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Research paper

Exploring carbon capture for maritime decarbonization: A case study on a military vessel

Giorgia Adami [a],*, Riccardo Rocchi [b], Massimo Figari [a]

[a] Department of Electrical, Electronics, Telecommunication Engineering and Naval Architecture (DITEN), University of Genoa, Genova (GE), Italy
[b] Ecospray Technologies S.R.L., Alzano Scrivia (AL), Italy

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ABSTRACT

The maritime industry faces mounting pressure to reduce its greenhouse gas emissions, with regulatory bodies increasingly targeting decarbonization. While much of this attention has centred on commercial shipping, military fleets continue to operate largely outside the scope of emission regulations, despite their non-negligible environmental footprint. This study investigates the potential of carbon capture technologies as a viable and immediate solution for reducing carbon dioxide emissions from naval vessels, including those employed in military contexts. It examines the current advancements in onboard carbon capture systems and outlines the evolving regulatory landscape and preliminary standards introduced by leading classification societies. Amine-based absorption and calcium looping are selected for detailed analysis through a case study on a modern destroyer. Their implementation is evaluated under realistic operational conditions, focusing on carbon dioxide capture rate, auxiliary power demand, volumetric and mass impact, and integration constraints. The comparative evaluation underscores the trade-offs in technological readiness, effectiveness, and adaptability for maritime use. Ultimately, the research offers valuable insight into the potential role of carbon capture in greening the military maritime sector and advocates for the expansion of decarbonization efforts to encompass naval operations.

1. Introduction

Climate change is one of the most critical challenges of our era, marked by rising global temperatures, more frequent extreme weather events, and rise in sea level that threaten both ecosystems and human societies. In response, the international community has established major climate agreements, with the Paris Agreement standing out as a key effort to curb global warming below 2 °C, striving for a 1.5 °C cap above preindustrial levels (United Nation Climate Change, 2025). Achieving these goals requires a substantial reduction in greenhouse gas (GHG) emissions across all sectors, including maritime transportation (Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2022a). The maritime industry is at a pivotal moment in its journey toward sustainability. Responsible for approximately 2.9% (International Maritime Organization, 2025) of global carbon dioxide (CO_2) emissions, international shipping has long been considered a difficult sector to decarbonize due to its dependence on fossil fuels, the long service life of vessels, the challenges posed by operational constraints such as limited onboard space, operational demands, and harsh environmental conditions. In this context, global regulatory frameworks, most notably those established by the International Maritime Organization (IMO), along with regional initiatives like the European FuelEU Maritime and Emission Trading System (EU ETS) are playing a crucial role in guiding the maritime sector toward a sustainable, low-carbon future. Although commercial shipping has increasingly been under scrutiny, military naval fleets remain a largely overlooked yet substantial source of emissions. Despite being responsible for an estimated 5.5% (Neimark et al., 2021) of global GHG emissions and playing a significant role in climate change, military operations remain excluded from the mandatory reporting mechanisms established by international climate agreements. Despite this regulatory exemption, military stakeholders have both a ethical and strategic responsibility to reduce their carbon footprint. At the same time, they must adapt to a changing landscape, shaped by rapid energy transitions toward cleaner sources and shifting geopolitical dynamics. As these changes unfold, the risk of fossil fuels shortages becomes more pronounced. In addition, armed forces are already confronting the operational consequences of climate change, often required to operate in increasingly extreme and unpredictable environments. Reducing their own greenhouse gas emissions is not only a matter of ethical responsibility but also a proactive measure to prevent even more severe or frequent operational challenges in the future. Strengthening

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* Corresponding author.
E-mail addresses: giorgia.adami@edu.unige.it (G. Adami), r.rocchi@ecospray.eu (R. Rocchi), massimo.figari@unige.it (M. Figari).

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climate resilience, therefore, becomes essential to safeguarding military readiness and the stability of defence operations in an evolving global context (NATO, 2021). At the same time it is crucial that any decarbonization strategy be carefully evaluated in light of the specific missions and operational profiles of different vessel classes. The vast majority of studies and technological advances in shipping decarbonization focus on commercial vessels, with much less attention paid to military naval fleets. This paper aims to bridge this gap by focusing specifically on the feasibility of decarbonization strategies for naval vessels.

In the commercial shipping sector, several solutions are being examined to increase energy efficiency, minimize emissions, and ensure compliance with regulatory GHG limits. These solutions include optimizing hull designs, implementing alternative propulsion systems, utilizing sustainable fuels and energy sources, and adopting innovative operational strategies (DNV, 2024a; Maloberti et al., 2025). Energy efficiency measures, including hull optimization, weather routing, and wind-assisted propulsion technologies, have the potential to reduce emissions of about 10%–30% (Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2022a; Figari and Vigna, 2023; Law et al., 2022; Wärtsilä, 2025a). However, while these technologies offer short-term benefits, they will not be sufficient to meet the progressively stricter emission limits. The use of alternative fuels represents a promising solution that can significantly reduce greenhouse gas emissions, support global decarbonization efforts, and promote long-term environmental sustainability (Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2022a). However, their adoption presents several challenges in a sector traditionally dependent on fossil fuels. Alternative fuels often exhibit distinct characteristics and issues compared to conventional fuels, particularly with regard to storage, combustion, and safety (Bureau Veritas, 2025). Moreover, innovative fuels can be derived from a range of sources, both fossil and “green”, which can affect their true GHG impact. Therefore, it is essential to adopt a Well-to-Wake (WtW) approach that accounts not only for the atmospheric impact, but also for the potential exploitation of biological resources in the case of biofuels (Bureau Veritas, 2025; Steer and for the World Resources Institute, 2015). Among alternative fuels, LNG, methanol, ammonia, biodiesels, and hydrogen are emerging as promising options (Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2022a; Bureau Veritas, 2025; DNV, 2018). LNG represents the most advanced alternative fuel for maritime applications, offering a reduction in GHG emissions of approximately 20% (DNV, 2025b). However, it is crucial to consider the impact of methane slip, which varies depending on the type of engine used (Pavlenko et al., 2020). Given the high global warming potential (GWP) of methane, this issue worsens the WtW emissions scenario in terms of equivalent CO_2 (CO_2eq). Methanol is one of the most promising emerging fuels. In 2024, methanol-fuelled vessels led the way among new fuels, with 119 orders, accounting for more than a third of the total orders in the existing order book (DNV, 2025a). However, to effectively reduce GHG emissions, methanol must be produced from renewable sources, raising concerns about availability and cost (Adami and Figari, 2024; Ammar, 2019). Moreover, its storage on board presents challenges due to its low flashpoint, toxicity, and low energy density (Adami and Figari, 2023). Ammonia and hydrogen are still in the early stages of development for onboard fuel applications, facing challenges such as specialized storage requirements, limited availability from renewable sources, and safety concerns related to toxicity, flammability, and handling. These issues hinder their widespread adoption in the maritime sector (Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2022a; Bureau Veritas, 2025; DNV, 2018). Due to limitations in feedstock availability and technological capabilities, no single alternative fuel is currently capable of meeting the demand of the entire maritime industry in the short term (Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2022a). Furthermore, the operational costs associated with alternative fuels are significantly higher compared to traditional solutions. The adoption of hybrid systems could facilitate the energy transition by combining different technologies with alternative energy sources, offering a more flexible solution during the transition period (Belvisi et al., 2024). From studies (Maloberti et al., 2024; Gallo et al., 2023), it is evident that adopting a hybrid configuration significantly reduces fuel consumption and the carbon footprint of vessels. In particular, when renewable fuels are used in hybrid configurations that combine generators, battery packs, and fuel cells, emissions can be reduced to as low as one-eighth of those produced by traditional diesel configurations (Maloberti et al., 2024). Furthermore, adopting a hybrid system with batteries helps eliminate harmful port emissions, improving air quality and protecting human health (Maloberti et al., 2025). Despite the advancements in alternative fuels and hybrid systems, achieving full decarbonization remains challenging due to fuel availability, technological constraints, and operational costs. In this context, carbon capture onboard represents a practical and effective solution to further reduce emissions in existing and newly built vessels in the short to medium term (Wärtsilä, 2025b; Long et al., 2021; Atzori, 2025).

This paper aims to explore the carbon capture technologies for transitioning the military maritime sector toward the net zero target. It first provides an overview of the latest advancements in the carbon capture field, highlighting key developments and research trends. Subsequently, it examines the relevant regulations and challenges associated with the implementation of carbon capture systems in maritime applications, an aspect that represents a significant innovation in this domain. Another key contribution of this study is the comparative analysis of four carbon capture technologies: amine-based absorption, molten carbonate fuel cells, calcium looping and cryogenic carbon capture (CCC); assessing their feasibility for naval applications. Although amine-based systems have been studied in the literature, MCFCs, calcium looping and CCC remain relatively under explored in the maritime sector. To further investigate their practical implications, the paper presents a case study in which two technologies are applied to a destroyer, evaluating feasibility, integration challenges, and critical issues specific to the military sector.

The remaining part of the paper is structured as follows: Section 2 reviews the current state of the art in maritime carbon capture, presenting four key technologies: amine-based absorption, MCFCs, calcium looping and cryogenic carbon capture. The section analyses the potential and limitations of each technology, focusing on their feasibility for onboard applications. It also examines the relevant regulatory framework that governs their implementation in the maritime sector. Section 3 presents the methodology. Section 4 focuses on a case study in which amine-based and calcium looping carbon capture technologies are applied to a destroyer, evaluating feasibility and issues related to the military sector. Finally, the paper concludes with a discussion of future developments and the way forward for carbon capture in the maritime industry.

2. State of the art: Carbon capture and storage onboard ships

Carbon Capture and Storage (CCS) is a key technology for reducing greenhouse gas emissions in land-based industries and has the potential to become a viable solution for the maritime sector (Tavakoli et al., 2024). CCS technologies capture CO_2 emissions generated by industrial activities and, in maritime applications, by combustion processes on board. The captured CO_2 is stored on site for a later use in industrial processes or geological sequestration (Tavakoli et al., 2024). Despite the continuous expansion of carbon capture technology, the industrial sector currently relies on three main categories:

- Pre-Combustion Carbon Capture: this process involves converting fossil fuels into a mixture of hydrogen and carbon dioxide, known as syngas, before combustion (Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2022);
- Post-Combustion Carbon Capture: it is a technology that removes CO_2 from exhaust gases after fuel combustion;

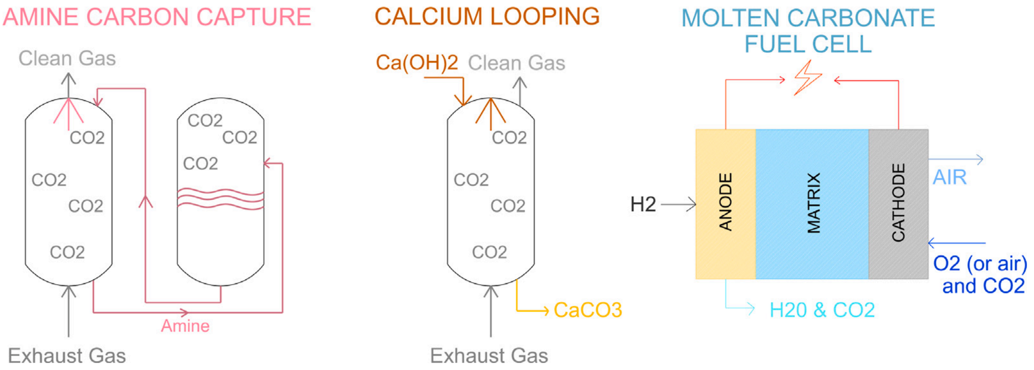

Fig. 1. Amine, calcium looping and MCFC carbon capture scheme (Ecospray, 2024a).

- Oxy-Fuel Combustion Carbon Capture: it is a process in which pure oxygen is used instead of air for the combustion of the primary fuel; this method produces a flue gas primarily composed of carbon dioxide and water vapour. The resulting high concentration of CO_2 in the exhaust stream simplifies the carbon capture process (Bureau Veritas, 2023).

Post-combustion carbon capture is particularly suitable for maritime applications, as it can be implemented downstream the conventional propulsion systems installed, allowing CO_2 removal without altering the propulsion machinery (Stec et al., 2021; Risso et al., 2023). Conversely, pre-combustion and oxy-fuel systems require complete redesign of propulsion systems, which limits their near-term feasibility for ships (Lloyd's Register, 2023). Several methodologies exist for capturing carbon dioxide in the post-combustion phase, including amine-based absorption, calcium looping, molten carbonate fuel cells (MCFC) and cryogenic carbon capture.

A comprehensive review of the literature highlights that the most advanced and widely studied technology for the onboard carbon capture is the solvent-based absorption (Long et al., 2021; Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2022; Stec et al., 2021; Luo and Wang, 2017; Feenstra et al., 2019; Einbu et al., 2022; Khan et al., 2023; Visonà et al., 2024). This technology operates using a liquid solvent, typically an amine-based solution, to chemically absorb CO_2 from exhaust gases (Fig. 1). The CO_2-rich solvent is then regenerated through a thermal process, releasing the captured CO_2 for storage or utilization while allowing the solvent to be reused in the system. No issues related to solvent impurities have been identified, as the solvent can be continuously regenerated without the accumulation of parasitic compounds that could compromise its effectiveness or lifespan. Since onboard storage is required, the captured CO_2 must be further processed, typically through compression and liquefaction, to reduce its volume and facilitate efficient storage. Amine-based capture systems can reduce onboard CO_2 emissions by up to 60%–80%, although their performance is heavily influenced by the energy demand for solvent regeneration and solvent selection (Long et al., 2021; Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2022; Visonà et al., 2024). Ship-specific factors such as layout constraints, mission profile, and available power also significantly affect system viability (Tavakoli et al., 2024). The substantial energy demand of the amine-based carbon capture system contributes to increasing fuel consumption, thereby significantly reducing the operational range of the vessel, assuming that the allocated fuel volume remains unchanged (Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, 2022). Furthermore, the implementation of this carbon capture system presents considerable challenges in terms of both weight and footprint (Visonà et al., 2024). The significant energy demand of amine-based carbon capture systems can be avoided by adopting molten carbonate fuel cells as an alternative solution.

MCFCs are efficient electrochemical devices with fast reaction rates, initially used in large power plants and now studied for CO_2 capture applications (Bosio et al., 2023) (Fig. 1). Unlike amine scrubbing, which requires substantial energy for solvent regeneration, MCFC technology enables simultaneous CO_2 capture and power generation, significantly reducing the overall energy consumption of the process (Ruffoni, 2022). This dual capability makes MCFCs a promising standalone option for onboard carbon capture, addressing both emissions and energy efficiency challenges in the maritime sector. The MCFC-based system has a lower Technology Readiness Level (TRL) compared with amine, despite its ability to efficiently capture CO_2 and its low operational costs (Bortuzzo et al., 2023). The main limitations arise from the space requirements and technological complexity of fuel cells, as well as the need for a reliable supply of hydrogen (H_2) or alternative fuels such as LNG, bio-LNG, ammonia, or syngas (Bortuzzo et al., 2023). Additionally, the implementation of this technology is further challenged by issues related to onboard H_2 production, the complexity of reforming/cracking processes, and the storage, disposal, and transportation of CO_2 (Bortuzzo et al., 2023).

Another option for onboard carbon capture is calcium-looping technology (Fig. 1), which offers potential advantages over amine-based and MCFC systems. This approach can reduce space requirements and can lower costs compared to the other two CCS technologies (Fredriksson, 2024). The process employs calcium hydroxide ($Ca(OH)_2$) as an absorbent and operates in two stages: carbonation and calcination. During the carbonation phase, $Ca(OH)_2$ reacts with CO_2 in the exhaust gases, forming calcium carbonate ($CaCO_3$). Due to the high thermal requirement (typically up to 950 °C (Zhang et al., 2024)) the calcination phase is usually regarded as technically challenging. Instead, this step is more plausibly envisioned as a shore-based process in scenarios involving solid sorbent regeneration. Avoiding on-board calcination also enables the storage of captured CO_2 in solid form, eliminating the need for complex liquefaction and cryogenic storage systems typically required for gaseous CO_2. Furthermore, the calcium carbonate generated could potentially be discharged into the marine environment, offering a feasible and sustainable solution for the management of CO_2 in maritime applications (Ecospray, 2023). However, the use of calcium hydroxide for CCS presents some key challenges. Firstly, the absorbent production process is energy intensive and increases CO_2 emissions throughout the chain Bortuzzo et al. (2023). Another challenge is the availability of calcium hydroxide at ports, especially in under-equipped facilities or during the initial stages of deployment. The final issue involves the management of large quantities of $CaCO_3$ produced, which may require careful consideration of disposal options (Ecospray, 2023).

Cryogenic carbon capture is based on lowering the temperature of the exhaust stream until the CO_2 fraction condenses or de-sublimates. In this way, CO_2 can be removed from the flue gas and stored onboard in liquid or solid state. However, its application on ships is limited by the high energy demand required to compress the flue gases with low CO_2 concentrations to liquefaction conditions (Jiang et al., 2024). A potential mitigation strategy is the use of cryogenic energy already available on LNG-fuelled vessels, particularly the energy released during the regasification process onboard, which can significantly reduce the additional energy demand typically associated with CO_2 separation (Jiang et al., 2024; Shu et al., 2025; Lebedevas, 2024).

2.1. Rule requirements

The adoption of carbon capture technologies in the maritime sector is a relatively recent area of study, and the regulatory landscape that rules the implementation remains underdeveloped in the current literature. This section aims to address this gap by providing a comprehensive overview of the emerging regulatory framework and technical requirements that can affect the deployment of carbon capture solutions in shipping.

As of mid-2025, the IMO has not issued binding regulations for the implementation of onboard carbon capture systems yet. Nonetheless, steps have been taken to incorporate CCS into the IMO Lifecycle Assessment (LCA) Guidelines. In March 2024, MEPC 81 established a dedicated working group to initiate the development of a regulatory framework, with further progress made during MEPC 83, which approved a draft work plan for regulatory adoption of CCS technologies (DNV, 2024b; IMO, 2025). At the regional level, the EU ETS currently offers the only economic mechanism that incentivizes CO_2 capture on ships. However, the lack of a standardized and verifiable methodology to quantify exempted emissions remains a key barrier to a verifiable implementation.

In parallel with these regulatory initiatives, several classification societies have published preliminary guidelines and technical specifications to facilitate the safe and effective integration of CCS onboard. Prominent organizations such as the American Bureau of Shipping (American Bureau of Shipping, 2023), Lloyd's Register (Lloyd's Register, 2024) DNV (DNV, 2023), China Classification Society (China Classification Society, 2023), and Nippon Kaiji Kyokai (Kyokai, 2024) have issued non-binding guidance documents covering aspects such as system integration, operational safety, onboard CO_2 storage, and retrofitting of existing vessels. These guidelines primarily focus on amine-based carbon capture systems, which currently represent the most technologically mature and commercially viable option for shipboard applications. The classification societies' current guidelines play a pivotal role in bridging the gap between experimental technology and practical deployment, and they lay the groundwork for the eventual standardization of CCS across multiple vessel types. Addressing both regulatory uncertainties and methodological gaps will be crucial for enabling the effective, scalable, and safe adoption of onboard carbon capture in maritime operations.

3. Material and methods

This research adopts a structured methodology to evaluate the feasibility of integrating carbon capture onboard military vessels (Fig. 2). The methodological framework is structured around these interrelated perspectives:

- **Operational and Environmental Performance:** this dimension addresses both the efficiency of CO_2 capture, expressed in terms of gross and net capture rates, and the broader operational implications, including energy requirements, fuel penalties, and mission endurance.
- **Architectural and Spatial Integration:** this aspect focuses on CCS systems impact the vessel's general arrangements, onboard volume allocation, and displacement.

The removal efficiency is evaluated using two complementary metrics: gross capture rate and net capture rate. The gross capture rate, as represented in Fig. 3, indicates the fraction of CO_2 captured from the entire exhaust gas stream. However, it does not reflect the effective CO_2 reduction relative to the original ship' emissions, because the capture system itself requires energy and generates additional emissions. It indicates the theoretical removal potential of the technology, assuming ideal conditions with no energetic or environmental penalties associated with its operation. In contrast, the net capture rate accounts for the additional emissions produced by the CCS, primarily from the increased fuel consumption required to meet its power demands, and thus represents the effective reduction in the overall carbon footprint of the vessel (Fig. 3). The net capture rate is evaluated as follows.

$$NetCaptureRate[\%] = \frac{M_{CO_2,\text{captured}} - M_{CO_2,\text{CCS}}}{M_{CO_2,\text{emitted,baseline}}} \cdot 100 \tag{1}$$

where $M_{CO_2,\text{captured}}$ is the mass of carbon dioxide captured [t], $M_{CO_2,\text{CCS}}$ represents the CO_2 emissions induced by the operations of CCS [t], and $M_{CO_2,\text{emitted,baseline}}$ [t] the carbon impact of the vessel without CCS.

Mechanical power, fuel consumption and CO_2 emissions related to the CCS operation are estimated using the following equations:

$$P_{\text{m\_CCS}} = \frac{\left(P_{\text{el}} + \frac{P_{\text{th}}}{\eta_{\text{th}}}\right)}{\eta_{\text{el}}} \tag{2}$$

$$\dot{m}_{fuel,\text{CCS}}\ [\text{g/h}] = P_{\text{m\_CCS}} \cdot \text{SFC}_{\text{DG}} \tag{3}$$

$$M_{CO_2,\text{CCS}}\ [\text{g}] = C_{\text{F\_DG}} \cdot \dot{m}_{fuel,\text{CCS}} \cdot h \tag{4}$$

where $P_{\text{m\_CCS}}$ in [kW] is the mechanical power that Diesel Generators (DG) have to deliver for CCS operation, P_{el} [kWe] and P_{th} [kWt] denote the electric and thermal power demands of the onboard CCS, respectively; η_{th} is the boiler efficiency, η_{el} is the DG efficiency. This expression represents the most general formulation. In cases where the thermal demand P_{th} is not required, as the heat is supplied by waste heat recovery systems, it can be assumed to be zero. The power consumption of the CCS components are derived from tests on the mock-up plants and from simulations. Eqs. (3) and (4) allow to evaluate the additional fuel consumption [g/h] and CO_2 emissions [g] related to CCS operativity. In these formulas SFC_{DG} represents the specific fuel consumption of DG [g/kWh], $C_{\text{F\_DG}}$ is the carbon coefficient of the fuel feeding the DG, and h represents the operating time of the system. It should be noted that the estimated fuel consumption is only related to the CCS operation and does not account for the increase in vessel displacement caused by the adoption of the CCS equipment. It is assumed that the additional electrical load required by the carbon capture system can be met by the existing onboard DG.

Moreover, the methodology investigates the operational implications of integrating CCS on a military vessel. This examination specifically quantifies the variations in the vessel's endurance at a defined reference speed, assuming a constant onboard fuel load. The following equation evaluates the endurance with the CCS onboard ships:

$$Range_{CCS}\ [\text{Nm}] = \frac{M_{fuel,\text{tot}}}{\dot{m}_{fuel,\text{tot}}} \cdot V \tag{5}$$

where $M_{fuel,\text{tot}}$ in the total mass of fuel stored onboard [t], $\dot{m}_{fuel,\text{tot}}$ represents the total fuel consumption [t/h] which encompasses the sum of the original vessel's fuel consumption at a reference speed and the additional consumption attributed to the operation of the onboard system, and V the reference speed [kn]. This calculated endurance can then be used to determine its percentage variation from the original requirement.

The architectural and spatial integration of Carbon Capture and Storage (CCS) systems considers the feasibility of incorporating these systems into the ship's existing general arrangement. The design procedure begins with the definition of the target gross capture and the computation of exhaust flow rates. Functional diagrams for both amine-based and calcium-looping CCS systems are subsequently developed, drawing upon experience from factory-based pilot plants. This methodology, representing a preliminary phase of the feasibility assessment for onboard CCS implementation in naval vessels, involves the symbolic placement of CCS units within the general arrangement to provide an

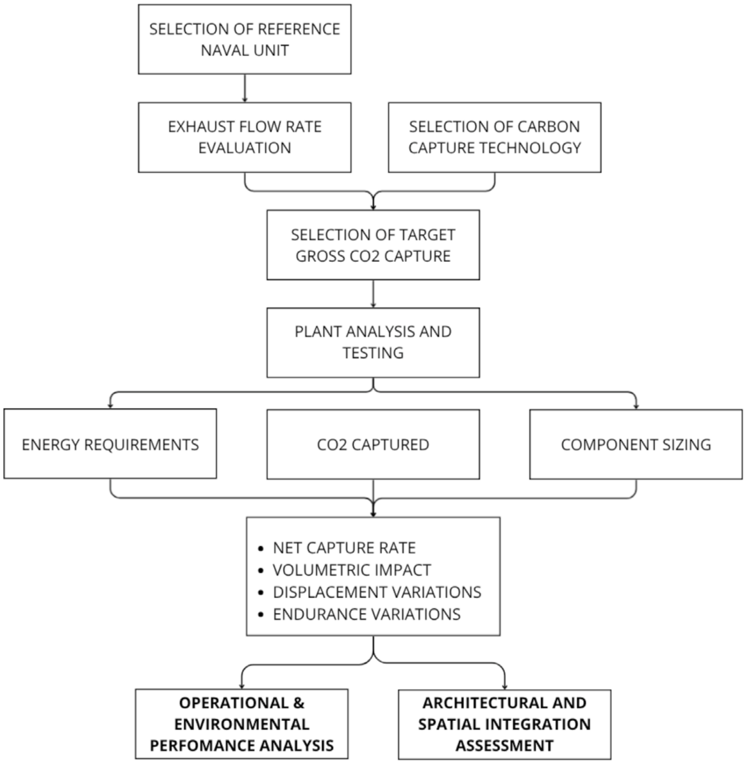

Fig. 2. Methodology flow chart.

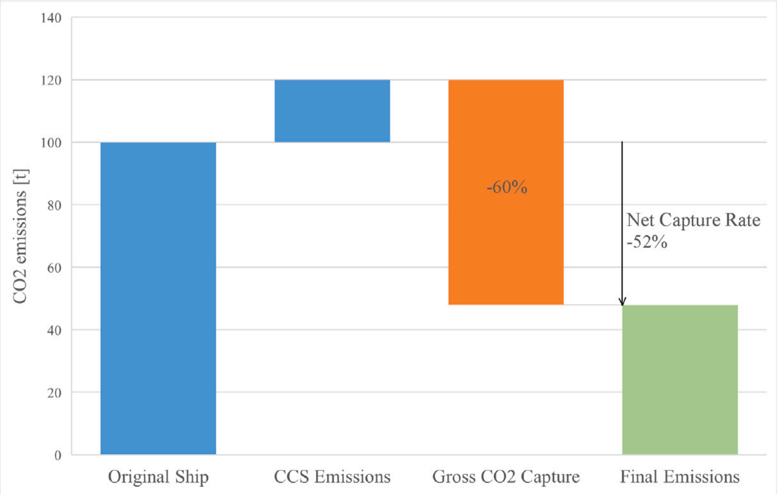

Fig. 3. Capture rate scheme.

initial estimate of their volumetric footprint. No modifications to the ship's existing design or internal layout are assumed at this stage. This is particularly relevant for military vessels, where the internal spaces are highly constrained and require meticulous planning to preserve operational and mission capabilities, including the optimal arrangement of weapon and navigation systems, as well as vessel survivability. Early-stage evaluation of the volumetric footprint enables an informed assessment of whether internal reconfiguration may be necessary, a critical consideration for naval applications. Subsequently, the impact of CCS system installation on vessel displacement is evaluated. These analyses are based on technical data provided by a leading CCS industry stakeholder. Any increase in displacement may influence vessel stability, speed, and fuel consumption, potentially resulting in operational trade-offs that must be carefully considered during the integration phase.

The relevant Key Performance Indicators (KPIs) considered in the study are: the net capture rate, the ships endurance, and the impact on both general arrangements and full-load displacement.

4. Case study

This study investigates the feasibility of integrating onboard carbon capture systems on a modern military destroyer. Fig. 4 shows the vessel's general layout, while Table 1 summarizes its main characteristics. A destroyer is a fast, versatile, and heavily armed warship designed for a wide range of military operations. It provides three-dimensional defense capabilities, ensuring protection against the aerial, surface, and underwater threats.

The examined vessel features an advanced propulsion configuration based on a Combined Diesel Or Gas Or Electric (CODOGOL) system,

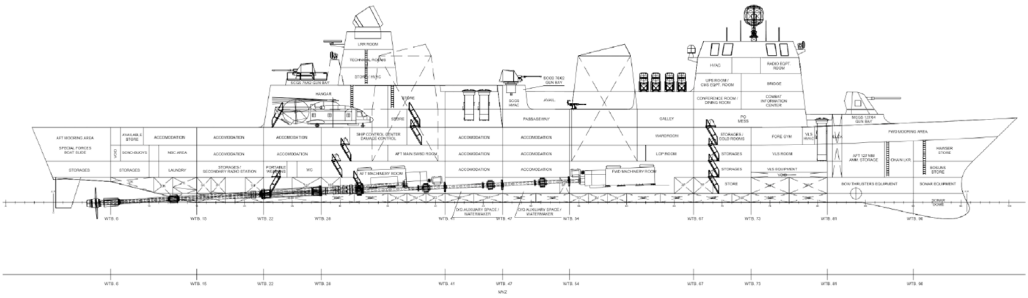

Fig. 4. Vessel's longitudinal section (Belvisi, 2021).

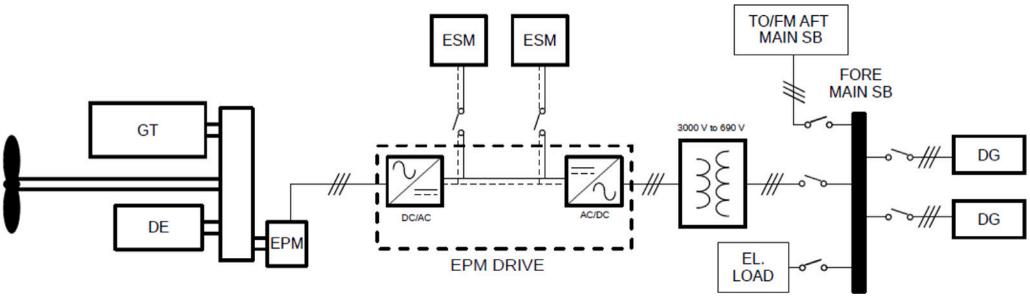

Fig. 5. Propulsion plant layout (one shaft) (Belvisi et al., 2024).

Table 1
Vessel's main data (Belvisi, 2021).

Data	Value	u.o.m
Length Overall (LOA)	165	m
Breadth (Bmax)	21.80	m
Draught (D)	12.60	m
Displacement, full-load (Δ)	8737	t
Displacement, End-of-Life (Δ_f)	9170	t
Range @18 knots	7000	Nm
	16	days

complemented by a Battery Energy Storage System (BESS) segmented into four independent Energy Storage Modules (ESM) (Belvisi et al., 2024, 2022). The maximum speed of 29 knots is reached using gas turbines, while the power required to maintain the cruise speed of 18 knots is provided by two diesel propulsion engines. In addition, two Electric Propulsion Motors (EPMs) support patrol speed, while four diesel generators supply electrical power. The propulsion plant is structured with two shaft lines, Fig. 5 outlines the plant configuration and Table 2 presents the sizing of the components of the propulsion system.

Based on industrial data, the performances of two carbon capture technologies: amine-based absorption and calcium looping were evaluated, considering their feasibility in terms of efficiency, operational constraints, and integration within the vessel's design. The analysis is carried out at a cruise speed of 18 knots, as this is the speed at which the vessel is expected to operate for most of its service life, according to the operational requirement. This choice excludes combat scenarios, where environmental requirements are of secondary importance, to avoid potential penalties on military effectiveness. A detailed comparison of these systems is presented in the following section. The original ship's data required for the two capture plant sizing are summarized in Table 3.

4.1. Amine-based carbon capture

The first carbon capture technology considered in this case study is amine-based absorption, a mature post-combustion solution widely adopted in stationary industrial applications. In the proposed configuration, exhaust gases are first treated in a Desulfurisation Tower (DeSOx), which ensures compatibility with chemical solvents, although low sulphur fuels are typically used in naval applications. The exhaust gas from all the machinery enters the DeSOx tower at approximately 350 °C and is cooled to approximately 35–40 °C before entering the absorber unit, which operates at nearly 40 °C. In the absorber, carbon dioxide is chemically bound to an amine-based solvent, producing a CO_2-rich solvent stream that leaves the bottom of the unit at about 40 °C. The CO_2-rich solvent is then routed to a regeneration unit (stripper tower), where it is heated to about 60 °C in order to release the absorbed CO_2, allowing the solvent to be reused in a closed-loop process.

Fig. 6 illustrates a possible system layout on board; for clarity, the schematic shows the capture system for a single shaft line, noting that the system is identical for the second shaft line. The captured CO_2 is subsequently cooled, compressed, and liquefied for storage on board. This liquefaction unit, which includes chillers, compressors, dryers, and pumps, is shared between the two shaft lines and designed to handle merged exhaust streams from the two capture systems. The carbon capture system was sized and analysed across three distinct capture rate scenarios (30%, 60%, and 75%) to thoroughly assess its scalability and the related impacts on the architectural configuration of the vessel. The sizing is summarized in Table 4, and the resulting integration layouts are presented in more detail in Section 5. The calculations are based on the assumption that the heating power required for solvent regeneration can be supplied by the vessel's high- and low-temperature (HT/LT) engine cooling systems. The objective is to supply hot water (in the range of 70 °C to 90 °C) sufficient to enable the operation of the regeneration column reboiler. The marine diesel engines typically provide a thermal power flow through the cooling water equal to approximately 40% of the mechanical output, at temperatures around 85 °C. Consequently, in the present case, about 2 MW of thermal energy can be recovered at cruising speed per shaft line. The assumption of complete heat recovery is fully satisfied for a 30% gross capture rate. However, for higher capture rates, the thermal demand increases and would require further investigation. It should be noted that Table 4 does not include the weight and volume of ancillary components, such as piping, which are expected to be negligible compared to the main

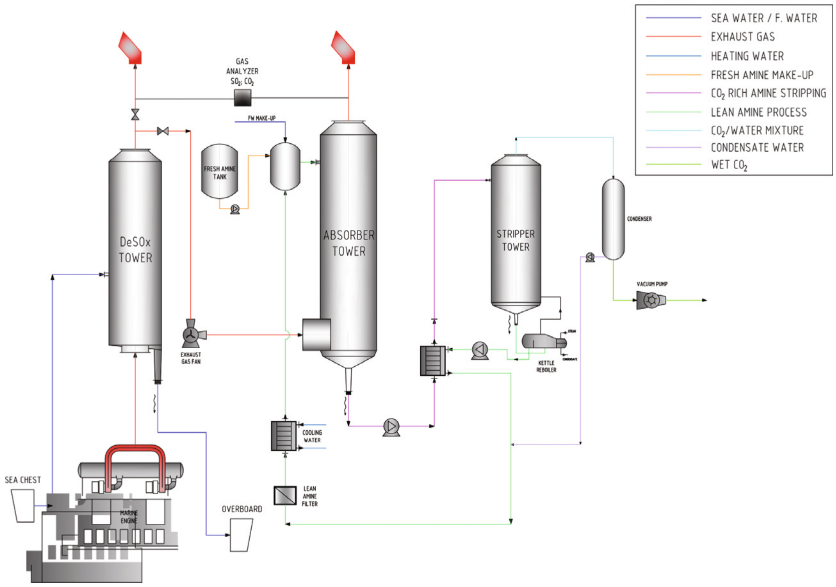

Fig. 6. Amine-based CO_2 capture system layout (Ecospray, 2024b).

Table 2
Sizing of the main propulsion and generation machinery (Belvisi et al., 2024).

Gas Turbines (GT)	2 × 30,600 kW @ 3600 rpm, 220 g/kWh min
Propulsion Diesel Engines (DE)	2 × 7,280 kW @ 1150 rpm, 188 g/kWh min
EPM	2 × 1,120 kW @ 880 rpm
Diesel Generators (DG)	4 × 2,240 kW/2,150 kWe @ 1800 rpm, 188 g/kWh min
BESS	4 × ESM (3,240 Ah @ 972 V)
ESM	18 (series) × 54 (parallel) modules (60 Ah @ 54 V)

Table 3
Data at cruise speed for one shaft (Belvisi, 2021).

Propulsion Diesel Engine Power	5.45	MW
Aux Diesel Engines Power	1.18	MW
Fuel Oil Consumption	1.351	t/h
Total Exhaust Gas Flow Rate (DE+Aux)	17	m^3/s
Total CO_2 Emissions (DE+Aux)	4.203	t/h

Table 4
Amine-based CCS main dimensions and weight (Ecospray, 2024b).

Main item list	Qty	L × W × H [m]	Total weight [t]		
		30%	30%	60%	75%
DeSOx Tower	2	2 × 2 × 10	100	115	145
Exhaust Gas Fan	2	2 × 1.5 × 2			
Water Pump	2	0.7 × 0.6 × 2.5			
CO_2 Absorber Unit	2	2 × 2 × 13			
Amine Stripping Unit	2	1 × 1 × 11			
Lean Amine Supply Pump	2	0.4 × 0.4 × 1			
Amine Stripper Supply Pump	2	0.4 × 0.4 × 1			
Amine Filter	2	1.2 × 0.5 × 0.5			
Amine Heat Exchanger	2	4 × 1 × 1			
Condenser Unit	2	1 × 1 × 3			
Pumps & Filter	2	1 × 2 × 3			
Vacuum Pump	2	7 × 2 × 2			
CO_2 Gas Analyzer	1	1 × 1 × 0.5			
Amine Buffer Tank	1	3 × 3 × 2			
CO_2 Liquefaction Plant	1	13 × 3 × 3	50	65	80
CO_2 Compressor Unit	1	5 × 3 × 3			
CO_2 1° Stage Chiller	1	2 × 2 × 2			
CO_2 2° Stage Chiller	1	5 × 2 × 3			
CO_2 Dryer Unit	1	1 × 1 × 2			

equipment. Furthermore, since this study represents a preliminary feasibility assessment, no detailed investigation of the precise placement of the system on board has been carried out, making accurate estimates of the weight and dimensions of these components unfeasible at this stage.

4.2. Calcium looping

The second technology considered in this study is calcium looping, an emerging post-combustion carbon capture process. The CL system, depicted in Fig. 7 relies on the chemical reaction between calcium hydroxide ($Ca(OH)_2$) and carbon dioxide to form solid calcium carbonate ($CaCO_3$). The proposed onboard setup includes a DeSOx tower, two parallel absorber units with slurry recirculation, a bubbling section to promote gas–liquid mixing, and buffer hoppers for intermediate storage. In this configuration, exhaust gases are introduced into absorber reactors containing an aqueous $Ca(OH)_2$ slurry, where carbon dioxide is captured through direct chemical absorption. To enhance gas–liquid interaction and maximize CO_2 removal, the exhaust gases are treated through a two-stage process consisting of a bubbling unit followed by an absorption column, both operating with the calcium hydroxide suspension. Calcium hydroxide must be stored in dedicated silos and replenished periodically. The $CaOH_2$ mass flow rate is related to the capture target; for a 30% CO_2 capture rate, approximately 11 m^3/h of calcium hydroxide suspension are needed, corresponding to a reagent mass flow of about 2150 kg/h, while for 60% capture the requirements roughly double. Unlike amine-based systems, calcium looping eliminates the need for onboard CO_2 compression and liquefaction, as the captured carbon is stored in solid form. This leads to significant energy savings and a simplified system architecture. Furthermore, $CaCO_3$ is generally considered environmentally benign and, under regulatory conditions that are not yet established, could be discharged into the sea (Bortuzzo and Bertagna, 2025). A recent study suggested that such discharge might even provide ancillary environmental benefits, as dispersed $CaCO_3$ can partially counteract ocean acidification by buffering seawater pH and supporting calcifying organisms (Zhang

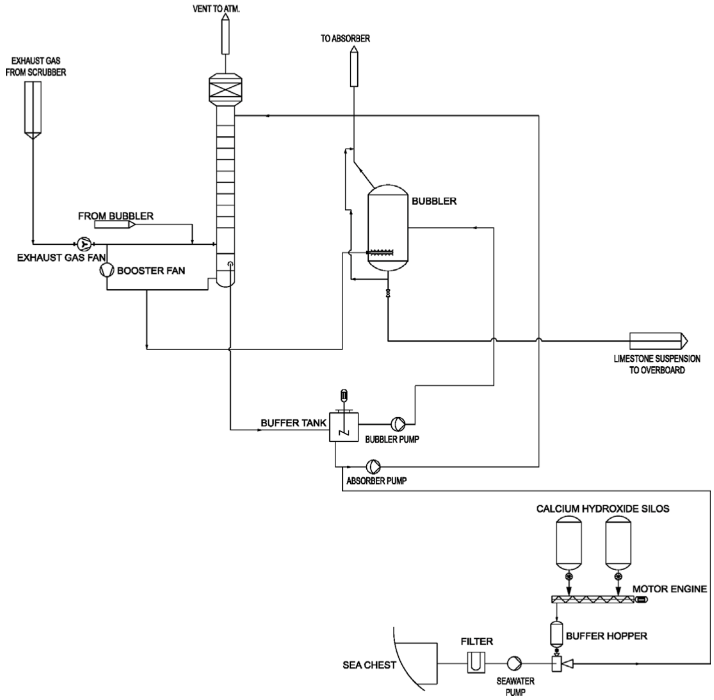

Fig. 7. Calcium looping-based CO_2 capture system layout (Ecospray, 2024b).

Table 5
Carbon capture system with calcium looping main dimensions and weight (Ecospray, 2024b).

Main item list	Qty	L × W × H [m]	L × W × H [m]	Total weight [t]	
		30%	60%	30%	60%
DeSOx Tower	2	2 × 2 × 10	2 × 2 × 10	60	90
Exhaust Gas Fan	2	2 × 1.5 × 2	2 × 1.5 × 2		
CO_2 Absorber Unit	2	2 × 2 × 13	2.5 × 2.5 × 13		
Lime Buffer Tank	2	5 m^3	5 m^3		
Bubbler	2	5 m^3	5 m^3		
Buffer Hopper	2	10 m^3	10 m^3		
Pumps and Fans	2	3 × 2 × 2.5	3 × 2 × 2.5		

et al.), although large-scale applications would require careful assessment of long-term ecological impacts and alignment with international regulatory frameworks (Bortuzzo and Bertagna, 2025). The storage in solid form or the discharge at sea represent important advantages with respect to amine CCS. From a regulatory perspective, $CaCO_3$ is not listed among prohibited wastes under Annexes I and II of the London Convention (RINA, 2025). According to the IBC and IMSBC codes, dry calcium hydroxide is classified as Group B for transport, while $CaCO_3$ in solid or suspended form is Group C, posing no identified hazards (RINA, 2025). Its disposal at sea could therefore be considered analogous to geological CO_2 storage, pending a technical assessment as outlined in Annex III of the London Convention, and may be allowed or incentivized by international bodies (RINA, 2025). This could be an important advantage for military vessels operating in remote or logistically constrained areas.

A conceptual integration layout is discussed in Section 5, where performance and operational impacts are further evaluated. Table 5 summarizes the size and weight of the main components required for installation, excluding the storage of the reagent.

5. Results

This section presents the main findings from the application of the proposed methodology to amine-based and calcium looping carbon capture technologies, as implemented on the reference destroyer. The analysis, as presented in Section 3, focuses on net CO_2 removal performance, endurance variations, and the implications of onboard integration in terms of space, and weight. These parameters are assessed at different CO_2 nominal capture rates to understand scalability and feasibility in naval applications. The results aim to inform future design trade-offs between environmental performance and operational constraints.

5.1. Operational and environmental performance

This subsection presents a comprehensive analysis of the CO_2 removal performance and the corresponding energy demands of the carbon capture systems. The main energy results of are presented in Table 6. These data quantify the increase in fuel consumption resulting from the operation of the carbon capture system and, consequently, its impact on the vessel's endurance. The endurance reductions reported in Table 6 are based on the increased fuel consumption associated with the auxiliary power demand of the carbon capture systems. As previously mentioned, these estimates do not consider secondary effects, such as the additional hydrodynamic resistance caused by increased ship's displacement. As such, the actual impact on operational range may be slightly underestimated, depending on the extent of integration and the resulting hull loading conditions. Based on these energetic considerations, Fig. 8 provides a detailed visualization of the estimated gross and net CO_2 capture efficiencies for all scenarios considered. It should also be noted that the system requires standard maintenance practices, comparable to conventional shipboard equipment. From a safety perspective, the amines, according to the Safety Data Sheet, can be considered toxic if not handled properly, necessitating adequate crew training in the correct use of personal protective equipment and in safe operational procedures.

5.2. Onboard integration analysis

This subsection provides a quantitative assessment of the additional mass and spatial requirements associated with the integration of carbon capture technologies onboard the reference destroyer. The analysis

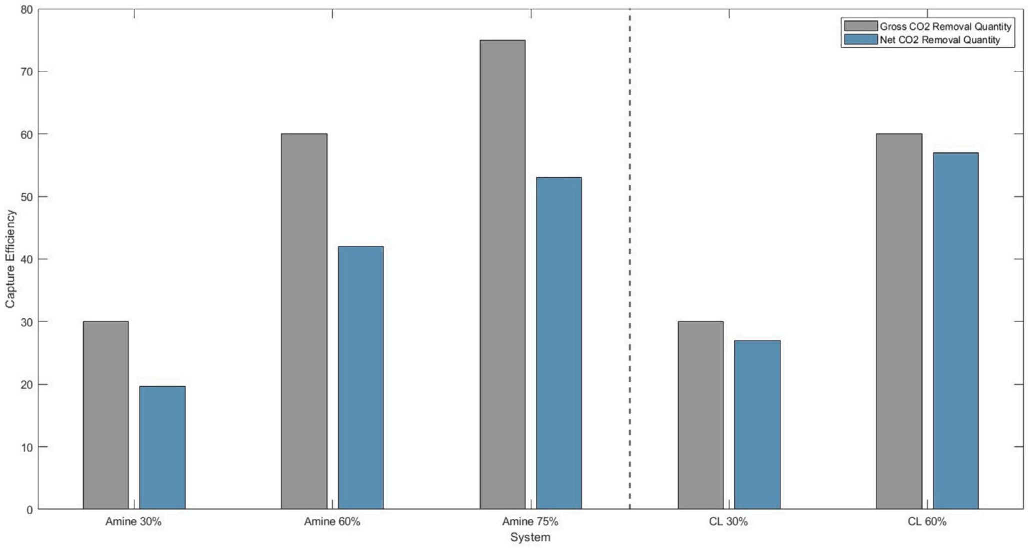

Fig. 8. CO_2 capture efficiency.

Table 6

Operational and environmental results.

Parameters		Amine			Calcium looping	
		30%	60%	75%	30%	60%
Add. Fuel Cons.	[kg/h]	226	453	585	78	78
Endurance Reduction	[%]	−8	−17	−22	−3	−3

Table 7

Design results.

Parameters		Amine			Calcium looping	
		30%	60%	75%	30%	60%
Liquid CO_2 production	$[\frac{m^3}{day}]$	53	107	136	–	–
Δ Full Load Departure	[%]	+15	+28	+35	+19	+37
Δ Full Load Arrival	[%]	+2.8	+4.2	+5.4	+0.7	+1.1
Additional Volume	$[m^3]$	1300	2600	3400	1000	1800

aims to quantify their impact on the displacement and internal arrangement of the vessel. The mission profile is assumed to last 16 days, a time frame used to assess the accumulation of captured CO_2 and the required quantity of calcium hydroxide for onboard storage. The CO_2 storage volume for amine-based capture, is evaluated on the base of the liquid CO_2 production reported in Table 7. For CL carbon capture, using the mass flow rate data provided in Section 4.2 and assuming a reagent density of approximately $2240\ kg/m^3$, the required storage volumes can be estimated. For a capture rate of 30%, a volume of approximately 370 m^3 is needed, while for a 60% capture rate the corresponding volume increases to approximately 740 m^3, sufficient to ensure CO_2 capture over the full endurance of the vessel at a cruising speed of 18 knots. To assess the impact of system integration on the full load displacement of the vessel (9170 tonnes), two distinct operational scenarios are defined: the departure scenario and the post-mission scenario. The first represents the initial state of the vessel at the beginning of the mission, while the post-mission scenario represents the state of the vessel at the end of the 16-days mission.

For the Amine-Based Carbon Capture System:

- Departure scenario: the CO_2 storage tanks are assumed to be empty, representing the minimum additional displacement attributed to the carbon capture system. The amine solvent is fully loaded and continuously regenerated during operation, meaning that its mass remains essentially constant throughout the mission. Minor solvent losses may occur, on the order of 1–5 ppm, but these are negligible relative to the total amount of solvent in circulation.
- Post-mission scenario: the CO_2 tanks are considered to be fully saturated with liquefied carbon dioxide.

For the calcium looping system:

- Departure scenario: the displacement includes the total mass of calcium hydroxide used for the capture process.
- Post-Mission scenario: the reagent tanks are considered empty. It is worth noting that for this scenario it is assumed that discharge of the $CaCO_3$ during navigation is allowed.

Table 7 summarized the most relevant parameters used to evaluate the onboard integration.

The spatial implications of integrating carbon capture systems achieving a 30% gross capture rate on the reference destroyer are illustrated in Figs. 9 and 10. The objective of these illustrations is to provide a qualitative indication of the volumetric impact and architectural constraints associated with each CCS technology when applied to a platform of this type. It should be emphasized that the configurations are merely conceptual and do not reflect an optimized integration strategy, which lies beyond the scope of the present study.

6. Discussion

The comparative assessment between amine-based and calcium looping carbon capture systems highlights critical trade-offs in terms of environmental performance, system complexity, and operational feasibility for naval applications. Amine-based absorption technology, as illustrated in Fig. 8 achieves the highest gross CO_2 capture efficiency, reaching up to 75%. However, this performance comes at the cost of substantial energy consumption, primarily due to capture and liquefaction of CO_2. These requirements substantially increase fuel consumption, resulting in a higher carbon footprint and consequently reducing the net capture efficiency to approximately 50%. Furthermore, additional fuel consumption results in a reduction in vessel endurance by up to 22% (Table 6), assuming the fuel tank volume remains unchanged. This aspect represents a critical challenge for military vessels, where operational endurance is a fundamental parameter that directly impacts mission effectiveness and strategic capabilities. The reduced endurance due to increased fuel consumption

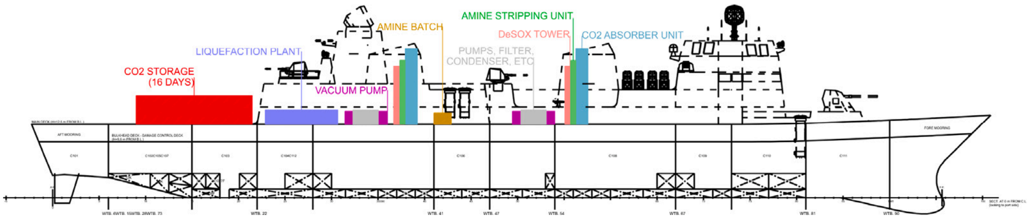

Fig. 9. Indicative positioning of an amine-based carbon capture unit on board (30% Capture Rate), illustrating the spatial footprint and potential integration constraints.

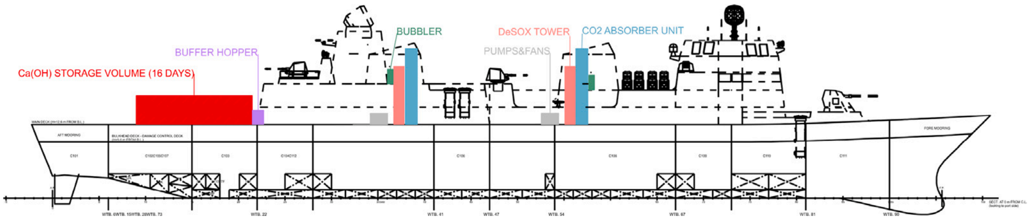

Fig. 10. Indicative positioning of an calcium-looping carbon capture unit on board (30% Capture Rate), illustrating the spatial footprint and potential integration constraints.

limits the ability of the vessels to sustain prolonged deployments without the need for frequent refuelling, thus constraining its flexibility. The capture based on amines, as highlighted in Fig. 9 and Table 7, poses notable integration challenges, with equipment and storage components occupying up to 3400 m^3, and contributing to a significant increase in displacement. These factors can compromise payload and may negatively impact vessel stability and combat readiness. Additionally, as previously mentioned, the system operates at relatively high temperatures and requires cryogenic, pressurized CO_2 storage conditions that raise concerns regarding onboard safety and vulnerability. In military contexts, such configurations may elevate the risk of system failure or damage propagation under combat scenarios.

In contrast, the calcium looping system analysed in this study is based on the assumption that the reaction by-product ($CaCO_3$) could be discharged into the sea. As previously discussed, the reaction by-product is considered to be an aqueous suspension of $CaCO_3$, which is biocompatible and could therefore be directly discharged overboard. As a result, no specific onboard containment or treatment infrastructure would be required, since the residue does not entail storage or complex handling operations. This assumption simplifies integration (Fig. 10) and reduces energy demand, limiting endurance loss to approximately 3% for both 30% and 60% capture rate (Table 6). However, this benefit comes with substantial trade-offs. The system does not include onboard regeneration of the reagent, requiring continuous consumption of calcium hydroxide during operation. Traditional $Ca(OH)_2$ production is associated with a significant carbon footprint, with approximately 1 t of CO_2 emitted per ton of $Ca(OH)_2$ produced (Castaño et al., 2021). The adoption of low-carbon or "green" reagents could mitigate these upstream emissions, but would further increase operating costs of about 30% (Ecospray, 2024b). Moreover, the quantity of calcium hydroxide required for long-range naval operations is considerable, leading to significant mass and volume requirements. This imposes constraints on onboard storage capacity and may reduce the availability of space for mission-critical systems, supplies, or personnel. Both systems also present operational and logistical burdens. Amine-based configurations require storage, handling, and periodic offloading of liquefied CO_2 under strict safety and environmental regulations. These operations may be particularly challenging for vessels deployed in remote areas or without access to specialized port facilities. Calcium looping, while eliminating CO_2 liquefaction and storage, introduces logistical dependency on a steady supply of bulk reagent and a compliant method for solid waste discharge, that is currently an unresolved regulatory issue. The spatial and weight implications highlighted for both CCS technologies indicate that a realistic implementation would be more appropriately addressed during the initial design of new naval units rather than as retrofits. Integrating CCS from the outset would allow a comprehensive assessment of the placement of weapon systems, sensors, and other mission-critical equipment, as well as an optimized distribution of all onboard installations. Such a holistic approach would ensure that decarbonization measures can be incorporated without compromising operational performance, survivability, or combat efficiency.

In summary, calcium looping offers distinct advantages in terms of integration simplicity and reduced energy demand, aligning better with the constraints of military platforms operating over long durations. However, it introduces significant challenges related to reagent sourcing, onboard storage, and environmental sustainability. On the other hand, amine-based systems, while more advanced, involve greater complexity, energy consumption, and vulnerability factors that may limit their operational viability in defense scenarios. While this study focuses on decarbonization technologies, the complementary role of operational measures is essential. Slow steaming represents the most immediate and impactful lever for military vessels during non-critical transit phases. This strategy is particularly effective because the high speeds required for naval operations often rely on propulsive assets like gas turbines or combined configurations. These high-power systems are inherently operating with high specific fuel consumption and, consequently, significant associated CO_2 emissive impact. Therefore, a holistic naval decarbonization strategy must integrate technological retrofits with appropriate, mission-dependent operational strategies.

7. Conclusions

This study explored the applicability of post-combustion carbon capture technologies on military naval platforms, addressing a sector that is currently excluded from most decarbonization efforts. A comprehensive review of the current state of the art, including recent regulatory developments and classification society guidelines, served as the contextual foundation for the analysis. A methodology was proposed to evaluate carbon capture solutions on naval vessels, considering not only technical feasibility but also capture efficiency and integration constraints. The methodology was applied to a destroyer-class vessel, analysing amine-based absorption and calcium looping technologies, selected among various options for their contrasting characteristics and implementation maturity. The findings suggest that configurations achieving a gross capture rate of approximately 30% currently offer the most viable balance between environmental benefit and onboard integration challenges. These setups result in an effective net capture of 20%–27%, depending on the selected technology, while limiting the impact on endurance and displacement. However, even these lower-range configurations pose significant space and weight constraints, particularly critical for retrofit applications, underscoring the importance of integrating carbon capture systems from the initial design phase.

Amine-based systems demonstrate superior gross capture performance but impose significant energy demands and integration complexities that adversely affect net capture efficiency, operational endurance, safety, and survivability of naval platforms. Consequently, further research is essential to improve the energy efficiency of these systems. Potential avenues include the development and implementation of next-generation solvents characterized by reduced regeneration energy requirements as well as the exploration of advanced absorption processes and hybrid configurations aimed at optimizing overall system performance. With regard to calcium looping, its operational simplicity and higher energy efficiency present compelling advantages. However, a critical challenge lies in the management of the by-product, calcium carbonate, generated during the capture cycle. The permissibility of marine disposal of this material, along with its associated environmental impacts, is contingent on evolving regulatory frameworks and classification society guidelines. Thus, a thorough understanding of forthcoming regulations concerning waste handling and disposal is imperative to ensure that the adoption of calcium looping technology remains both environmentally compliant and sustainable in the long term. These findings highlight the trade-offs between environmental performance and system integration constraints in military applications. While both technologies show potential for short- to medium-term implementation, their feasibility is highly dependent on vessel type, mission profile, and logistic support. The present results apply specifically to the destroyer-class vessel analysed, future work should explore carbon capture solutions across a broader range of naval platforms, as the optimal technology and integration strategy is expected to vary significantly with vessel type, mission requirements, and spatial constraints. Another important extension of this study would be the analysis of more onerous operational scenarios, such as combat conditions, to evaluate CCS performance under peak power demand and to quantify any transient impacts on propulsion availability and platform responsiveness. In parallel, a dedicated investigation into the detailed spatial allocation of CCS components is required. Such work should consider the optimal positioning of capture units relative to weapon systems, sensors, and other mission-critical equipment, while also assessing implications for damage control, survivability, and maintenance access. These assessments are essential to ensure that decarbonization measures can be implemented without compromising the vessel's operational capability. Future research should focus on addressing the key technical and operational challenges associated with both technologies, including improving energy integration for amine-based systems and developing effective waste management strategies for calcium looping. In addition, comprehensive assessments of the impact on vessel performance and mission readiness are needed to support informed decision making regarding the implementation of carbon capture in naval environments.

CRediT authorship contribution statement

Giorgia Adami: Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Riccardo Rocchi:** Validation, Data curation. **Massimo Figari:** Writing – review & editing, Supervision, Resources, Project administration, Methodology, Conceptualization.

Abbreviations

The following abbreviations are used in this manuscript:

AUX	Auxiliary Engine
B	Breadth
BESS	Battery Energy Storage System
$CaCO_3$	Calcium Carbonate
$Ca(OH)_2$	Carbon Hydroxide
CCC	Cryogenic Carbon Capture
CCS	Carbon Capture and Storage
CL	Calcium Looping
CODOGOL	COmbined Diesel Or Gas Or Electric
CO_2	Carbon Dioxide
CO_2eq	Equivalent Carbon Dioxide
D	Draught
DE	Propulsion Diesel Engine
DG	Diesel Generators
DeSOx	Desulphurization
EPM	Electric Propulsion Motor
ESM	Energy Storage Modules
ETS	Emission Trading System
EU	European Union
GHG	Greenhouse Gases
GT	Gas Turbine
GWP	Global Warming Potential
H	Height
H_2	Hydrogen
HT/LT	High-Temperature/Low-Temperature
IBC	International Bulk Chemical Code
IMO	International Maritime Organization
IMSBC	International Maritime Solid Bulk Cargoes Code
KPI	Key Performance Indicators
L	Length
LCA	Life Cycle Assessment
LNG	Liquefied Natural Gas
LOA	Length Overall
MCFC	Molten Carbonate Fuel Cell
TRL	Technology Readiness Level
W	Width
WtW	Well to Wake Emissions
Δ	Displacement

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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