dioxide funnel emissions onboard. Fig. 4 illustrates the analytical model employed to estimate the energy sacrifice associated with OCC system, while accounting for the diverse characteristics of each fuel type in our analysis.

3.1. Vessel case studies

Four case studies are examined, with three container vessels of different cargo capacities and power demands, as well as voyage distances (See Table 2 and Fig. 1 in the annex). For each vessel, three fuel options are considered; MDO, methanol and LNG (See Table 3). For each, the total voyage fuel consumption is calculated, which includes the additional energy required to capture the consequent emissions, as a proportion to the energy required for completing the trip. The power

[2] In this study, only the MEA solvent dissolved in an aqueous solution, will be considered as it is amongst the most effective and studied chemical absorbents in the industry (Chai et al., 2022).

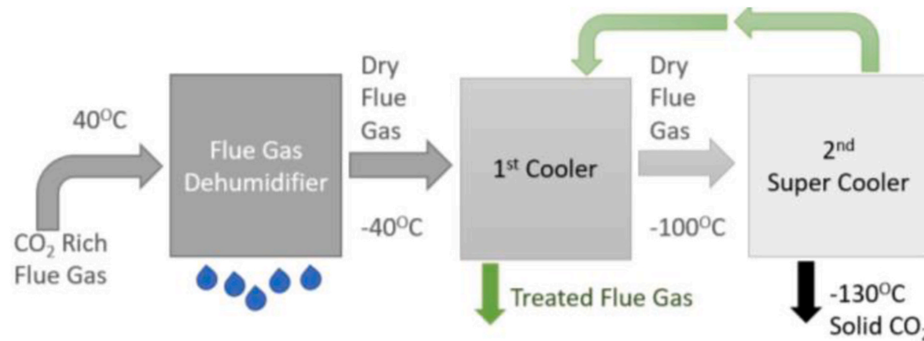

Fig. 3. Cryogenic carbon capturing process diagram: The incoming flue gas is super-cooled through multiple heat exchangers, essentially solidifying CO_2 which falls on a conveyor-belt mechanism and then is transported for storage (Font-Palma et al., 2021).

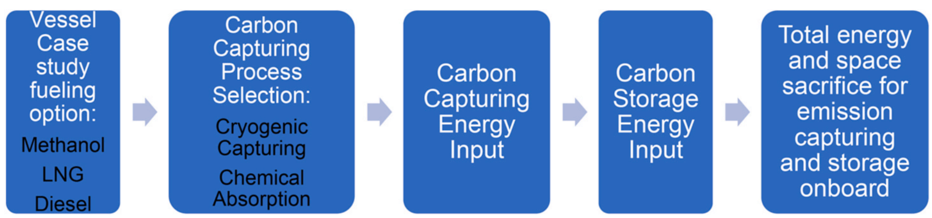

Fig. 4. Model analysis for estimating energy sacrifice of CCS.

Table 2
Container vessel specifications for various sizes, installed power, subsequent speed and trip. duration, to cover the wide spectrum of container ship fleets in shipping (MAN Energy Solutions, 2024).

Case Study	Container Vessel Type	Installed Power Output (MW)	Average speed (kts)	Voyage duration (days)
A	Small feeder – 400 TEU	2.5	12	3
B	Panamax – 3800 TEU	24	19	3
C	Panamax – 3800 TEU	24	19	15
D	Ultra Large Container Vessel (ULCV) - 20,000 TEU	64	20	15

requirements for propulsion, are based on realistic power profiles acquired from equivalent vessels, as well as data gathered from towing tank tests carried out at the University of Southampton, appropriately scaled for each container ship (Manias et al., 2024).

3.2. Powertrain operation

The total fuel consumption and emissions of each fuel and vessel type were calculated using the power demands, based on engine test data from dual fuel generator sets running on MDO and LNG. These were then converted to a methanol combustion equivalent through a dynamic Python simulation, developed to estimate emissions and performance data in large ship engines, where data are not publicly available. The same model can be adjusted accordingly to match different engine properties and fuels (Manias et al., 2024). Theoretical Otto 2-Stroke thermodynamic cycle is used to calculate the total consumption and CO_2 eq emissions, whilst being ignited through MDO pilot fuel injection. This is standard industry practice (Svanberg et al., 2018; MAN Energy Solutions, 2025) and is also applicable to LNG combustion. It is important to note that methanol has a lower flame temperature during combustion, whilst it also absorbs heat from its surroundings during vaporization during the compression phase. Although these effects could boost an engine's thermal efficiency, for the purposes of this study it is assumed that overall thermal and mechanical efficiencies remain unchanged (Tol and Bosklopper, 2020).

Fig. 5 shows the methanol combustion results in terms of the expected fuel consumption per useful work output (g/kWh), as well as the variation of pilot fuel utilisation against load, based on available literature (Ning et al., 2020). The same figure shows the expected percentage of methanol substitution with diesel with respect to the load the engine is subjected to, where the lower the load, the higher the energy contribution from diesel. Moreover, due to the lower specific energy density of methanol compared to diesel, at higher loads, fuel consumption, increases due to the higher contribution of methanol. For each of our respective fuelling scenarios, it is important to characterise and quantify the exhaust gases in terms of the carbon content, mass flow and the variation in temperature between the different fuels due to their different combustion characteristics.

The same approach has also been used for the LNG fueling scenario, although the pilot fuel requirements are significantly lower, and the specific energy density of LNG is more than twice that of methanol (Fig. 6).[3]

[3] As shown in Figs. 5 and 6, the specific fuel consumption (SFC) decreases with increasing engine load up to approximately 70–80 %, after which a modest rise is observed. This trend reflects the characteristic efficiency curve of large marine engines, where higher loads improve combustion stability and thermal efficiency until excessive in-cylinder temperatures, incomplete air–fuel mixing, and elevated mechanical losses begin to offset these gains. The sharper increase in SFC for methanol between 50 % and 100 % load results from its lower heating value and reliance on diesel pilot fuel, which affects overall energy balance. Similarly, the LNG-fuelled engine shows an increase in SFC beyond 70 % load due to mixture enrichment and reduced volumetric efficiency. These results align with published dual-fuel engine data (MAN Energy Solutions, 2024; Wärtsilä, 2023) and account for both 2-stroke diesel and 4-stroke Otto-cycle operating modes, which collectively influence the observed efficiency characteristics.

Table 3
Key properties of main fuels examined. (Verhelst et al., 2019; Baykara, 2018).

Fuel Type	MDO	LNG	Methanol
ρ (kg/m[3])	890	440	780
Lower Calorific Value (LCV) (MJ/kg)	42.8	50	19.9
Volumetric Energy Density (MJ/L)	38	22	15.6
Boiling point (°C)	60	−163	64.7
Flammability limits (Air conc. [% v/v])	1.3–6	5–15	6–36.5
Ignition temp. (°C)	350–380	537	433
CO_2 to Fuel mass ratio	3.2:1	2.75:1	1.375:1
Other harmful emissions	NO_x, PM	CH_4 (x 30 in CO_{2e}), NO_x	NOx, Formaldehydes

CO_2 concentration in the exhaust gas (dimensionless), and 0.15 represents the typical CO_2 loading capacity of MEA (kg CO_2/kg MEA).[4] This equation quantifies the required solvent flow rate to ensure effective CO_2 capture, based on the exhaust gas CO_2 concentration and the solvent's absorption capacity (Dugas and Rochelle, 2009).

The energy input required for heating the gas or solvent streams is calculated using two alternative expressions:

$$\dot{Q}_{in} = \frac{\dot{m}^* \, C_p{}^*(T_{in} - T_{out})}{\eta_{thermal}}, \text{ in } \frac{kJ}{kg.S} \quad (2)$$

where $\dot{Q}_{in}$ in is the energy input rate per kilogram of CO_2 captured(kJ/kg·s), $\dot{m}$ is the mass flow rate (kg/s), C_p is the specific heat capacity (kJ/kg·K), T_{in} and T_{out} are the inlet and outlet temperatures (K), and $\eta_{thermal}$ is the thermal efficiency of the system (dimensionless). This formulation estimates the energy needed to raise the temperature of the gas stream, accounting for system inefficiencies.

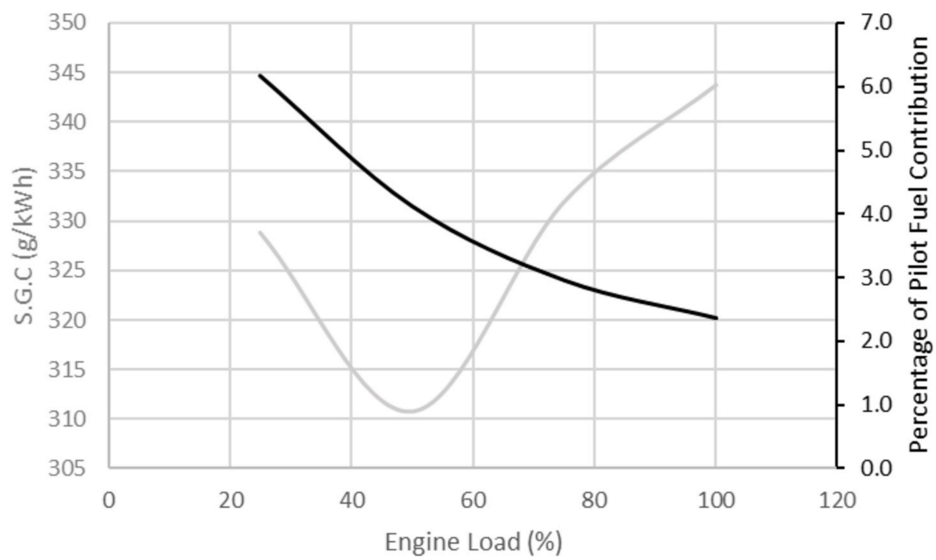

Fig. 5. Pilot fuel variation depending specific gas (methanol) consumption against load.

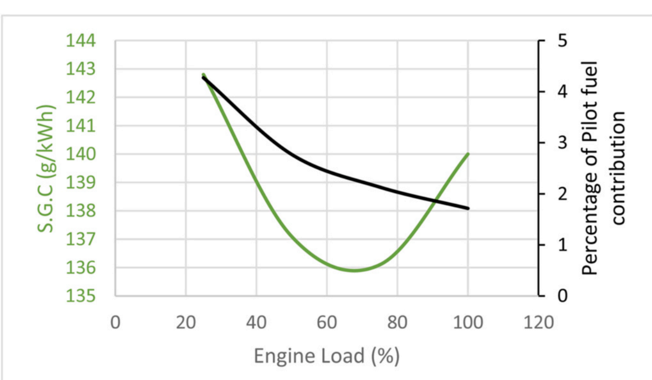

Fig. 6. Pilot fuel variation and specific gas (LNG) consumption against load.

Alternatively, when enthalpy changes better represent the energy requirement:

$$\dot{Q}_{in} = \frac{\dot{m}_{CO2}{}^* \, (h_{in} - h_{out})}{\eta_{thermal}}, \text{ in } \frac{kJ}{kg.S} \quad (3)$$

where $\dot{m}_{CO2}$ is the mass flow rate of captured CO_2 (kg/s), and h_{in} and h_{out} denote the specific enthalpies at the inlet and outlet, respectively (kJ/kg). This formulation is particularly relevant for processes like solvent regeneration or CO_2 compression, where phase changes or other enthalpy-related effects contribute to the energy balance.

In both capturing processes considered, exhaust gases are assumed to be cooled to approximately 40 °C through water spraying techniques between the economizer exit and the capturing system entry. All resulting water condensates are removed from the exhaust stream. The associated energy consumption for condensate removal is negligible, consistent with established findings (Aziz et al., 2020) and thus omitted from the calculations. This framework enables an estimation of the dominant energy contributions—principally heating and solvent

3.3. Carbon capturing energy

The theoretical energy input requirements for the carbon capturing systems are calculated using three key equations:

$$\dot{m}_{MEA} = \dot{m}_{ex}{}^* \frac{C_{CO2}}{0.15}, \text{ in } \frac{kg}{S} \quad (1)$$

where $\dot{m}_{MEA}$ is the mass flow rate of the monoethanolamine (MEA) solvent (kg/s), $\dot{m}_{ex}$ is the exhaust gas mass flow rate (kg/s), C_{CO2} is the

[4] A working loading of 0.15 kg CO_2/kg MEA was assumed, representing the solvent's working capacity under the specified operational conditions, consistent with literature values for 30–35 wt% MEA solutions (Dugas and Rochelle, 2009; Lawal et al., 2010).

regeneration—required for carbon capturing processes in maritime applications.

3.4. Chemical process

In this method, the main energy consumption is in terms of heat. The following parameters are considered: the mass flow of CO_2-rich exhaust gases ($\dot{m}_{ex}$); the maximum amount of CO_2 absorbed per kg of aqueous MEA solution which is 0.150 kg (Dugas and Rochelle, 2009); the percentage of CO_2 in the exhaust that is dependent on the fuel source ($C_{CO2\%}$); the temperature change of the engine exhaust gas entering and exiting the economizer used for scavenging waste heat from the ship's engines (ΔT_{ex}); the heat exchange efficiency of the economizer and stripper unit (ηthermal; assumed to be 80 %); the mass flow of MEA within the chemical absorption unit required to capture 90 % of the CO_2 in the exhaust gases ($\dot{m}_{MEA}$); the specific heat capacity of CO_2-rich MEA solution, cpmea (4.2 $\frac{kJ}{kg.K}$); the temperature change required to release CO_2 from aqueous MEA laden with CO_2 within the absorber unit (+120 °C) and the absorber unit (+40 °C), ΔT_{MEA} (Chen et al., 2001).

3.5. Cryogenic process

When considering a cryogenic absorption approach, the main energy parameters relate to the power required to cool the exhaust gases and freeze CO_2. These parameters are: the mass of exhaust flow and the relative concentration CO_2 composition ($\dot{m}_c$); the specific heat capacity of exhaust gas, cpex (1.2 $\frac{kJ}{kg.K}$); the temperature change (ugh the dehumidifier (ΔT_{deh}); the specific heat capacity of dehumidified exhaust gas (cpex.d); and the total energy required for the change of state from gaseous to solid CO_2 at −130 °C, within the range of desublimation temperature range (Hoeger et al., 2021).

3.6. Waste heat recovery system

Thermal energy is required to drive the endothermic reaction of the MEA solvent to release CO_2. Although heat is considered as wasted energy, resulting from the combustion of fuels, this does not guarantee its abundance on board. To measure the amount of useful thermal energy that would allow for the development of high-pressure and temperature steam for internal heating, knowledge of the capacity and operating principles of the economizers employed on board is required (Theotokatos et al., 2020).

The final heat output is dependent upon the heat content of the exhaust. Different types of fuels employ different combustion principles which affect exhaust temperatures and mass flows, ultimately affecting the waste heat recovery capabilities of a system. Figs. 2, 3 and 4 in the annex show the exhaust flow characteristics of different fuels, specifically for the 25 MW vessel. Confidential engine test data have been provided by major engine manufacturers, but information across the entire power range examined (2.5–64 MW) is only available for the diesel and LNG fuelling scenarios. The exhaust mass flow can be scaled linearly (Wärtsilä, 2021) with the increasing power output for each vessel case study, assuming other exhaust properties and their dependence on engine load remain the same.

Published studies indicate that the heat release (in kJ) of methanol combustion is ~15 % less than that of diesel (Jamrozik et al., 2019; Hassan et al., 2021). This is also confirmed by consideration of equations (4)–(12):

$$\dot{m}_{in} = \dot{m}_{out} \tag{4}$$

$$\dot{m}_{inlet\ air} = \frac{P_{turbo} * V_{(enginedisplacement)}}{R * T_{Inlet}} * \frac{rpm}{120} \tag{5}$$

$$\dot{m}_{fuel} = \frac{\dot{m}_{inlet\ air}}{AFR} \tag{6}$$

$$\dot{m}_{exhaust} = \dot{m}_{fuel} + \dot{m}_{fuel} * AFR, \tag{7}$$

$$efficiency = \frac{\dot{m}_{fuel\ input} * LCV}{Power} \tag{8}$$

Assuming the methanol engine obtains the same efficiency as its diesel counterpart:

$$\dot{m}_{diesel} + \dot{m}_{diesel} * AFR_{diesel} = \dot{m}_{exhaustdiesel} \tag{9}$$

$$\dot{m}_{methanol} + \dot{m}_{methanol} * AFR_{methanol} = \dot{m}_{exhaustmethanol} \tag{10}$$

$$\dot{m}_{diesel} * LCV_{diesel} = \dot{m}_{methanol} * LCV_{methanol} \tag{11}$$

$$\dot{m}_{diesel} * \frac{LCV_{diesel}}{LCV_{methanol}} + \dot{m}_{diesel} * \frac{LCV_{diesel}}{LCV_{methanol}} * AFR_{methanol} = \dot{m}_{exhaustmethanol} \tag{12}$$

Methanol's stoichiometric air-fuel ratio (AFR) is 6.4:1, whereas for diesel this is 14.4:1. To achieve the same power output, a 210 % higher fuel input rate of methanol is required (see equation (8)). From consideration of equation (12), methanol combustion can result in higher exhaust flow values compared to diesel if a stoichiometric ratio is used for both scenarios.

This percentage difference is totally dependent upon the actual AFR sustained during a particular engine's operation, which are generally designed to be run on a "lean mode", meaning AFR values higher than the stoichiometric ratios are expected for each case respectively. Higher than stoichiometric ratios lead to smaller percentage differences in the final exhaust gas flow, as a result of the lower fuel mass contribution. Due to an absence of engine test data, it is assumed that exhaust mass flow during methanol combustion remains the same (Fig. 4 of the annex). The total heat output is based on the measured temperature change and the exhaust flow through the economizer. It is assumed that exhaust gases exit the economizer at 150 °C. Equation (1) is used to find the total heat input.

3.7. Life cycle analysis, GHG fuel intensity, and economic analysis

This study employs a LCA approach in accordance with the IMO's LCA Guidelines (IMO, 2021).[5] The methodology provides a comprehensive evaluation of the environmental impacts associated with marine energy carriers, encompassing the entire well to wake (WtW) from fuel production (WtT) to combustion onboard ships (TtW).

The system boundary of the LCA encompasses all stages from fuel production (upstream processes) to onboard fuel use (downstream processes), extending further to the CO_2 geostorage facilities and utilisation industries (See Fig. 7).

Fuel production emissions were considered in Rotterdam, as the vessels operate within EU waters and routinely bunker there. Rotterdam was selected as the reference port owing to its status as one of the largest bunkering hubs in Europe, its representativeness for EU maritime fuel supply chains, and the availability of reliable, peer-reviewed WtT emission data. The adopted WtT values were sourced from existing literature for the specified fuels in Rotterdam (Guyon et al., 2025) and combined with the TtW emissions of each vessel to calculate the WtW emissions for each case.

The core objective of this assessment is to quantify GHG emissions, resource and energy consumption, and associated environmental impacts. The WtW GHG emissions are calculated using Equation (13), which aggregates upstream (WtT) and downstream (TtW) emissions, expressed in grams of CO_2 eq per megajoule based on the lower calorific value ($gCO_2e/MJ(LCV)$):

$$GHG_{WtW} = GHG_{WtT} + GHG_{TtW} \tag{13}$$

[5] IMO plan to incorporate OCC in IMO LCA guidelines and is working on a regulatory framework for OCC.

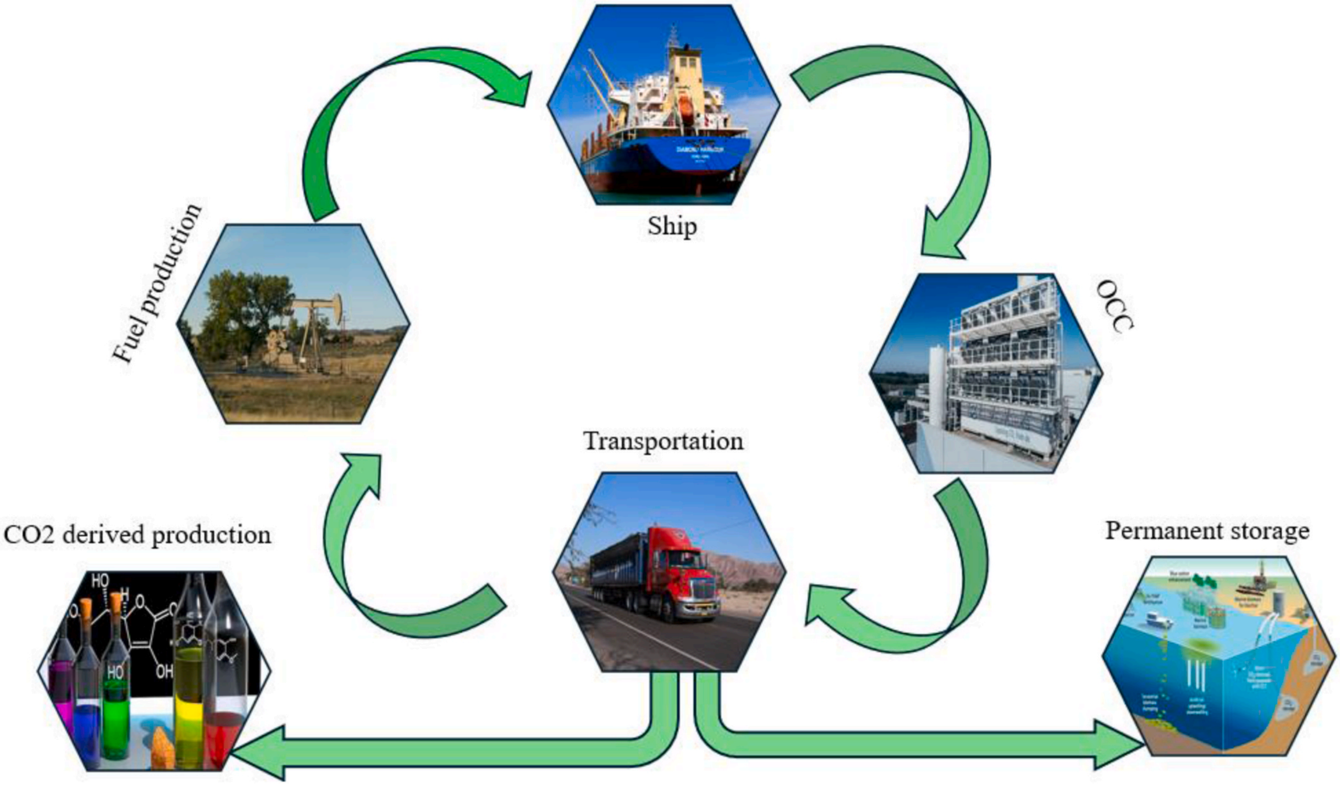

Fig. 7. System Boundary of Life Cycle Assessment for Onboard Carbon Capture system in Shipping.

Where.

- $\mathbf{GHG_{WtW}}$ ($gCO_2e/MJ(LCV)$) represents the total well-to-wake emissions per energy unit associated with the use of fuel or electricity onboard the vessel.
- $\mathbf{GHG_{WtT}}$ ($gCO_2e/MJ(LCV)$) denotes upstream (well-to-tank) emissions related to fuel production, processing, and delivery to the ship.
- $\mathbf{GHG_{TtW}}$ ($gCO_2e/MJ(LCV)$) represents downstream (tank-to-wake) emissions resulting from fuel combustion or electricity use onboard.

The economic evaluation in this study is conducted at a techno-economic screening level rather than through detailed equipment sizing. The cost analysis integrates three elements: (i) incremental fuel penalties associated with the additional energy demand of OCC systems, monetised using Rotterdam bunker prices[6]; (ii) benchmark abatement costs of \$ 337 ± 10 % per tonne of CO_2, reported by Project COLOSSUS (GCMD, 2024), which encompass OCC system CAPEX, OPEX, and the costs of handling, transport, and permanent storage; and (iii) the relative costs of compliance under the IMO Net-Zero Framework (\$ 100/t CO_2 for Tier 1 RUs and \$ 380/t CO_2 for Tier 2 RUs) (DNV, 2025b). This approach enables a comparative evaluation of OCC against market-based compliance measures, while acknowledging that detailed vessel-specific sizing for CAPEX/OPEX breakdowns remain essential for future work.

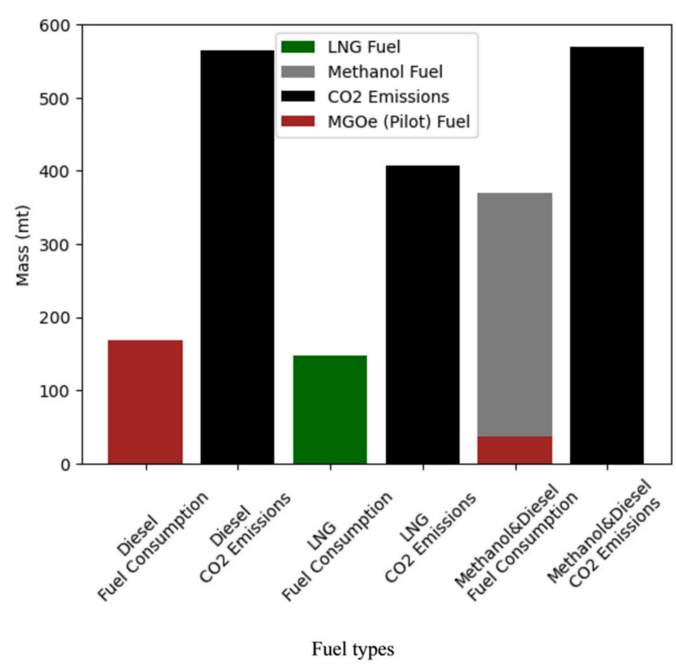

Fig. 8. Vessel Case B fuel consumption mass and emissions for a 3-day voyage, travelling at 19 kts used as an example. Note: the resulting CO_2 emissions are included (black) for all fuel scenarios examined, with diesel (brown) being required for methanol utilisation (grey).

4. Results

4.1. Voyage emissions and consumption

The simulation used for modelling the energy requirements for the

[6] The vessels studied are assumed to operate within European waters and to bunker fuel in Rotterdam, with fuel prices assumed as follows: MDO at \$ 701.5/ton, LNG at \$ 799/ton, and grey methanol at \$ 323.5/ton. Reference: Rotterdam Bunker Prices - Ship & Bunker.

different OCC systems, was implemented on all the vessel case studies examined for the three different fuelling scenarios. To illustrate the expected consumption and resulting emissions, we use Vessel Case B. This case study is used as an example, highlight the time-domain based results gathered from the dynamic Python simulation. For all other cases examined, only the final results are shown in Fig. 8.

For the methanol fueling scenarios, the use of a pilot fuel clearly impacts emissions and must be accounted for when calculating the final emissions. Overall, the consumption and emission values gathered were compared to available data and deemed realistic.

4.2. Energy requirements for Onboard Carbon Capture by absorption

The greatest proportion of energy demand for the chemical absorption process is heat. Consequently, it is imperative that the on-board engines can provide sufficient heat to the chemical stripper unit. Equations (1) and (2) allow the estimation of the heat input per kg of CO_2 captured (Fig. 9), assuming an average thermal efficiency of 80 % within the chemical capturing system.

As illustrated in Fig. 9, the average thermal duty required by the stripper unit is approximately 3.5 MJ per kilogram of CO_2 released, which is consistent with literature values (Osman et al., 2020). The total energy input for pumping MEA throughout the system, is based on the maximum expected flow rate per scenario, calculated with Equation (1). With a density of 0.98 kg/m3 for a 35 % aqueous MEA solution (w/w), the pumping power required is 75 kW per m3/s of required liquid flow, to capture CO_2 at the predetermined rate.

Assuming an economizer thermal conductivity efficiency factor of 80 %, the heat output of the exhaust system compared to the stripper unit's needs for dissociating CO_2 from the MEA solution is displayed in Fig. 10. In the LNG fuelled scenario, the exhaust heat is just sufficient. However, the other scenarios require the addition of a boiler to provide necessary heat, and this additional energy input needs to be accounted for in the overall energy footprint of the system.

Results shown in Fig. 10 are further supported by Fig. 11, showing the stripper heating input required and the economizer's output, in real time, for the corresponding emission output. The final component of OCC is the efficient containment and storage of the captured CO_2. It is important to note is that CO_2 storage will have to be in a liquid state, as it might not permitted to store CO_2 in a solid state by International Gas Carrier (IGC) code, due to safety concerns (IMO, 2014). The same storage characteristics are selected as in the chemical absorption cases examined, which would be 20 bar and −25 °C. The energy requirements for this process can be evaluated using a typical refrigeration cycle Coefficient of Performance (CoP) of 80 %, as well as a pressure enthalpy table (Table 4) for CO_2 to estimate the enthalpy change from gas to liquid at 20 bar and −25 °C.

Using Equation (3) and Table 4, the theoretical energy input for CO_2 liquefaction and storage, in the conditions discussed, is calculated to be 534 kJ/kg of CO_2. In reality the liquefaction process occurs in stages, where CO_2 is compressed (Sen et al., 2015) and cooled several times until the final storage state is reached. However, the theoretical value estimated, includes efficiency losses and is reasonable (Aspelund et al., 2006). Using this value, Figs. 12–14 present the total fuel consumption for each of the vessel scenarios discussed, along with their corresponding capture rate.

Based on the available heat on board, as well as the equivalent carbon emissions of each fuel, for both MDO and Methanol, almost 30 % additional fuel is required to power the chemical absorption process on board. The reason, from Fig. 2 (of the annex) and Figs. 10 and 11, is the lack of sufficient heating input from the economizer during the voyage. For the LNG combustion scenario, the additional fuel required is a more reasonable 15 %. However, we note that these calculations do not account for the additional CO_2 eq. emissions resulting from methane slip that can make up a significant portion of a vessel's GHG footprint, with at least a 4 g CH_4/kWh (Ushakov et al., 2019) contribution to emissions adding an additional 20 % to the CO_2 eq footprint of the vessel.

Accounting for the additional fuel consumption and emissions, the final average energy required for capturing with chemical absorption and storing CO_2 on board a vessel is 3.9 MJ per kg of CO_2 captured, not including the heat energy scavenged from the economizer, as this utilizes waste combustion energy. This value is higher than the theoretical energy required to capture and store CO_2, as it considers the total fuel energy consumed that is subjected to energy conversion losses occurring during fuel combustion and electricity generation.

4.3. Cryogenic capturing

Applying Equations (2) and (3) in Table 4, the theoretical cooling energy required to freeze CO_2 from the exhaust gas is estimated at 1.1 MJ/kg of CO_2. Considering a realistic coefficient of performance of 0.7 for the refrigeration system, the actual energy input required is 1.57 MJ/kg of CO_2.

From solid state capture at −130 °C and atmospheric pressure to the specified storage condition, the energy input would be just for compression, as it is assumed that the rest of the energy would be

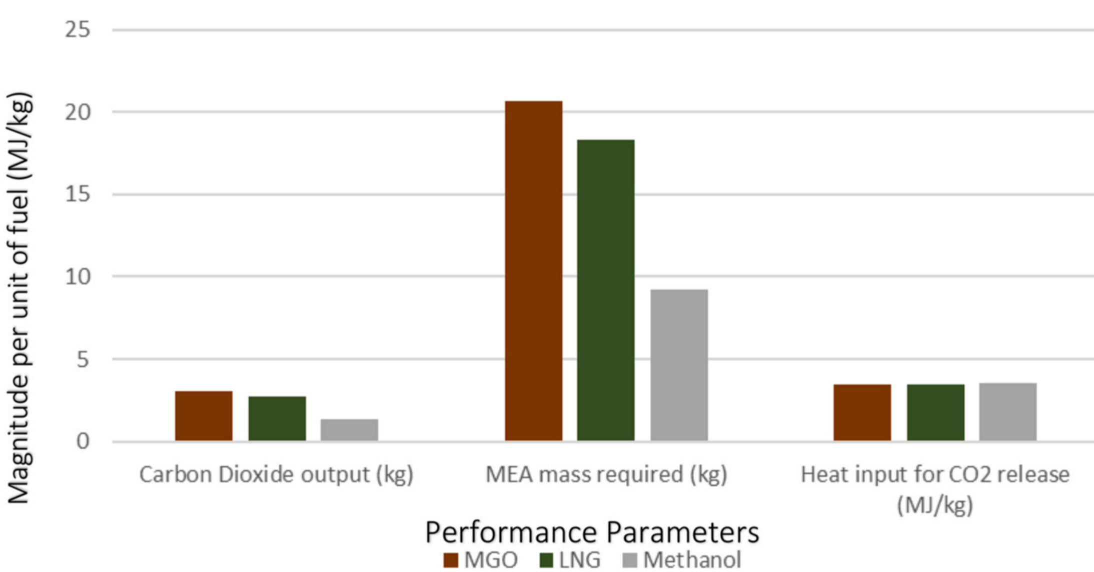

Fig. 9. Heating duty (MJThermal) in stripper unit per kg of CO_2 captured, depending on fuel source.

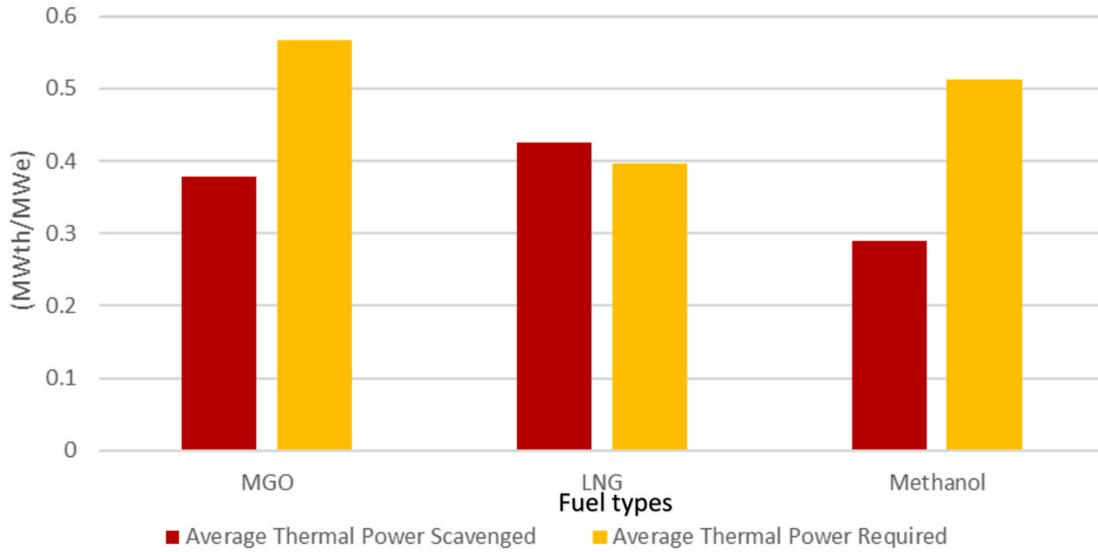

Fig. 10. Comparison of economizer heat input to Stripper unit energy requirement per MW output, of each fuelling scenario for Vessel Case B.

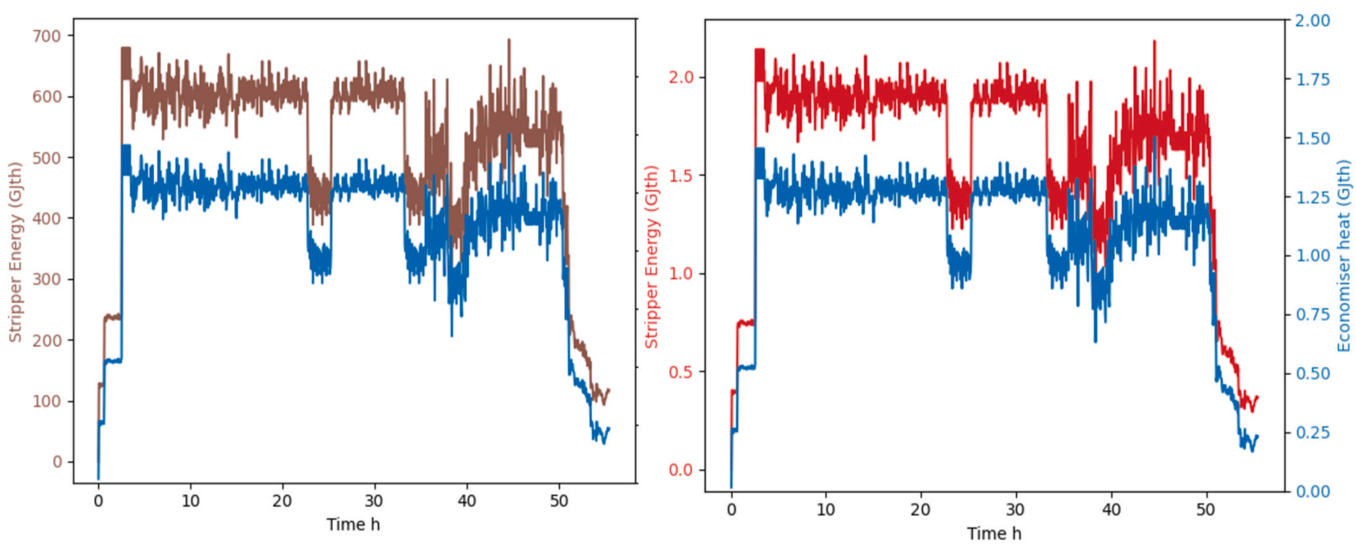

Fig. 11. CO_2 emissions output from ship's engines (grey) against thermal output from exhaust gas economizer (LEFT) and the required Thermal energy for CO_2 stripper unit (red) against the thermal energy supplied via the exhaust economizer (RIGHT) Note: This figure illustrates how during the 3 day trip of the 3800 TEU container vessel, there are times when thermal energy supplied by the exhaust gas economizer is insufficient for the stripper unit, requiring the use of a separate boiler unit. The same graph also illustrates the variations of CO_2 emissions vary during this voyage.

Table 4
CO_2 enthalpy chart depending on temperature and pressure (Lemmon et al., 2005).

Pressure (bar) Temperature (°C)	2	10	15	20	25	30
−50	n/a	93.0	93.1	93.2	93.4	93.5
−40	n/a	435.0	113.0	113.0	113.5	113.2
−30	n/a	445.5	133.4	133.4	133.4	133.4
−20	n/a	455.0	445.5	154.5	154.4	154.3
+130	581	n/a	n/a	n/a	n/a	n/a
	CO_2 Enthalpy state, h in (kJ/kg)					

repurposed for the cryogenic process through heat exchangers. The compression energy input is expected to be 200 kJ/kg CO_2. Similar studies in terms of cryogenic carbon capturing have shown a maximum total energy input of 2.8 MJ/kg of CO_2 stored, which is significantly higher than the theoretical figure gathered of 1.77 MJe/kg of CO_2 captured, yet within the range of expected energy investment values gathered from similar case studies (Tuinier et al., 2011). With this being the final value, Fig. 15 through 17 show the total amount of energy required to capture CO_2 via cryogenic means on board, for all fuelling scenarios examined.

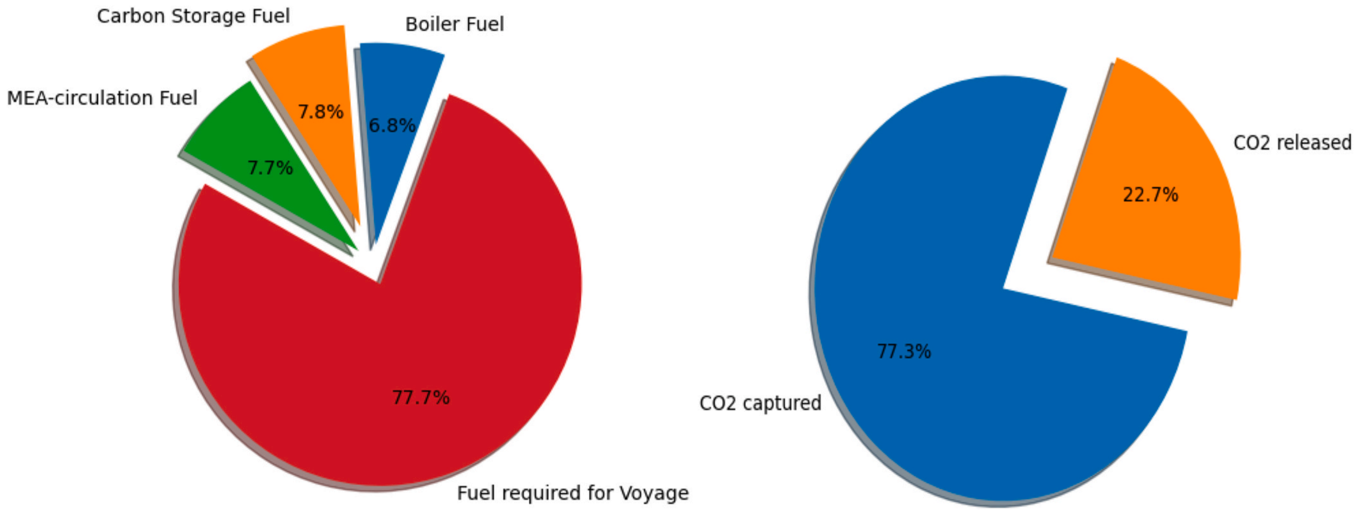

Fig. 12. MDO Chemical Carbon Capturing and Storage fuel consumption breakdown and resulting carbon footprint.

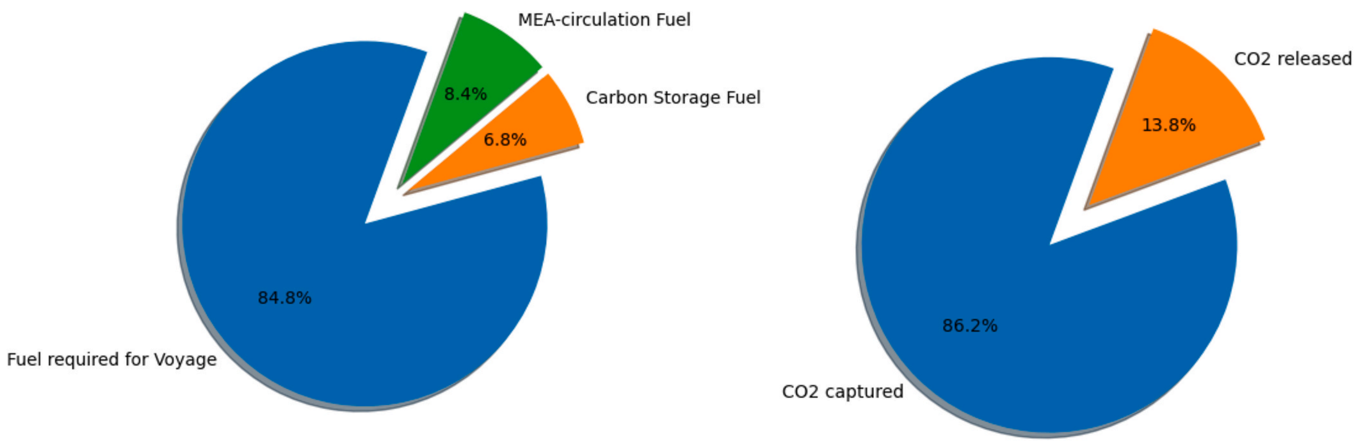

Fig. 13. LNG Chemical Carbon Capturing and Storage fuel consumption breakdown and resulting carbon footprint.

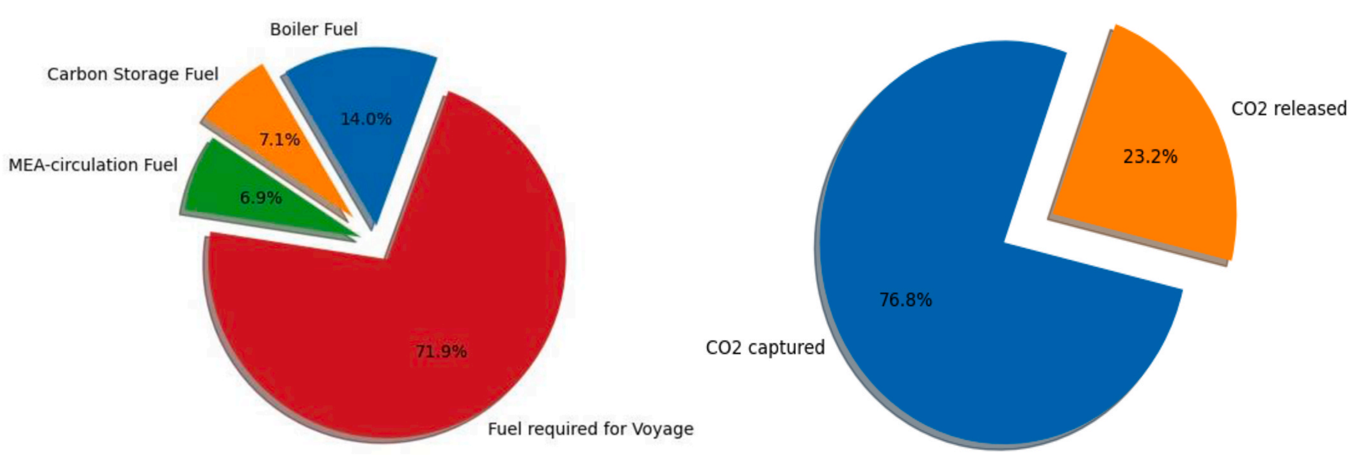

Fig. 14. Methanol Chemical Carbon Capturing and Storage fuel consumption breakdown and resulting carbon footprint.

Since cryogenic carbon capturing requires the use of large refrigeration plants, the energy inputs required are mainly electrical energy from the generators. As such, most of that energy input is subjected to efficiency losses of the internal combustion engines, requiring more fuel energy when compared to recovering the already wasted heat as in the chemical absorption process scenario. As such, when a cryogenic absorption process is employed a minimum of 20 % fuel consumption increase is witnessed for all the cases investigated. This yields a final capturing energy value of 4.1 MJ/kg of CO_2 captured (Font-Palma et al., 2021), a value that approaches the expected total energy investment of 5 MJ/kg of CO_2 captured when using DACC systems (McQueen et al., 2021; Erans et al., 2022; Chowdhury et al., 2023).

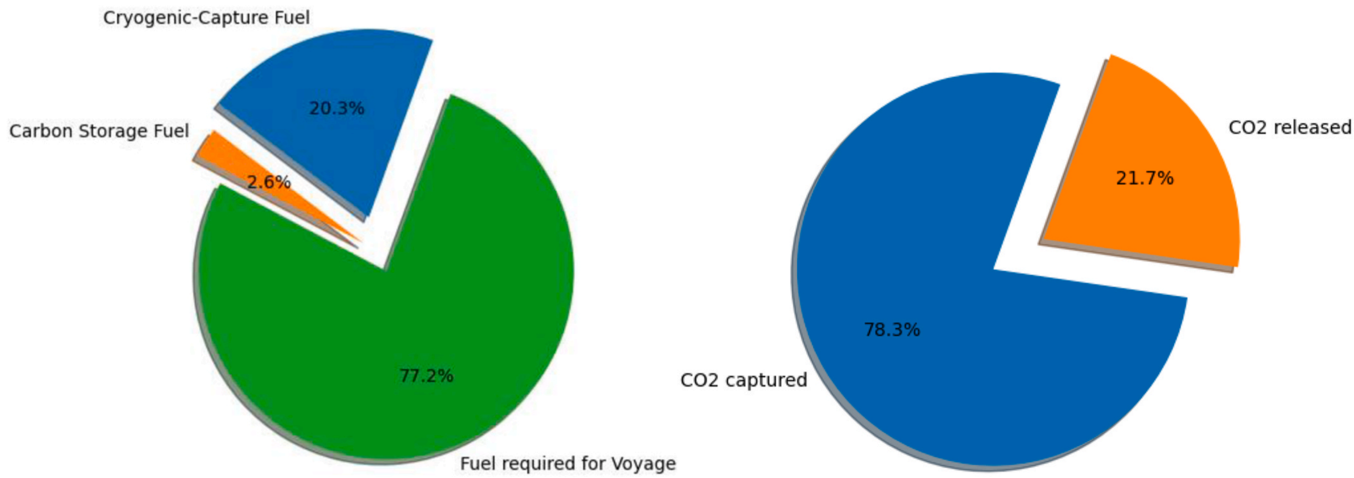

Fig. 15. MDO Cryogenic Carbon Capturing and Storage fuel consumption breakdown and resulting carbon footprint.

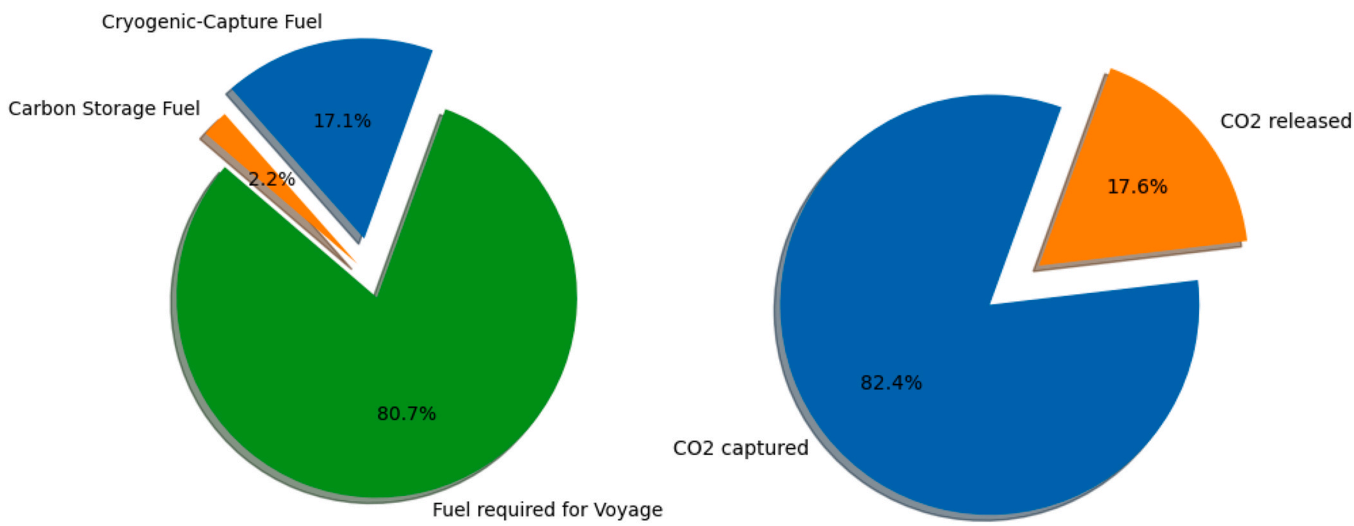

Fig. 16. LNG Cryogenic Carbon Capturing and Storage fuel consumption breakdown and resulting carbon footprint.

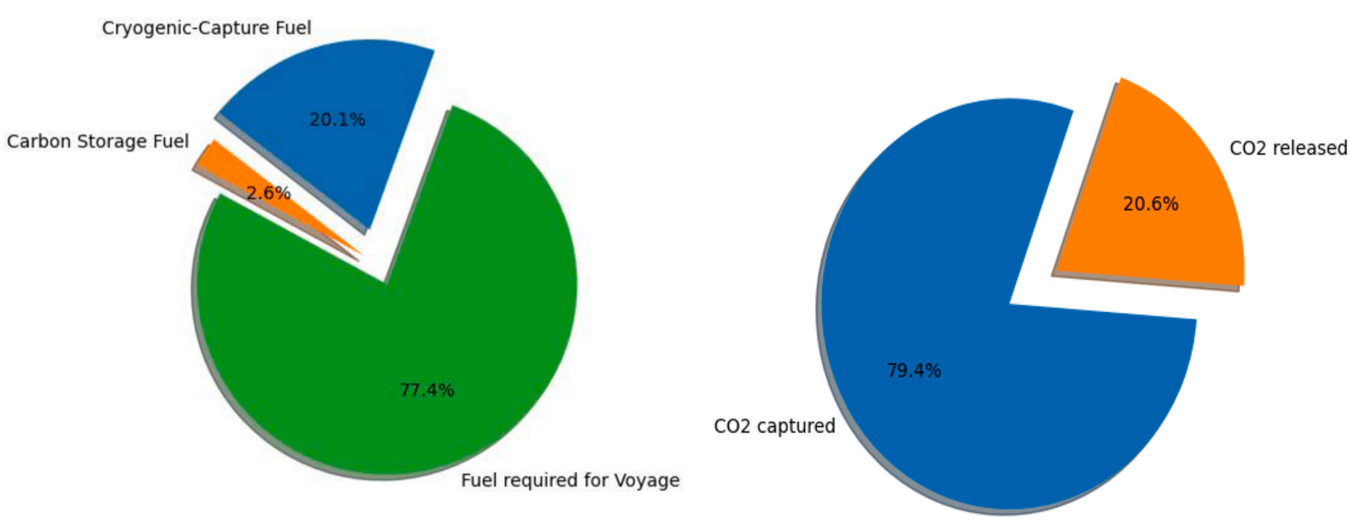

Fig. 17. Methanol Cryogenic Carbon Capturing and Storage fuel consumption breakdown and resulting carbon footprint.

4.4. Sensitivity analysis

To estimate the total fuel-equivalent energy required for MEA-based OCC, both the auxiliary energy for solvent circulation and CO_2 compression, as well as the thermal energy required for solvent regeneration, were considered, as expressed in Equation (14):

$$E_{kg}^{MEA} = E_{aux} + \frac{Q_{th(1-f_{wh})}}{\eta boiler} \tag{14}$$

Where E_{aux} denotes the auxiliary energy requirement for solvent pumping and CO_2 liquefaction (3.9 MJ/kg CO_2), Q_{th} is the thermal duty of the stripper unit (3.5 MJ/kg CO_2), f_{wh} represents the fraction of stripper heat supplied by waste-heat recovery, and ηboiler is the efficiency of the auxiliary boiler (0.85) (Osman et al., 2020; Damartzis et al., 2022). For the conservative case without waste-heat recovery $(f_{wh} = 0)$, the energy requirement is:

$$E_{kg}^{MEA} = 3.9 + \frac{3.5}{0.85} = 8.02 \text{ MJ} \Big/ \text{kg}CO_2.$$

Converted to a tonne basis, this equals approximately 8.0 GJ per ton CO_2, representing the upper bound of energy consumption for MEA-based systems. When partial or full waste-heat recovery is available, the total energy requirement decreases to 5.96 GJ per ton CO_2 at $f_{wh} = 0.5$ and 3.9 GJ/t CO_2 at $f_{wh} = 1.0$.

The results indicate that three main parameters govern the relative performance of the two technologies: (i) the proportion of waste heat available for solvent regeneration, (ii) the efficiency and fuel source of auxiliary power generation, and (iii) the corresponding fuel energy penalty. When the fraction of recoverable waste heat (f_{wh}) is below approximately 0.95, the total energy consumption of MEA systems exceeds that of cryogenic separation—8.0 GJ/t CO_2 versus 4.1 GJ/t CO_2, respectively—making cryogenic capture energetically more efficient for vessels operating on MDO or methanol, where waste-heat recovery potential is limited. Under these conventional operating conditions, both the MEA reboiler, and cryogenic refrigeration units are powered by onboard fuel, meaning that cryogenic systems exhibit slightly higher indirect emissions due to their greater electrical demand. Nevertheless, for short-sea and feeder vessels with limited waste heat, the lower total energy requirement of cryogenic separation offsets this penalty, resulting in 15–30 % lower overall fuel consumption and lower energy costs compared with MEA systems.

Conversely, for LNG-fuelled vessels equipped with efficient economisers capable of meeting nearly all stripper heat requirements $(f_{wh} \geq 0.95)$ MEA systems remain marginally superior, achieving total energy demands of 3.9 GJ/t CO_2. Within the current operational context—where auxiliary power is derived from marine fuels—MEA-based chemical absorption remains the preferred option for vessels with substantial waste-heat recovery capacity, whereas cryogenic systems are more advantageous in safety-critical or space-constrained ship designs with limited thermal integration potential.[7]

4.5. CO_2 storage space requirements

The installation of carbon capture and storage equipment on board can occupy a significant amount of space on the vessel (Damartzis et al., 2022). This might require the use of machinery designated compartments that are vital for the safe operation of the vessel, or impact operating costs due to the reduction of the ship's cargo carrying capacity and consequent loss of revenue generation. That said, the space required for the carbon capture machinery, is relatively minor compared to the space requirements of the entire OCC and storage emissions mitigation system (Tavakoli et al., 2024).

With the chemical absorption process, the first part of the system considered is the exhaust gas economizer, which needs to be sized appropriately to guarantee the heat output required. Products are already available in the market for the engine sizes presented in the case studies, with the 400 TEU vessel being used as an example for the expected carbon capturing plant space occupation (Fig. 5 of the annex). This also applies for the rest of machinery equipment, such as the generator sets, electrical boards, the scale of which can be compared to the carbon capturing equipment.

Apart from the economizer, the scrubbing unit shown in Fig. 5 of the annex is based on similar designs found for powerplants and vessels across the globe (Mitsubishi Heavy Industry, 2021), after it was scaled appropriately to the predicted power output and consequent exhaust flow. The scaling is done linearly, with the exhaust flow being expressed as kg/kW. The same applies for the CO_2 stripper unit.

The CO_2 storage unit (Fig. 6 of the annex) comprises a regular cylindrical type C tank, as per the IGC code (IMO, 2014) to keep CO_2 in the preferred liquid state. It is important to understand that the mass of the byproduct of combustion is more than that of the fuel used for all the fuelling scenarios. For comparison purposes, the CO_2 storage unit is mounted next to where the fuel tank is located. Due to the added mass, it is suggested that storage tanks are mounted closest to the lowest point of the vessel's hull. This helps maintain a low centre of gravity and reduces the sloshing effect within the tank. Storing captured CO_2 in on-deck containers, by contrast, may pose stability challenges. Regardless, it is assumed that CO_2 will have to be discharged at each port stop.

Fig. 18 shows the percentage of cargo space lost in terms of equivalent numbers of containers and corresponding space, for each vessel case study and fuelling option available, with each TEU container taking up 38.5m3. The same figure also illustrates that carbon capture and storage approaches are most effective when employed on small vessels travelling short distances or for large vessels on long voyages.

Table 5 demonstrates fuel consumption of the container vessel voyages investigated. Although it is difficult to predict the space requirement for cryogenic carbon capturing equipment, due to the requirement of a conveyor belt and a separate system that allows enough time for CO_2 to melt, it is expected to require a space sacrifice at least that of chemical absorbing methods (Font-Palma et al., 2021). Finally, as the carbon captured and stored on board takes up the largest amount of storage space, it is important to note how fuel capacity for the same trip will be even less in terms of volume. When combining the capturing machinery equipment, the stored carbon and the fuel onboard, it is expected that total storage sacrifice, should be much less than 10 %.

4.6. LCA analysis of the vessels and cost

Referring to the IMO LCA guidelines and relevant IMO zero framework, the GFI of each fuel scenario using the well-to-wake (WtW) approach, both with and without the implementation OCC was calculated. The results reveal that grey methanol, with a GFI of 100 g CO_2 eq/MJ, has the highest WtW emissions, approximately 12 % higher than MDO, which registers at 89.5 gCO_2 eq/MJ. This disparity is primarily attributed to the upstream production emissions of grey methanol (Svanberg et al., 2018). In contrast, LNG exhibits a WtW GFI of 78.85 g CO_2 eq/MJ, around 12 % lower than MDO, despite methane slip during combustion, which limits its overall emission advantage (Manias et al., 2024; Vakili et al., 2025b).

Table 6 shows the amount of fuel consumption without and with OCC (MEA capture process) with consideration of energy penalty and the amount of CO_2 emission per unit of energy. The abatement potential of OCC has been evaluated by calculating the reduction in CO_2 emissions per unit of energy (gCO_2 eq/MJ), using the WtW approach to derive the adjusted GFI for each fuel when coupled with OCC. This analysis shows that in case of chemical absorption, the GFI of LNG can be reduced to

[7] Ship will increase its weight during navigation due to the progressive increase in the mass of CO_2 stored onboard in tanks (which is unfavourable despite the consumption of fuel from a stochiometric perspective).

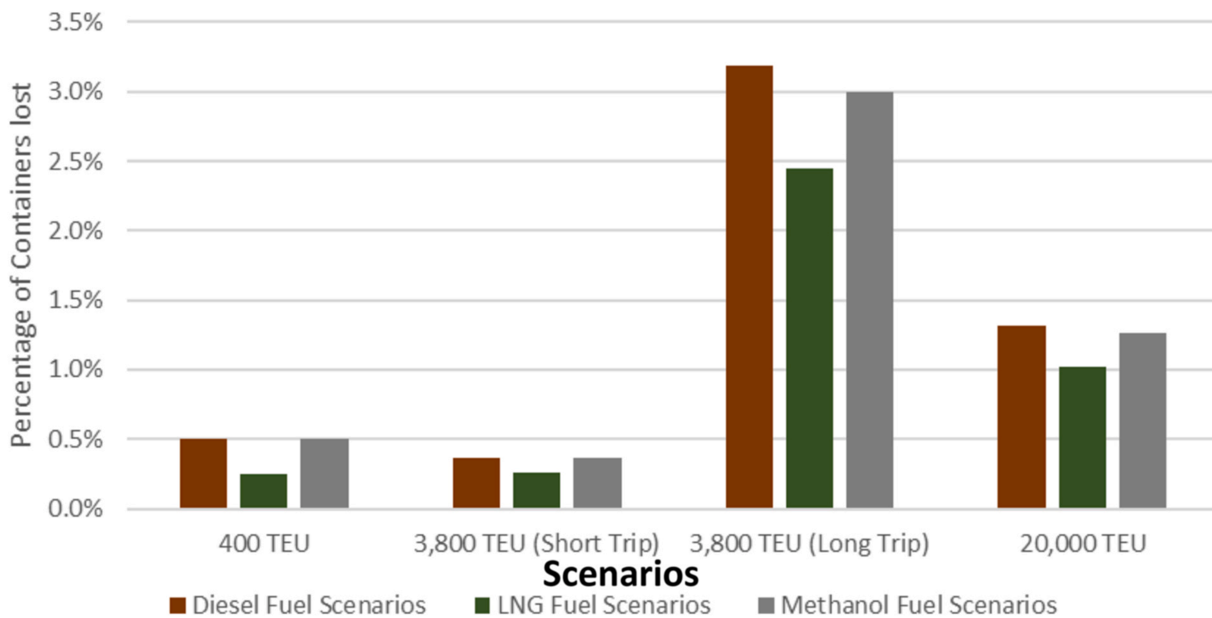

Fig. 18. Percentage of cargo loss for each container vessel case study examined. Note: The percentage illustrated is purely in terms of the space occupied by liquid CO_2 captured, which is expected to be the main occupier. It does NOT include the space occupied by the storage tank walls or the transfer pipes, yet these are expected to occupy the least amount of space overall, within the cargo holds.

Table 5
Fuel consumption of the studied container vessels.

Case Study	Diesel Consumption (mt)	LNG Consumption (mt)	Methanol (only) Consumption (mt)
Vessel A	18.0	15.2	57.4
Vessel B	179	151	570
Vessel C	1628	1425	4800
Vessel D	3539	3122	10,667

Table 6
Comparative analysis of fuel consumption, emissions, and CO_2 capture for container vessels using MDO, LNG, and methanol with and without OCC.

Fuel type	Case study	Fuel consumption without OCC (mt)	Fuel consumption with OCC per trip (mt)	Emission per trip with OCC (tCO_2e).	CO_2 Capture (t)	TtW (gCO_2eq/mj)	WtW (gCO_2eq/mj)	WtW after Penalty (gCO_2eq/mj)	Reduction of WtW after Capturing (gCO_2eq/mj)	Reduction (%)
MDO	Vessel A	18	23.16	88.69	39.91	74.90	89.50	116.35	63.99	41.49
	Vessel B	179	230.37	882.04	396.92					
	Vessel C	1628	2095.23	8022.17	3609.97					
	Vessel D	3539	4554.69	17,438.86	7847.49					
LNG	Vessel A	15.20	17.92	49.29	22.18	55.00	78.85	90.67	49.87	36.75
	Vessel B	151	178.06	489.68	220.35					
	Vessel C	1425	1680.42	4621.16	2079.52					
	Vessel D	3122	3681.60	10,124.41	4555.98					
Methanol	Vessel A	57.40	79.75	109.66	49.34	77.50	100.30	130.39	71.71	28.50
	Vessel B	570	791.97	1088.96	490.03					
	Vessel C	4800	6669.26	9170.23	4126.60					
	Vessel D	10,667	14,821.04	20,378.94	9170.52					

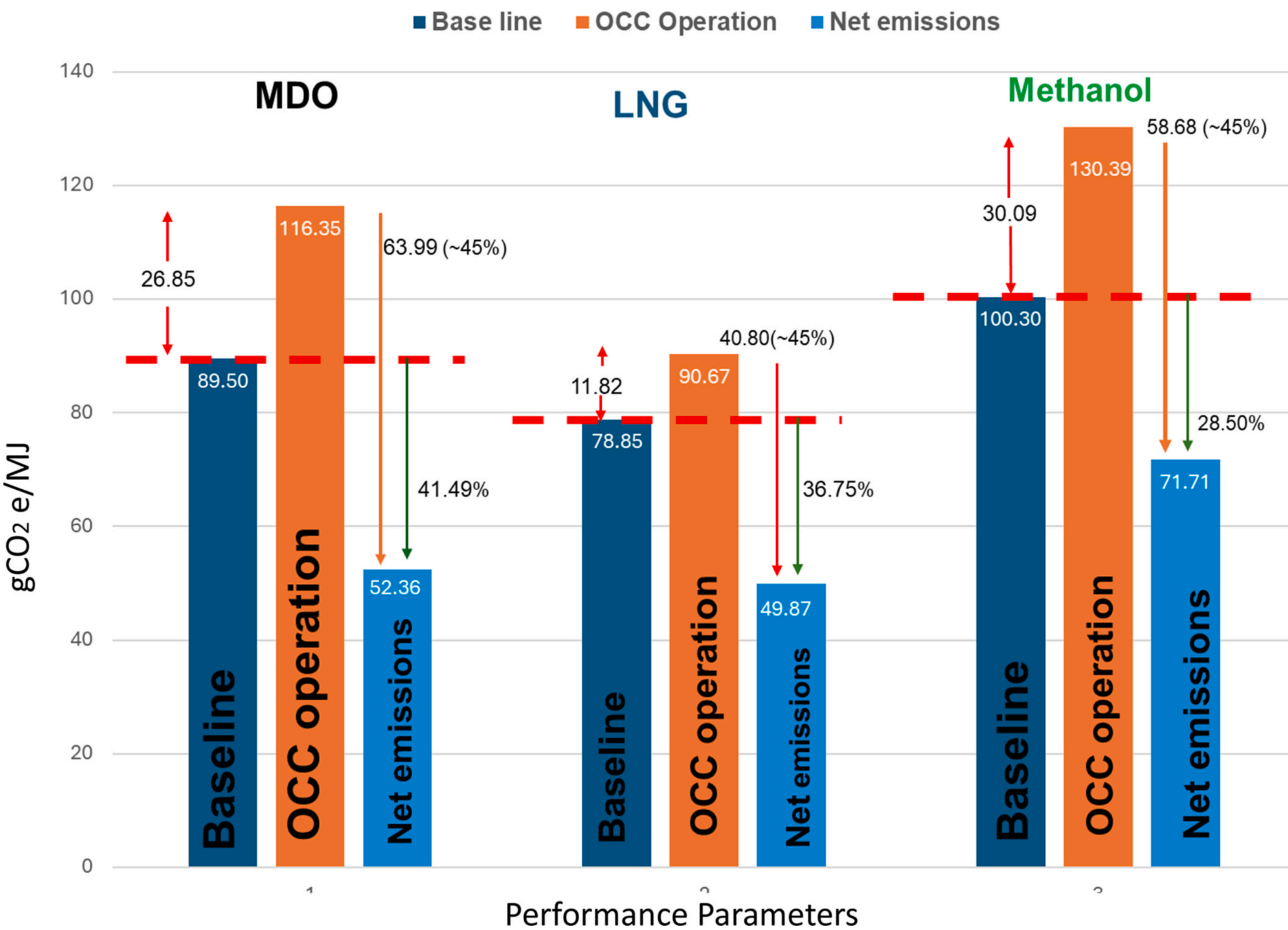

Fig. 19. Net WtW GHG emissions of OCC system for different fossil fuels, with MEA capture process. Baseline represents the GHG emissions due to the vessel operation without OCC.

49.9 gCO_2 eq/MJ, representing a 36.8 % improvement, whereas MDO achieves a 41.5 % reduction, reaching 52.5 gCO_2 eq/MJ (see Fig. 19). The least improvement is observed with methanol, achieving only a 28.5 % reduction to 72.7 g CO_2 eq/MJ. Meanwhile, considering the Cryogenic absorption process WtW after using OCC were 59.07, 52.04, and 66.19 gCO_2 eq/MJ for MDO, LNG, and methanol, respectively and the WtW improvement compared to the baseline is around 34 % (See Fig. 20).

When comparing these adjusted GFIs to the IMO's Direct and Base Compliance Targets under the Net-Zero Framework, it becomes evident that MDO with OCC can meet regulatory requirements by 2035 without incurring Tier 1 RU costs ($ 100 per tonne of CO_2). However, after 2035, depending on the regulations, it would need to purchase Tier 2 RUs. The associated RU costs and the fuel cost are estimated to be approximately $ 49,000, $ 492,000, $ 4.40 million, and $ 9.70 million per voyage for vessels A, B, C, and D, respectively. These figures are around 51 % more than deploying of OCC technology, making OCC adoption financially advantageous to avoid future RU expenses (See Table 7).

Similarly, methanol-fuelled vessels equipped with OCC systems can maintain GFI levels below the Direct Compliance Target until 2031 and remain compliant with the Base Target until 2034. While the potential RU costs for these vessels range from approximately $ 52,000 to $ 9.77 million, the costs associated with deploying OCC systems vary between $ 36,000 and $ 6.90 million per voyage for the case studied vessels, rendering the technology economically favourable—by a factor of ~1.45—for shipowners to avoid paying RU penalties by 2031.

For LNG-fuelled vessels, compliance with the Direct Compliance Target is achievable by 2032 without OCC (Vakili et al., 2025b). However, the deployment of OCC can further reduce GFI levels well below the Direct Target beyond 2035. Despite this, the post-2032 RU costs for LNG-fuelled vessels are lower than the initial-year abatement costs[8] associated with OCC deployment, suggesting that paying RU penalties would be more cost-effective (~27 %) than adopting the technology in the initial years. Nevertheless, OCC deployment could become economically advantageous from 2033 onwards, as the cumulative RU penalties would eventually surpass the OCC implementation costs.

5. Discussion

Two leading OCC technologies—chemical absorption and cryogenic separation—were assessed in this study. The analysis indicates that both chemical and cryogenic capture systems can be integrated with conventional fuel-based power systems such as MDO, LNG, and methanol. A comparative assessment across fuel–technology combinations indicate clear operational synergies. LNG combined with MEA-based OCC demonstrates the highest overall efficiency, particularly when waste-heat recovery is available to offset the solvent regeneration energy demand. Methanol paired with cryogenic capture systems offers a safer

[8] The abatement cost for OCC was estimated at $ 337 ± 10 % per tonne of CO_2, based on the findings of *Project COLOSSUS* (Global Centre for Maritime Decarbonisation, OGCI, & Stena Bulk, 2024). This value encompasses the full chain of costs, including OCC system CAPEX, OPEX, onboard operation, handling, transportation, and permanent storage (https://www.gcformd.org).

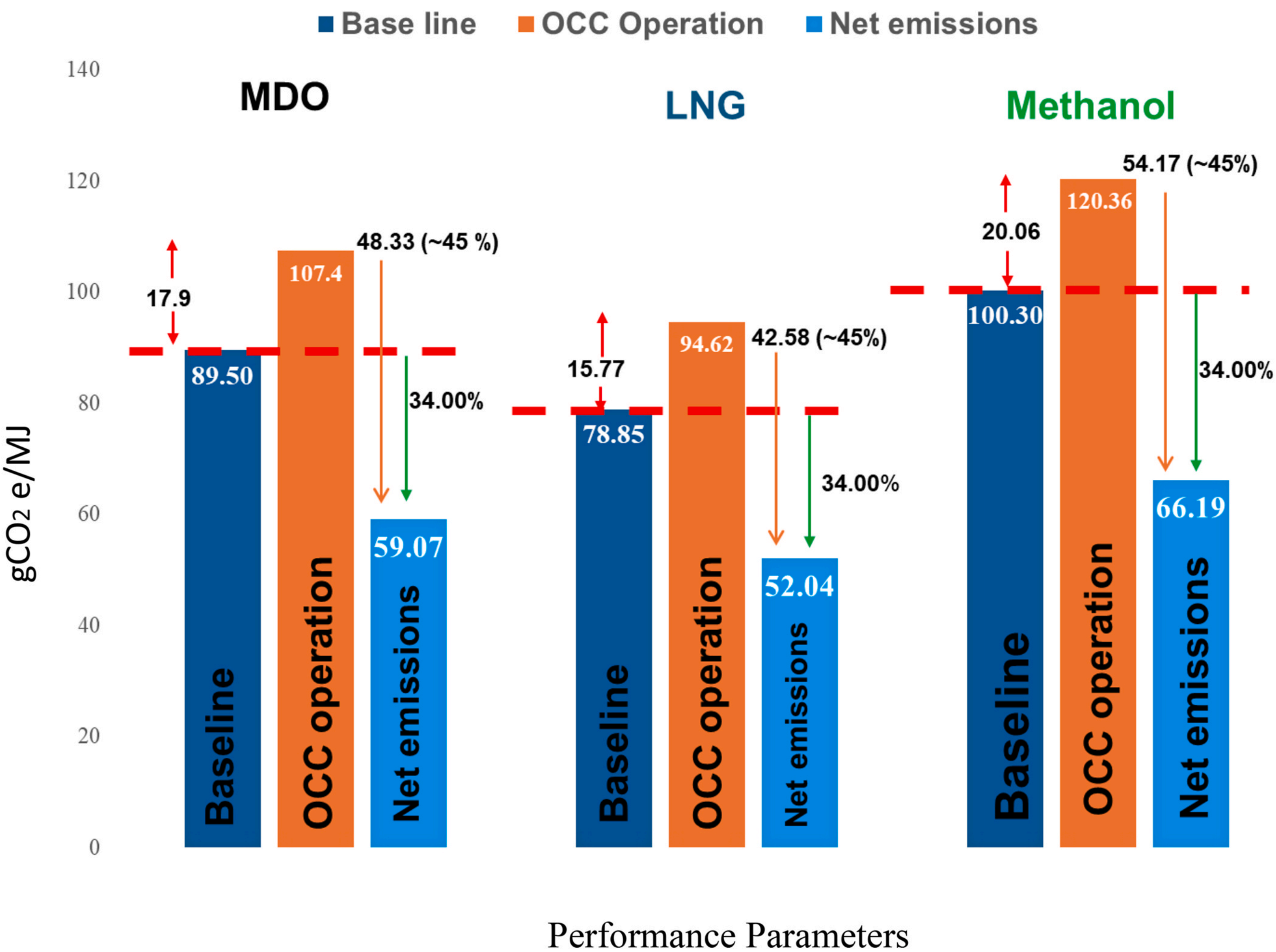

Fig. 20. Net WtW GHG emissions of OCC system for different fossil fuels, with Cryogenic capture process. Baseline represents the GHG emissions due to the vessel operation without OCC.

Table 7
Per-voyage cost comparison of OCC and IMO RU purchases across vessel case studies and fuels.

Case Study	MDO + OCC abatement cost ($)	MDO RUs ($)	LNG + OCC abatement cost ($)	LNG RUs ($)	Methanol + OCC abatement cost ($)	Methanol RUs ($)
Vessel A	32,859	49,489	26,883	21,158	36,038	52,368
Vessel B	326,7619	492,138	267,259	210,236	358,141	520,079
Vessel C	2,971,883	4,475,979	2,456,120	1,967,568	3,145,986	4,405,122
Vessel D	6,460,377	9,730,031	5,351,139	4,303,250	6,906,239	9,772,781

and more compact option for short-sea and low-heat operations, where waste-heat availability is limited. MDO coupled with MEA absorption serves as a transitional bridge solution, providing moderate capture rates and cost effective relative to alternative decarbonisation pathways.

Building on these comparative insights, the following discussion elaborates on the specific operational, safety, and environmental trade-offs between the two technologies. Chemical absorption systems, while technologically mature and capable of producing high-purity CO_2 streams, face operational and safety challenges due to the handling of hazardous amine-based solvents and the need for regular replenishment of degraded solvents, along with thermal energy input, which increases material and energy consumption during ongoing capture operations (Zanobetti et al., 2024). In contrast, cryogenic separation may offer a safer and more cost-effective alternative, albeit at the expense of lower overall environmental performance. This is primarily attributed to the substantial indirect emissions arising from the high electricity consumption required for refrigeration and compression processes, which consequently results in an overall increase in energy demand.

The deployment of OCC introduces a notable energy penalty, with fuel consumption increasing by approximately 15 %–30 %, depending on the fuel type and the availability of waste heat for solvent regeneration or system integration. This added energy demand impacts not only vessel-level operational efficiency but also affects voyage economics, CO_2-offloading, including refuelling strategies, port turnaround schedules, and overall fleet logistics. In particular, vessels powered by methanol or MDO face further limitations, as these engines typically cannot supply sufficient waste heat through their economisers to support the chemical absorption process (MAN Energy Solutions, 2025). Consequently, additional auxiliary heating—from boilers—is required, raising total fuel consumption by over 30 % and reducing carbon capture efficiency. In contrast, LNG-powered vessels can provide adequate waste heat for solvent regeneration, yet they present a separate challenge in the form of unaddressed methane slip, which contributes an additional 20 % to the vessel's total CO_2 eq emissions.

The strategic planning of decarbonisation infrastructure is becoming as critical with the development of ZnZ technologies (Vakili and Ölçer, 2023), underscoring the systemic implications of OCC adoption across the maritime value chain. Beyond onboard technical challenges, OCC implementation introduces significant operational considerations throughout the broader maritime logistics system. Its integration necessitates the development of port-side infrastructure for the offloading, transport, purification, and processing of captured CO_2. The requirement for such CO_2 reception facilities—particularly at major hub ports—may substantially affect vessel routing, port selection, and the architecture of global shipping networks. As a result, ships may increasingly prefer ports equipped with CO_2 handling capabilities, potentially reshaping port hierarchies and influencing future infrastructure investment priorities.

When evaluated from a WtW emissions perspective, the environmental performance of OCC technologies is shown to be strongly fuel dependent. Among the fuels assessed, MDO-fuelled vessels equipped with MEA-based OCC systems demonstrated the most favourable reduction in GHG intensity (~41.5 %), followed closely by LNG-fuelled vessels (~37 %), and methanol-fuelled vessels (~28.5 %). These findings are broadly consistent with trends reported in the literature and can be largely attributed to the high upstream emissions associated with grey methanol production and the continued need for diesel as a pilot fuel in methanol combustion systems (Xu et al., 2022).

Although cryogenic capture technologies offer slightly superior theoretical efficiency in capturing CO_2, they exhibit a higher net energy requirement in operational settings—approximately 4.1 MJ/kg CO_2, compared to 3.9 MJ/kg CO_2 for chemical absorption using MEA. This discrepancy stems from the cryogenic system's reliance on auxiliary electrical power generation, which is subject to additional energy conversion losses (Ushakov et al., 2019). The sensitivity analysis indicated that MEA-based systems require a total of approximately 8.0 GJ/t CO_2 when no waste heat is available, reflecting the additional fuel required to supply thermal energy for solvent regeneration. This demand decreases to 5.96 GJ/t CO_2 with partial waste-heat recovery and to 3.9 GJ/t CO_2 when all stripper heat is recovered from exhaust gases. In contrast, the energy requirement for cryogenic separation remains nearly constant at 4.1 GJ/t CO_2, as it relies primarily on electrical power rather than waste heat. Consequently, cryogenic systems become energetically advantageous for vessels with limited waste-heat recovery potential—such as small methanol- or MDO-fuelled ships—whereas MEA-based systems remain more efficient for LNG-fuelled vessels or large ships with extensive waste-heat integration.

This contrast highlights a fundamental trade-off between theoretical thermodynamic performance and practical system integration, particularly in maritime applications where energy is primarily generated by internal combustion engines. At the same time, it is important to note that this value lies within the expected range of total embedded energy for onshore DAC technologies (McQueen et al., 2021; Erans et al., 2022; Chowdhury et al., 2023), particularly when the systems are powered exclusively by renewable energy sources. For transport and energy system researchers, these findings emphasise the importance of assessing the full energy flow and integration impacts of decarbonisation technologies. Relying solely on theoretical process efficiencies risks underestimating the real-world energy penalties and may lead to suboptimal policy or investment decisions. Systems-based modelling approach that captures both direct and indirect energy demands, such as deployed here, are essential for accurately evaluating the sustainability and feasibility of OCC deployment in shipping.

A critical system-level finding of this study is the significant impact of OCC systems on vessel payload capacity. The substantial volumetric requirements for CO_2 storage tanks represent one of the primary technological limitations to the widespread adoption of OCC within the maritime sector (DNV, 2024). As shown in analysis, onboard storage of captured CO_2 can reduce available cargo capacity by up to ~10 % on smaller vessels, potentially diminishing operational revenue and, paradoxically, offsetting the environmental gains of carbon abatement if additional voyages are required to meet transport demand (Vakili et al., 2023). Although frequent offloading of CO_2 at ports may offer a viable mitigation pathway, this solution is contingent upon the establishment of harmonised regulatory frameworks and investment in specialised port infrastructure (DNV, 2024)—both of which are currently undeveloped in global maritime governance.

From a design and retrofitting perspective, integrating OCC into existing fleets is particularly challenging for older vessels that lack sufficient waste heat recovery capabilities. Conversely, newbuild vessels offer greater flexibility, allowing for the incorporation of modular OCC system designs that optimise spatial integration, enhance vessel stability through lower centres of gravity, and reduce sloshing effects associated with liquid storage—thus improving overall navigational safety (ABS, 2023). Future research and development should focus on minimising the physical footprint of both the capture and storage components. This includes the development of advanced capture agents (e.g., high-capacity solvents or solid sorbents), optimisation of internal heat and mass transfer performance, the engineering of novel materials, and compact systems designs aimed at improving overall storage efficiency. While the density of liquefied CO_2 remains relatively stable under typical storage conditions, research efforts focus on reducing system footprint, enhancing thermal insulation, and exploring alternative storage media that may offer more compact or modular configurations for maritime applications (Zanobetti et al., 2024). Such innovations are essential to improving the techno-economic viability of OCC and enabling its integration without compromising vessel performance or commercial capacity.

Our analysis also incorporated a WtW assessment, using HFO as the baseline fuel for benchmarking. By quantifying the CO_2 abatement potential of OCC in terms of emissions reduced per unit of fuel energy (g CO_2 eq/MJ), an adjusted GHG fuel intensity was calculated for each fuel scenario. This allows OCC to be evaluated as a compliance-equivalent technology, offering an alternative pathway for vessels to meet environmental performance targets in the near-to medium-term.

Given the technological and regulatory barriers impeding the immediate uptake of ZnZ fuels—such as green hydrogen and green ammonia—it is anticipated that large-scale adoption of such fuels may not materialise until after 2035 (Vakili et al., 2025a). In contrast, OCC technologies do not face the same complex constraints (e.g., infrastructure, storage, safety), making them viable interim and transitional solutions to support compliance with IMO decarbonisation objectives.

Extending this comparison, the study finds that an MDO-fuelled vessel equipped with an MEA-based OCC system can achieve a gross CO_2 capture rate of approximately 41 %, maintaining a GFI of 52.36 g CO_2 eq/MJ, which is below the IMO's direct compliance threshold until 2035. In contrast, an HFO-fuelled vessel under similar conditions achieves a GFI of 66.70 g CO_2 eq/MJ, that is only compliant until 2031. Beyond this, depending on the regulatory trajectory, the vessel would require the purchase of RUs.

For LNG-fuelled vessels, compliance is achievable by 2032 without OCC (Vakili et al., 2025b), but the integration of OCC enables continued compliance with direct targets well beyond 2035. This highlights a strong synergy between LNG and OCC technologies. Furthermore, replacing fossil LNG with bio-LNG, in conjunction with OCC, may enable compliance with the more stringent GHG reduction targets expected by 2040. Grey methanol-fuelled ships, on the other hand, can meet the Direct Compliance Target around 2030 and remain under the Base

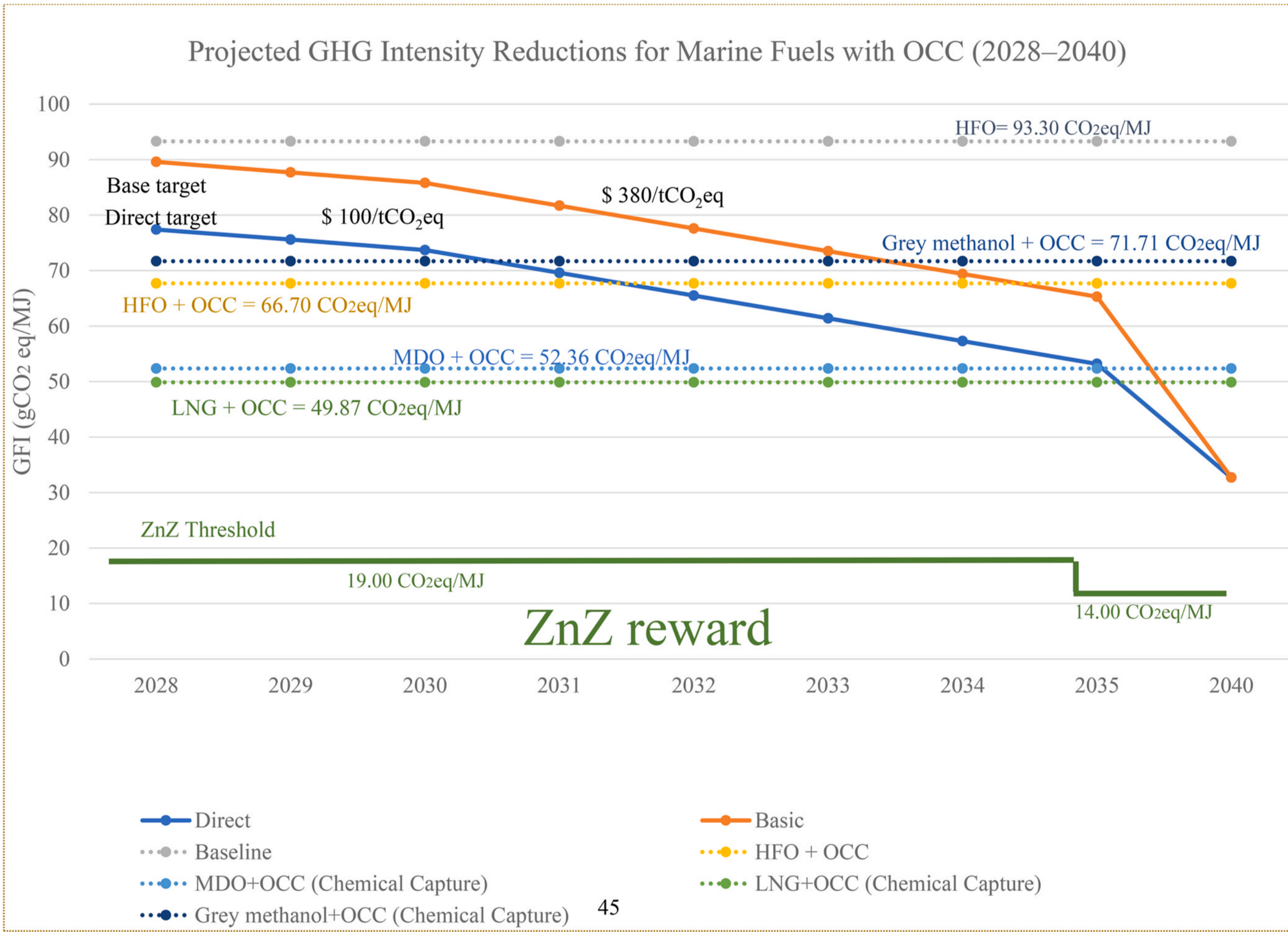

Fig. 21. Impact of OCC on greenhouse fuel intensity (GFI) for various marine fuels under chemical capture scenarios (2028–2040).

Compliance Target until approximately 2033, even with OCC deployed. However, the relatively high WtW emissions associated with grey methanol limit its long-term viability without significant improvements in upstream production sustainability (Svanberg et al., 2018) (see Fig. 21).

This study presents one of the first sector-specific cost comparisons between the implementation of OCC systems and the purchase of RUs under the IMO's proposed Net-Zero Framework. The analysis reveals that, under this framework, OCC becomes more economically attractive than relying solely on market-based compliance mechanisms—particularly for vessels powered by MDO and methanol. For instance, for an MDO-fuelled vessel, the projected voyage cost of purchasing RUs by 2035 is approximately $ 4.31 million, while the voyage cost of OCC implementation is estimated at $ 1.94 million—offering a 2.2-fold economic advantage in favor of OCC adoption. Even when accounting for potential increases in RU unit prices and anticipated reductions in OCC system costs over time, OCC is expected to remain the more cost-effective option.

For LNG-fuelled vessels, RU payments may appear more cost-effective in the early years of compliance. However, over time, the cumulative cost of RUs is expected to exceed the capital and operational expenditure associated with OCC deployment, making abatement technologies the more favourable option by the mid-2030s. Furthermore, the projected increase in the cost of RUs over time enhances the cost-effectiveness and economic attractiveness of deploying OCC technologies.

6. Conclusions

This study presents an integrated techno-economic and environmental assessment of OCC system for maritime transport under the IMO's Net-Zero framework, focusing on container vessels powered by MDO, LNG, and methanol. Through a combination of simulation modelling, LCA, and economic analysis, the results highlight OCC as a feasible transitional solution for decarbonising shipping in the short to medium term—particularly as the industry progresses towards the IMO's 2050 net-zero targets. However, the optimal OCC configuration is influenced by vessel type, operational profile, and the potential for onboard energy integration, highlighting the importance of flexible decarbonisation strategies within the maritime sector. Comparative analysis suggests that LNG combined with MEA-based OCC delivers the highest efficiency, particularly when waste-heat recovery is available. Methanol integrated with cryogenic capture systems is more suitable for short-sea or low-heat operations, whereas MDO coupled with OCC represents a transitional and cost-effective solution for near-term implementation.

Chemical absorption systems, while technologically mature and effective in reducing GHG emissions (up to 41.5 % for MDO-fuelled vessels), present operational constraints due to their reliance on hazardous solvents and thermal integration. In contrast, cryogenic separation offers greater operational safety and modularity but requires higher electrical input, reducing its overall environmental performance. Both systems incur an energy penalty in the range of 15–30 %. Additionally, they introduce spatial constraints, with onboard CO_2 storage potentially reducing cargo capacity by up to ~10 % on smaller vessels. These factors underscore the importance of vessel-specific assessments to optimise design and retrofitting strategies.

The analysis indicates that MEA-based chemical absorption systems require up to 8 GJ of additional fuel energy per tonne of CO_2 captured when no waste heat is available, whereas cryogenic separation systems demonstrate superior energy performance under such conditions—particularly for MDO- and methanol-fuelled vessels, where waste-heat recovery potential is limited. Conversely, MEA-based systems remain more effective for LNG-fuelled ships, where abundant waste heat from economisers can be utilised to satisfy the solvent regeneration demand with minimal additional fuel consumption.

Economically, the integration of OCC becomes increasingly attractive when compared to the projected costs of purchasing RUs under the IMO's Net-Zero Framework. For MDO- and methanol-fuelled ships, OCC offers up to a 2.2-fold cost advantage, with LNG-fuelled vessels also benefitting from long-term savings. The synergy between OCC and cleaner fuels—particularly bio-LNG—presents a pathway to meet increasingly stringent GHG intensity thresholds expected post-2035.

However, OCC cannot be regarded as a "silver bullet" for achieving maritime decarbonisation. Despite its benefits, residual emissions remain, meaning OCC alone cannot deliver absolute zero emissions. The large-scale deployment of this technology depends on the development of CO_2 reception and storage infrastructure at ports, harmonised international regulatory frameworks, and robust Monitoring, Reporting, and Verification mechanisms to ensure credited compliance for captured and permanently stored emissions.

To enable widescale adoption, policy and investment must converge. Priorities include: (i) regulatory clarity on CO_2 handling and Cross-Border accounting, (ii) strategic development of port infrastructure at major transshipment hubs, (iii) integration of OCC into LCA, reporting systems, and GHG pricing mechanisms (iv) targeted R&D to improve system compactness, energy efficiency, and capture performance. Establishing green shipping corridors equipped for CO_2 handling will further accelerate adoption.

6.1. Limitations and future research

Future research should prioritise the optimisation of OCC through advanced waste-heat recovery, solvent durability enhancement, and hybrid integration with e-fuel and biofuel systems. Developing multi-criteria optimisation models that couple OCC with vessel architecture, operational logistics, fuel cost dynamics, and port infrastructure availability will be essential to maximise performance and cost-effectiveness. Equally important is evaluating stakeholder readiness—including shipowners, port authorities, and seafarers—to ensure the practical feasibility, safety, and social acceptance of OCC as part of a comprehensive maritime decarbonisation strategy. Collectively, these actions can position OCC as a credible transitional measure bridging the gap between conventional fuels and the full realisation of zero-emission maritime transport.

The financial analysis presented in this study is positioned as a comparative screening tool rather than a full capital-budgeting model. Its purpose is to evaluate the relative cost-effectiveness of OCC system deployment versus continued use of conventional fuels with IMO'S RUs. The framework integrates OCC-related CAPEX and OPEX, incremental fuel penalties, and costs of CO_2 handling, transport, and permanent storage, benchmarked at \$ 337 ± 10 % per tonne of CO_2. These values are compared with RU compliance costs under the IMO Net-Zero Framework (\$ 100–380/t CO_2), thereby providing decision-makers with insights into which fuel–OCC system pathway offers the most cost-effective compliance option.

While this approach provides a robust life cycle sustainability assessment perspective, it does not account for detailed investment appraisal metrics. Future research should therefore include comprehensive capital-budgeting methods such as net present value, internal rate of return, weighted average cost of capital, cash-flow modelling, and retrofit downtime. Incorporating these elements will allow for investment-grade decision-making and a more accurate evaluation of the long-term financial viability of OCC system in the shipping sector.

CRediT authorship contribution statement

Seyedvahid Vakili: Writing – review & editing, Writing – original draft, Visualization, Validation, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Panos Manias:** Writing – review & editing, Writing – original draft, Visualization, Software, Resources, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Stephen Turnock:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Investigation, Funding acquisition. **Damon Teagle:** Writing – review & editing, Writing – original draft, Validation, Supervision, Resources, Project administration, Investigation, Data curation.

Declaration of competing interest

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

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Annex.

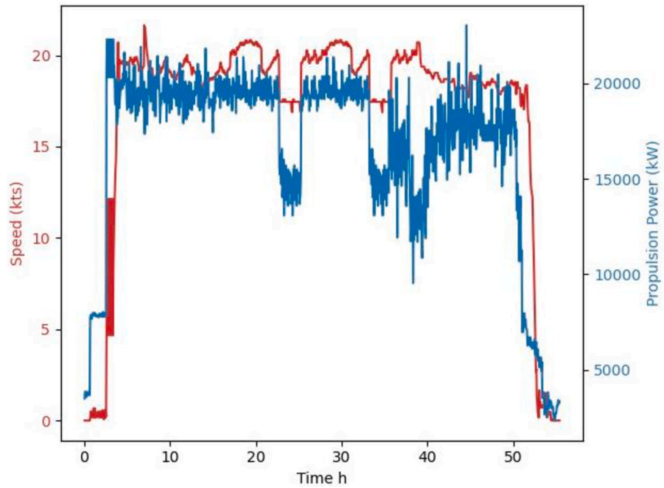

Fig. 1. The Figure illustrates the onboard propulsion power requirement and vessel speed over a 3-day voyage for case study vessel B, excluding the OCC system's power demand. The figure highlights different voyage phases influenced by environmental and operational factors such as sea state, reduced steaming speeds, and port departure/approach conditions. This time-based simulation captures the detailed variations in energy demand and efficiency with changing engine load for both the OCC and propulsion systems.

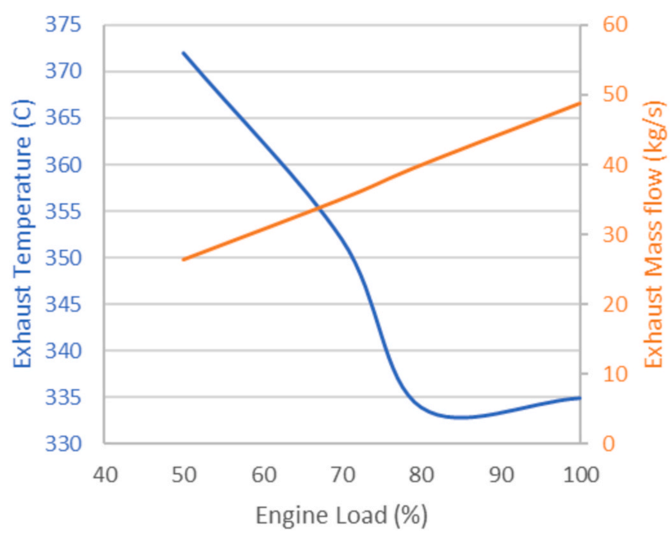

Fig. 2. 25 MW Diesel engine Exhaust flow Characteristics.

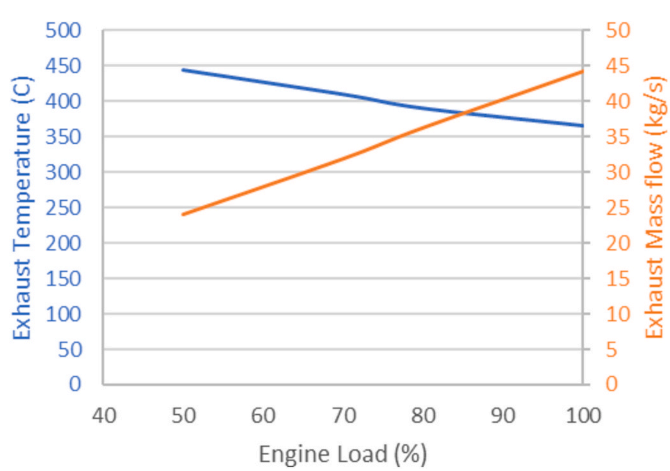

Fig. 3. 25 MW Otto cycle LNG Engine exhaust flow characteristics.

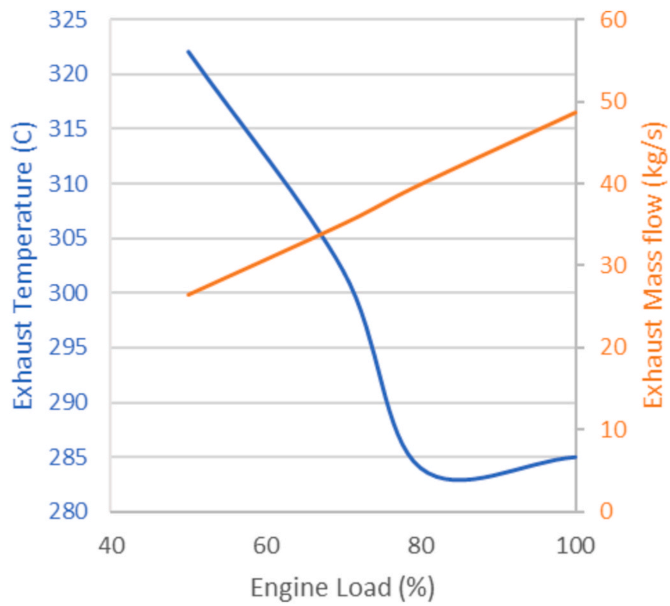

Fig. 4. 25 MW Methanol Engine exhaust flow characteristics.

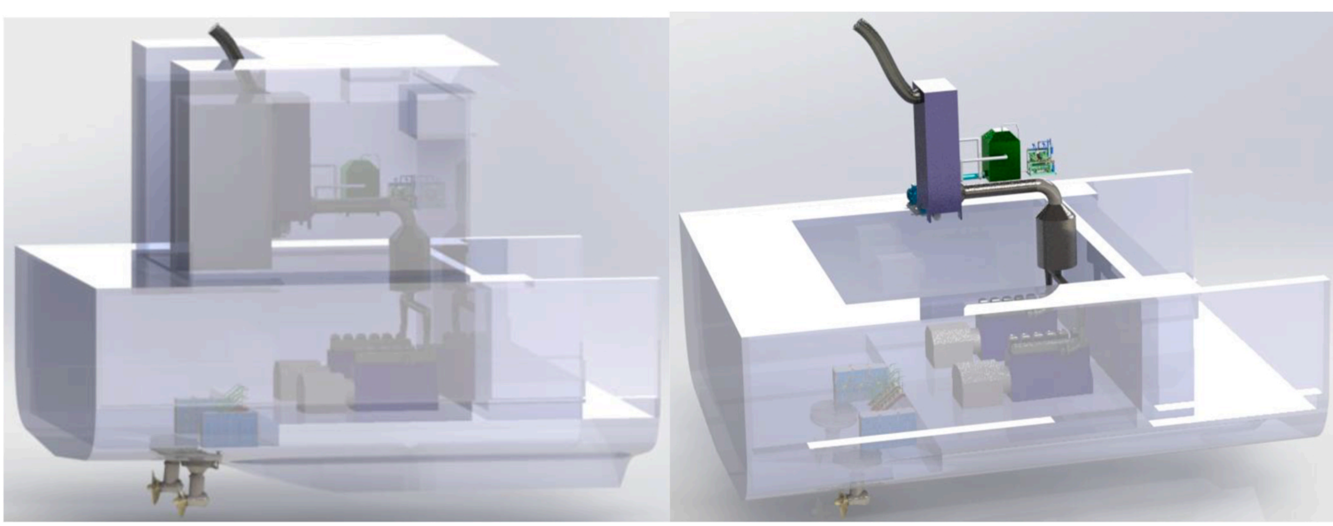

Fig. 5. Illustration of machinery space occupation from chemical carbon capturing system design onboard the 400 TEU vessel.

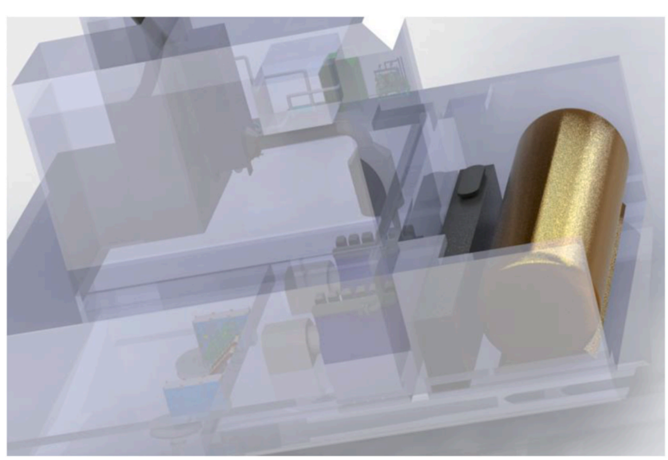

Fig. 6. CO_2 storage unit volume (in gold) compared to MDO fuel tank (in black) in terms of scale. Note: the tank size for the CO_2 storage unit is almost three times larger than the volume of the fuel used, as well as heavier with the CO_2 mass 3.2 times heavier than the carbon in the original fuel. The CO_2 storage tank itself could be smaller than the fuel tank, in practice, as CO_2 could be offloaded at every port stop, yet the same could be applied in terms of bunkering for fuels.

Data availability

The data that has been used is confidential.

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