CO2 capture from ships: An in-depth multi-criteria screening of CO2 capture technologies

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Abstract:

Shipping is the backbone of global freight. However, due to its currently strong reliance on fossil fuels, it accounts for 3 % of global greenhouse gas emissions, highlighting both the need and challenge of achieving the required rapid decarbonization. Over the past decade, Onboard carbon capture and storage (OCCS) has gained interest as a potential mitigation strategy while alternative fuels continue to develop. However, several capture technologies could be considered to capture the resulting CO2. In order to identify the most promising ones, this study performs a screening of different capture technologies (including absorption, membrane-assisted liquefaction, adsorption-assisted liquefaction, calcium-looping) through the case of a combination carrier under retrofit and newbuilding scenarios.

Overall, the results indicate that retrofit installations can reduce CO2 emissions by at least 45 %, even when using the existing ship power system. Once the utility (heat and power) is assumed sufficient (newbuilding scenario), up to 90 % reduction rates become feasible. Although the additional fuel usage is not negligible in the retrofit and newbuilding scenarios, the net emission reduction remains substantial, making onboard CCS a viable decarbonization measure. Among the process options, the absorption system demonstrates high capture potential with various heat sources but faces deployment challenges due to tall columns and chemical handling. Electricity-driven capture (membrane- and adsorption-assisted liquefaction) offers simpler configurations with competitive energy demands, with membrane-assisted liquefaction appearing to be the most energy-efficient and compact. Calcium-looping, and its hybridization with MEA, is a potential alternative when accessible energy for OCCS is limited onboard and when the sorbent material costs are low.

Finally, it is important to note that several factors such as ship type, sailing distance, fuel costs, and regulations will impact the performance of OCCS. Therefore, a detailed design and cost analysis are likely necessary to understand the competitiveness of OCCS compared to alternative approaches to reduce emissions from ships.

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CO_2 capture from ships: An in-depth multi-criteria screening of CO_2 capture technologies

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ABSTRACT

Shipping is the backbone of global freight. However, due to its currently strong reliance on fossil fuels, it accounts for 3 % of global greenhouse gas emissions, highlighting both the need and challenge of achieving the required rapid decarbonization. Over the past decade, Onboard carbon capture and storage (OCCS) has gained interest as a potential mitigation strategy while alternative fuels continue to develop. However, several capture technologies could be considered to capture the resulting CO_2. In order to identify the most promising ones, this study performs a screening of different capture technologies (including absorption, membrane-assisted liquefaction, adsorption-assisted liquefaction, calcium-looping) through the case of a combination carrier under retrofit and newbuilding scenarios.

Overall, the results indicate that retrofit installations can reduce CO_2 emissions by at least 45 %, even when using the existing ship power system. Once the utility (heat and power) is assumed sufficient (newbuilding scenario), up to 90 % reduction rates become feasible. Although the additional fuel usage is not negligible in the retrofit and newbuilding scenarios, the net emission reduction remains substantial, making onboard CCS a viable decarbonization measure. Among the process options, the absorption system demonstrates high capture potential with various heat sources but faces deployment challenges due to tall columns and chemical handling. Electricity-driven capture (membrane- and adsorption-assisted liquefaction) offers simpler configurations with competitive energy demands, with membrane-assisted liquefaction appearing to be the most energy-efficient and compact. Calcium-looping, and its hybridization with MEA, is a potential alternative when accessible energy for OCCS is limited onboard and when the sorbent material costs are low.

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1 Introduction

Shipping is often considered an cost -efficient and eco-friendly mode of freight transport with low specific greenhouse gas (GHG) emissions [1]. These advantages encourage the broader use of shipping and its integration with other transport modes to minimize emissions from the transport sector. Yet, shipping is one of the major contributors to global GHG emissions, accounting for approximately 3 % [2]. In addition, shipping emissions have continued to rise with global economic growth, as the sector is the backbone of international trade [3]. Therefore, cutting GHG emissions from ships is crucial to achieving a zero-emission society [4].

In response to the need to achieve the goal of the Paris agreement, the International Maritime Organization (IMO) plans to establish a GHG emission regulation for the shipping sector, targeting net-zero emissions by 2050 [5–7]. The EU has also introduced a regulation, FuelEU Maritime, to gradually decrease the well-to-wake (WtW) GHG emission intensity of fuel energy used onboard [8]. FuelEU Maritime will take effect in 2025, accompanied by a penalty mechanism for non-compliance. The EU Emissions Trading System (ETS) has also been extended to ships entering and leaving the European Economic Area (EEA) from 2024, providing further incentives for the reduction of ship emissions [9,10]. Therefore, the search for effective and immediate measures to deeply reduce GHG is on the rise.

Despite these regulatory pressures, progress in emission reduction has been slow for the shipping industry, and recent fuel shifts, such as the use of liquefied natural gas (LNG), have been leading to only limited emission reduction due to upstream emissions, combustion emissions and methane slip [2]. Zero-carbon fuels like ammonia and hydrogen are expected to play a key role. Still, their deployment faces challenges due to their low technological maturity and insufficient supporting infrastructure [11], their foreseeable high costs in the coming decade [12]. In parallel, carbon capture and storage (CCS) has emerged as a viable and near-term solution for the maritime sector before zero-carbon fuels become economically and technically feasible [11]. As a result, the IMO has also started developing a dedicated framework for deploying OCCS as an emission reduction measure [5].

Previous life cycle assessment (LCA) studies have clearly shown that onboard CCS (OCCS) can provide a large net GHG emissions reduction impact, even when including the upstream emissions of the fuels used and the emissions derived from the activities to handle captured CO_2 for permanent storage [13,14]. Detailed evaluation of OCCS on existing ships also validates its technical feasibility for deployment in marine applications [15,16]. Once deployed, the economic burden of OCCS is found to be lower than that of using biofuels to achieve the same emission reduction impact, positioning OCCS as a competitive option to alternative fuels [17]. The economic performance of OCCS is expected to be further improved as the EU ETS has recently extended to include captured CO_2 onboard if it is permanently stored [9].

Since the majority of existing ships and new orders are still based on hydrocarbon fuels [11], post-combustion CO_2 capture can be a readily accessible measure for emission reduction as an end-of-pipe solution that can be integrated with existing ship power systems. OCCS could thus enable existing fossil-fueled ships to comply with emissions regulations and extend their operational lifespans [14], complementing the role of zero-carbon fuel.

The potential benefits of OCCS have resulted in various studies investigating post-combustion carbon capture systems for ship applications. In previous studies, chemical absorption has been the most widely explored technology for OCCS, due to its high technology readiness level (TRL) based on long industrial experience in onshore applications. The solvent-based capture process has been applied to diverse ship types, such as a crane vessel [18], LNG carriers [19,20], oil tankers [15,16,19,21], container ships [22,23], small-sized ships [24–26], and even hypothetical ships [27,28]. The wide range of vessels for absorption-based capture means that various marine engines and fuels are already considered, determining the exhaust gas conditions and capture performance [14,17,29].

While chemical absorption has been the most studied CO_2 capture technology for ships, its limitations, including operational complexity, use of chemicals, and tall equipment [15], highlight the need for alternative capture technologies for ships. Emerging options such as physical adsorption [26,30], membrane [22], cryogenic [31,32], and calcium looping-based processes [33,34] are being evaluated for maritime applications to assess their performance and technical feasibility. However, their relatively low TRL has made these process options less prioritized, while the absorption system has reached pilot-scale testing [35–37]. Furthermore, studies on capture technologies show that they have distinctive characteristics depending on their operating principle, making it challenging to determine an optimal capture solution for OCCS. As the shipping industry has not fully explored emerging capture technologies, further investigating the potential performance of these could lead to the identification of more practical and efficient solutions for CO_2 capture from ships. Although some reviews compare the competitiveness of different CO_2 capture processes [34,36,38,39], these comparisons are primarily based on literature studies without a common design basis and actual simulations, thus significantly limiting reliability of their conclusions regarding respective competitiveness.

This study thus aims to provide an objective and in-depth comparison of different onboard capture solutions to identify the most promising technologies for OCCS. In order to do so, a consistent, transparent, and comprehensive assessment of both conventional (chemical absorption) and five emerging CO_2 capture technologies (based on physical adsorption, membrane, cryogenic, calcium looping, and their combinations) for ship applications through detailed process simulations under consistent design and operational assumptions. The technology solutions for OCCS are assessed by different key performance indicators (KPIs) to characterize their potential and competitiveness. Furthermore, this work includes all CO_2 sources to be treated by the capture system on a ship, including exhaust from auxiliary boilers and generators, which are often overlooked in OCCS assessments despite their impact on capture performance. Indeed, capturing CO_2 solely from propulsion engines yields a limited CO_2 reduction capability, highlighting the need to treat all onboard exhaust gases to enable the deep decarbonization of ships [14,15,17]. Finally, two ship scenarios, based on a retrofit and newbuild approach, are considered to understand how this could impact performance and technology selection.

The paper is structured as follows. First the targeted ship is presented together with the considered CO_2 capture technologies. Secondly the methodology used for evaluation is summarized while more detail can be found in Supplementary Information. The results are then presented and discussed, before final conclusions drawn.

2 Target ship scenarios and CO_2 capture technologies

2.1 Target ship

In this work, a combination carrier from Klaveness Combination Carriers ASA (see Table 1) is used as a target ship for OCCS, as this ship type is one of the largest CO_2 emission sources in the shipping industry [15]. This ship is powered by heavy fuel oil (HFO) to operate a 9.6 MW propulsion engine while producing electricity via three auxiliary engines (maximum 3.3 MW_{el}) and heat through a saturated steam boiler (maximum 6.3 MW_{th}).

Compared to other ship types, this vessel has a large boiler to heat wet cargo, such as crude oil, for unloading. Thus, during the laden voyage, a significant amount of heat is available for CO_2 capture by using the boiler. In addition, the combination carrier utilizes a waste heat recovery unit (WHRU), which collects low-temperature heat from the exhaust gas, further increasing the excess heat on the ship for OCCS. As a result, this ship is expected to be a suitable candidate for deploying CO_2 capture facilities due to the relatively large amount of energy available for OCCS [40]. Detailed information on the vessel and the ship power system can be found in Section 3.

Table 1. Specification of the target vessel, BAIACU.

Item	Unit	Value
Type	-	Combination carrier
Cargo	-	Dry bulk or wet cargo
Gross tonnage	tonne	54043
Length overall	m	228
Depth	m	23
Sailing time	day	20

2.2 Deployment scenarios

The technology options for onboard CO_2 capture can be categorized based on their primary driving source. Given the isolated and limited space of the ship environment, the type of energy and material required for capture technology becomes a critical factor in its feasibility and maximum performance. Together with the type of capture technologies, the allowable level of ship modification is a key factor for selecting and designing a CO_2 capture process.

Thus, to reflect realistic deployment scenarios and potential associated constraints, this study examines two distinctive scenarios: retrofitting an existing ship and designing a new target ship (newbuilding) for OCCS integration. In the retrofit scenario, an existing bulk carrier is analyzed to determine the maximum achievable capture rate of OCCS systems while maintaining the existing auxiliaries, including generators and boilers. In contrast, the newbuilding scenario aims to achieve high CO_2 capture rates for deep decarbonization by assuming expansions of the auxiliaries and space to host OCCS. This newbuilding scenario also considers changes in the power system, such as exhaust gas recirculation (EGR), to highlight the benefits of increased CO_2 concentration in the exhaust gas for the capture systems.

2.2.1 Retrofit scenario

As a reference, the retrofit scenario considers the BAIACU vessel without any modifications to its current ship machinery system. This means that the existing propulsion engine, auxiliary generators, and boiler operate with the same capacity. Consequently, the performance of a CCS facility will be limited to the capacity of the current power system onboard. In addition, using the existing machinery implies that CO_2 capture processes, which require changes to the ship power system, such as exhaust gas recirculation (EGR), are excluded from the scenario.

Structural modifications to the ship are also minimized to allow for easy deployment of CCS units. As discussed in previous work [15], most of the available space for a CCS system is on the deck and in the funnel. The limited space for OCCS can constrain the dimensions of a capture process, such as the maximum height, which can influence capture efficiency. Therefore, the retrofit scenario aims to evaluate the maximum achievable CO_2 reduction potential of post-combustion capture processes when the ship modifications are kept to a minimum level.

2.2.2 Newbuilding scenario

Maximizing the capture potential of CCS technologies often requires extensive modifications, which are not feasible for retrofitting. In contrast, a newly built ship can be designed to accommodate an OCCS system, allowing for improved performance of the capture processes. Thus, in this newbuilding scenario, high CO_2 capture rates are targeted, while the required expansion of the auxiliaries and space is expected to be achieved by redesigning the ship. The CO_2 capture rate can be targeted at over 90 % to deeply reduce CO_2 emissions from the shipping sector or at desired levels, depending on policy and market conditions. Thus, this scenario will assist in identifying the role of OCCS in the shipping industry for new vessels compared to other emission reduction methods, such as e-fuels.

As a part of the design flexibility, exhaust gas recirculation (EGR), which increases the CO_2 concentration of the engine exhaust gas, is also considered to improve the capture efficiency. Since the space and energy requirements for OCCS are no longer issues in the newbuilding scenario, there are fewer limitations on selecting OCCS technology options than in the retrofit scenario.

2.3 Process options for onboard CCS

Six CO_2 capture processes are considered for onboard carbon capture[1]:

- Monoethanolamine-based absorption (MEA+liq) with liquefaction conditioning [41], serving also of reference process;

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[1]The processes using MEA require a dedicated, liquefaction-based CO_2 conditioning step. Accordingly, simple downstream addition of this step is denoted with "+," whereas a hyphen ("-") indicates a hybrid of two process concepts.

- Vacuum Swing Adsorption - liquefaction hybrid (VSA-liq) [42,43] using the zeolite 13X sorbent;
- Membrane-liquefaction hybrid (Mem-liq) [44] using the Polaris membrane [45];
- Cryogenic supersonic (Cryo) [46];
- Carbonator of calcium looping[2] (CaL) [33];
- Carbonator of calcium looping - absorption hybrid with liquefaction conditioning (CaL-MEA+liq).

Detailed descriptions of the capture technologies are provided in Section S.2 of the Supplementary Material. It is worth noting that these can be organized in three categories: 1) Heat-driven process – MEA+liq 2) Electricity-driven processes – VSA-liq, Mem-liq, and Cryo 3) Material-driven processes – CaL and CaL-MEA+liq. By examining the wide range of capture technologies, this work aims to identify the most feasible and effective CO_2 capture solutions for retrofit and newbuilding scenarios. Their dependence on heat, electricity, or materials will directly impact ship design, energy consumption, operational complexity, and integration into existing or new ship designs, particularly critical in space- and energy-constrained maritime environments. In this work, the available capture technology options for retrofit and newbuilding scenarios vary based on the technology readiness level (TRL) and characteristics, as described in Section S.2 of the Supplementary Material. In particular, the cryogenic supersonic process is not considered for the newbuilding scenario due to the high capture performance required while having a low TRL. The CaL and absorption hybrid is only studied for the newbuilding scenario due to the complex process structure. Table 2 summarizes the retrofit and newbuilding scenarios with the relevant capture processes.

It is worth noting that the target capture rates for the CaL-based systems will differ from those of other capture systems. When standard cycled sorbent materials are used, an onboard CaL concept is expected to require substantial space for solid storage, which can be impractical for retrofitting. Therefore, for the retrofit scenario, the CaL system is designed to achieve the same CO_2 emission reduction performance as the reference process (absorption) to determine whether the space requirement is acceptable. For the newbuilding scenario, the CaL concept targets 85 and 90 % capture rates, which will have a CO_2 reduction effect comparable to other capture units with 90 and 95 % capture rates, as the carbonator does not consume energy.

Table 2. Two scenarios for onboard CO_2 capture technologies (simple downstream addition of a process step is denoted with “+,” whereas a hyphen (“-”) indicates a hybrid of two process concepts.).

Scenario	Retrofit scenario	Newbuilding scenario
Characteristics	Bulk carrier HFO Diesel engine Limited available heat Limited available power Limited space	Bulk carrier HFO Diesel engine with EGR No limit on available heat No limit on available power No limit on space
Capture technology	- Absorption + liquefaction - VSA-liquefaction - Membrane-liquefaction - Cryogenic supersonic[3] - Carbonator of CaL	- Absorption + liquefaction - VSA-liquefaction - Membrane-liquefaction - Carbonator of CaL - CaL-absorption + liquefaction[4]
Target	Maximum achievable CO_2 capture	90 and 95% of CO_2 capture

[2] Compared to a conventional looping system, it is important to note that the carbonator is located onboard while the regeneration of the $CaCO_3$ is assumed to take place calciner on land at port.

[3] Cryogenic supersonic process is not considered in the newbuilding scenario due to the low TRL and the demanding capture performance

[4] CaL-absorption + liquefaction process is not considered in the retrofit scenario due to the complex system structure

3 Modelling approach and design basis

3.1 Ship power system with OCCS

Figure 1 introduces the ship power system with CO_2 capture and storage units on the BAIACU vessel. The combination carrier is run by a single propulsion engine, three auxiliary engines, and a boiler. The main engine provides propulsion power for the ship and does not directly influence the available energy for onboard CCS. However, its load affects the amount of exhaust gas and, thus, the energy demand of the capture process. The auxiliary engines and boiler operate to meet the baseload of electricity and heat on the ship during the laden voyage.

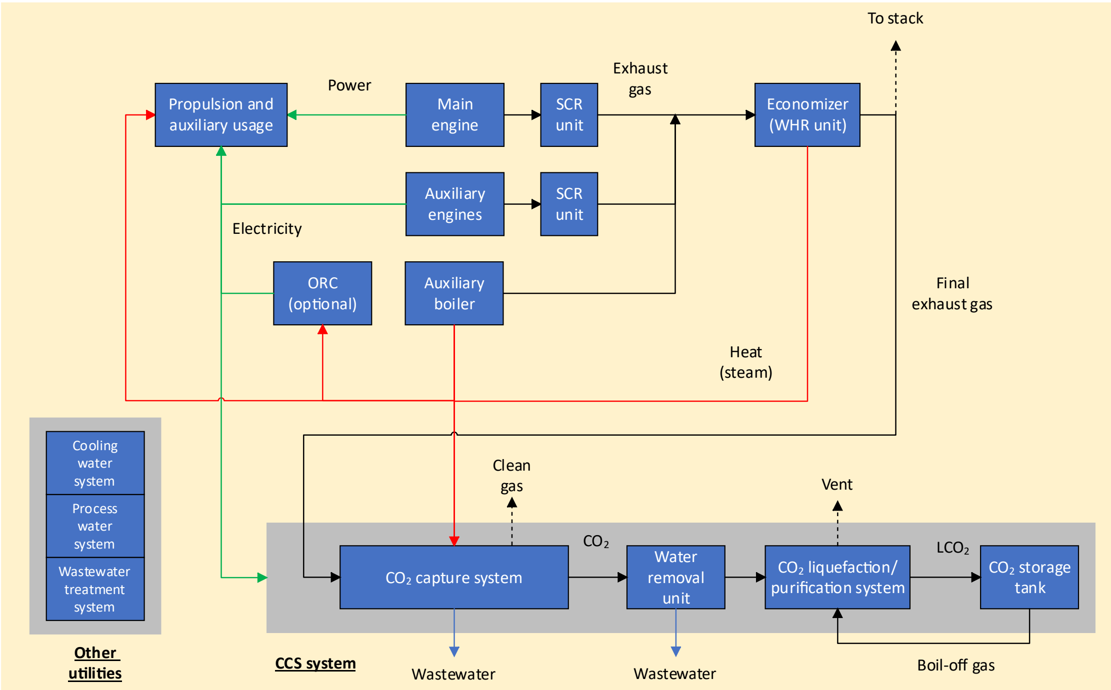


Figure 1. Overall system block diagram on a vessel with OCCS.

All the engines on the ship are equipped with selective catalytic reduction (SCR) units to reduce NOx emissions. Exhaust gases from these SCR units are mixed with the boiler exhaust gas before being sent to a waste heat recovery unit (WHRU), also referred to as the economizer, which produces saturated steam. In this study, the economizer capacity is assumed sufficient to recover residual heat in the exhaust gas regardless of the utility load. If the recovered heat from the economizer exceeds the total heat demand on the ship (including both the baseload and the CCS system), the surplus heat is used by an organic Rankine cycle (ORC) for electricity generation. The final exhaust gas from the economizer is delivered to a CO_2 capture process to produce high-purity CO_2 with a concentration of over 90 mol%. The captured CO_2 is conditioned to reach liquid state for storage conditions (i.e. 15 barg), including required removal of impurities (reaching a concentration above 99.5 % and meeting Northern Light purity requirements).

While in the retrofit scenario, it is assumed that the CO_2 capture and liquefaction can only be use the remaining engine and boiler capacities, it is important to remember that the newbuilding scenario assumes that the engine and boiler capacities is designed to cover all heat and power needs of the CO_2 capture and liquefaction system thus overcoming potential limitation in CO_2 capture rate inherent to the retrofit scenario.

Finally, for both the retrofit and newbuild scenarios, it is worth noting that establishing the energy balance of the entire system, including both ship and OCCS systems, is complex. Indeed, once an OCCS system is installed, the auxiliary load increases to cover the energy demand of the capture unit. The increased heat and power generation result in a higher exhaust gas flow rate, thereby raising the energy demand of the capture unit to maintain the capture rate. When the auxiliary load changes, variations in the CO_2 content of the final exhaust gas entering the capture unit can also occur, as it is a mixture of exhaust gases from the main engine, the auxiliary engine, and the boiler, each having different CO_2 concentrations. These varying CO_2 concentrations influence the energy efficiency of the capture system, which in turn influences the auxiliary load. Variations in the exhaust gas flow rate also impact on the amount of waste heat collected from the economizer, thereby altering the demand for the auxiliary boiler. In order to overcome this challenge, a generic tool was developed to reflect such complex relationships and used to provide an accurate energy balance of the entire system, including the estimated increase in fuel consumption. This tool determines the loads of the auxiliary engines and boiler that give energy balance with the ship baseload and the CCS energy demand at a given capture rate. This tool can also find the maximum CO_2 capture rate compatible with a given ship machinery system. The schematic of this energy balance tool, which employs an iterative procedure, is illustrated in Figure S-1 of the Supplementary Material, while the specifications and design basis for the ship power system and the capture processes applied in the energy balance tool are presented in the next section.

3.2 Design basis

A detailed design basis is established for objective comparison and simulate the ship power system on the BAIACU vessel and various CCS processes. Considering a long-haul laden voyage at stable sailing conditions, the ship is assumed to be operated at a fixed engine load and vessel speed (see Table 3). Although the actual engine load profiles vary significantly during a voyage due to weather and sea conditions [17], this work focuses on a steady-state operation to evaluate and compare the different technological options for CCS at the early design phase.

Table 3. The voyage characteristics of the target vessel.

Item	Unit	Value
Sailing average engine load	%	85
Sailing average speed	Kn/h	13
Sailing distance	km	12000
Sailing time	h	480

As discussed in Section 2.2.2, the main change in the design specification for the newbuilding scenario is the use of EGR on the propulsion engine. EGR is a concept that recirculates exhaust gas from the engine and replaces some of the air intake, as presented in Figure S-2 in the Supplementary Material. EGR is useful for downstream CO_2 capture units for two reasons. Firstly, with EGR, the exhaust gas becomes richer in CO_2, which improves the energy efficiency of the capture system. Secondly, the reduced exhaust gas flow rate resulting from recirculation also decreases the size of the onboard capture system. The EGR rate[5] typically ranges from 30 % to 40 %, depending on the configuration [47]. In this work, an EGR of 41 % is adopted based on experimental validation performed by SINTEF Ocean [15]. It is worth noting that, as indicated in Table S-1 in the Supplementary Material, applying EGR to the propulsion engine can result in a slight decrease in efficiency and thus higher fuel consumption and CO_2 emissions. In addition, the reduced exhaust flow rate means that the waste heat recovered from the economizer will decrease unless the heat from the EGR cooler is collected. However, the heat recovery from the EGR cooler is not considered in this work as the temperature of the heat can be constrained by the cooling arrangement, which is often linked to other cooling circuits around the engine. Thus, optimal use of waste heat around the engine will require dedicated analysis and modifications of the engine system, which was deemed beyond the scope of the study.

[5] Corresponding to the proportion of exhaust flue gas recycled.

The EGR concept is applied only to the propulsion engine in the newbuilding scenario. Therefore, the auxiliary engines maintain the specifications for both the retrofit and newbuilding scenarios. The auxiliary boiler and WHRU, referred to as the economizer, also remain unchanged for the two scenarios. The performance and specifications of the ship power system (propulsion engine and auxiliaries) are presented in Section S.1 of the Supplementary Material.

Table 4. Exhaust gas mixture at the baseload condition.

Item	Unit	Retrofit HFO No OCCS	Newbuilding HFO-EGR No OCCS
Exhaust gas temperature	°C	259	258
Exhaust gas pressure	kpa	106	106
Exhaust gas mass flow rate	kg/h	53407	41590
Exhaust gas CO_2 flow rate	kg/h	4969	5138
Exhaust gas CO_2 concentration	mol%	6.14	8.16

Table 4 presents the final exhaust gas conditions of the retrofit and newbuilding scenarios when no OCCS is applied. As discussed in Section 3.1, the newbuilding scenario has a higher CO_2 concentration than the retrofit scenario due to EGR in the propulsion engine. However, the CO_2 fraction in the mixed exhaust gas varies depending on the duty of the auxiliaries with OCCS, as the CO_2 concentration of the exhaust gas from the auxiliary engines and boiler differs from that of the main engine. It should be noted that the capacity of the auxiliaries is fixed only for the retrofit scenario, while the newbuilding scenario is assumed to have sufficient capacity for a given capture rate.

As shown in Table 5, the BAIACU vessel requires 2.2 MW of heat and 0.5 MW of electricity during the laden voyage. The heat baseload of the ship is estimated by assuming that the baseload does not exceed the maximum WHRU capacity, which occurs at the maximum load of the main engine and the auxiliaries. With the baseload energy consumption, the available heat and power for CCS will be around 4.1 MW of heat and 2.8 MW of electricity, excluding the WHRU and ORC capacity. An ORC using iso-butane is applied to produce electricity when there is excess heat from the WHRU, providing a 10 % heat-to-power efficiency. Other waste heat sources, such as ship cooling water system, compressor intercoolers, etc., are not considered in this screening work to avoid complex system configurations.

Table 5. Energy baseload of the BAIACU vessel and available energy for CCS.

Item	Unit	Value
Maximum heat production	MW_{th}	6.29+WHRU
Heat baseload	MW_{th}	2.20
Maximum available heat for CCS	MW_{th}	4.09+WHRU
Maximum electricity production	MW_{el}	3.33+ORC
Electricity baseload	MW_{el}	0.50
Maximum available power for CCS	MW_{el}	2.83+ORC

The modelling of the CO_2 capture and conditioning for the different capture processes are presented in Section S.2 of the Supplementary Material. The captured CO_2 is assumed to be compressed and dehydrated before being liquefied by an ammonia refrigeration cycle as introduced in Figure S-15 in the Supplementary Material [48]. This liquefier is only applied to the absorption system, as others have their own processing steps to store CO_2. The liquefaction system is also designed to meet the CO_2 specifications from the Northern Lights project for industrial-scale CO_2 transport and storage (see Table S-12 in the Supplementary Material). In this work, 15 barg liquid CO_2 at a high purity of over 99.5 mol% is targeted, while recovering at least 99.9 % of the CO_2 in the captured CO_2.

Compared to land-based applications, the dimensions of some process equipment are restricted due to the available space on the targeted ship. Previous work shows the maximum height and footprint of OCCS on the BAIACU vessel [15]. Based on the layout analysis, the maximum equipment height of the absorption processes is set at 18 m (see Table S-13 in the Supplementary Material). The system height of the adsorption process is also fixed at 10 m, considering the multi-train configurations with a large footprint. The carbonator height in the calcium looping process is constrained to 10 m in this work. In the newbuilding study, the dimensions of process equipment are no longer constrained when designing capture systems. However, the maximum height of process units is set to the same as in the retrofit scenario. Other design specifications for OCCS can be found in Section S.3 of the Supplementary Material.

3.3 Key performance indicators for screening

Identifying suitable process options for OCCS requires considering multiple criteria to reflect the constraints and aspects relevant to maritime applications. As a result, several key performance indicators (KPIs) are adopted in this study to guide the selection of suitable CO_2 capture processes:

- Specific CO_2 emissions of the ship with OCCS represent the CO_2 emissions per amount of fuel energy consumed. This specific emission value focuses on the amount of onboard CO_2 emissions from the stack, which can be interpreted as tank-to-wake (TtW) CO_2 emissions.

$$\text{Specific CO}_2\text{ emissions }[\text{gCO}_2/\text{MJ}_{\text{fuel}}] = \left(\frac{\text{CO}_2\text{ emission from ship with CCS}}{\text{Lower heating value of fuel}}\right) \quad \text{(Eq.1)}$$

- The CO_2 capture and reduction rates are evaluated by considering the amount of CO_2 captured and the amount of CO_2 avoided to measure the emission reduction potential.

$$\text{CO}_2\text{ capture rate }[\%] = \left(\frac{\text{Exhaust gas to OCCS system}}{\text{Exhaust gas}}\right)\left(\frac{\text{Captured CO}_2\text{ via OCCS system}}{\text{CO}_2\text{ in Exhaust gas to OCCS system}}\right) \times 100 \quad \text{(Eq.2)}$$

$$\text{CO}_2\text{ reduction rate }[\%] = \left(1 - \frac{\text{CO}_2\text{ emission from ship with CCS}}{\text{CO}_2\text{ emission from ship without CCS}}\right) \times 100 \quad \text{(Eq.3)}$$

- The additional fuel consumption can be considered as a proxy for variable operating expenditure (OPEX) and process efficiency linked to OCCS implementation. Indeed, OCCS utilities such as heat and power on ships are generated by fuel usage. Thus, the OPEX of a capture system is directly linked to the additional fuel consumption needed. The additional consumption linked to OCCS can also be normalized to the avoided emissions to measure the energy efficiency of the process.

$$\text{Extra fuel consumption }[\text{kg}_{\text{fuel}}/\text{h}] = \text{Total fuel usage with OCCS} - \text{Total fuel usage without OCCS} \quad \text{(Eq.4)}$$

$$\text{Specific fuel consumption }[\text{kg}_{\text{extra fuel}}/\text{kg}_{\text{CO2,avoided}}] = \frac{\text{Total fuel usage with OCCS} - \text{Total fuel usage without OCCS}}{\text{CO}_2\text{ emission from ship without OCCS} - \text{CO}_2\text{ emission from ship with OCCS}} \quad \text{(Eq.5)}$$

Equipment volume/space required by the capture process gives an indication of the cost of the system, the feasibility of the integration of OCCS on the ship, as well as the level of modification that may be required. Hence, this work adopts the volume of the capture system as a high-level proxy for capital expenditure (CAPEX), while a detailed techno-economic analysis will be conducted on the promising technology options selected in this study considering also detailed integration onboard the ship.

Current technology maturity is an essential parameter for the rapid deployment of OCCS in the marine industry. Therefore, the Technology Readiness Level (TRL) based on the current status of onboard capture technologies will be discussed at the end of this study.

Since this is an early design phase, some KPIs are assessed based on high-level (or proxy type of) evaluations, while future work will perform detailed evaluations and onboard integration studies for the most promising solutions. However, other performance parameters of OCCS systems are also presented to provide a detailed analysis of simulation results for the retrofit and newbuilding scenarios as follows.

4 Results and discussion

4.1 Retrofit scenario

The deployment constraints of the retrofit scenario, using only the existing onboard machinery, can limit the performance of capture processes. Thus, the primary focus of this scenario is to identify the maximum CO_2 capture rate achievable by each capture system under the retrofit condition. Therefore, all results of this subsection reflect these maximum achievable capture rates, which differ between technologies.

The exhaust gas conditions (CO_2 concentration, temperature, etc.) from the retrofit scenario are also different from the target ship as more fuel is used to supply energy for OCCS, which in turn affects the characteristics of the exhaust gas entering capture units. This effect results in a slightly higher CO_2 concentration in the MEA-based capture case due to the more extensive use of the boiler (see Figure A-1 in Appendix for detailed information). On the other hand, the temperature and recoverable waste heat of the exhaust gas remain similar across the capture technologies. This heat collected alone is insufficient to meet the heat demand of the ship, even without capture, thus requiring additional fuel usage. The only exception is the CaL process, where substantial heat can be extracted from the carbonator, covering well above the heat demand for ship operation.

Considering the exhaust gas conditions, the absorption process in the retrofit scenario requires 3.6 MJ_{th}/ $kgCO2_{captured}$ and 1.0 MJ_{el}/ $kgCO2_{captured}$, as shown in Figure 2. Indeed, although the absorption system is primarily heat-driven, exhaust gas compression and CO_2 liquefaction require noticeable power consumption. The electricity-driven capture technologies require a specific power consumption of 2.6-2.8 MJ_{el}/ $kgCO2_{captured}$ with the membrane-liquefaction hybrid and the cryogenic supersonic concepts demonstrating the highest energy efficiency. Assuming a 50 % fuel-to-power conversion efficiency, the electricity-driven systems require 5.2-5.6 MJ_{th}/$kgCO_2$,captured thus being slightly more efficient than the absorption process. Finally, the material-driven capture concept (CaL) presents no major energy input as the material regeneration is conducted onshore.

Based on these calculated heat and power requirements with the characteristics of the ship energy system, the achievable capture rate can be calculated together with the avoided level of emissions as illustrated in Figure 3. For the absorption process, the spare boiler capacity limits the achievable capture rate to 77 % and leads to a 64 % reduction in CO_2 emissions compared to the ship without CCS. In contrast, the electricity-driven processes achieve a capture rate of less than 60 %, due to the limited spare power capacity on the ship, thus resulting in a 41-47 % reduction in CO_2 emissions. The low capture rates of the electricity-driven capture is a non-negligible drawback for retrofit deployment, although they have relatively low specific fuel consumption (15-25 % lower) compared to the MEA system (see Figure 3). Thus, to achieve high capture rates for the retrofit scenario, process concepts utilizing both energy forms (heat and electricity) can be an option for deep decarbonization of existing ships. In addition, utilization of waste heat sources other than the economizer, such as cooling water system and compressor intercoolers, will further increase the available energy for capture.

This retrofit scenario also results in a noticeable increase in fuel consumption. In particular, the absorption process uses 54 % more fuel than the reference ship due to its higher capture rate and specific fuel consumption, while others see a 30 % increase as seen in Figure 4. Unlike other capture options, the CaL-based concept achieves negative specific fuel consumption while reducing CO_2 emissions to the same level as the absorption capture process (64 %). Figure A-1 in Appendix shows that the heat generated from the material-driven system fully covers the auxiliary boiler duty required for ship operation, thereby saving its fuel usage. As a result, the CaL system reduces fuel consumption by 5 % compared to the reference ship, resulting in negative fuel consumption. This reduced fuel demand enables the CaL process to meet the same CO_2 reduction rate as absorption, but with a lower CO_2 capture rate. Notably, the surplus heat from the CaL system exceeds the heat baseload for ship operation. Although not considered here, this excess heat could be used for power production, further reducing the fuel usage of the ship.

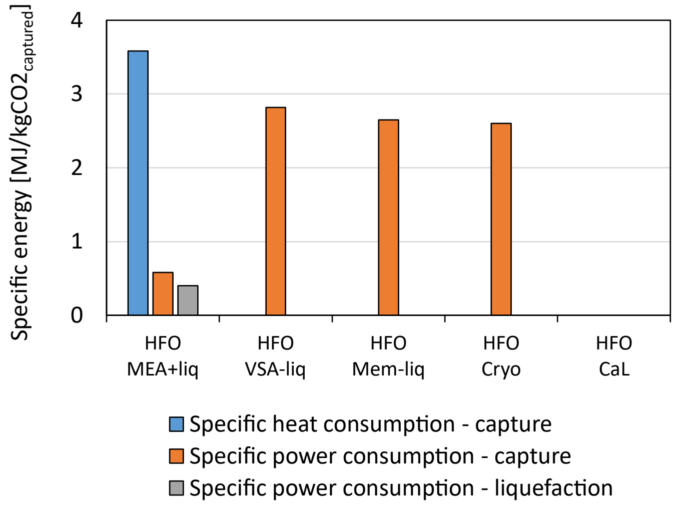


Figure 2. Specific energy consumption of OCCS systems in the retrofit (HFO) scenario.

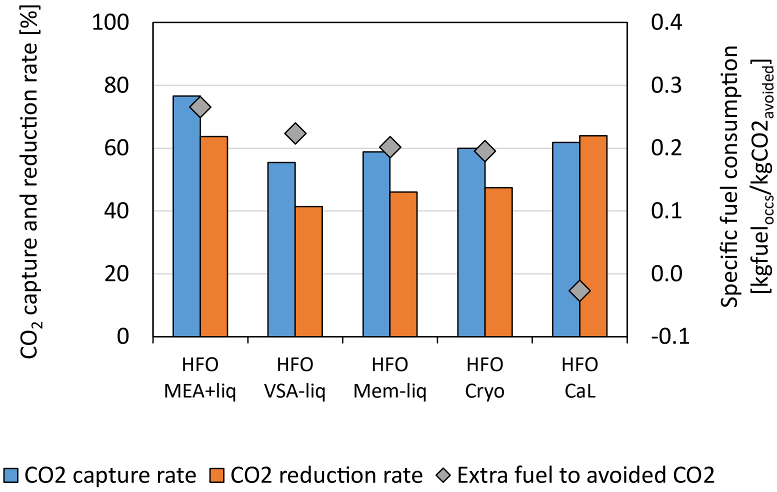


Figure 3. CO_2 capture and reduction rate with specific fuel consumption of OCCS systems in the retrofit (HFO) scenario.

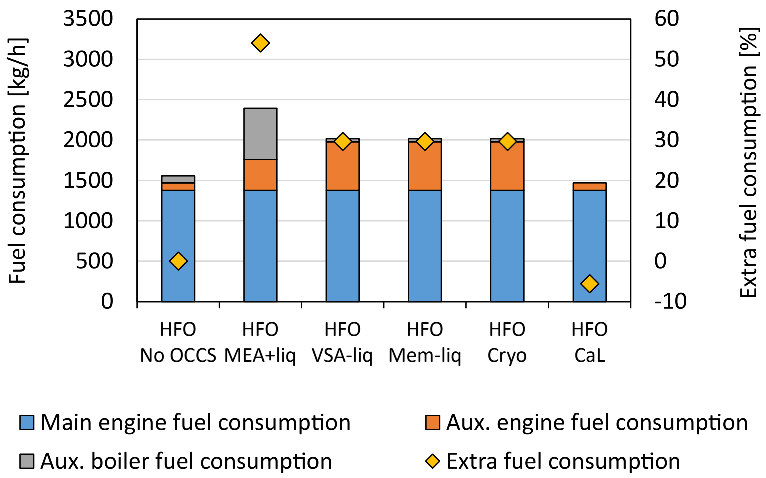


Figure 4. Total and extra fuel consumption of OCCS systems in the retrofit (HFO) scenario.

Despite increased fuel use, Table 6 highlights that all capture systems can limit CO_2 emissions to 2-3 t/h in the retrofit scenario. Table 6 further demonstrates that even when considering total fuel usage onboard, OCCS can reduce the tank-to-wake (TtW) specific CO_2 emissions of the target ship by at least 55 %, making it an effective measure for CO_2 reduction under the IMO and FuelEU Maritime regulations. However, under the specific emission-based regulations, the CaL process appears to have a higher CO_2 intensity per unit of fuel energy used onboard than the reference process (absorption). While both systems have similar net CO_2 emissions, the lower fuel consumption of the CaL concept results in a higher intensity metric, indicating that such intensity-based regulations may not fully reflect the benefits of fuel-saving capture technologies. Finally, as highlighted in Figure 5, emissions from the auxiliaries can become significant with OCCS, making it important also to capture their CO_2 to reach low emissions.

Table 6. Specific CO_2 emissions based on fuel energy used onboard in the retrofit (HFO) scenario.

HFO scenario	Unit	No OCCS	MEA+liq	VSA-liq	Mem-liq	Cryo	CaL
Net CO_2 emission	kg_{CO2}/h	4969	1801	2909	2684	2610	1801
Total fuel consumption	kg_{fuel}/h	1555	2395	2016	2016	2016	1469
HFO lower heating value	MJ/kg_{fuel}	40.5	40.5	40.5	40.5	40.5	40.5
TtW Specific CO_2 emissions	$gCO2/MJ_{fuel}$	78.9	18.6	35.6	32.9	32.0	30.3
Specific emissions reduction	%	-	76.5	54.8	58.3	59.5	61.6

For retrofitting, another challenge is the limited capacity of the auxiliary units. Since the retrofit scenario aims to maximize the capture rate, each capture process pushes either the auxiliary boiler or engines to their limit, depending on the primary energy source for the CCS unit, as shown in Figure 6. However, such long-term and high-load operations will be impractical and thus the actual capture rate for the retrofit case is expected to be lower than reported in this study when accounting for necessary standby capacity of the auxiliaries for robust and reliable ship operation. The only exception is the CaL-based process where none of heat and power is used in large quantities, thereby maintaining sufficient redundancy in the onboard auxiliaries and high capture rates. Another solution for retrofit can be capture systems that use both heat and power so that high-load operation of an auxiliary unit is avoided.

Regarding space requirements, the evaluation shows large variations between capture technologies as shown in Figure 7 (see Section S.5 of the Supplementary Material for details). The most volume-intensive technology is VSA-liq and is 46 % larger than the absorption process. The multi-train configuration of the adsorption system requires a large space and involves a high capital cost. Due to the multiple large-sized columns (DCC, absorber, water wash, desorber), the MEA-based process requires the second-largest onboard space. Meanwhile, the membrane- and cryogenic-based processes (Mem-liq and Cryo) are nearly six and ten times smaller than the adsorption system due to the compact membrane modules and the supersonic nozzle. The small footprint makes these technologies well-suited for ships where space consumption needs to be minimized. However, in all cases, liquid CO_2 storage is by far the main contributor to space demand in the retrofit scenario. As a result, the flowrate of CO_2 captured (t/h) will drive space requirements, which depends on ship size, sailing time, and the emission reduction target.

Similarly, although the capture unit occupies relatively small space in the CaL concept, the solid inventory (both raw and with reacted CO_2) can be substantial. If fresh sorbent is used in every cycle, this storage remains comparable to the most compact solution. However, if the sorbent is recycled between trips, it tends to deactivate, increasing the required onboard inventory. The latter case makes the total space for OCCS with storage around 50 % larger than that of the absorption process at a similar CO_2 reduction rate, posing a major retrofit challenge. Hence, using fresh or novel material [49] to keep high conversion can cut the solid storage by up to 60 % (see low and high solid inventory in Figure 7), making this concept the most compact retrofit option. However, this approach leads to high running costs due to the material cost, and this trade-off should be further studied. More information on the relationship between sorbent conversion and solid inventory is provided in Section S.2.4 of the Supplementary Material.

In any case, apart from the high inventory CaL process, all capture systems studied can be accommodated within the available space for the capture system, excluding storage, on the vessel (2840 m^3).

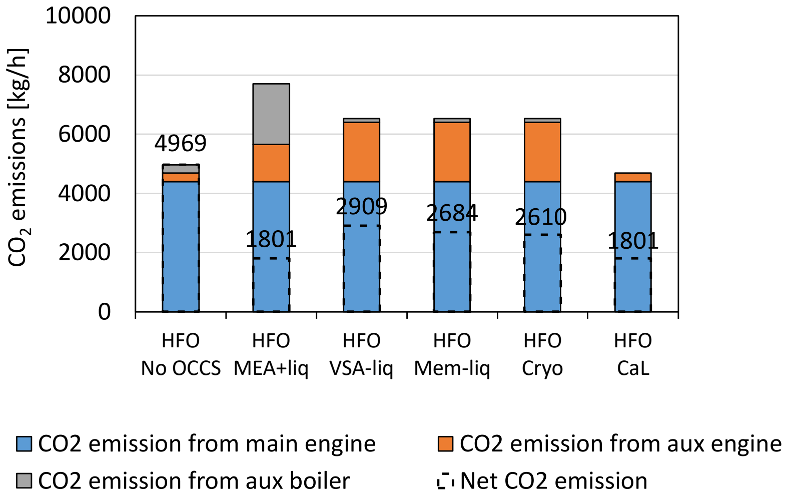


Figure 5. Total and net CO_2 emissions of OCCS systems in the retrofit (HFO) scenario.

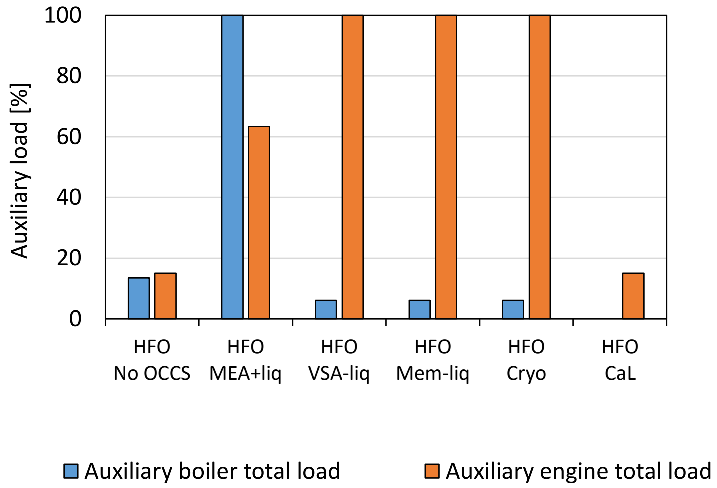


Figure 6. Auxiliary boiler and engine load of OCCS systems in the retrofit (HFO) scenario.

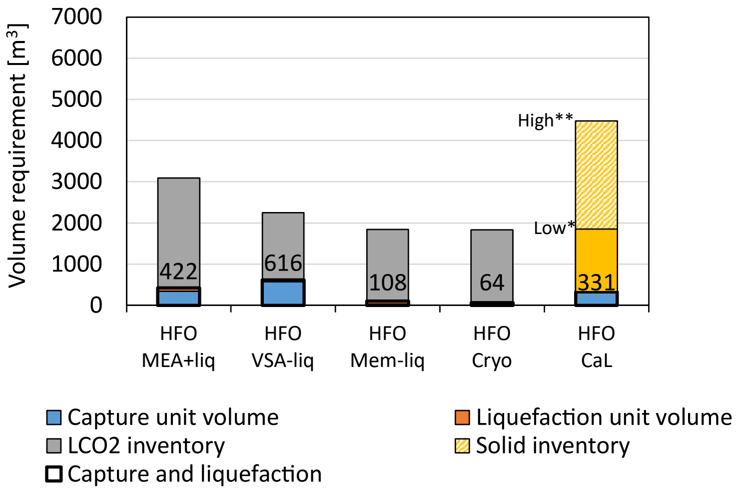


Figure 7. The volume of OCCS systems in the retrofit (HFO) scenario (Low*: solid inventory based on high conversion of fresh sorbent, High**: solid inventory based on low conversion of cycled sorbent).

4.2 Newbuilding scenario

Compared to the retrofit scenario, a key feature of the newbuilding scenario is the integration of EGR with the main engine. As a result, the CO_2 content in the exhaust gas from the propulsion engine increases by 2.2 %-pt (from 6.0 to 8.2 mol%), as shown in Section S.1 of the Supplementary Material. Since the propulsion engine contributes the majority of the final onboard exhaust gas, EGR leads to a higher CO_2 concentration in the stream sent to the CCS systems. While the CO_2 content of the final exhaust gas increases across all capture cases, similar trends to the retrofit scenario are observed: 1) Heat-driven capture processes result in higher CO_2 concentration due to the higher CO_2 content from the boiler; 2) Electricity-driven capture processes result in lower CO_2 concentrations due to the lower CO_2 content from the auxiliary engines; 3) The reduce boiler use in the CaL and CaL-MEA+liq processes also decreases the CO_2 concentration in the final exhaust gas; 4) These trends are further amplified by higher capture rates.

The newbuilding scenario also enables more heat to be extracted from the economizer with OCCS compared to the retrofit scenario. This is due to the increased flow rate of the final exhaust gas at elevated capture rates (90 % and 95 %), resulting from the higher utility consumption of the capture systems. Consequently, the waste heat recovered in the newbuilding scenario is found to be sufficient to cover the boiler baseload (2.2 MW_{th}) for ship operation, except in the absorption and membrane-liquefaction hybrid processes with a 90 % capture rate (see Figure A-2 in Appendix for details).

The benefits of EGR, via increased CO_2 concentration in the final exhaust gas, are clearly reflected in the specific energy consumption of the capture systems studied. Figure 8 indicates that the specific energy consumption of the absorption process in the newbuilding scenario (3.7 $MJ_{th}/kgCO2_{captured}$) is nearly the same as that of the retrofit scenario (3.6 $MJ_{th}/kgCO2_{captured}$) despite the quite higher capture rate (90 vs 77 %). However, when the capture rate is increased to 95 %, which is a heavy-duty condition for most capture technologies, the specific energy consumption increases sharply. Otherwise, the membrane-liquefaction process exhibits the lowest energy consumption at higher capture rates (90 % and 95 %).

It is important to note that all 90 % capture cases result in CO_2 emissions reduction above 80 % (see Figure 9) and that, except for the VSA process, all capture systems achieve CO_2 emission reductions above 90 % when operating at a 95 % capture rate. In practice, this means that OCCS enables compliance with the IMO and FuelEU Maritime regulatory targets for 2040 and 2050 and can even be considered a long-term emissions reduction measure for the shipping industry. Interestingly, the absorption system no longer provides the highest reduction in emissions. Instead, the membrane-liquefaction hybrid and material-driven[6] processes achieve the highest CO_2 reduction rates while also yielding the lowest specific fuel consumption. The adsorption system, on the other hand, exhibits a relatively large increase in specific fuel consumption at a capture rate of 90%, resulting in the lowest CO_2 reduction rate. Finally, the CaL-based concepts can achieve a 90 % emissions reduction even at a lower than 90 % capture rate due to the associated fuel savings, as discussed in the retrofit scenario.

The newbuilding evaluation highlights a significant increase in fuel consumption compared to the ship without CCS, as shown in Figure 10. For example, the absorption process leads to a 70 % increase in fuel consumption in the 90 % capture case. At the same capture rate, the electricity-driven technologies require 56-87 % more fuel than the ship without CCS. For the latter, this increase is nearly twice that of the retrofit scenario, despite achieving only a 30 % point higher capture rate (60 % to 90 %). Furthermore, fuel consumption with heat- or electricity-driven processes at 95 % capture is approximately double that of the ship without CCS, reaching up to a 130 % increase in the case of the VSA-based process. Such a large increase in fuel demand may require an expansion of onboard fuel storage, increasing space and weight burdens. As in the retrofit case, the material-driven processes actually reduce fuel use below that of the ship without capture, thereby avoiding the need for additional fuel storage.

[6] It is worth noting that the specific energy consumption of the CaL-MEA+liq hybrid is linked to the absorption part, as the CaL unit does not require energy.

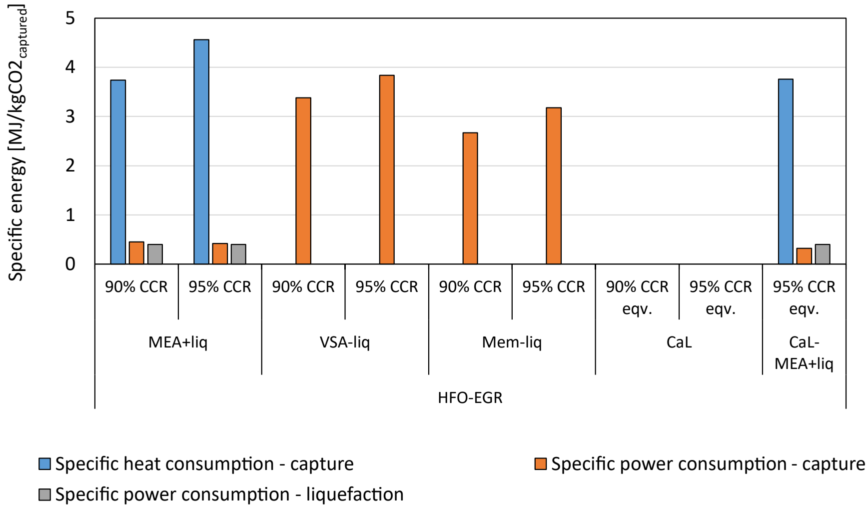


Figure 8. Specific energy consumption of OCCS systems in the newbuilding (HFO-EGR) scenario.

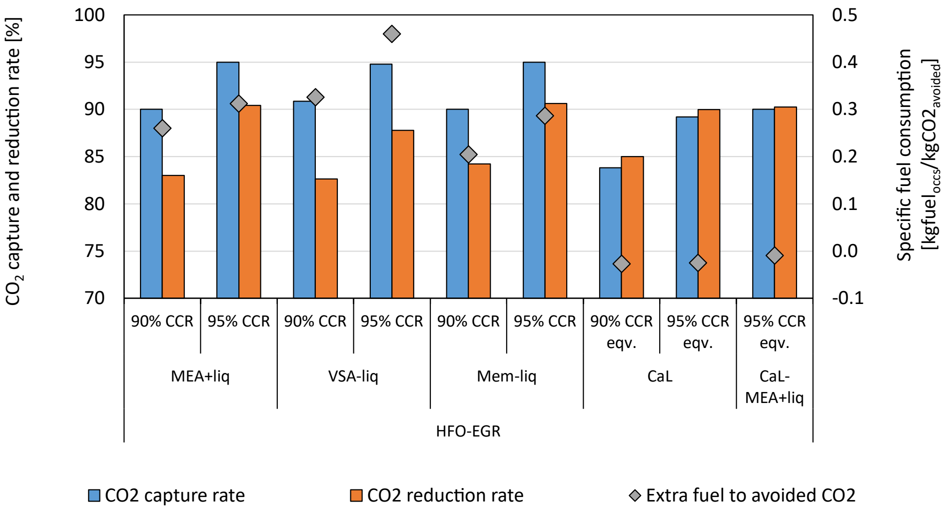


Figure 9.CO_2 capture and reduction rate with specific fuel consumption of OCCS systems in the newbuilding (HFO-EGR) scenario.

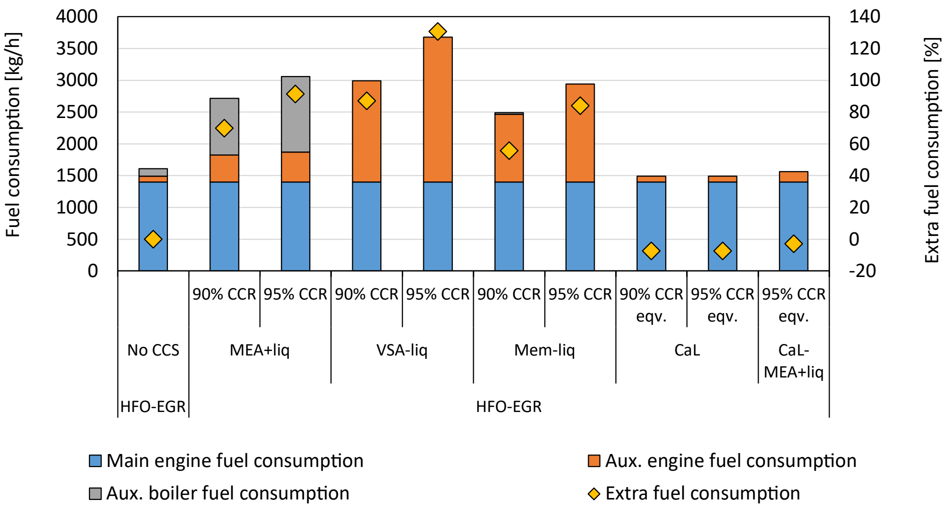


Figure 10. Total and extra fuel consumption of OCCS systems in the newbuilding (HFO-EGR) scenario.

This increased fuel consumption also has a significant impact on the energy system of the ship. For example, the absorption process in the newbuilding scenario requires a 40-90 % increase in the auxiliary boiler capacity compared to the original size, while the existing auxiliary engines are sufficient for electricity supply (see Figure 11). In contrast, the membrane-liquefaction process demands a large increase in the auxiliary engine capacity, ranging from 80-160 %. The VSA-liquefaction system requires an even larger expansion, reaching 2.5 to 4 times the original. This increase in the auxiliary engine capacity is particularly important as it is more complex and space-consuming than expanding boiler size due to the associated fuel supply, cooling water, and generator sets. Hence, heat- and material-driven capture could lead to simpler machinery modifications than the electricity-driven options. Notably, the CaL-based concepts can replace the onboard auxiliary boiler while requiring only low-load operation of the auxiliary engines, thereby minimizing the equipment footprint within the machinery room.

Although the newbuilding scenario demands extensive fuel usage and auxiliary load, all the capture technologies enable deep decarbonization for ships. As illustrated in Figure 12, a ship equipped with CO_2 capture can emit as little as 0.5 tCO2/h at a 95 % capture rate, which is one-tenth of the emissions from the ship without capture and one-fourth of those from the retrofit scenario. However, the CO_2 emissions rise sharply when the capture rate drops to 90 % or lower, as seen in the retrofit scenario. This highlights the importance of targeting high capture rates for OCCS units to ensure long-term regulatory compliance and support their continued role in maritime decarbonization.

This is further confirmed in Table 7, which also presents specific CO_2 emissions that are comparable to the tank-to-wake (TtW) GHG intensity defined by the FuelEU Maritime regulation. Yet, as observed in the retrofit scenario, the CaL-based systems exhibit a smaller reduction in the specific CO_2 emissions due to the intensity-based calculation method. Therefore, as with the wind-assisted propulsion correction factor in the FuelEU Maritime equation, a similar adjustment may be required to ensure a fair and accurate representation of such fuel-saving capture technologies.

Although there is no space limitation in the newbuilding scenario, the use of space comes at a cost either through higher construction costs for hull extension or reduced revenue when cargo capacity is occupied by OCCS. As shown in Figure 13, all capture technologies in the newbuilding scenario require an acceptable amount of space, even at high CO_2 capture rates, since their volumes remain below the retrofit scenario constraint (2840 m^3) (see Section S.5 of the Supplementary Material for further details). Among the capture options, the membrane-liquefaction and CaL-based concepts are more space-efficient than the other capture systems, whereas the VSA-based system demands the largest capture unit volume due to its multi-train configuration. Notably, the volume of the capture unit could be further reduced through column configuration optimization, which would keep space requirements within acceptable limits, although it would likely reduce energy performance.

Table 7. Specific CO_2 emissions based on fuel energy used onboard in the newbuilding (HFO-EGR) scenario.

Scenario	Process	CO_2 capture rate	Net CO_2 emission [kg/h]	Total fuel usage [kg/h]	HFO LHV [MJ/kg]	TtW specific emissions [gCO2/MJ]	Specific emissions reduction [%]
HFO-EGR	No CCS	-	5138	1587	40.5	79.9	-
	MEA+liq	90%	873	2694	40.5	8.0	90.0
		95%	492	3037	40.5	4.0	95.0
	VSA-liq	90%	893	2970	40.5	7.4	90.7
		95%	628	3660	40.5	4.2	94.7
	Mem-liq	90%	811	2470	40.5	8.1	89.9
		95%	481	2921	40.5	4.1	94.9
	CaL	90% eqv.	771	1469	40.5	13.0	83.8
		95% eqv.	514	1469	40.5	8.6	89.2
	CaL-MEA+liq	95% eqv.	500	1541	40.5	8.0	90.0

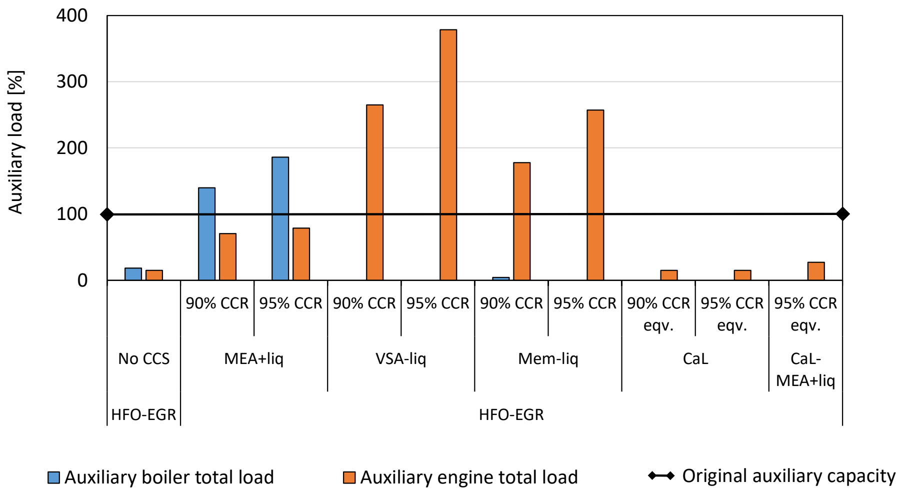


Figure 11. Auxiliary boiler and engine load of OCCS systems in the newbuilding (HFO-EGR) scenario.

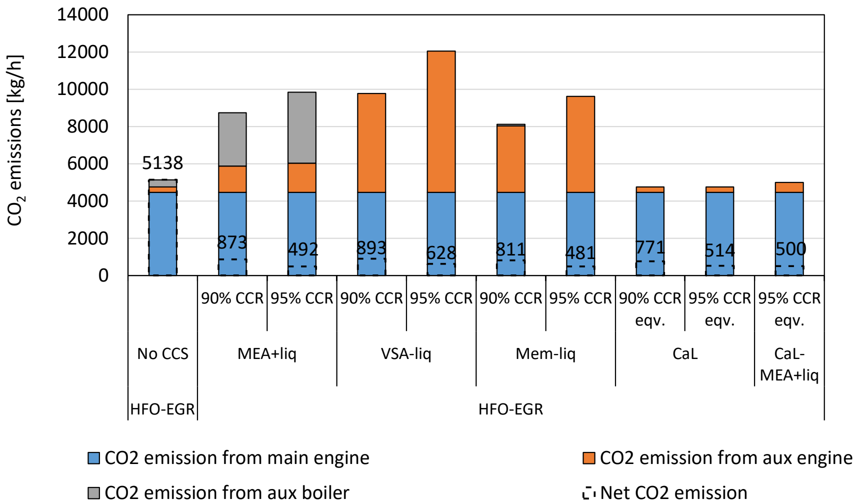


Figure 12. Total and net CO_2 emissions of OCCS systems in the newbuilding (HFO-EGR) scenario.

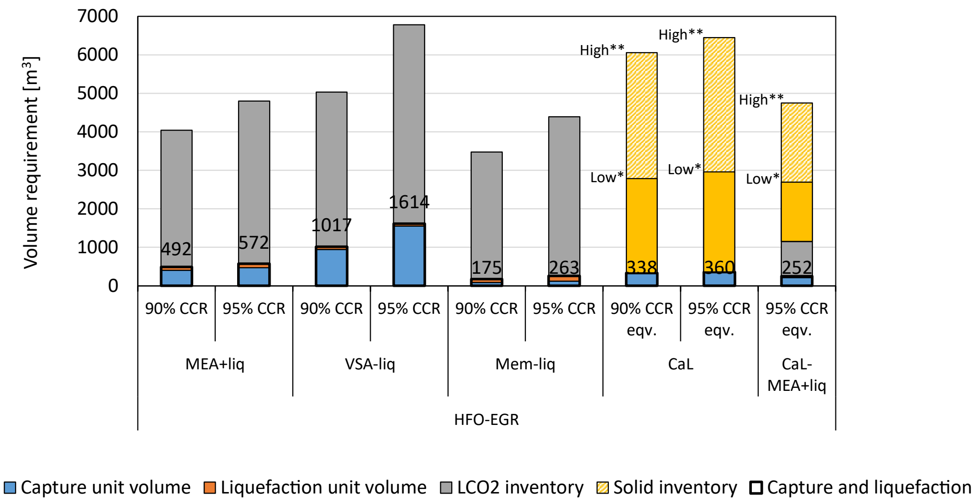


Figure 13. The volume of OCCS systems in the newbuilding (HFO-EGR) scenario (Low*: solid inventory with high conversion of fresh sorbent, High**: solid inventory with low conversion of cycled sorbent).

As in the retrofit scenario, the storage space required for captured CO_2 is considerably larger than that needed for the capture unit. Indeed, the liquid CO_2 inventory for the heat- and electricity-driven processes ranges from 3300 to 4200 m^3, depending on capture system efficiency, while the solid inventory required for the CaL capture process reaches 6000 m^3. These large storage volumes exceed the space constraint of the retrofit scenario. Although OCCS could be accommodated in a newbuilding ship, this would come at cost through hull extension or lost cargo space.

However, similar to the retrofit scenario, the space requirement for the CaL process could be significantly reduced by using fresh or novel sorbents [49] to maintain high conversion, cutting the solid storage volume by up to 60 % (see low and high solid inventory in Figure 13). This approach makes the CaL concept the most compact option even for the newbuilding scenario (see Section S.2.4 of the Supplementary Material for more details). Integrating calcium looping with absorption, as proposed in the CaL-absorption hybrid concept, could also reduce the solid inventory, as only half of the final exhaust gas would be directed to the CaL part. Although the CO_2 captured by the absorption section needs to be stored as liquid CO_2, the overall capture and storage volume is about 30 % smaller than that of the standalone CaL concept at a 95% capture rate. As a result, the CaL-absorption hybrid is the second most compact option, and both CaL-based approaches can reach similar compactness if the above suggested measures to reduce solid inventory (fresh and novel material) are implemented.

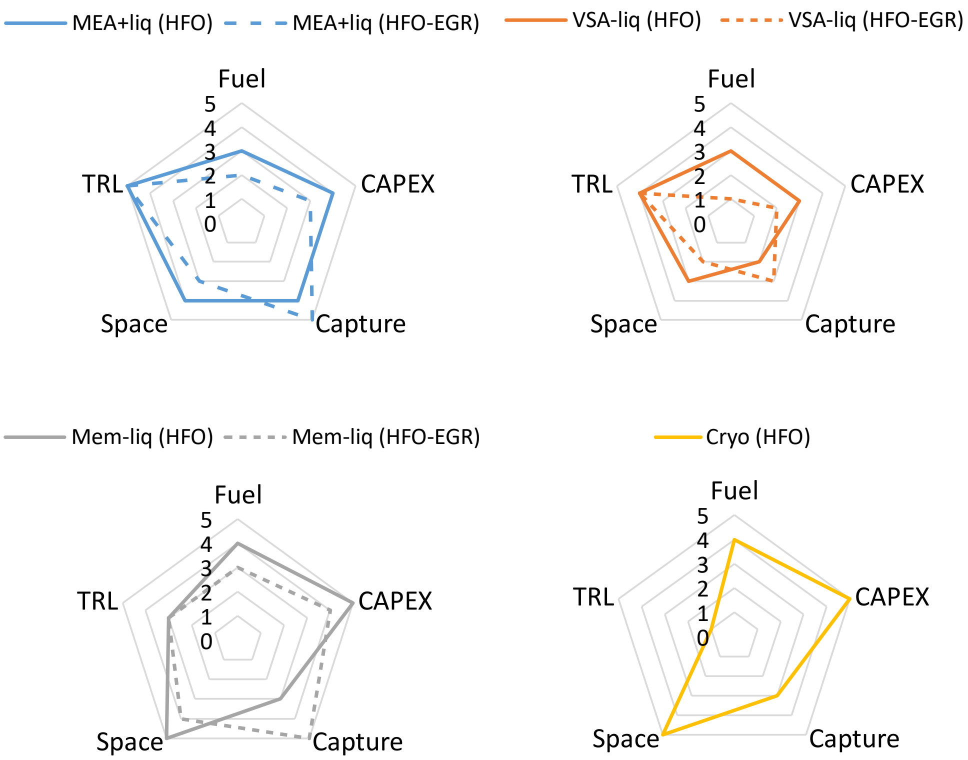
4.3 Summary and discussion

Figure 14 summarizes and compares key performance metrics of the OCCS systems for the target combination carrier in the retrofit and newbuilding scenarios. For the retrofit scenario, it is important to distinguish short- and long-term emissions reduction measures. For existing fleets that require immediate compliance with upcoming GHG regulations, the absorption system is a promising short-term retrofit option due to its high TRL and reliable performance. The process can also be operated using only the available onboard waste heat. This operation mode gives a modest capture rate with minimal additional fuel usage, which will be sufficient to meet early-phase reduction targets. As regulations tighten, capture can be easily increased by boiler operation, thus providing flexibility in fleet decarbonization strategies. In the long-term, as the technology matures, the membrane-liquefaction hybrid is a potential retrofit measure. The electricity-driven concept offers the best additional fuel-to-avoided CO_2 ratio and a small footprint, which are key criteria for retrofitting. The calcium-looping system can be a promising alternative with limited additional fuel usage. However, its large solid inventory and onboard arrangement would make it challenging for retrofits.

The newbuilding scenario requires a balanced view between near-term deployment and long-term operations. The membrane-liquefaction hybrid provides high efficiency and a compact design at high capture rates. However, the large expansion of the auxiliary engines and continuous high-load operation pose a heavy long-term operational burden and high fuel costs. The CaL-MEA hybrid is, however, a more strategically balanced solution for newbuild ships. First, this hybrid does not require additional fuel; instead, it saves fuel by reducing the original boiler load for ship operation through heat recovery from the carbonator. The marginal electricity requirements also provide sufficient operational margin during ship operation. This hybrid approach, where the capture load is shared between CaL and absorption, makes the overall system volume comparable to the membrane-liquefaction process at high capture rates, even with cycled material, thereby minimizing concerns about sorbent costs. In addition, the capture load between the CaL and the MEA parts can be controlled, for example, CaL- or absorption-only modes, offering full operational flexibility. This flexibility is a favorable characteristic given future uncertainties in the prices of sorbent, fuel, and CO_2.

From a process-specific perspective, overall, the membrane-liquefaction system performs best in both the retrofit and newbuilding scenarios. Yet, each technology option presents different trade-offs in energy demand, space requirements, and technology maturity, indicating that the optimal solution is case-specific to ship conditions.

- Absorption (MEA) is the reference capture technology, performing well in the retrofit scenario with abundant boiler duty. Yet, it becomes less attractive at high capture rates (newbuilding scenario) due to reduced energy efficiency and increased fuel consumption. Nevertheless, the absorption process remains promising for ship types where sufficient waste heat from various sources is available for OCCS.
- Membrane-assisted liquefaction delivers the best overall performance for both the retrofit (low capture) and the newbuilding (high capture) scenarios. Across a wide capture rate range, it stays compact and fuel-efficient, making it highly suitable for ships. However, there are uncertainties in the long-term properties of membrane materials [50,51], which may affect performance and the relative ranking of capture options.
- Adsorption-liquefaction hybrid suffers from a significant fuel penalty above 90 % capture. However, it is competitive at moderate capture levels (such as 50 %), making it a viable low-duty OCCS option. Nevertheless, the additional energy consumption for utility systems (for example, water removal) needs to be further evaluated.
- Cryogenic supersonic is another attractive retrofit solution, offering the smallest footprint and lowest fuel consumption at relatively low capture rates. However, this process requires further validation at scale due to low TRL.
- Calcium looping is the most compact OCCS concept with no major fuel consumption when fresh or advanced sorbents are used, making them ideal for ship applications. The CaL-MEA hybrid system can reduce space demand compared to the stand-alone CaL process if cycled sorbent is considered. Despite these advantages, the low TRL is still a barrier for large-scale deployment of the CaL-based concept and a better understanding of costs (sorbent material cost and solid handling) is required.



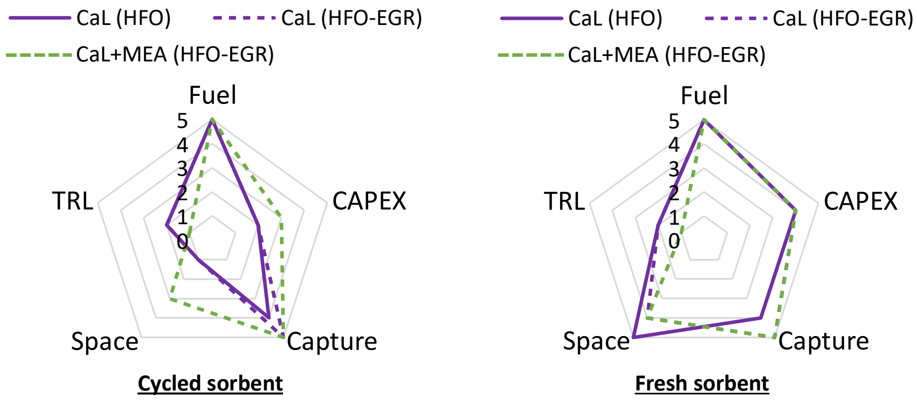


Figure 14. Overview of OCCS systems for the retrofit (HFO, solid line) and newbuilding (HFO-EGR, dotted line) scenario (0: bad – 5: good).

5 Conclusion

This screening study explores onboard CO_2 capture systems as a greenhouse gas mitigation measure for the shipping industry, focusing on a combination carrier. In the retrofit scenario, reducing CO_2 emissions via OCCS is challenging due to limited energy and space onboard, yet the studied technologies achieve at least a 45 % CO_2 reduction, validating their effectiveness for a short- and mid-term measure. In addition, utilizing various waste heat sources or biofuel blending can further reduce CO_2 emissions, ensuring long-term compliance with regulatory targets. Novel capture concepts utilizing multiple energy sources such as heat and power can be another approach to increase the capture performance for retrofitting. In contrast, in the newbuilding scenario, where heat, power, and space are sufficient, OCCS becomes a stand-alone option for deep decarbonization, achieving up to 90 % CO_2 reduction with most capture processes studied.

Among capture options, heat-driven capture (absorption) is practical with waste heat but constrained by tall columns and chemical handling. In contrast, electricity-driven capture systems provide simpler configurations with competitive energy use. Overall, the membrane-assisted liquefaction is the most energy- and space-efficient option, while calcium-looping (and Cal+MEA hybrid) is especially promising when auxiliary energy is limited and inexpensive fresh sorbent is available. Process selection, however, is highly case-specific, depending on various factors such as ship type, power system, energy demand, fuel price, and regulatory context.

Additional fuel consumption for OCCS is found to be non-negligible, except for the CaL-based concepts that require no major energy input. However, this study demonstrates that net emission reductions via OCCS are aligned with the IMO and EU long-term trajectories. Thus, deploying OCCS on existing and new ships will bridge the decarbonization gap until alternative fuels become readily available. A comprehensive analysis, including cost, safety, and regulatory assessment, is now needed to confirm commercial viability and to facilitate its deployment in the maritime sector.

Acknowledgment

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Appendix

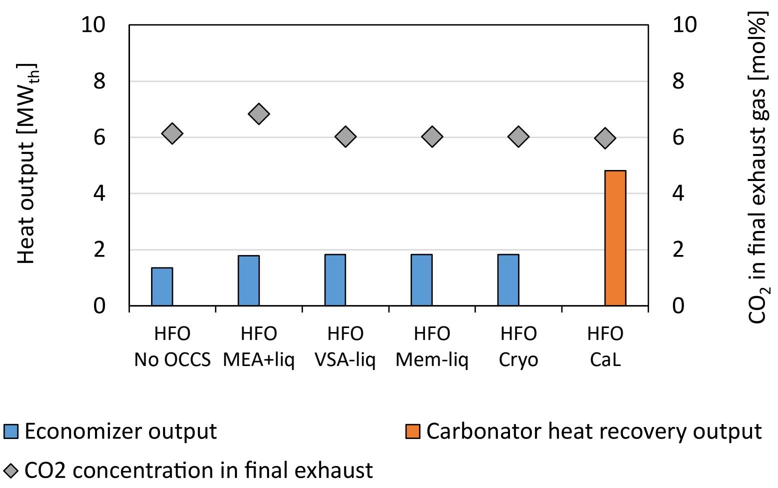

Figure A-1. CO_2 concentration in the final exhaust gas and the amount of heat recovered from the OCCS systems for the retrofit (HFO) scenario.

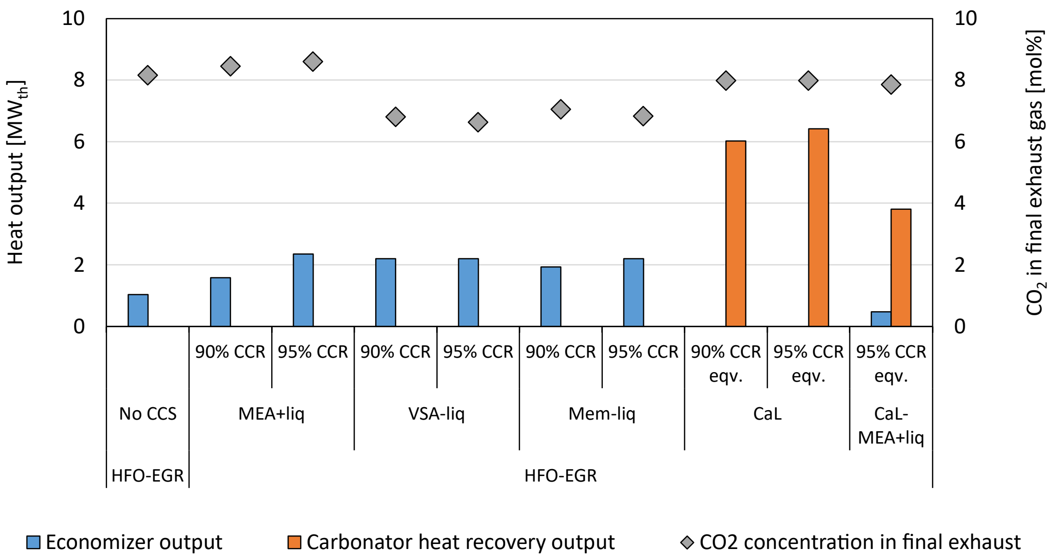

Figure A-2. CO_2 concentration in the final exhaust gas and the amount of heat recovered from the OCCS systems for the newbuilding (HFO-EGR) scenario.

Nomenclature

Abbreviations and symbols

CaL: calcium looping

CAPEX: capital expenditure

CCS: co2 capture and storage

Cryo: Cryogeic supersonic

EEA: European Economic Area

EGR: exhaust gas recirculation

Eqv.: equivalent

ETS: Emissions Trading System

GHG: greenhouse gas

HFO: heavy fuel oil

IMO: International Maritime Organization

KPI: key performance indicator

LCA: life cycle assessment

LHV: Lower heating value

Liq: liquefaction

LNG: liquefied natural gas

MEA: Monoethanolamine

Mem: membrane

OCCS: Onboard co2 capture and storage

OPEX: operating expenditure

ORC: organic Rankine cycle

Pt: point

SCR: selective catalytic reduction

TRL: technology readiness level

TtW: tank-to-wake

VSA: Vacuum Swing Adsorption

WHRU: waste heat recovery unit

WtW: well-to-wake

A+B: downstream addition of process step B to A

A-B: hybrid of A and B process concepts

Subscripts

avoided: amount of CO2 emissions reduced compared to a ship without OCCS

captured: amount of CO2 emissions captured

el: electricity

extra fuel: amount of fuel increased compared to a ship without OCCS

fuel: fuel

th:thermal energy

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