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Onboard Carbon Capture: Detailed evaluation of CO_2 Capture Technologies for Maritime Applications

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Abstract

Onboard CO_2 capture and storage (OCCS) is an emerging measure for decarbonizing the maritime industry, as alternative fuels are not readily available [1,2]. CO_2 capture is a relatively mature and end-of-pipe solution that can be deployed on ships in a timely manner to respond to increasing regulatory pressures, such as FuelEU Maritime [3]. Thus, the CCShip project aims to develop cost-effective solutions for OCCS and better understand when it can be more attractive than alternative solutions to reduce CO_2 emissions from ships.

For maritime applications, post-combustion CO2 capture (PCCC) is the most likely pathway due to its compatibility with existing ship power systems. As a result, onboard CCS (OCCS) studies focus on the most mature PCCC option: absorption processes [4,5]. However, more work has been required to understand its potential better. Therefore, the CCShip project explores promising technology options for OCCS, evaluating their performance with a focus on oil-fueled marine vessels (BAIACU from Klaveness) that offer substantial potential for emission reduction through CCS [6]. High CO2 capture rates are also targeted for deep decarbonization of the shipping industry, and all CO2 sources, including auxiliaries, which are often overlooked in other studies, are considered. The feasibility study on the different capture systems is summarized in Figure 1.

- Heat-driven process
  - Absorption (MEA) [7]
- Electricity-driven process
  - VSA-liquefaction hybrid (VSA-liq) [8,9]
  - Membrane-liquefaction hybrid (Mem-liq) [10]
  - Cryogenic supersonic (Cryo) [11]
- Material-driven process
  - Carbonator of calcium looping (CaL) [12]
  - CaL-absorption hybrid (CaL+MEA)

The screening results indicate that the membrane-liquefaction hybrid concept performs well in both retrofit and newbuilding cases regarding capture efficiency and space demand, while the absorption process remains competitive. However, this screening analysis relies on simplified assumptions that may affect the actual feasibility and performance of the technologies in practical conditions. Therefore, this work performs a detailed design and evaluation of the promising capture technologies for an existing ship.

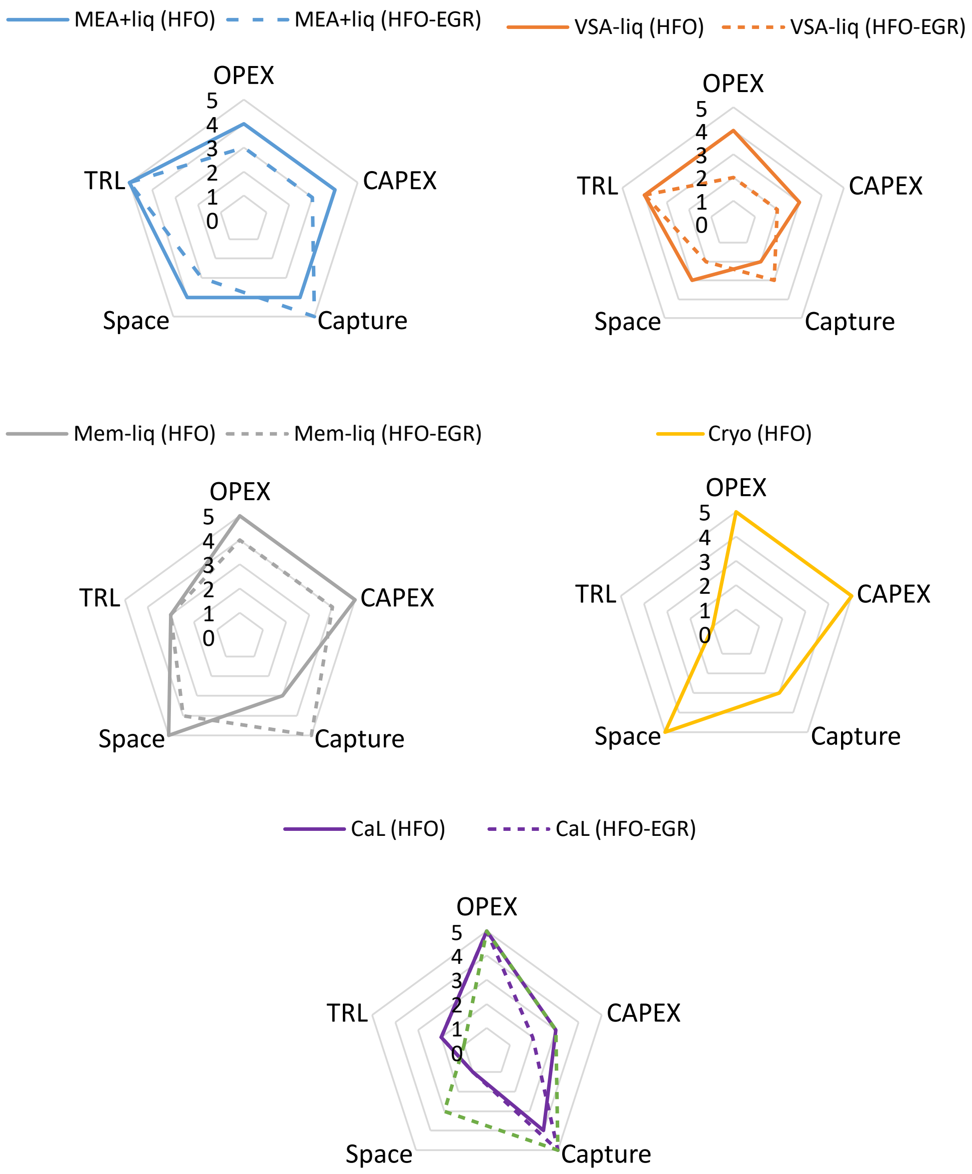

Figure 1. Overview of OCCS systems for the retrofit (HFO, solid line) and newbuilding (HFO-EGR, dotted line) case (0: bad – 5: good).

As a first step, the membrane-liquefaction hybrid, which is identified as the most energy-efficient concept in the screening work, is further evaluated against chemical absorption as a reference for the following cases: retrofitting an existing ship to achieve the maximum CO_2 capture rate with a fixed machinery system (retrofit case) and building a ship with a new design to reach a 90 % and 95 % capture rate, assuming auxiliary capacity expansion (newbuilding case). The target ship is an oil tanker (BAIACU from Klaveness) with a 9.6 MW propulsion engine, operating at 85% load, considering it as a design specification for the capture facility.

The detailed evaluation reveals that the membrane-liquefaction hybrid is less compact, occupying a larger footprint and volume with a lower capture rate than the absorption process (see Table 1 and Table 2). However, the hybrid concept is still advantageous for the installation arrangement on the target ship as the height of the equipment is lower than that of the towers in the absorption system. The lower specific fuel consumption is another benefit, maximizing CO_2 reduction with the same fuel usage.

This study also demonstrates that utility consumption is not negligible for the target ship. Table 3 highlights that the demand for cooling water is significant for the membrane-liquefaction hybrid concept since part of the capture duty is covered by the liquefaction part. Thus, a major capacity upgrade of the cooling water system onboard is expected. The absorption system requires significant make-up water due to the warm seawater and cooling water temperatures assumed for warm region operation, representing a worst-case scenario. For the membrane-liquefaction hybrid system, the water collected from the knock-out drums exceeds the make-up water demand, requiring only additional energy to condition the recovered water and ensure low impurities.

Nevertheless, the two promising capture concepts can be accommodated on the target ship within the available space for OCCS (ca. 400 m^2) [4], thus not requiring major ship design modifications. However, this detailed assessment also reveals potential challenges in deploying the capture systems, particularly for high CO_2 capture rates as required in the newbuilding case. Scaling up the capture system for high capture rates intensifies the challenges and introduces major modifications to the ship machinery system for utility consumption.

This study highlights key areas that require attention for the deployment and operation of onboard CCS systems. While the installation space is reasonable, the make-up water, cooling water, and chemical supply systems pose challenges due to their demand and the potential need for capacity upgrades of the existing systems. Further detailed evaluations will be conducted for other promising capture technologies to evaluate their feasibility and operational challenges. This comprehensive evaluation of OCCS will provide insights into its actual potential and role in the transition to green shipping compared to alternative solutions through the CCShip project.

Table 1. Space requirement of the absorption system for the retrofit and newbuilding case.

Section	Retrofit 76 % capture		Newbuilding 90% capture		Newbuilding 95% capture	
	area m2	height m	area m2	height m	area m2	height m
DCC	11	9	11	9	12	9
DCC around	31	2	32	2	36	2
Absorber	17	16	18	16	20	16
Absorber around	9	1	15	1	14	1
Stripper	6	14	7	14	10	14
Stripper around	20	1	39	1	42	1
Lean amin tank	14	3	18	3	22	3
Reflux accumulator	14	2	15	3	13	3
Amine storage tank	7	2	8	2	9	2
CO2 compressor train	14	2	20	2	21	2
Refrigeration system	14	3	23	3	25	3
Total	157		206		224	

Table 2. Space requirement of the membrane-liquefaction system for the retrofit and newbuilding case.

Section	Retrofit 59 % capture		Newbuild 90% capture		Newbuild 95% capture	
	area m2	height m	area m2	height m	area m2	height m
DCC	10.7	9.0	11.3	9.0	12.8	9.0
DCC around	4.1	1.0	4.0	1.0	4.1	1.0
Membrane module	32.8	6.0	63.9	6.0	87.8	6.0
Membrane system	127	4.4	190	4.0	162	4.0
CO2 compressor train	45.0	2.5	54.6	2.5	65.5	2.5
Refrigeration system	35.3	3.4	52.6	3.4	59.6	4
Total	255	-	376	-	392	-

Table 3. Performance of the absorption and membrane-liquefaction hybrid concepts for the retrofit and newbuilding cases.

Parameter	Unit	Retrofit 76% cap	Newbuild 90% cap	Newbuild 95% cap	Retrofit 59% cap	Newbuild 90% cap	Newbuild 95% cap
		Abs+liq			Mem-liq		
CO_2 capture rate	%	76.6	90.0	95.0	58.8	90.0	95.0
CO_2 avoidance rate	%	63.8	83.0	90.4	46.0	84.2	90.6
Specific heat	MJ/kgCO2	3.6	3.7	4.6	0.0	0.0	0.0
Specific power	MJ/kgCO2	1.0	0.8	0.8	2.7	2.7	3.2
Specific CW demand	$kgCW/kgCO2_{captured}$	69.5	100.1	117.6	126.9	146.3	154.8
Specific makeup water demand	$kgH2O/kgCO2_{captured}$	0.9	0.6	0.5	0.3	0.1	0.1
Specific makeup MEA demand	$kgMEA/kgCO2_{captured}$	0.002	0.002	0.002	0.0	0.0	0.0
Specific extra fuel consumption	$kgfuel/kgCO2_{avoided}$	0.27	0.26	0.31	0.20	0.20	0.29

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