Journal of Cleaner Production 452 (2024) 142032

Contents lists available at ScienceDirect

Journal of Cleaner Production

journal homepage: www.elsevier.com/locate/jclepro

Exploring the technical feasibility of carbon capture onboard ships

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ARTICLE INFO

Handling Editor: Panos Seferlis

Keywords:
Maritime industry
Carbon capture
Low-emission shipping
Retrofit
Newbuidling

ABSTRACT

International shipping is crucial for freight transport, but it relies primarily on fossil fuels, contributing 3% of global greenhouse gas emissions. This calls for urgent action to decarbonize the shipping industry. While renewable-based e-fuels are a strong candidate for decarbonization of this sector in the long run, deploying these to the required scale will take significant time, considering technical modifications onboard the vessels, as well as the changes in fuel production and infrastructure for distribution. Carbon capture from ships is another route to emission reduction that can be implemented faster due to the relatively high maturity of the technology. Tankers, dry bulk carriers, and container vessels contribute a majority of global shipping emissions and are therefore prime candidates for carbon capture and storage. Solvent-based post-combustion capture is chosen for this study as it is mature and suitable for marine applications, though technical, economic, environmental, and practical challenges remain. This paper assesses the technical feasibility of the capture system for ships; both retrofit and newbuild vessels. While achieving zero-emissions presents a significant challenge, it is feasible to attain 70%–90% CO_2 reduction through carbon capture in the near term. This reduction is crucial for transforming the industry into a more sustainable and environmentally friendly state. The limitation of space onboard is identified as a key factor in determining the viability, and the 70%–100% increase in energy consumption between existing ships and newbuild will be a substantial operational challenge. However, the high fuel consumption of the capture system could be economically acceptable if the price of alternative fuels remains high.

1. Introduction

The maritime industry is responsible for the transportation of around 80% of global trade, while accounting for 3% of global greenhouse gas emissions (UNCTAD, 2017). Seaborne trade grows at approximately 3% per year, and thus the shipping industry must improve its carbon intensity significantly to reduce greenhouse gas emissions. The International Maritime Organization (IMO) has set targets to reduce the carbon intensity of international shipping by at least 40% in 2030 compared to 2008 levels and close to zero by 2050 with an indicative checkpoint for at least 70% on 2040 (IMO, 2023).

Currently, ships rely on fossil fuels for energy generation, with heavy fuel oils (HFO) accounting for roughly 64% of the usage and marine gas oil (MGO) or marine diesel oil (MDO) accounting for up to 32%. Liquefied natural gas (LNG) constitutes the remaining 4%. Minuscule volumes of liquefied petroleum gas (LPG) and methanol, both of fossil origin, are also part of the fuel mix. The maritime industry is actively exploring the use of low-carbon footprint fuels (Zhang et al., 2023), such as green or blue ammonia and hydrogen, biofuels and bio-LNG (Mukherjee et al., 2023), and synthetic carbon-based fuels such as e-methanol, e-diesel, and e-LNG (Balcombe et al., 2021). These fuels have the potential to significantly reduce greenhouse gas emissions and make shipping climate-neutral. However, it is important to consider the upstream emissions associated with the production of these fuels when evaluating their overall environmental impact and to ensure that the entire life cycle of the fuel is taken into account (Lloyd’s Register, 2020). Currently, 99% of the hydrogen, ammonia and methanol produced today are of fossil origins with a higher well-to-wake footprint and thus impairing the environmental benefits of switching to these. While engines and shipboard systems for hydrogen, ammonia, and methanol are under development, these fuels also require extensive shoreside infrastructure. The high energy consumption to produce these fuels with electricity is likely to make them expensive(Ueckerdt et al., 2024). Therefore, it is crucial to find feasible technologies that can also reduce the emissions from ships in the coming years.

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https://doi.org/10.1016/j.jclepro.2024.142032
Received 2 November 2023; Received in revised form 20 February 2024; Accepted 29 March 2024

Nomenclature

CAPEX	Capital expenditure
CCS	Carbon capture and storage
CO	Carbon monoxide
CO_2	Carbon dioxide
DWT	Dead weight tonnage
HFO	Heavy fuel oil
IMO	International maritime organization
LNG	Liquefied natural gas
LPG	Liquefied petroleum gas
MDO	Marine diesel oil
MGO	Marine gas oil
NO_X	Nitrogen oxide
OCCS	Onboard carbon capture and storage
OPEX	Operating expenditure
SCR	Selective catalytic reduction
SO_X	Sulfur oxides
THC	Total hydrocarbons
TRL	Technology readiness level

Carbon capture and storage (CCS) plays a crucial role in reducing greenhouse gas emissions in industries on land, and they could also become a viable option in the maritime sector. While there is growing interest in alternative fuels, CCS could offer a solution for ships that still rely on fossil fuels, presenting a practical way to reduce emissions in the maritime industry. In the recent study of DNV (DNV, 2023b), CCS emerges as a substantial contributor to decarbonizing the shipping sector when compared to alternative solutions.

CCS technology involves capturing carbon dioxide (CO_2) emissions from the ship's exhaust gas system, intermediate storage onboard, offloading in port for transport, and permanent storage. Alternatively, CO_2 can be used in industrial or chemical processes or can be transformed (Carbfix hf, 2023). Several ongoing research efforts are exploring the feasibility and effectiveness of CCS systems for the maritime sector. These efforts involve process modeling and cost analyses of CCS systems for different types of ships (Long et al., 2021).

However, the maritime sector is very diverse and therefore it is important to understand the feasibility and challenges of implementing CCS onboard different types of vessels. Complex and expensive environmental technology such as onboard carbon capture and storage (OCCS) will likely be most cost-effective on vessels with large engines, high fuel consumption, and ample space in the engine room or in or near the casing. According to the IMO 2018 report, tank, bulk and container vessels are responsible for more than 60% of the emissions from the shipping industry. Although these types of vessels are fewer in number, they have high fuel consumption and emissions. Table 1 provides data on the number of ships in various categories, with the first three rows representing dry bulk carriers, tankers, and container vessels. The table shows that these three categories emitted 666 million tonnes of CO_2 in 2018, which is significantly higher than the emissions produced by other categories, which produce 228 and 162 million tonnes respectively. When the data in the table are normalized, it becomes apparent that studying one case within the first three groups of ships can have an impact on reducing carbon emissions more than eight times compared to studying a case within the last two groups. Dry bulk carriers and oil tankers have available space on deck, while this space is valued for cargo on container vessels. Therefore, bulk and tanker vessels can be the most promising candidates for onboard OCCS.

This paper aims to contribute to ongoing efforts to reduce greenhouse gas emissions in the maritime industry by providing the technical challenges associated with the implementation of CCS onboard ships. While there are several capture technologies suitable for the maritime industry, solvent-based post-combustion capture has been identified as a highly promising technology due to its high technology readiness level (TRL) (Feenstra et al., 2019; Cousins et al., 2015; Awoyomi et al., 2020). The paper will investigate the feasibility of implementing CCS on both existing vessels and newbuild ships, taking into account factors such as general arrangement, power, energy and heat balance, fuel consumption, engine type, and machinery configuration. The retrofit vessel focuses more on utilizing the available space onboard, considering the general arrangement and possible limitation in installation of OCCS equipment in the engine room and the casing. The newbuild case offers more freedom to extend the length of the vessel. While prior researches has investigated the feasibility of onboard carbon capture, this study takes a unique approach by conducting an in-depth analysis on quantifying the heat and power consumption, as well as space and footprint requirements, along with water and cooling capacity needs of the capture system for the two specific scenarios.

In the upcoming sections, we will take a closer look at different aspects of carbon capture on ships. First, in Section 2, we explore the challenges of integrating carbon capture technology with ship power generation. Then, in Section 3, we outline the specific case studies for further discussion. Section 4 will provide a detailed analysis of the existing case, where we retrofit existing ships with carbon capture systems. Moving on to Section 5, we focus on the newbuild case, where we examine how to design ships with integrated carbon capture systems efficiently. To wrap it up, we summarize the main goals and importance of our research in Section 6, emphasizing the importance of CCS in reducing emissions within the maritime industry.

2. Integrating carbon capture with ship power generation: Technical and economic challenges

Installing CCS technology on a ship is a more complex undertaking than in onshore facilities that must address specific requirements: for example, space limitation, safety considerations for crew members, the enhanced degradation of materials in a marine environment, vibrations, constant motions and accelerations, etc. Also, a shipboard installation does not enjoy the same access to service personnel as an onshore facility, while the requirements to operability and reliability are high. Integrating OCCS into the machinery system can also significantly impact the overall performance and operations of the ship. In this regard, it is crucial to evaluate the key parameters that must be taken into account to ensure successful integration. This section presents the critical aspects that must be investigated when installing CCS onboard a ship. Fig. 1 presents a summary of all the factors discussed in this section, divided into two columns: the factors that are "Considered" in the case studies and the factors that are "Not Considered" in the case studies.

Given the extensive and long experience for onshore applications, post-combustion CO_2 capture technologies can be an immediate and ready-to-deploy option to reduce the emissions from the shipping industry, while also being considered as a long-term solution (DNV, 2023b). Therefore, various technology options for post-combustion CO_2 capture have been considered for ship applications such as chemical absorption (Feenstra et al., 2019), physical adsorption, membrane (Oh et al., 2022), cryogenic, and calcium looping processes (Sweeney, 2020). These concepts can be categorized into three types, heat-driven, electricity-driven, and material-driven systems.

Chemical absorption systems are representative of the heat-driven concepts where chemical solvents absorb CO_2 in the exhaust gas and it is heated to separate high purity CO_2. This heat-driven system is advantageous for use on a ship since the waste heat from the exhaust gas can be readily available to the capture unit (Einbu et al., 2022).

Adsorption processes utilize the adhesion of CO_2 on adsorbents, which are regenerated by temperature or vacuum swing. Thus, depending on the regeneration measure, the adsorption concept can be either a

Table 1
A general figure of the main CO_2 producers in the maritime industry (IMO, 2020).

Ship type	No. of vessels 2008	No. of vessels 2018	DWT 2008 (t)	DWT 2018 (t)	Total CO_2 2008 (Mt)	Total CO_2 2018 (Mt)
Dry Bulk	7827	11,948	55,801	69,392	194.3	193.4
Tanker	11,382	24,143	52,946	27,709	221.3	240.7
Container	4,681	5337	36,756	50,661	213.6	232.1
Other cargo	27,727	30,868	5787	6580	265	228
Passenger and services	53,176	165,137	461	1426	241	162

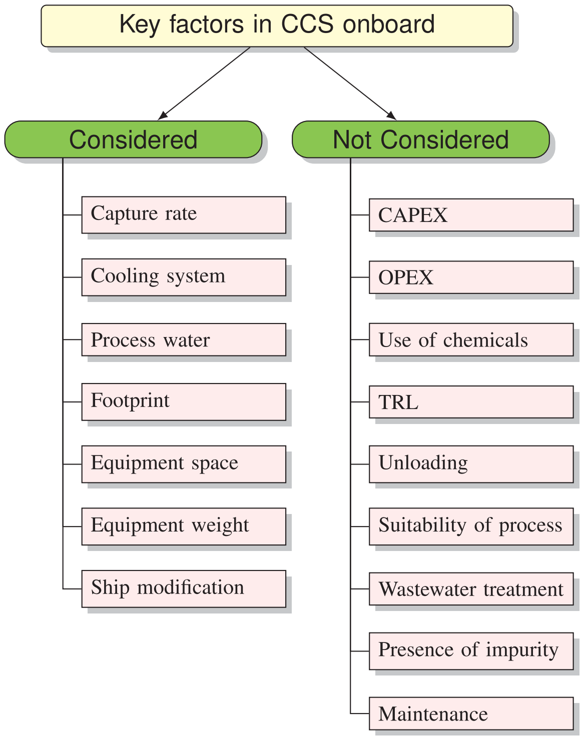

Fig. 1. Critical elements to take into account when fitting CCS on a vessel. Those elements that are grouped as "Not Considered", are just beyond the scope of evaluating the case studies in this research and should not be seen less significant.

heat or electricity-driven system. A typical characteristic of this process is the large footprint due to multi-train configurations (Bui et al., 2018), which will not be favorable to be deployed on ships.

The membrane process, on the other hand, is a compact and electricity-driven system with a reasonable energy consumption (Russo et al., 2018). However, the energy efficiency tends to decrease when aiming for deep CO_2 reduction, limiting its applications (Anantharaman et al., 2014).

Cryogenic systems are based on the solidification of CO_2 at cryogenic temperatures, which is derived by power input (Font-Palma et al., 2021). This concept, however, is still in the early stage of development.

Another early-phase technology for ship applications is calcium-looping (Arias et al., 2017). This material-driven process uses calcium oxide to capture CO_2 while producing a significant amount of heat. Therefore, the energy cost for the operation of the capture unit will be marginal. However, the high operating temperature and large space requirement for the solid inventory will be challenging for ships, and the cost for the regeneration of the sorbent onshore needs to be considered.

To determine the optimal solution for onboard CO_2 capture, a comprehensive analysis of the potential technology options is required considering all the critical elements presented in Fig. 1. However, in this work, the absorption process is regarded as the reference system for ship applications, considering the maturity of the technology. The design and performance of the capture system is presented in Supplementary information in detail and the selection of capture technologies for ships will be further discussed in the following sections with different criteria.

2.1. CO_2 capture and avoided rates

The aim of OCCS is to reduce CO_2 emissions, and its performance can be assessed by two parameters;

CO_2 capture rate,

$$\text{CO}_2 \text{ capture rate} = \frac{\text{Captured CO}_2 \text{ emissions}}{\text{CO}_2 \text{ emissions without OCCS}} \tag{1}$$

and CO_2 avoided rate,

$$\text{CO}_2 \text{ avoided rate} = 1 - \frac{\text{CO}_2 \text{ emissions with OCCS}}{\text{CO}_2 \text{ emissions without OCCS}} \tag{2}$$

The former indicates the amount of CO_2 captured from the flue gas entering an OCCS system, while the CO_2 avoided rate represents the reduction in CO_2 emissions facilitated by OCCS compared to a ship without OCCS. The avoided rate considers the extra emissions resulting from the energy consumption of an OCCS system, offering a more comprehensive measure for the entire system with the vessel. Instead, the capture rate is a better measure for the capture unit, reflecting the efficiency of the capture process.

2.2. Capital expenditure

Capital expenditure (CAPEX) accounts for the investment costs associated with the engineering, manufacturing, and installation of the CCS. It includes not only the equipments (blower, adsorber, desorber, heat exchangers, pumps, liquefaction, storage tanks, etc.), but also its integration onboard the ship and auxiliary systems. In land-based carbon capture applications, operating expenses are typically the main driver of costs (Roussanaly et al., 2021). However, for offshore (Roussanaly et al., 2019) and onboard carbon capture applications (Ros et al., 2022), CAPEX has a greater impact on total cost of ownership. To make costs comparable between different projects, an annualized capital cost is often calculated. This is calculated by multiplying the CAPEX by a capital recovery factor calculated based on the project lifetime and the discount rate (typically a lifetime of 25 years and a discount rate of 8%). However, for the retrofit case, the remaining lifetime can be shorter, resulting in a higher contribution of CAPEX to the total cost. Although there are currently a limited number of techno-economic analyses of onboard CO_2 capture, the results from five studies are summarized here. As shown in Fig. 2, capital cost has been reported between 42 and 300 €/tonne. Although other factors such as CO_2 concentration are also influential, capital costs are significantly dependent on the total captured CO_2. Compared to inland industrial applications, CO_2 capture units are mainly on a small scale. Hence, the size of the power production is in the order of a few megawatts for the large vessels, and thus the capture capacity of the plants is above twenty thousand tonnes per year. Several cases in the literature reported capital costs between 50 and 100 € per tonne of CO_2 for this range of capture flow.

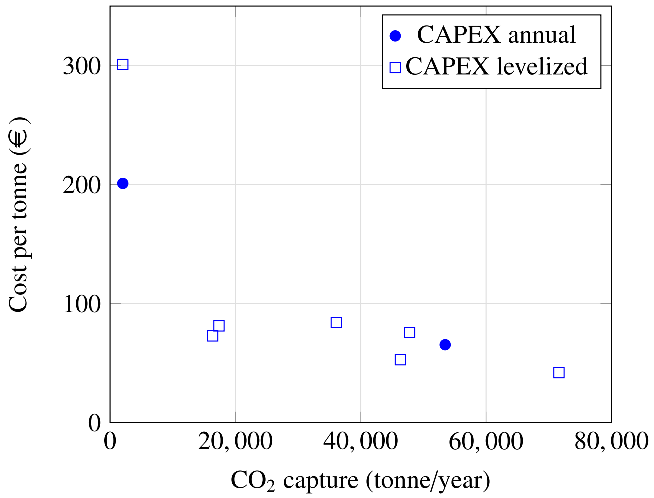

Fig. 2. Capital cost of onboard carbon capture reported by several studies.[1] The much higher cost at a low CO_2 capture included the labor, maintenance and use of chemicals (Monteiro, 2020, Ros et al., 2022, Luo and Wang, 2017, Güler and Ergin, 2021, Awoyomi et al., 2020, Oh et al., 2024).

2.3. Operational expenditure

Operational expenditure (OPEX), which includes fixed and variable OPEX, plays a crucial role in the overall costs of CCS onboard ships. Fixed OPEX comprises costs that remain constant regardless of the load of the capture system, such as preventive maintenance, labor, insurance, and taxes. Variable OPEX, on the other hand, encompasses costs that vary with the capture system's load and operating hours, including fuel costs, maintenance for rotating components, and solvent make-up for the capture process, if applicable. When the capture rate increases, the cost per tonne of captured CO_2 decreases, as illustrated in Fig. 3. Among other factors, additional fuel consumption emerges as a critical component of overall cost. For example, Luo and Wang (2017) examined a scenario in which increasing the capture target from 73% to 90% more than doubled the total capture cost (from 77.5 €/tonne CO_2 to 163 €/tonne CO_2). This significant cost increase resulted from the consumption of additional fuel, which was not required in the lower capture rate, as the recovered heat is enough for the process. The red circles in Fig. 3 represent a scenario in which fuel is burned to achieve a higher capture rate.

In practice, the heat and power needs of the OCCS significantly depend on the chosen technology, and depending on the ship, it is possible to have the required heat available at no extra cost. However, new ships usually come equipped with Waste Heat Recovery Units (WHRUs). These ships are highly energy efficient and utilize the heat from the funnel for everyday operations. Any additional heat for the other processes could lead to increased fuel consumption. But, in cases where WHRUs are not installed, there is an option to install them in the funnel. This integration with CCS can help minimize the need for additional fuel consumption.

2.4. Use of chemicals

The implementation of CO_2 capture onboard ships can introduce new chemicals on the ships that can lead to additional risks and drawbacks (corrosion, emissions into air or water, health impact, etc.) (Roussanaly et al., 2023). This can, for example, be the case for chemical absorption which is the most mature and the leading contender for onboard CO_2 capture (Feron et al., 2020). Furthermore, the introduction of new material onboard also requires new storage and handling systems, resulting in additional space requirements and costs (Zhang et al., 2014).

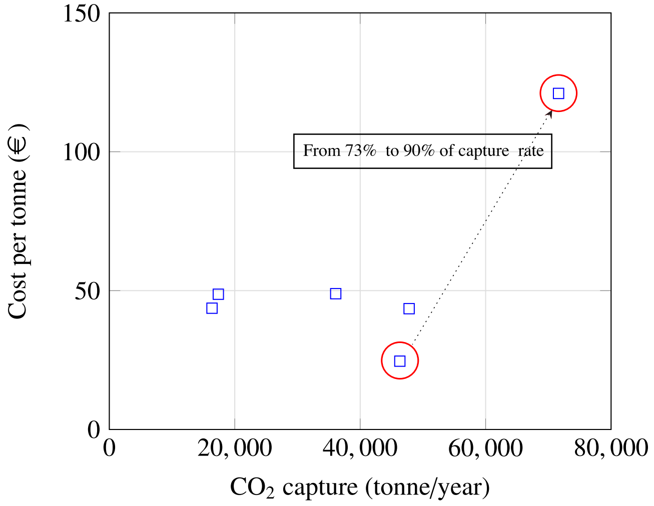

Fig. 3. The expected operational cost for installing carbon capture (Awoyomi et al., 2020, Luo and Wang, 2017, Ros et al., 2022).

2.5. Cooling system

A cooling system is essential for both the capture unit and the liquefaction of CO_2. Initial evaluation of the absorption system indicates that this cooling water consumption is not negligible. A higher cooling water flow rate requires a larger cooling system including pumps, tanks, and piping, which could result in higher cost (Al Baroudi et al., 2021). A more detailed design and sizing of the cooling system has been studied for the case studies.

2.6. Process water

Certain capture technologies can also require water not only for cooling but also as input to the process (Meldrum et al., 2013). For example, a waterwash is used to prevent large solvent losses in the amine-based capture system. Furthermore, the amine concentration in the lean amine solvent must remain around the target value, which also requires water makeup in the process. Producing the high-quality water required can result in non-negligible cost (for example, 1–2 USD/tonne CO_2 (Kandil and Hussein, 2020)). The makeup water consumption and its influence on total fuel consumption have been further evaluated in the case studies.

2.7. Equipment footprint

Since machinery rooms on ships are typically designed to be compact and efficient, accommodating a variety of equipment and systems that require careful management for safe operation is very difficult. This space constraint becomes even more critical in retrofit cases, where there is limited area available in the ship's machinery room and deckhouse. Fig. 4 illustrates how the area inside one of the floors of the machinery room is fully occupied by the current machinery system, leaving no additional space to install a new system for the capture process. The limited space available in the machinery room is a crucial aspect of ship design. The upcoming section explores various approaches to allocate space for the installation of the capture system.

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[1] Some of the numbers were given in kg per hour, which have been multiplied to be compatible with the rest of the numbers.

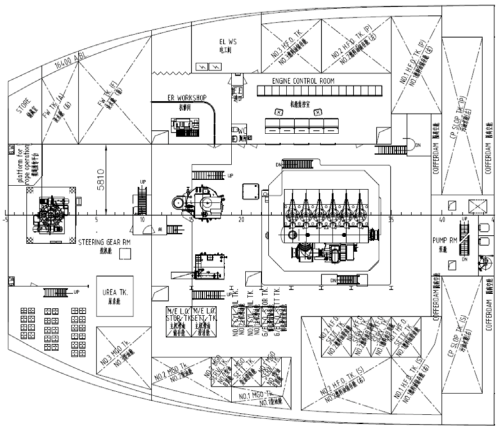

Fig. 4. An example of one of the floors in the machinery room of a existing vessel.

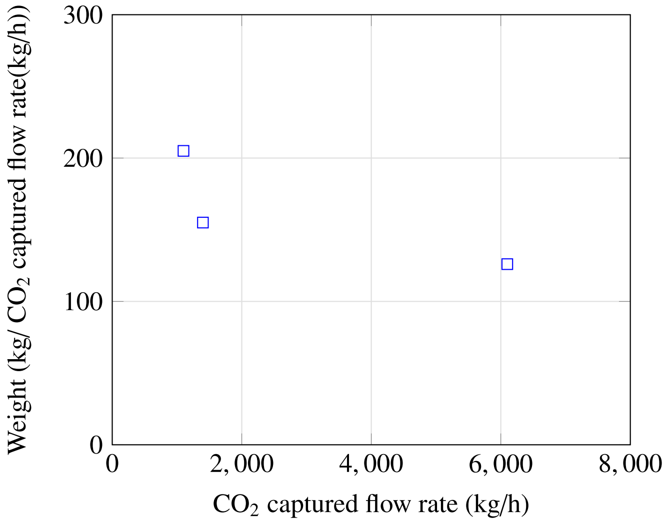

Fig. 5. The weight of the capture system based on kg/h CO_2 captured flow rate (Monteiro, 2020, Güler and Ergin, 2021, Feenstra et al., 2019).

2.8. Equipment space

Many ships have height limitations imposed by radar vision or bridge overpasses, which can restrict the total height of the vessel. To comply with these restrictions, it may be necessary to use compact or low-profile carbon capture technologies that can fit within the specified height limitations. To assess the feasibility of implementing current capture technology on both retrofit and newbuild ships, an arrangement of the capture system has been studied to account for height restrictions.

2.9. Weight

The weight of the carbon capture system is a critical factor in determining the feasibility of its installation onboard a ship. When the equipment is heavy, additional structural support or foundation work may be necessary, leading to increased complexity and costs. Fig. 5 illustrates the weight estimates of the capture system when installed on a ship. Incorporating the weight of the capture system alters the draft of the ship and leads to increased fuel consumption. To assess the impact of the capture system's weight on the overall fuel consumption, an evaluation will be presented for both retrofit and newbuild scenarios.

2.10. Ship modification level

In both the newbuild and retrofit cases, some degree of modification to the general arrangement of the vessel is necessary to install the carbon capture equipment. This includes the installation of equipment to capture, process, store, and offloading CO_2. The extent of modifications required can vary depending on the specific carbon capture technology that is being implemented. Some technologies may necessitate significant alterations to the vessel's general arrangement, while others may integrate more easily into existing systems if space is available. In the worst-case scenario, the OCCS must be installed in cargo spaces. On newbuilds, the vessel can be built with a few meters extra length to allow for a larger engine room if necessary. However, this approach also has a cost, as it involves modifications to the vessel structure. Furthermore, it could affect, marginally, the resistance, stability, maneuverability, and overall operational efficiency of the ship. Finally, many ships face restrictions of main dimensions in port, channels, fairways, sounds, and locks.

Further in this study, the retrofit case involves modifications focused on utilizing the space available in engine rooms, casing, and on deck. This approach aims to minimize the alterations to the existing structure of the ship while successfully incorporating the carbon capture system. On the other hand, in the context of the newbuild ship, the possibility of extending the ship's length to accommodate the capture system is being explored, with a primary goal of assessing the impact of this modification on fuel consumption.

2.11. Technology readiness level

Some carbon capture technologies, such as post-combustion capture using amine solvents, have reached a relatively high TRL level (7–9), and other technologies, such as post-combustion capture based on ionic liquids, are still in the early stages of development (TRL 3–5) and have not yet been deployed on a commercial scale. The study by (Bui et al., 2018) gives more detail of the TRL as of 2018. For the current study, the amine-based capture method, which has the highest TRL, has been considered.

2.12. Unloading

Although the experience gained from LNG carriers is highly valuable for the unloading system, it is essential to consider the variety of components involved in the transfer of CO_2 from the ship storage tanks to the onshore facilities. These components include transfer hoses and connections, pumps and compressors to transfer CO_2, onshore storage tanks to store the transferred CO_2, and monitoring and control systems to ensure safe and efficient transfer.

2.13. Suitability of the process for onboard

It is important to consider the dynamic nature of a ship and its potential impact on the performance of the carbon capture system. Waves and weather conditions can cause the ship to pitch and roll, which may affect the system's performance and pose safety concerns. However, system performance may not necessarily be negatively affected (Ros et al., 2022).

2.14. Wastewater treatment

For certain capture technologies, several steps of the process can result in the production of water containing impurities. It is, for example, the case of the water wash section of the absorber, which contains some of the solvent and its degradation products. To ensure proper operations, some of this water must leave the process and be treated before it can be safely released into the environment so that it does not affect the aquatic environment (Dong et al., 2019).

2.15. Presence of impurities

Due to the wave and wind, engines may encounter time-varying loads, which can cause fluctuations in the engine's response and performance. The load on the engine can vary in fixed or variable frequency, which can affect the composition of the exhaust gases and finally the purity of the captured CO_2. For example, lean burn spark ignition natural gas engines may suffer from high methane slip and instantaneous higher excess air ratio during transient marine conditions (Tavakoli et al., 2020), which can change the gas composition and thus the purity level of the captured CO_2. In the context of carbon capture for ships, impurities present in the flue gas sent to capture can impact the efficiency of the capture process (IEA, 2008), the design of the liquefaction process, and the optimal conditions for the storage of liquefied CO_2. For example, impurities such as sulfur oxides (SO_X) and nitrogen oxide (NO_X) can lead to solvent degradation, thus significantly affecting performance over time. The impurities left in the captured CO_2 also increases the duty of the liquefaction unit for deep purification (Morken et al., 2017). Among all types of engines, two-stroke diesel engines, which are commonly used as the propulsion power source for deep-sea vessels, are generally more robust in responding to load variations.

2.16. Maintenance

As with any system, carbon capture processes require routine inspections and cleaning of components, replacement of worn or damaged parts, and calibration or testing of sensors and monitoring equipment. Additionally, increasing the number of rotating components such as pumps, compressors, and fans increases the maintenance requirements of the system, as these components are typically subject to wear and tear.

In the following sections of this paper, we will conduct a more in-depth analysis of the factors labeled as "Considered" in Fig. 1 for our case studies.

3. Definition of the case studies

The impact of installing carbon capture and storage on ships has been studied in two different scenarios.

- Retrofit case: the BAIACU vessel owned by Klaveness (see Fig. 6) is chosen as the case study which is a combination carrier that transports both dry bulk cargo and wet cargo like crude oil. The specification of the Baiacu vessel is given in Table 2. As a retrofit case, the main dimensions of the ship are kept unchanged to deploy an OCCS unit, while the energy consumption and corresponding fuel usage are studied. In this case, the maximum capture rate is limited by the power and heat available in the machinery room.
- Newbuild case: this scenario explores various redesign options to accommodate a CCS system with a high CO_2 capture rate, with the aim of minimizing CO_2 emissions from the vessel. The main goal of the newbuild case is then to prevent a reduction in cargo space with a minimum extension of the ship length during CCS integration while maintaining the original ship specifications from the retrofit case.

For a clear and consistent analysis, we assume the same route for both retrofit and newbuild cases so that the impact of different CO_2 reduction levels on ship operation can also be analyzed. The capture rate has an effect on both the specific heat and power consumption per kilogram of CO_2 captured, and the size of CO_2 storage. The ultimate storage volume is a major factor in the overall size and weight of the system. Since the IMO's ambition for 2040 aims at 70% reduction in CO_2 emissions and for 2050 is close-to-zero CO_2, this paper focused on the 70% and 90% CO_2 reduction target, respectively. It should be emphasized that 70% or 90% represents the desired CO_2 avoided rate; therefore, it requires a higher capture rate than 70% and 90% due to the extra flue rate generated by additional fuel consumption during process, as mentioned in Section 2.1.

Fig. 6. Baiacu is one of the sixth of in total eight contracted CLEANBU combination carriers in Klaveness Combination Carriers (KCC) (Klaveness, 2021).

Table 2
Vessel specification.

Item	Unit	Specification
Name	–	Baiacu
Gross tonnage	GT	54,043
Summer Deadweight	tonne	82,397
Length Overall (LOA)	m	228
Length (LPP)	m	224
Beam	m	35
Depth	m	23

3.1. Voyage routine

The volumes of CO_2 in the exhaust gas are determined by the power of the engine, the operating hours and the carbon content of the fuel. Power is in turn determined by the speed of the vessel, the loading condition (draft and trim), the fouling of the hull, the efficiency of the propeller and environmental factors such as waves, wind, and current, among others. The amount of accumulated CO_2 for storage is also determined by the distance traveled between storage offload. In this work, the average speed is assumed to be maintained at 14 knots. A normal route for this ship takes approximately 20 days to cover a distance of about 6500 nautical miles at this speed. These figures are averaged values, and actual data may vary for different voyages.

4. Retrofit case

The purpose of this section is to present a retrofit case study for the deployment of CCS technology. Given the significant contribution of bulk carriers to CO_2 emissions in the maritime industry as shown in Table 1, it is reasonable to consider this type of ship as a case study to evaluate the suitability and practicality of OCCS. Also, since they are on deep-sea travel, defining fixed operation routes or regular intervals for offloading stored CO_2 is more applicable.

4.1. Specification of fuel

Most large vessels burn HFO on global trade routes and MGO/MDO in sulfur emission control areas. The BAIACU vessel is equipped with fuel tanks for 20% diesel oil and 80% HFO. OCCS can be dimensioned for 20/80 operation on MGO and HFO. Depending on the

Table 3
Heat and power sources in the machinery room. The first three columns are provided by the ship owner, while the last column is calculated.

Component	Power (MW)	Heat (MW)	Fuel rate (kg/h)	Flue rate (kg/h)
Main engine	9.6	0.0	1379	48,482
Aux engine No. 1	1.3	0.0	242	8500
Aux engine No. 2	1.3	0.0	242	8500
Aux engine No. 3	0.8	0.0	145	5120
Boiler	0.0	6.3	637	11,803
WHRU	0.0	2.2	0.0	0.0

journey, engines may operate exclusively on HFO, which has a slightly lower carbon content per kg of fuel (3.114 vs 3.206 according to IMO (IMO, 2020)). According to the data provided by the ship owner, low sulfur heavy fuel oil with a sulfur content of less than 0.5% instead of the 2.7%, is being used. The sulfur level in the fuel affects not only the composition of exhaust gases but also the minimum temperature at which these gases can be effectively treated. When sulfur oxide compounds are present in the exhaust and the exhaust temperature falls below 160 degrees Celsius (the dew point of sulfuric acid), corrosive mixtures can form on the exhaust pipes, leading to corrosion.

When the engine runs on HFO, the selective catalytic reduction (SCR) system is not in operation. However, when the engine operates in an emission control areas, it burns MGO and uses SCR to remove NO_X to comply with emission regulations. Nevertheless, there can be unreacted ammonia in the SCR, resulting in ammonia slip. This slip occurs when too much ammonia is injected or when injection temperatures are too low for ammonia to react effectively. By installing the CCS system onboard, this unreacted ammonia can pass through the SCR and enter the CCS system, potentially increasing impurity levels.

For simplicity, this study primarily considers HFO with low sulfur content and without investigating the impact of SCR on flue gas composition, as it represents a significant portion of the ship's journey.

4.2. Heat and power source

Table 3 provides a list of the heat and power sources in the machinery room of the vessel. The machinery room consists of one main engine, three auxiliary engines, one auxiliary boiler, and one waste heat recovery system. The table gives the fuel consumption associated with each section when operating at full load. The boiler is used solely for generating heat and steam, which can be used for various purposes such as heating cargo holds, providing hot water for the crew, warming up cargo prior to unloading, and heating HFO to reduce its viscosity. The amount of flue gases in the exhaust manifold is also shown in the last column, with the main engine contributing the most to the total mass flow rate compared to other power sources. The machinery room is configured with all engines and boilers installed in parallel, with the exhaust flow directed to a common waste heat recovery unit. By identifying the different heat and power sources on the ship, it is possible to determine the maximum capture rate based on heat and power availability.

4.3. Exhaust gas conditions

In this work, the flue gases generated from the main engine, the auxiliary engines and the boiler are mixed and sent to the downstream of the capture system. To estimate the flue gas conditions, it is assumed that the main engine operates at 85% load, while the loads of the auxiliary engines and boiler are varied to meet the base heat ($2.2MW_{th}$), base power (0.5 MW_{el}), and the energy requirements of the OCCS. However, the boiler load will also be influenced by the amount of heat collected from the WHRU. The conditions of the total flue gas, such as the CO_2 concentration will be a key parameter impacting the energy efficiency of capture technologies, while temperature and flow rate will determine the amount of heat collected from the WHRU.

Table 4
Operating conditions of the WHRU without OCCS. The data is sourced from the ship owner.

Parameter	Unit	Value
WHRU type	–	Saturated steam
Supply temperature	°C	258.92
Supply pressure	kPa	105.93
Supply mass flow rate	kg/h	53,408
Exit temperature	°C	175.00
Exit pressure	kPa	104.42
Produced steam temperature	°C	165.00
WHRU capacity	MW_{th}	1.35

Table 5
Power plant duty for the existing case.

Parameter	Unit	Value
CO_2 avoided rate	%	70
Power by main engine	kW	8160
Power by aux engine	kW	2230
Heat by boiler[a]	kW	6902
WHRU	kW	1,822

[a] Minor upgrade is needed.

The composition of the engines are taken from similar engine test results conducted at the M-LAB in SINTEF Ocean. Table 4 demonstrates the potential for heat recovery in the original flue gas. For simplicity, it is assumed that the auxiliary engine and the main engine have the same gas temperature, although in real engines, the auxiliary engines, being 4-stroke, typically have a higher exhaust temperature. The heat supplier is a saturated steam system at 7 bara.

4.4. Energy balance of ship machinery with CCS

To capture CO_2, OCCS units require substantial energy (heat and electricity), increasing the auxiliary loads to accommodate the base loads of the ship and the capture system. The higher duty of generators and boiler results in increased fuel consumption and CO_2 flow rate compared to the ship without CCS. Thus, the CO_2 capture rate of an OCCS unit must be higher than the reduction target or the avoided rate (for example, more than 70% in this retrofit case) to compensate for the additional flue rate generated by the operation of the CCS system. It is worth noting that the increased auxiliary loads and subsequently the increased flue gas entering the capture system, will necessitate a larger equipment size and higher capital costs on capture plant.

Thus, as presented in Table 5, the duty of the auxiliary engines and boiler at 70% of the avoided rate increases the fuel consumption by 60% from 1555 kg/h to 2480 kg/h. The amount of CO_2 in the final flue gas is 7980 kg/h, of which 81% (6488 kg/h) is captured to achieve a 70% reduction in CO_2 emissions compared to the ship without CCS. This is the input for the storage volume.

4.5. Possible arrangement for capture system

Since the above and below the main deck are already occupied, it is nearly impossible to accommodate new installations in these areas. Taking into account the space requirements of carbon capture technology, it becomes evident that extending the decks above the main deck is the only viable solution for retrofit cases.

This extension can be fully used to accommodate the CO_2 capture unit, as shown in Fig. 7, or a part of the installation, can be allocated in the funnel area, as shown in Fig. 8. The advantage of utilizing this area is its proximity to the vessel center line and the funnel. This location provides more space, and results in less complex piping to connect the capture unit to the flue gas stack. In addition, the extension of the deck

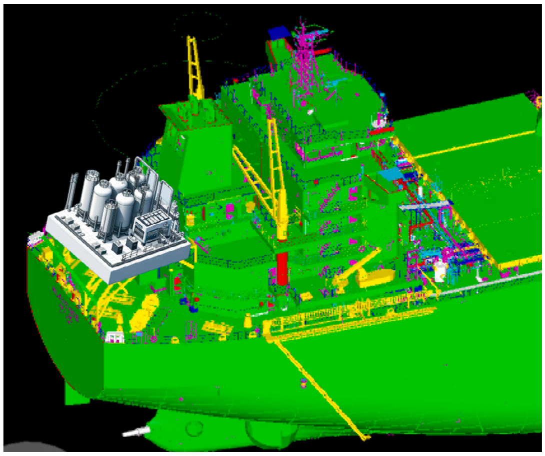

Fig. 7. An arrangement for the high columns and all the machinery in the extension of accommodation deck.

allows a maximum height of 18 meters for process equipment. This is particularly beneficial for capture systems that include tall process units, such as absorption-based capture technologies.

In extension, as shown in Fig. 9, the light green area represents the available space, while the brown area represents the zone attainable with minor modifications, such as the repositioning of the crane if applicable. When modifications are implemented, the total footprint in one of the extensions exceeds 150 m^2. However, extending Deck A provides a maximum height of up to 18 m, while extending Deck C allows a maximum height of 12 meters (Decks are shown in Fig. 8). Based on the literature review, 12 meters may not be sufficient for the entire absorber (Lee et al., 2021, Güler and Ergin, 2021, Akram et al., 2016, Feenstra et al., 2019). This is why the second arrangement, which can incorporate high columns in the funnel box as shown in Fig. 8, is more practical to attain the necessary installation height. Depending on the extent of modifications made to the funnel, the bottom of the columns might possibly begin from the main deck. In such a scenario, the ship's height provides ample space for accommodating the columns, allowing the extension to commence from any of the decks (A, B, C or D).

4.6. Possible arrangement for storage

Storage is responsible for the largest space and weight requirements compared to other components in the CCS unit on the target vessel mainly due to the long duration of the voyage. At standard temperature and pressure (1 bara and 273 K), the carbon dioxide density is relatively low (1.98 kg/m^3). Therefore, captured CO_2 must be stored in a high-pressure or liquid form to minimize storage space and cargo loss. In particular, liquid CO_2 will be more favorable for ship applications, as it has a higher density (around 1100 kg/m^3 at 15 barg liquid) than CO_2 at high pressure (786 kg/m^3 at 110 bara and 303 K). Taking into account the target CO_2 avoided rate and a 20-day voyage, 3114 tonne of CO_2 must be stored, which requires a storage capacity of 2830 m^3 in liquid form.

An approach to find a place is to combine cargo holds number 7 and 6, utilizing the hatch area for storage, as shown in Fig. 10. However, this installation significantly increases the risk of sloshing in the cargo, potentially affecting the vessel's motion, even if the vessel structure permits such modification. By accepting this alteration, two storage tanks with a maximum diameter of 8 meters and a length of 25 meters can be installed on the hatch for cargo hold number 7 and can provide a total capacity of 2512 m^3. This volume is still 11% less than the required capacity.

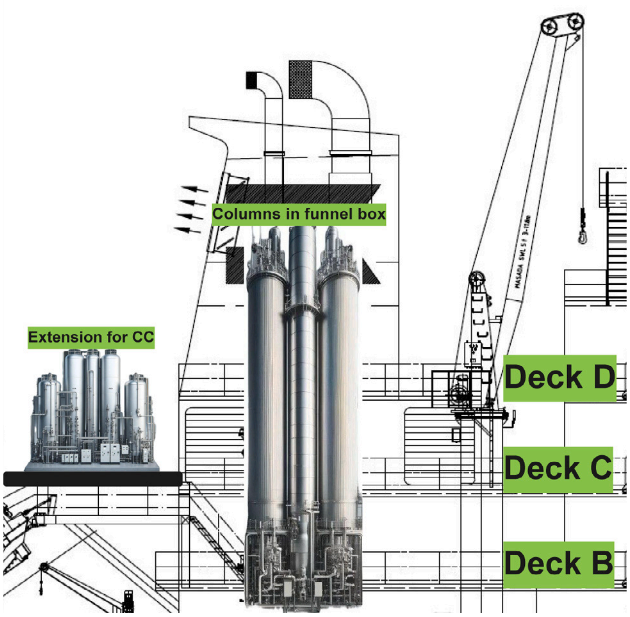

Fig. 8. An arrangement for the high columns in the funnel box and the machinery in the extension of accommodation deck.

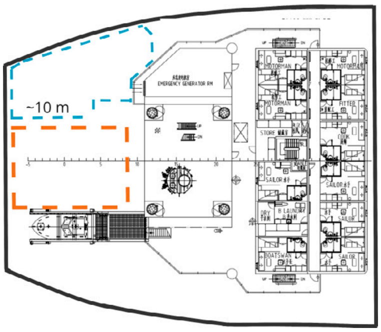

Fig. 9. The footprint on the extension of Deck B can be doubled by making some minor modification.

A more viable option is to sacrifice some cargo hold capacity. Four standing storage tanks, each with a diameter of 7.1 meters and a length of 18 m, could provide a total volume of 2830 m^3. As shown in Fig. 11, and considering the cargo hold capacity as 97,000 m^3, this results in a loss of approximately 3.5–10.0% of the total cargo capacity depending on the type of storage. The phase diagram of CO_2 illustrates that at atmospheric pressure, CO_2 can exist in only either a gaseous or solid state. Thus, liquid CO_2 can only be maintained at a combination of low temperature and high pressure, significantly exceeding atmospheric levels. Consequently, to preserve CO_2 in a liquid form, a CO_2 cargo tank must be of pressure or semi-refrigerated type (IEA, 2004). If the shape of the cargo tank in the cargo space resembles Type A or prismatic tanks, which mirror the shape of the cargo, the loss of cargo could be reduced to approximately 3.5%. However, these tanks cannot maintain the liquid state of CO_2. Meanwhile, Type C tanks, which can be used in practice, lead to a significant increase in cargo loss due to storage shape.

4.7. Extra weight

Fig. 5 shows that for CO_2 captured at around 6500 kg/h, the equipment weighs about 100 kg per unit of capture flow rate. This makes the total weight of the capture process approximately 650 tonnes. Adding this to the storage weight, the total OCCS weight exceeds 3700 tonnes by the end of the voyage.

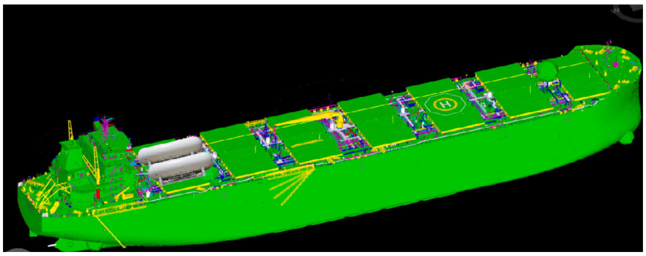

Fig. 10. An arrangement for the storage on the main deck on hatch area.

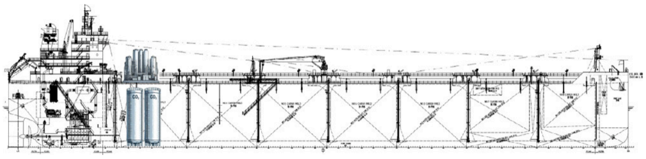

Fig. 11. An arrangement for the storage on the cargo hold and the capture plant in the hatch area in an expense of more than 3.5% of cargo loss, depending on the storage type.

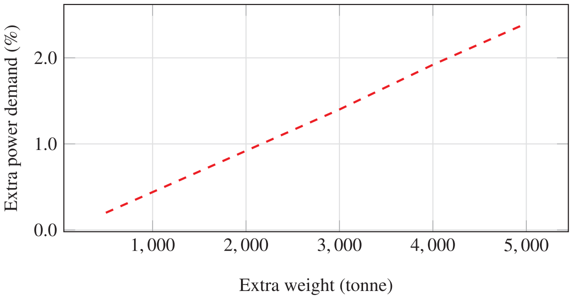

Fig. 12. Effect of extra weight on the fuel consumption of the ship.

The additional propulsion power required due to extra weight has been calculated by using the Hollenbach method. This method, which is based on calm water conditions, uses regression analysis from 433 ship models considering their main dimensions. However, it is important to note that its simplified hull dimensions might not capture all details affecting resistance prediction (Hollenbach, 1998).

The resistance analysis for this case study shows a linear correlation between the additional weight and the propulsion load, resulting in an additional 1.8% fuel consumption for the additional weight from OCCS, as shown in Fig. 12. Since CO_2 storage gradually fills during a voyage, it is reasonable to account for half of the total storage weight when considering the additional fuel consumption. Moreover, if the storage occupies cargo space, the extra fuel consumption resulting from the added weight becomes invalid.

4.8. Process water production

Process water production is often necessary in carbon capture systems to compensate for CCS unit losses. Ship-based water production methods, such as reverse osmosis, multistage flash, and multieffect distillation, vary in energy requirements. Since the details of the production methodology and the effectiveness of different methods are not within the scope of this work, previous research findings are used as inputs for further calculations. According to previous literature, approximately 1 kWh of energy is needed to produce one liter of freshwater (Elagouz et al., 2014). For methods of production with higher capacity, such as multistage flash evaporators developed by Wartsila (Wärtsilä, 2021), the energy consumption for water production can be lower, dropping to around 0.2 kWh per liter with a water production capacity of 150 m^3 per day. However, the production of process water may need even higher energy demand compared to freshwater production due to the lower impurity level requirements.

Table 6
Sizing of the heat exchangers in a range of flow rate (Alfa Laval, 2024b).

Model	DN Size	H (mm)	W (mm)	Max flow rate (m^3/h)
T10	DN 100	1,054	470	160
T15	DN 150	1,833/1,781	610/650	370
T21	DN 200	2,082	755	650
T25	DN 250	2,761	913	1,000

In the retrofit vessel, the amine-based capture system demands 4.5 m^3/h of make-up water, which requires a water production unit of 5.7 to 7.3 meters long and about 3.0 meters wide (Wärtsilä, 2021). The size of the unit is significant in comparison with the available machinery room, thus the installation for the freshwater system will be viable only in the extended area. To generate 4.5 m^3/h of make-up water, a 900 kW power plant is required. To account for this additional fuel consumption onboard, the duty of the capture unit needs to be increased to meet the 70% emission reduction target. However, this large make-up water demand is mainly due to the water loss through the water wash section with warm cooling water assumed as the design specification in this work. Thus, this hourly consumption will be a peak value in a actual voyage. In addition, the requirement for make-up water can be decreased through process intensification of the amine-based capture process.

4.9. Cooling system capacity

Our simulation for the absorption system shows a significant cooling water usage of 500 m^3/h at 36 °C and 4 bara. We assumed high-temperature cooling water, typical for ship design in warm seas, for this study. This leads to a required heat exchanger capacity of 6 MW. There is not any information about the original ship's cooling system, but a 6 MW margin is unexpected. Therefore, a new cooling system is assumed to be considered for the capture plant. Table 6 shows that the T21 heat exchanger from Alfa Laval is suitable for our case.

4.10. Liquefaction

According to the studies (Deng et al., 2019), each tonne of CO_2 needs 100 kWh of energy for the liquefaction process. To liquefy the captured process in this existing case, more than 700 kW of power is needed, which has already been considered during the energy balance of the ship for the avoided rate of 70%. This liquefaction system is significant in terms of power it needs and footprint it requires. For the retrofit case, as for freshwater production, the extension area is the only viable location for the installation of the liquefaction process.

4.11. Final fuel consumption for retrofit vessel

Table 7 outlines the increased fuel consumption due to the auxiliary engines, the boiler for the capture process, the freshwater plant, and the liquefaction process. Combined, these factors lead to a 71% rise in fuel consumption and at least a 3.5% reduction in cargo capacity for a 70% emission reduction rate.

It is, however, expected to have an additional 1%–2% increase in fuel consumption on the main engine due to the extra weight, along with the extra power and heat required for the freshwater production unit, making the total fuel consumption more than 72%. It should be noted that this extra fuel consumption and corresponding emissions are not included in the simulation of the OCCS system.

Table 7
Additional fuel consumption with CCS for the existing case.

Section	Consumption (kg/h)	Consumption (%)
Main engine		
Weight	24	(2.0)
Heat for capture unit	613	(54)
Power for capture unit	182	(16)
Power for liquefaction	130	(12)
Power for process water	180	(16)
Total	1129	(100)

5. Newbuild case

When investigating a newbuild case, an important question arises about the most suitable engine to be paired with the carbon capture process. In recent years, natural gas engines have gained popularity in the shipping industry due to their cleaner combustion compared to traditional diesel engines. Previous research consistently suggests that ships burning LNG are best suited for integrating the carbon capture system (Feenstra et al., 2019, Trivyza et al., 2019). LNG is stored in liquid form at extremely low temperatures (−162 °C), and the abundance of cold energy available on the ship can be used to effectively integrate the CCS system, such as liquefying CO_2 for storage.

In a traditional power plant burning HFO and MGO, the sulfur content in the exhaust gas also limits the amount of heat recoverable since the flue gas temperature can only be lowered to the sulfuric acid dew point in the waste heat recovery unit. LNG power plants, on the other hand, have a significantly lower sulfur content, allowing for greater heat recovery from the exhaust gas with approximately 40–60 °C lower WHRU outlet temperature compared to HFO and MGO cases. Additionally, LNG has a lower carbon-to-hydrogen ratio (C/H) compared to HFO and MGO, while boasting a 5%–10% higher heating value. These factors contribute to a potential 20%–25% reduction in carbon emissions for natural gas engines compared to diesel engines for the same power output, assuming the same combustion efficiency.

Furthermore, the available data confirm that lean burn spark ignition engines and low-pressure dual-fuel engines have relatively low emission factors, and with a CO_2 amount of 472 and 444 grams per kilowatt hour. On the contrary, diesel engines have CO_2 amount exceeding 500 g/kWh (Stenersen and Thonstad, 2017). Although natural gas engines show favorable composition and emission characteristics, the main concern is the potential for methane slip, which requires careful management to mitigate its impact (Tavakoli et al., 2021).

Overall, the choice of LNG-powered engines presents advantages for integrating the carbon capture process due to cleaner combustion, enhanced heat recovery, lower carbon emissions potential, and compliance with emission regulations. However, the choice of fuel for a ship will depend on other factors as well:

- First, when using natural gas engines for propulsion, one of the critical factors to consider is the storage condition of the fuel. Natural gas is typically stored in a liquefied form to reduce its volume for transportation and storage. However, LNG has a lower energy content per unit volume than traditional diesel fuel. Specifically, one liter of LNG has only half the energy content of one liter of diesel fuel. To store the same amount of energy as traditional diesel fuel, a ship would need to allocate more space for LNG storage.
- Second, the fraction of CO_2 in the exhaust gas is a crucial number for the capture process. The lower the fraction, the higher the specific energy per kg of captured CO_2 required. Therefore, even though the lower concentration of CO_2 means a lower kg of CO_2 emitted, it does not necessarily mean that less energy is required for CO_2 capture.

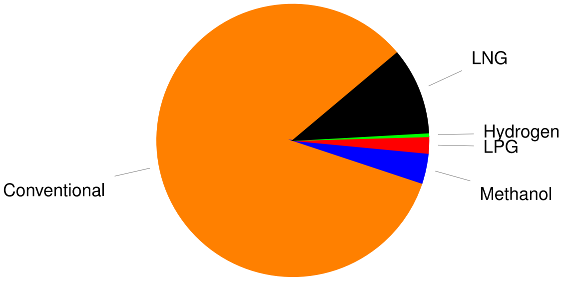

Fig. 13. Contribution of fuels in the maritime industry based on order(DNV, 2023a) excluding LNG carriers.

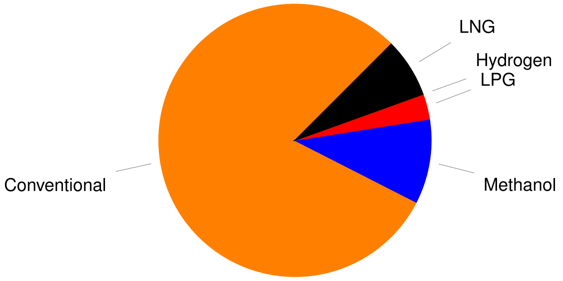

Fig. 14. Contribution of fuels in the maritime industry based on contract (DNV, 2023a) excluding LNG carriers.

- The third factor is the future of maritime fuels. According to available market data, over 95% of the fuel used in the maritime industry is conventional fossil fuels. While, as shown in Fig. 13, the contribution of natural gas-fueled ships increases to more than 10% of the fuel used by the ships in order, still more than 85% of the new ships on order will use conventional fossil fuels. In the longer term, as shown in 14, 80% of the fuel will also be a conventional fossil fuel, while methanol is expected to be the most favored alternative fuel with 9% and then LNG with only 6% of total fuel use. Thus, conventional fossil fuels are expected to remain the primary fuel for the maritime industry due to the slow transition.
- Last but not least, large-scale two-stroke marine diesel engines have been widely accepted as the primary propulsion system for large merchant ships. According to IMO figures (IMO, 2020), these types of engine account for almost 40% of the total number of engines, demonstrating its dominance in terms of Dead Weight Tonnage (DWT). This popularity is mainly attributed to its exceptional thermal efficiency, reliability, and capacity to utilize lower-grade fuels such as HFO (Boretti, 2019). Recognized as one of the most efficient variations of internal combustion engines (Mollenhauer and Tschöke, 2007), this type of engine is well known and well respected among crew members. As a result, this advantage firmly establishes the two-stroke diesel engine as the preferred option for vessels undertaking deep-sea voyages.

Numerous previous studies have predominantly emphasized natural gas propulsion, given its compatibility with cryogenic integration (Ros et al., 2022, Feenstra et al., 2019, Monteiro, 2020). However, the choice of diesel propulsion remains a domain that merits deeper investigation. Taking into account that the primary market for carbon emission reduction still relies on traditional diesel and HFO engines, diesel propulsion has been selected for the newbuild case in this work to address the energy and space requirement when targeting deep CO_2 reduction of the vessel.

Table 8
Main dimension of the auxiliary engines.

	Original engine (m)	Upgraded engine (m)
Overall length	6100	9110
Overall width	1020	1780
Overall height	2840	3950

Table 9
Main dimension of the boiler.

	Original (m)	Upgraded (m)
Height	7.1	7.7
Diameter	2.6	3.1
Width	3.8	4.5

5.1. Design objective

The primary objective of this newbuild ship is to achieve deep decarbonization of the vessel, reaching the net-zero target of IMO. Therefore, the CO_2 avoided rate of more than 90% is targeted based on the current capture technology, while maintaining the original cargo capacity of the BAIACU bulk carrier. The space requirements and dimensions of the capture system, including height and footprint, have been carefully considered based on the identified demand, and the design of the ship has been modified to minimize the modifications. If the ship operation with OCCS does not reach the net-zero emission goal, using some percentage of biofuel can fill the gap between the avoided capture rate and the near-zero emission target.

5.2. Machinery sizing

This section focuses specifically on the size of the auxiliary engines and boilers in the machinery room for the newbuild case. It is assumed that the main engine will remain relatively unchanged even with the addition of the capture system and the extra weight of the CO_2 storage. The plan is to have abundant auxiliary heat and power available to fully support the high-duty capture process, which requires that the auxiliary engines and boilers are sized accordingly.

Based on an initial evaluation, achieving an avoided rate greater than 90% would probably require 80% increase in the boiler capacity for the heat-driven technology and 160% increase in the auxiliary engine capacity for the electricity-driven technologies compared to the original design of the ship.

The current power plant has three auxiliary engines from DAIHATSU 6DE-23, with dimensions as Table 8. Increasing the power output to 2.6 times in case of using electricity-driven technology would involve using the DAIHATSU 6DE-33 model as one alternative, with a power output ranging from 2700–3600 kW, with different dimensions, which requires increasing the dimension of the accommodation for the auxiliary engines in all three directions. Assuming that the width and height of the machinery can find place for the new auxiliary engines, the new engine type is about three meters longer than the original auxiliary engine. To accommodate the increased length, about three meters should be added to the total length of the machinery room and consequently to the length of the ship for the electricity-driven technologies.

Increasing the capacity of the boiler increases the size and dimension of the boiler. When the output of the marine boiler changes from 10,000 to 18,000 kg/h of steam capacity for the newbuild ship, the dimensions can change according to Table 9, based on the supplier's information (Alfa Laval, 2024a).

This means that the boiler would require more than half a meter of extra length compared to the original boiler. Furthermore, the impact of the boiler upgrade results in an eight-tonne increase in the newbuild ship compared to the original, which was 18 tonnes. When comparing this to the sizing and weight changes in electricity-driven technology, where the additional weight increases from 69 tonnes to 138 tonnes, it becomes evident that heat-driven technology offers some advantages in the context of newbuild cases.

5.3. Exhaust gas recirculation

Diesel propulsion system requires the use of a SCR or Exhaust Gas Recirculation (EGR) to reduce NO_X emissions in exhaust pipes. When combined with CCS, the incorporation of EGR provides a dual advantage. EGR is a methodology that can increase the fraction of CO_2 in exhaust gas, improving the energy efficiency of the capture process, while eliminating the need for an SCR system. This makes more space for other machinery in the carbon capture system.

The impact of EGR on engines varies depending on factors such as engine type, EGR percentage, and other design considerations. Different engine manufacturers may experience different performance and emission output responses to EGR. The main changes in engine attributed to EGR can be categorized as follows:

1. Decrease in NO_X emissions,
2. Reduction in the excess air ratio,
3. Alteration of exhaust gas temperature,
4. Change in specific fuel consumption.

As the primary objective of implementing EGR in engines is to reduce NO_X emissions by substituting a portion of fresh air with exhaust gas, it is inevitable that parameters 1 and 2 will be affected. Fig. 15 illustrates the trend of NO_X emissions and lambda reduction resulting from EGR. The impact of EGR on exhaust gas temperatures can vary among different engines. Some engines report an increase in the temperature of the exhaust gases at lower engine loads where the EGR percentage is higher than at higher engine loads (SINTEF Ocean and MAN). Other engines with EGR maintain the exhaust gas temperature very close to that of the original engine (WIN-GD). The exhaust temperature can be an influential factor in the capacity of the heat recovery system. However, any increase in exhaust temperature indicates that some extra fuel is burned. In this study, it is assumed that the exhaust temperature remains constant for engines with EGR.

The effects of EGR for a diesel engine on the exhaust gas composition compared to a non-EGR engine are illustrated in Fig. 16. The feasible range of EGR for diesel engines is limited as evidenced by test results indicating up to 30% at 100% engine load, up to 40% at engine load of 50%–80%, and up to 50% at lower engine loads. To obtain more realistic data for analysis, certain figures derived from tests conducted at SINTEF Ocean have been utilized in this case study. When the EGR percentage is 0, the gas composition remains similar to that of the base engine. As the percentage of EGR increases, the EGR displaces fresh air, resulting in a notable reduction in fresh gas availability, a lower exhaust flow rate, an elevated mass fraction of CO_2, and lower mass fractions for O_2.

Table 10 has been prepared to summarize the significance of using EGR on the main engine. The table demonstrates a reduction in the mass flow rate of the exhaust gas with EGR, indicating a lower workload and a smaller size of the capture process. As seen in Supplementary information, the size expansion of the capture unit for the newbuild is minor although the CO_2 capture rate has increased significantly compared to the retrofit case. In addition, the EGR engine results in a 2mol% point higher CO_2 fraction in the feed gas for the CCS system compared to the retrofit case (see Supplementary information), compensating for the energy penalty with such a high CO_2 capture rate (Subramanian and Madejski, 2023). However, EGR introduces a reduction in recoverable heat from exhaust gas, mainly because of the lower flow rate. This assumption holds true when a WHRU is installed after the exhaust recirculation piping.

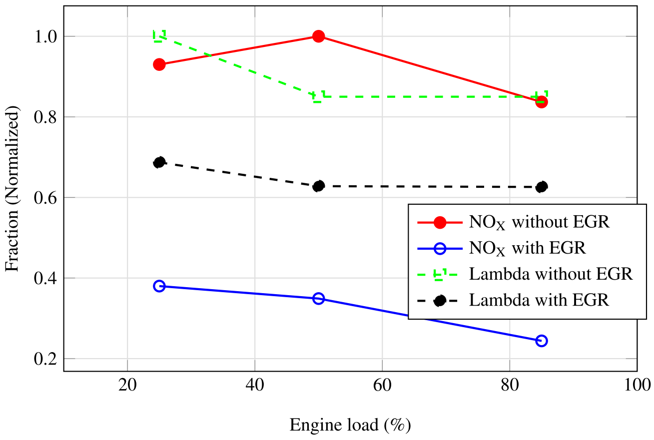

Fig. 15. Effect of EGR on lambda and NO_X emission on marine engine. The Y-axis has been normalized by the maximum mass fraction, which is in load 50% for NO_X and 25% for lambda.

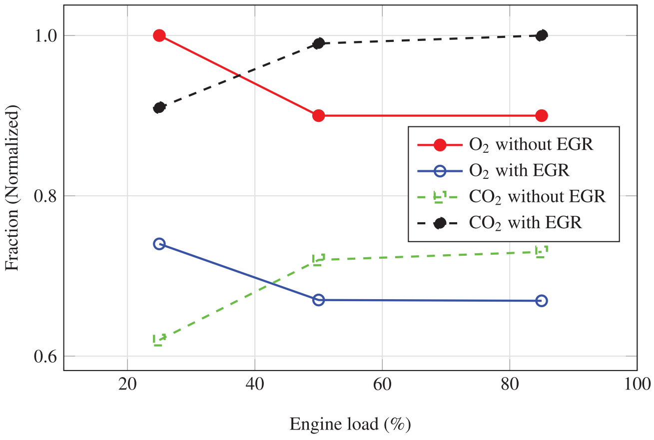

Fig. 16. Effect of EGR on CO_2 and O_2 on marine engine. The Y-axis has been normalized by the maximum mass fraction, which is in the load 85% for CO_2 and 25% for O_2.

Table 10
Parameters influenced by EGR in the main engine.

Parameter	Unit	Without EGR	With EGR
Total mass flow rate	kg/h	48,482	36,072
Recoverable heat	kW	1241	916
Exhaust temperature	°C	260	260

5.4. Redesigning for the newbuild ship

To maintain the cargo capacity and accommodate the carbon capture system, an extension of the length of the ship becomes necessary. Specifically, a one-meter extension for heat-driven capture and a three-meter extension for electricity-driven capture are required due to the larger size of the new boiler and engines. For this study, we opted heat-driven technology, resulting in a machinery room length increase equal to the original ship's length plus one meter.

If we assume that the width and depth of the ship remain unchanged from the base design, each additional meter in length creates an additional 350–400 m^3 of space for CO_2 storage. To achieve a CO_2 avoidance rate of over 90% in the context of deep decarbonization, an extension of 12 meters becomes necessary. Therefore, the total extension, which accommodates the machinery room, capture unit and storage space, should be 13 m. A schematic of the new extended-length ship design is shown in Fig. 17. This extension of 13 meters allows the storage of all captured CO_2 to be stored in the space below the main hull, while the main hull area can be used to house the capture plant.

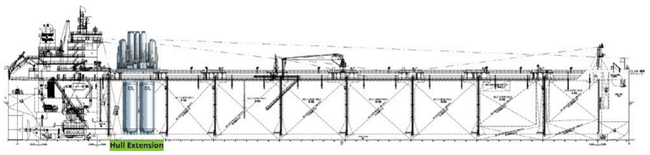

Fig. 17. Proposed arrangement for extending the length of the ship for accommodating for the captured CO_2.

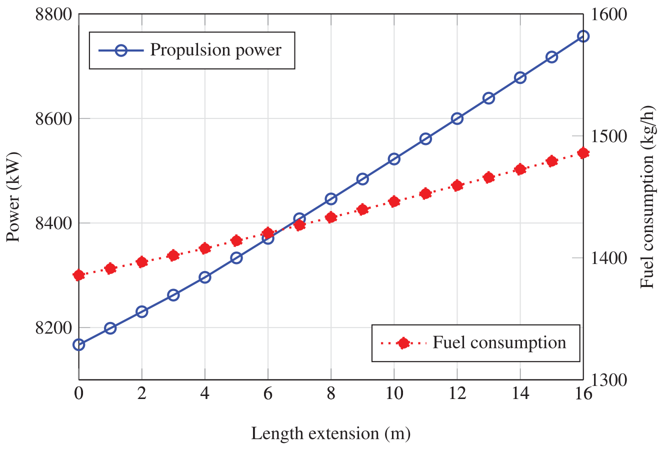

Fig. 18. Effect of increasing the length of the hull on the total power of the main engine and the fuel consumption of the main propulsion system.

The influence of increasing the length of the ship has been shown in Fig. 18. The effect of extending the ship's length on propulsion power is modeled in a manner similar to the approach used for calculating the impact of additional weight, as described in Section 4.7, employing the Hollenbach method. This model primarily considers calm water resistance as the influencing factor for predicting changes in propulsion power. While taking other factors into account can yield more accurate results, it also adds complexity to the modeling process. with a 13 meter extension, the propulsion power increases from 8160 to 8640 kW. This contributes to an increase in the fuel consumption for propulsion by approximately 6.0%. Together with the additional fuel consumption due to the weight of the capture system according to Fig. 18, the total fuel consumption of the main engine for this newbuild case increases up to 8%.

5.5. Liquefier and process water plant

Due to the higher CO_2 avoided rate compared to the existing case, the amount of power needed for CO_2 liquefaction and the production of process water reach 1050 kW and 1120 kW, respectively. In the newbuild case, we require an area similar to what was presented for the existing case. However, we have a higher mass flow rate for the liquefaction and process water plant. The ample extension space (13 × 20 square meters) on the main hull due to the increased length of the ship makes it convenient to accommodate all new installations, and there is no significant challenge to find room for these processes. Regarding process water production, the main specifications align with those in Section 4.8, the primary difference being the total water flow rate increasing from 4.5 m^3/h in the existing case to 5.6 m^3/h in the newbuild, means the energy requirement for water production is equivalent to 1.1 MW. However, this requirement is a worst-case scenario with warm cooling water and the make-up water demand will be reduced by using lower temperature cooling water and process intensification of the capture system.

Table 11
Additional fuel consumption with CCS for the newbuild case.

Section	Consumption (kg/h)	Consumption (%)
Main engine		
Extension	80	(4.5)
Weight	28	(1.5)
Heat for capture unit	1068	(59)
Power for capture unit	194	(11)
Power for liquefaction	187	(11)
Power for process water	240	(13)
Total	1797	(100)

5.6. Final fuel consumption for newbuild case

Table 11 gives the fuel consumption of the main engine, the auxiliary engines and the boiler for the capture process, the fresh water plant, and the liquefaction process. As shown, heat production contributes to most of the additional fuel consumption, making up 59% of it, while the power for capture and liquefaction represents a share 11%. Water production also plays a significant role, forming 13% of the extra fuel consumption by the CCS system. However, unlike the retrofit case, this scenario needs an upgrade in the propulsion power. This upgrade comprises 5.7% power upgrade for the 13 meter extension of the length of the ship (4.5% of the extra fuel consumption), and an additional 2.0% for the increased weight (1.5% of the extra fuel consumption).

Similar to the retrofit case, our model does not account for the additional flue gas generated by the upgraded main engine and the flue gases from the freshwater plant. Taking these factors into consideration, it is reasonable to anticipate a slightly higher percentage of fuel consumption for the 90% CO_2 avoidance rate scenario.

5.7. Comparison of case studies

Table 12 provides an overview of three scenarios: the original ship configuration, a retrofit with a 70% CO_2 emission avoidance rate, and a newbuild configuration targeting a 90% CO_2 emission avoidance rate. As shown in Table 12, there are significant changes in power and heat demand when carbon capture systems are implemented. In the retrofit case, the main engine provides additional power to accommodate the extra weight added to the ship, while in the newbuild case, it caters to both the increased weight and the extended length of the ship.

Although the results confirm high fuel consumption, a techno-economic study (Oh et al., 2024) indicates that an OCCS system gives a lower CO_2 avoided cost compared to bio-Diesel, targeting the identical ship emission reduction. In addition, a recent study urges that the price of alternative fuels, such as green and blue hydrogen, is expected to remain high for a while (Ueckerdt et al., 2024), which will make them less economically attractive compared to OCCS.

Finally, one crucial aspect to consider is the fuel storage capacity required for the newbuild scenario. According to ship documents, the fuel storage capacity for our case studies is approximately three times greater than that needed for the original configuration. Consequently, significant ship modifications are not necessary, despite the doubling of fuel consumption in the newbuild scenario. However, some adjustments are needed to ensure safety margins, and these modifications may have an impact on the size of the ship.

6. Conclusion

The present study aimed to identify, discuss and highlight key challenges associated with the installation of carbon capture technology onboard ships. As presented, the cost of capital expenditure, operational expenditure, and additional fuel consumption is significant.

To evaluate the suitability of current ship designs for carbon capture installation, one retrofit vessel and one newbuild ship are being studied. The retrofit case focused on a bulk carrier ship named BAIACU, while the newbuild case examined the same ship design without limitations on power and heat availability or on the ship length extension. By analyzing the fuel composition, the heat and power balance of the ship, the voyage, the final exhaust gas composition, and the possible arrangement for the capture system and CO_2 storage, the following can be concluded:

Table 12
A summary of the comparison of the original case, retrofit and newbuild case. All the units are in kW.

Case	Without CCS	Retrofit CCS	Newbuild CCS
CO_2 avoided rate	–	70%	90%
Main engine	8,160	8,280	8,750
Aux engine 1	500	850	1,100
Aux engine 2	0	850	1,100
Aux engine 3	0	530	614
Boiler	1,000	6,902	12,025
WHRU	1,300	1,822	2,200
Fuel demand increase	–	≥ 70%	≥ 100%

- The retrofit case faces challenges such as space limitations and the need for additional power and heat.
- Reducing 70% of the CO_2 results in the storage size of approximately 2800 m^3 of CO_2 over a 20-day voyage. Finding sufficient space for CO_2 storage without compromising cargo capacity is a challenge.
- Considering the market of diesel fueled ships in the coming years, it is proposed to use a two-stroke diesel engine with a high percentage of EGR for the newbuild when integrating it with CCS.
- The advantage of this two-stroke EGR engine lies in the consistent flue gas composition when subjected to maritime load oscillations, while the CO_2 mass fraction in the exhaust gas is higher than that of a normal diesel engine.
- The required increase in the length of the ship to accommodate the carbon capture system results in a 6% increase in fuel consumption of main engine.
- The final fuel consumption can be 70% and 100% higher than the base ship without OCCS for emission reductions of 70% and 90%, respectively.

Although the results confirm high fuel consumption and the need for space and footprint for installation, further studies are required to understand when carbon capture onboard can be a more cost- and environmentally efficient decarbonization strategy than alternatives that are expected to maintain high prices. Furthermore, the high capture rate has the potential to significantly reduce the CO_2 emissions of the shipping industry, which may not be attainable through other alternative solutions in due time. This substantial reduction in emissions can transform the shipping industry into a cleaner and more environmentally friendly mode of transportation, effectively mitigating its historically high contribution to CO_2 production.

It is important to note certain limitations of this study, such as a lack of a detailed design implementation, safety considerations, ship stability analysis with the additional equipment, and the increased fuel tank size. These aspects, although potentially of critical significance, have not been addressed in this research.

CRediT authorship contribution statement

Sadi Tavakoli: Writing – review & editing, Writing – original draft, Visualization, Supervision, Methodology, Investigation, Formal analysis. **Gunnar Malm Gamlem:** Writing – original draft, Methodology. **Donghoi Kim:** Writing – review & editing, Writing – original draft, Investigation, Formal analysis. **Simon Roussanaly:** Writing – review &

editing, Writing – original draft, Project administration, Methodology, Funding acquisition. **Rahul Anantharaman:** Writing – original draft, Methodology, Formal analysis. **Kevin Kusup Yum:** Writing – original draft. **Anders Valland:** Supervision, Project administration, Funding acquisition.

Declaration of competing interest

The authors declare the following financial interests/personal relationships which may be considered as potential competing interests: The publication is supported by the KSN project CCShip under the MAROFF program of the Research Council of Norway (RCN project number 320260). The authors would like to acknowledge the following partners for their support: the NCCS Research Centre and its partners (Aker Carbon Capture, Allton, Ansaldo Energia, Baker Hughes, CoorsTek Membrane Sciences, Equinor, Fortum Oslo Varme, Gassco, KROHNE, Larvik Shipping, Lundin Norway, Norcem, Norwegian Oil and Gas, Quad Geometrics, Stratum Reservoir, Total, Vår Energi, Wintershall DEA), Calix Limited, Klaveness, Wärtsilä, and the Research Council of Norway.

Data availability

No data was used for the research described in the article.

Acknowledgments

The publication is supported by the KSN project CCShip under the MAROFF program of the Research Council of Norway (RCN project number 320260). The authors would like to acknowledge the following partners for their support: the NCCS Research Centre and its partners (Aker Carbon Capture, Allton, Ansaldo Energia, Baker Hughes, CoorsTek Membrane Sciences, Equinor, Fortum Oslo Varme, Gassco, KROHNE, Larvik Shipping, Lundin Norway, Norcem, Norwegian Oil and Gas, Quad Geometrics, Stratum Reservoir, Total, Vår Energi, Wintershall DEA), Calix Limited, Klaveness, Wärtsilä, and the Research Council of Norway.

Additional information

Supplementary information is available for this paper.

Appendix A. Supplementary data

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.jclepro.2024.142032.

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