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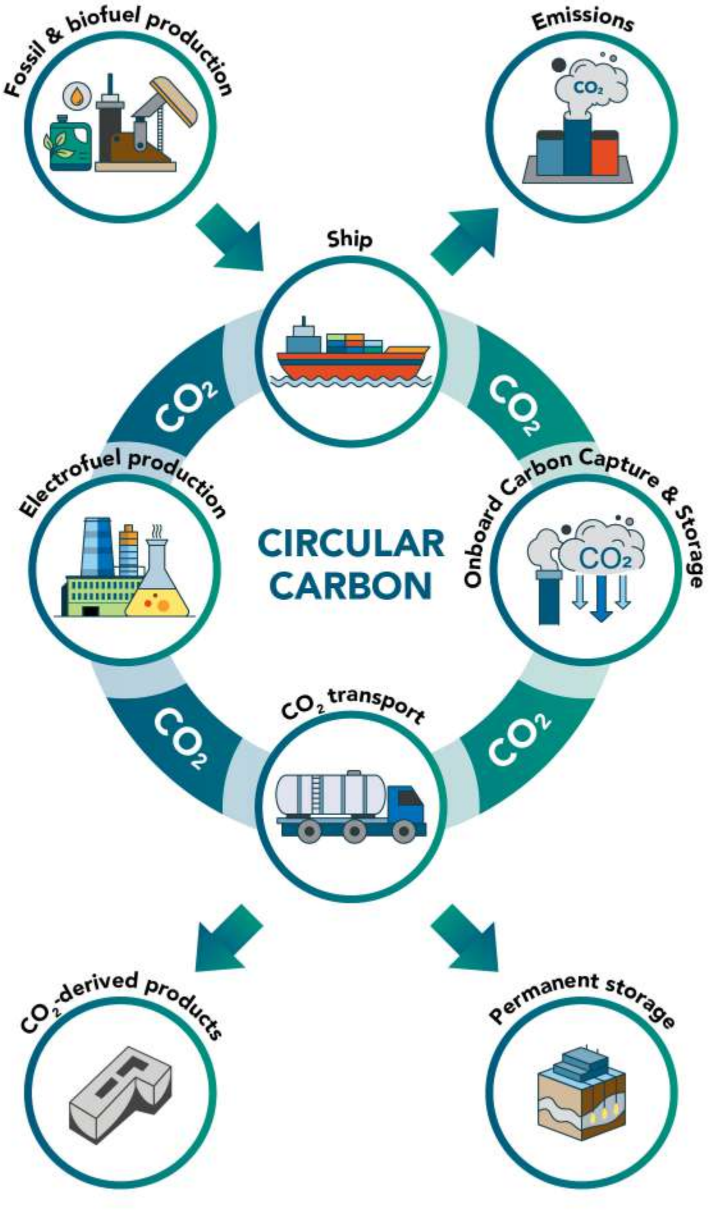
Carbon Capture, Offloading Onshore, Storage, Utilisation and Permanent Storage



Life cycle assessment of GHG emissions and cost analysis of OCCS across the carbon value chain

Executive Summary

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This study provides a life cycle assessment (LCA) of the GHG emissions associated with the deployment of onboard carbon capture and storage (OCCS) systems across the carbon dioxide (CO_2) value chain, from fuel production to the disposition of captured CO_2, either through utilisation or permanent storage.

Data and information were gathered from literature and industry partners to help evaluate the overall GHG emissions footprint of the total value chain. Several solutions capturing CO_2 emissions stemming from different fuel use, i.e., heavy fuel oil (HFO), liquefied natural gas (LNG), methanol and biodiesel, were analysed.

OCCS is regarded as one of the solutions that could play a key role in maritime decarbonisation. While the plethora of current studies assess the technical and operational feasibility of CO_2 emissions reduction potential of these solutions onboard vessels, there has been limited work to evaluate the overall GHG emissions of deploying these solutions across the associated value chains, i.e., including the well-to-tank (WtT) emissions of the fuel consumed from which the captured CO_2 is generated, onboard tank-to-wake (TtW) emissions with OCCS, and the consequential emissions from transporting captured CO_2 for permanent storage or utilisation (Figure 1).

This holistic analysis of the net GHG emissions avoidance of OCCS deployment should facilitate proper comparison with other decarbonisation strategies. Three distinct value chain pathways were evaluated considering the base study of deploying monoethanolamine (MEA)-based OCCS on an HFO-fuelled ship, including permanent storage of captured CO_2 in reservoirs (Carbon capture and storage - CCS), fixation by imbibing captured CO_2 in concrete (Carbon capture and utilisation - CCU), and using captured CO_2 as a feedstock to produce e-methanol (CCU). These pathways were evaluated to estimate the GHG emissions savings and the full cost of avoidance across the carbon value chain. These scenarios were selected on the basis of Project REMARCCABLE (GCMD, OGCI, *Stena Bulk* et al., 2024), during which a techno-economic assessment was conducted to evaluate the feasibility of installing a MEA-based OCCS system onboard the *Stena Impero*, a medium range (MR) tanker.

The GHG emissions savings were evaluated considering the HFO baseline of 93.3 gCO_2eq/MJ, aligned with the GHG fuel intensity (GFI) of fossil fuel in 2008 level on a well-to-wake (WtW) basis, as defined during the 83rd session of MEPC in April 2025.

(For additional information regarding the LCA framework adopted for this study, refer to the Appendix in the main report).

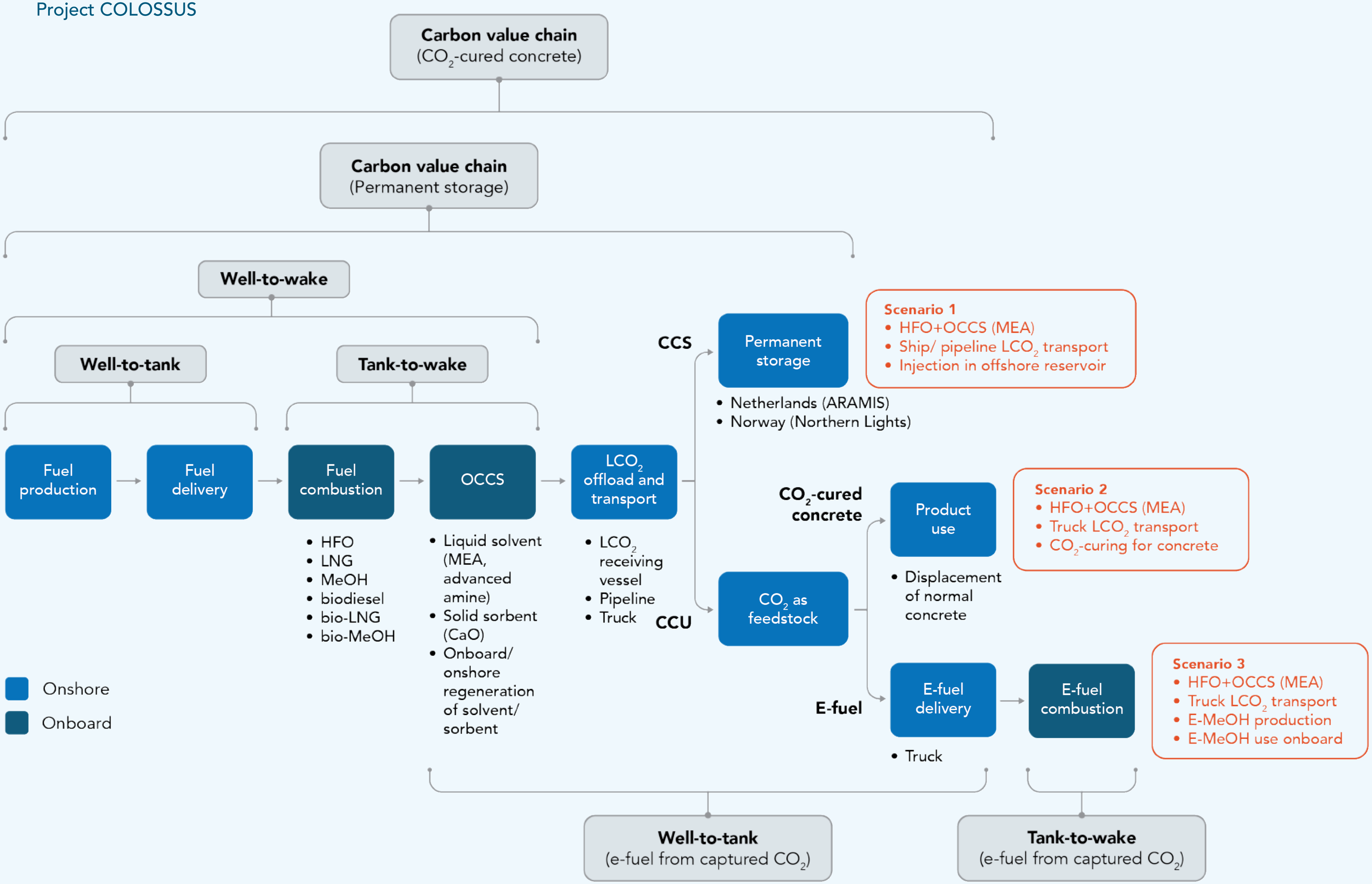


Figure 1 – Carbon value chain of OCCS, including the different fuel options, OCCS solutions, WtT and post-capture scenarios considered in this study

Inclusion of fuel WtT GHG emissions reduces the net emissions savings of OCCS deployment

Operating an OCCS incurs a fuel penalty; onboard an HFO-fuelled ship, an OCCS technology having a maximum gross capture rate of 90% can generate ~83% GHG emissions savings. When its WtT GHG emissions associated with HFO production and transportation to the vessel is considered, the net GHG emissions savings for this vessel is considerably lower, at ~61% (Figure 2).

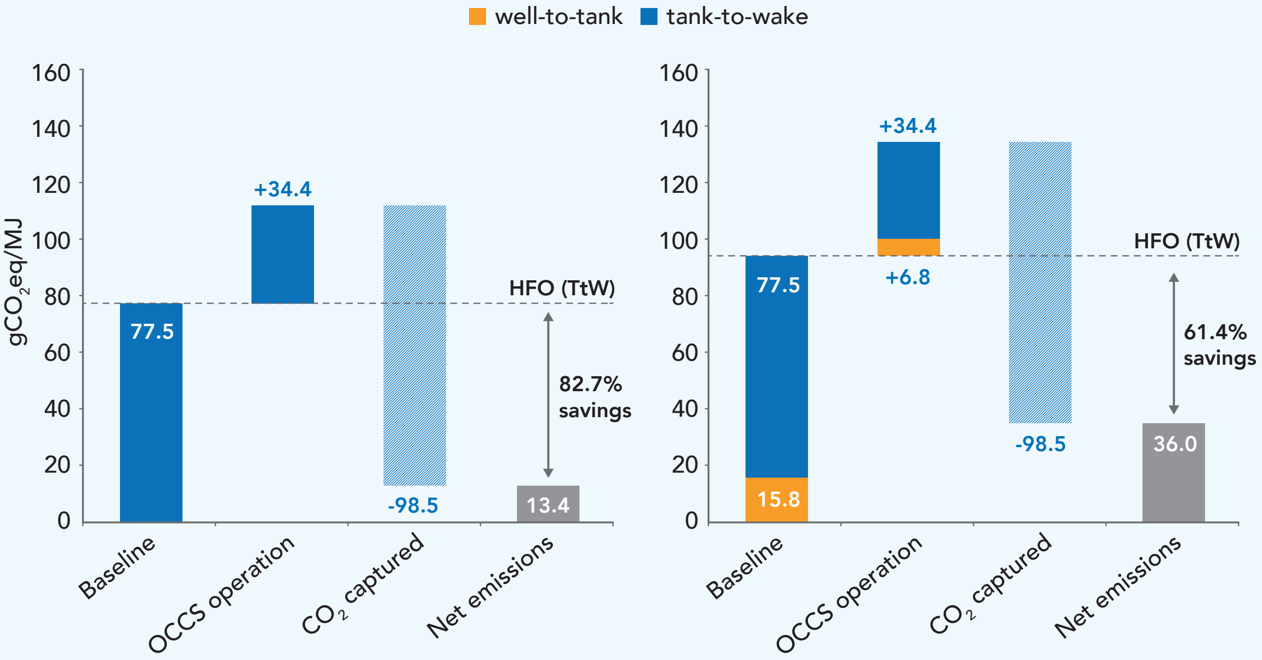


Figure 2 – Net onboard TtW and WtW GHG emissions of an HFO-fuelled ship equipped with OCCS (90% gross capture rate, 41% fuel penalty) with a heat recovery system. OCCS emissions include the extra fuel consumption due to the onboard capture and liquefaction of the CO_2, chemicals and materials required for OCCS operation. Baseline represents the GHG emissions due to the vessel operation without OCCS.

A practical gross capture rate for OCCS

The gross capture rate is defined as the ratio between the amount of CO_2 captured and the total amount of CO_2 in the exhaust, including the exhaust from burning the extra fuel required to run the OCCS system (fuel penalty). While a 90% gross capture rate is technically possible onboard vessels, OCCS operating onboard vessels are constrained by the practical challenges of storing large amounts of liquid CO_2 onboard. A practical limit of 40% gross carbon capture rate is therefore considered for this study, based on the onboard space constraints of *Stena*

Impero per detailed in the Project REMARCCABLE report (GCMD, OGCI, *Stena Bulk* et al. 2024). This capture rate was also recommended by the Exhaust Gas Cleaning Systems Association (EGCSA). Referring to Figure 3, a 40% gross capture rate is achieved by treating 44.4% of the exhaust with OCCS, which is designed to remove 90% of the CO_2 in the treated gas flow. This configuration will yield 28.5% net WtW GHG emissions savings, given a fuel penalty just below 6%. The calculations assumed that the waste heat recovery from exhaust gas is able to supply about 35% of the heat required to strip the CO_2 from the amine when all the exhaust gas is treated with OCCS.

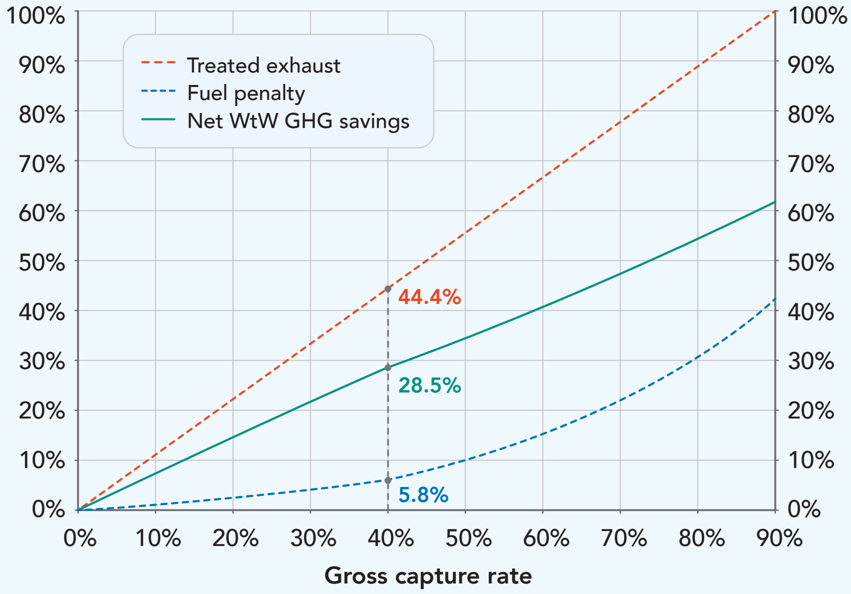


Figure 3 – Net WtW GHG emissions savings and fuel penalty with MEA-based OCCS for different gross capture rates, with full availability of heat via recovery system (chemicals and materials required for OCCS operation are included). 40% gross capture rate was selected as the practical limit for OCCS with the corresponding fuel penalty and net GHG emissions savings.

Net WtW GHG emissions associated with different OCCS capture technologies

The overall emissions in the carbon value chain vary depending on the technology configuration adopted for capturing CO_2. Although capture using MEA and onboard solvent regeneration with CO_2 liquefaction is the most common and mature OCCS technology, other concepts are emerging. The technologies analysed in this study are listed in Table 1, while the life cycle GHG emissions of these different OCCS solutions applied on an HFO-fuelled ship are presented in Table 2.

Table 1 – OCCS technologies analysed

OCCS technology	Capture type	Solvent / sorbent type	Solvent regeneration	Description
MEA capture	Amine-based	MEA	Onboard	The most mature technology with MEA as solvent
Advanced amine capture	Amine-based	Advanced amine	Onboard	Uses emerging, patented amines with higher extraction performance
MEA offloading	Amine-based	MEA	Onshore	CO_2-rich amine is stored onboard and then offloaded at port. Solvent regeneration is performed onshore with the option of using lower-emissions footprint heat sources
Alkaline capture	Alkali-based	Quicklime (CaO)	None	CO_2 is stored in the form of calcium carbonate ($CaCO_3$) and then discharged overboard; conceptual stage and currently under study
Calcium looping	Alkali-based	Quicklime (CaO)	Onshore	CO_2 is stored onboard in the form of calcium carbonate and then offloaded at port. Regeneration of quicklime (CaO) is performed onshore for reuse onboard: emerging solution with limited demonstration

Table 2 – Net WtW GHG emissions (in gCO_2eq/MJ) and onshore GHG emissions related to different onboard capture technologies. Assumes a 40% gross capture rate. Compared to HFO baseline: 93.3 gCO_2eq/MJ.

Category	MEA capture	Advanced amine	MEA offloading	Alkaline	Calcium looping
Main engine emissions for ship propulsion (after capture)	62.3	62.3	62.3	62.3	62.3
Fuel penalty for OCC(S) (aux engine + aux boiler)	3.6	2.8	1.0	0.5	0.5
Chemicals	0.5	0.1	0.2	47.9	0.5
Plant construction	0.3	0.3	0.3	0.3	0.3
Onshore energy consumption	-	-	0.3-9.7	-	0.5-13.6
Total GHG emissions	66.7	65.5	64.1-73.5	111.0	64.1-77.2
			% of HFO baseline		
Net WtW GHG emissions	**71.5%**	**70.2%**	**68.4%**	**119.0%**	**68.2%**
Onshore GHG emissions	**-**	**-**	**0.3-10.4%**	**-**	**0.5-14.6%**
Net GHG emissions savings	**28.5%**	**29.8%**	**31.3-21.2%**	**-19.0%**	**31.3-17.3%**

Considering an HFO-fuelled ship equipped with an onboard OCCS system designed for 40% gross capture of CO_2, advanced amine solutions have higher GHG emissions savings compared to solutions that deploy MEA as the solvent. Supplying adequate heat to strip the CO_2 from the amine and the power for liquefaction of captured CO_2 make up much of the energy penalty associated with operating onboard amine-based capture systems. This energy penalty is made up by burning additional fuel oil in the auxiliary boiler and engines, which in turn produces proportionally more CO_2 emissions.

Since it is the separation of CO_2 from amine that is most energy-intensive, one way to overcome this energy penalty is to perform the separation onshore instead of onboard by storing the CO_2-rich amine solution and offloading it at ports for regeneration. This process transfers the energy debit for separating CO_2 and regenerating amine onshore. Low carbon energy sources can then be used for stripping, compressing and liquefying captured CO_2 in an onshore facility. This alternative can result in higher GHG emissions savings across the value chain compared to conventional onboard CO_2 stripping, i.e., 31.3% vs 28.5% in Table 2. However, if high carbon intensity grid electricity and natural gas are used for onshore amine regeneration and CO_2 liquefaction, the resulting GHG emissions savings is worse off compared with regeneration onboard, i.e., 21.2% vs 28.5%.

The alkaline CC system involves carbonation of calcium oxide to capture CO_2 to form $CaCO_3$ and the intention for this yet proven solution is to release the product at sea. Since the sorbent is not regenerated, its energy penalty is the least among the technologies assessed. Instead, fresh CaO must be supplied to the system for single-use capture; the consumption of CaO, which itself is energy-intensive to produce, increases the GHG emissions footprint of the carbon value chain of this solution.

An alternative way to address this issue is to offload $CaCO_3$ and treat it onshore in a calciner to recover CaO, which can then be reused for subsequent onboard capture (calcium looping). Calcination, however, requires a significant amount of energy. Just like MEA offloading, the onshore energy mix thus determines the overall GHG emissions savings of calcium looping. Indeed, the two scenarios have similar GHG balances since the energy demand associated with regenerating the sorbents is shifted from onboard to onshore. However, the uncertainty of availability of large amounts of low carbon energy, particularly heat, at key port locations in the near future make onshore regeneration less viable currently compared to MEA and advanced amine capture.

Net WtW GHG emissions associated with different marine fuels

OCCS solutions can be applied to ships running on a variety of marine fuels. Four different fuel scenarios were considered in assessing the GHG emissions savings across the carbon value chain for an MEA capture system operating on a vessel that uses HFO, fossil LNG, fossil methanol, and biofuels (biodiesel, bio-LNG, biomethanol).

Compared to HFO, LNG propulsion offers several synergies with OCCS. Its exhaust gas has negligible sulphur, negating the need to strip sulphur before the exhaust gas enters the CO_2 stripper, significantly simplifying hardware integration. Further, the heat released from LNG regasification can be used for CO_2 liquefaction, reducing the overall energy penalty of the OCCS system. Similarly, the exhaust gas from fossil methanol propulsion also has low sulphur content, though cold energy recovery is not available to liquefy the CO_2. To capture 40% of the total CO_2 emitted onboard, the emissions associated with OCCS on an HFO-fuelled ship is 6.2 gCO_2eq/MJ, while that for LNG and methanol ships are 2.7 and 5.9 gCO_2eq/MJ, respectively. The results of the analysis are shown in Figure 4.

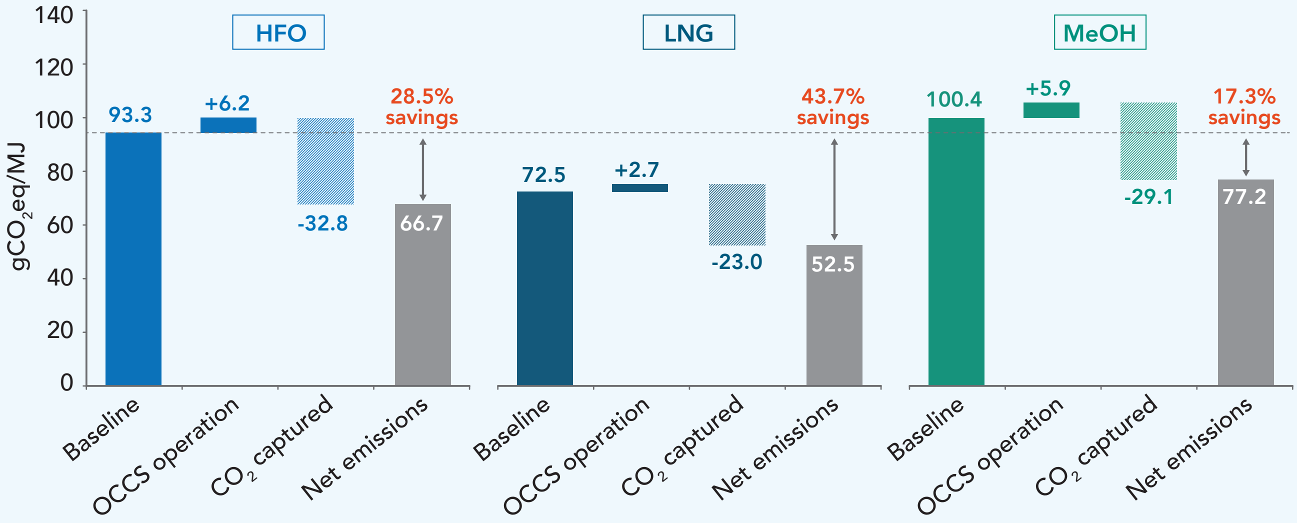


Figure 4 – Net WtW GHG emissions of OCCS for different fossil fuels, with MEA capture process (40% gross capture rate). Baseline represents the GHG emissions due to the HFO-fuelled vessel operation without OCCS

Combustion of biofuels is considered carbon neutral. When CO_2 from biomass-derived energy sources is captured, it is possible to achieve negative emissions, which means that CO_2 is removed from the carbon cycle within biosphere and atmosphere on a life cycle basis. The LCA of OCCS when an MEA capture system is installed on a vessel using 100% biofuels (B100) for propulsion is calculated based on the WtT GHG emissions of several types of biofuels, and the results are summarised in Figure 5. OCCS on a vessel using biodiesel from used cooking oil (UCO) results in the most GHG emissions savings (up to 121%). OCCS on a vessel deploying biomethanol can result in a comparable WtW GHG emissions savings of up to 119%, that with bio-LNG up to 98%, and that with second-generation biofuels, such as vegetable oil, up to 89%. A 1.5% methane slip (defined as the ratio of the unburned fuel to the fuel injected in the engine) was included in the analysis of OCCS deployment with bio-LNG propulsion because CH_4 is a potent GHG, whether its carbon originates from biomass or from fossil fuels.

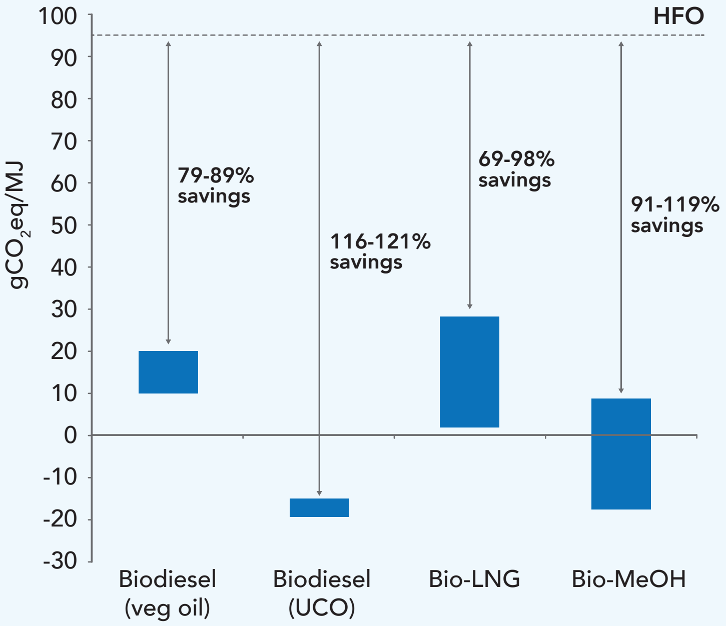


Figure 5 – Ranges of net WtW GHG emissions and corresponding savings of carbon capture with different biofuels (B100), compared to HFO baseline (40% gross capture rate)

Of the biofuels, the life cycle GHG emissions are lowest for those whose biomass feedstock is derived from waste streams, such as biodiesel made from used cooking oil. More commonly used today are blends of biodiesel (B24 and B30); they provide GHG emissions savings in the 13-26% range. The use of OCCS solutions in conjunction with biodiesel propulsion can boost GHG emissions savings considerably (See Figure 6).

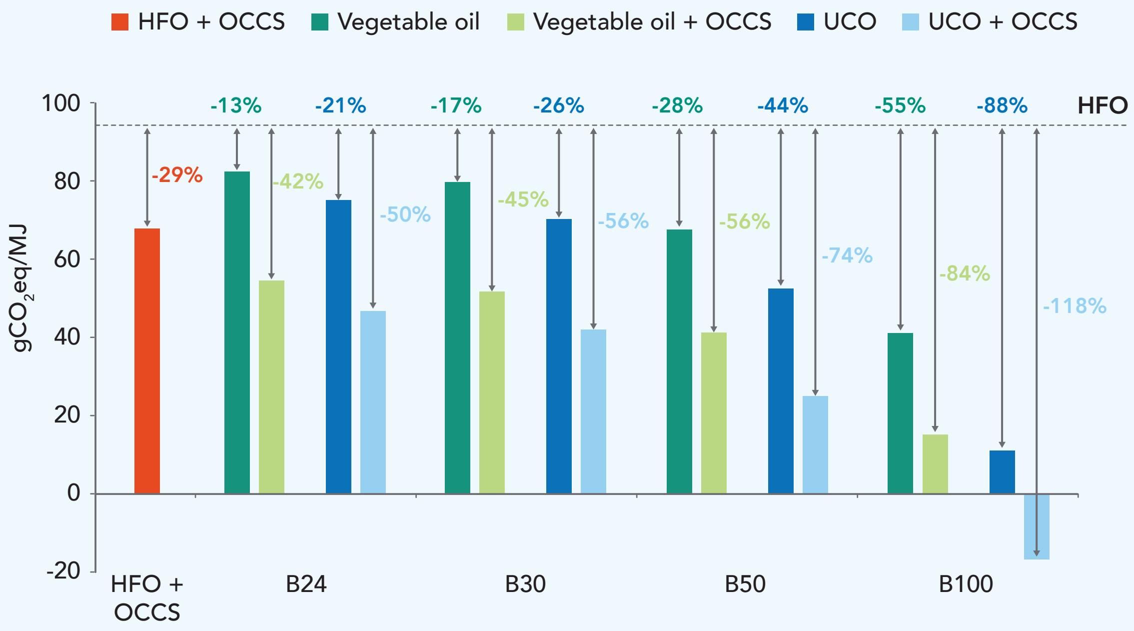


Figure 6 – Average net WtW GHG emissions and savings achieved with different biodiesel blends and OCCS with a 40% gross capture rate, compared with the HFO baseline emissions without OCCS. Transport and storage/ use of CO_2 are not included. Default WtW GHG emissions values of pure biodiesel are 42 and 11 gCO_2eq/MJ for vegetable oil biodiesel and UCO biodiesel, respectively.

Carbon value chain GHG emissions associated with post-capture CCS and CCU pathways

Scenario 1 – Carbon capture and storage

Long-term storage of captured CO_2 in spent oil and gas wells, as well as in saline aquifers (CCS), is considered the most viable pathway to managing large volumes of CO_2 compared to its utilisation (CCU). This study estimated the emissions associated with the CCS pathways post-capture, i.e., including the transport to the permanent storage of CO_2. This GHG emissions footprint varies in the range of 9-34 gCO_2eq for each kg of CO_2 captured, depending on the distance to the location of the permanent storage site and the amount of fuel used by vessels carrying captured CO_2. Two distinct permanent storage sites were considered: ARAMIS reservoir offshore Rotterdam (scenario 1a) and Northern Lights reservoir offshore Øygarden (scenario 1b). Overall, 201-227 gCO_2eq are emitted across the carbon value chain for each kg of CO_2 captured and stored, including OCCS and post-capture GHG emissions. Considering the transport of captured CO_2 from Rotterdam to Øygarden for permanent storage (i.e., the Northern Lights project), Figure 7 shows the net carbon value chain GHG emissions savings to be just above 27%, when a 40% gross capture is assumed.

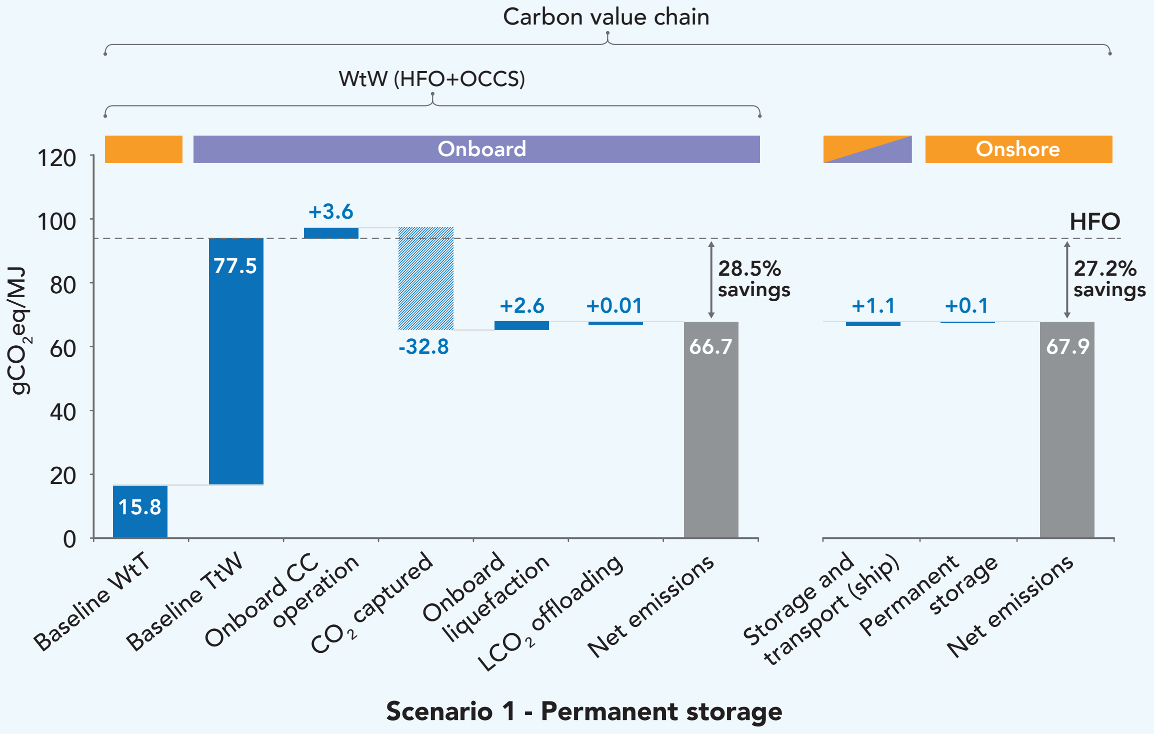


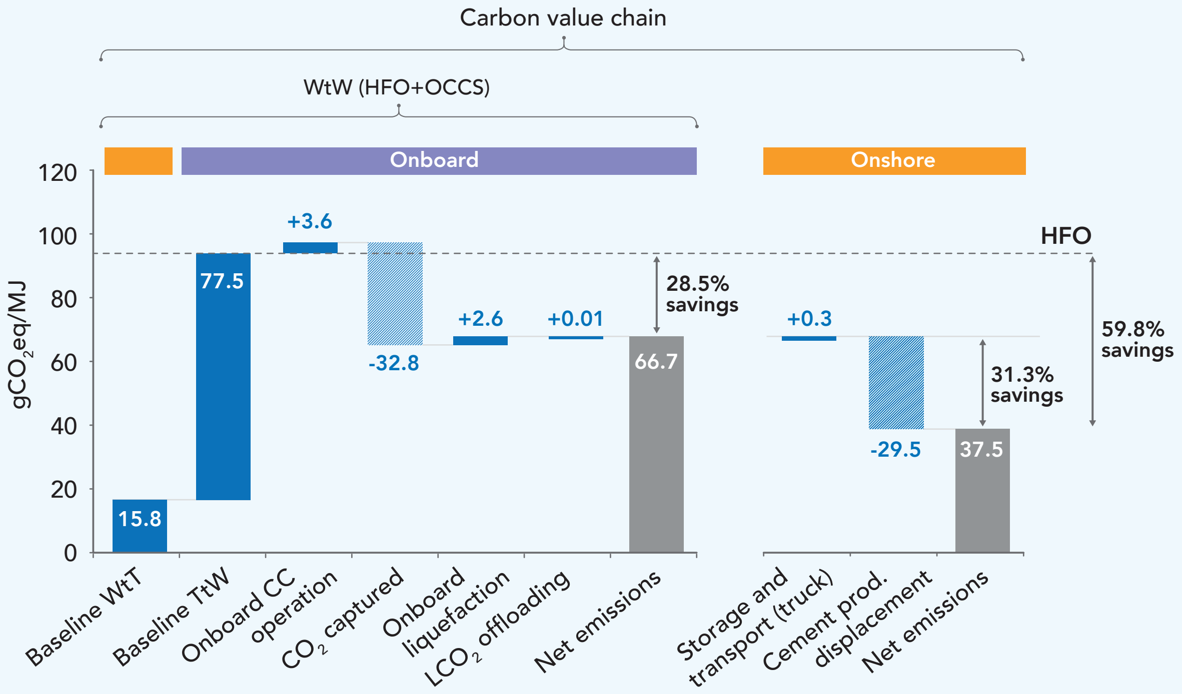
Figure 7 – Net carbon value chain GHG emissions and savings for OCCS with permanent storage of captured CO_2 under scenario 1b, Rotterdam to Northern Lights reservoir in Norway (40% gross capture rate). Baseline represents the GHG emissions due to the HFO-fuelled vessel operation without OCCS.

Scenario 2 – Carbon capture and utilisation: CO_2-cured concrete

One of the promising carbon capture and utilisation (CCU) pathways involves "fixing" CO_2 in infrastructure materials, such as CO_2-cured concrete. The displacement of carbon-intensive cement used in conventional concrete-making removes additional carbon from the atmosphere. For each kg of captured CO_2 incorporated, an average of 0.9 kg of CO_2 is avoided from cement production. Figure 8 illustrates an overall net GHG emissions savings of 60% across the carbon value chain when captured CO_2 is fixed in concrete.

However, the attribution of the GHG emissions savings would have to be considered carefully:

1. If the carbon credits are attributed to the shipowner, the CO_2 utilisation entity, i.e., the concrete producer, has no incentive to use CO_2 for curing, as they cannot claim the emissions credit from the otherwise displaced CO_2 during cement production.
2. If the carbon credits are claimed by the concrete producer, then the GHG emissions savings of the shipowner is 28.5%.



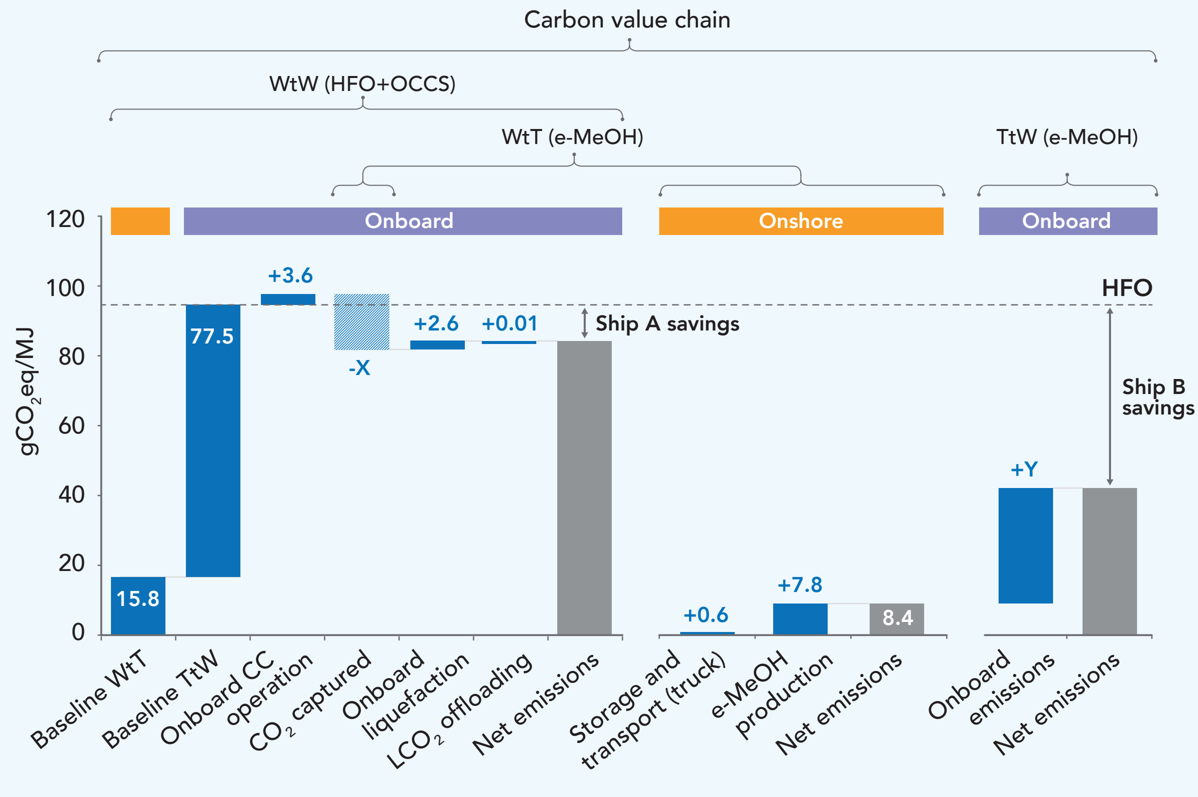
Scenario 2 - Concrete production

Figure 8 – Net carbon value chain GHG emissions and savings for scenario 2, Port Hedland to Zhoushan (40% gross capture rate), considering the emission credits generated by onboard capture and onshore CO_2-cured concrete production. This process displaces the production of carbon-intensive cement required by conventional concrete process. Baseline represents the GHG emissions due to the HFO-fuelled vessel operation without OCCS.

Scenario 3 – Carbon capture and utilisation: E-fuel

The last scenario of this analysis considers using captured CO_2 as a feedstock for synthesising e-methanol by combining it with hydrogen from electrolysis. This assessment uses the same basis as that of concrete production in scenario 2 where GHG emissions are considered from onboard capture to e-methanol production, accounting for the distance between the production plant and the offloading port.

Figure 9 shows the GHG emissions savings related to the operation of two ships. The first runs on HFO and captures 40% of onboard exhaust CO_2, and the second runs on e-methanol produced with captured CO_2 from the first ship. The net GHG emissions of both ships depend on how the carbon credits are assigned among the two users of the same CO_2 molecule. Such credits have different values on an energy basis for the vessel capturing CO_2 and the vessel consuming e-methanol (A and B, respectively) due to mass balance and calorific values.



Scenario 3 - E-fuel production

Figure 9 – Net carbon value chain GHG emissions and savings for scenario 3 (40% gross capture), considering the emission credits generated by carbon captured onboard an OCCS-installed HFO-fuelled vessel (Ship A) and CO_2 from the combustion of e-methanol made from such captured carbon in an e-MeOH-fuelled vessel (Ship B). Baseline represents the GHG emissions due to the HFO-fuelled vessel operation without OCCS.

Referring to Table 3, when the credits of captured CO_2 are claimed by Ship B, the net GHG emissions of Ship A (HFO-fuelled with OCCS) are higher than our baseline vessel that uses HFO and captures CO_2 with MEA (+6.6% because the benefits are “given away” to Ship B). Since Ship B is claiming the credits for using e-methanol produced from captured CO_2, its onboard emissions are essentially zero in the overall GHG balance. The only GHG emissions of Ship B are thus from those associated with the upstream production of e-methanol. Assuming renewable energy is used for fuel production, its net GHG emissions is 8.4 gCO_2eq/MJ, representing a GHG emissions savings of 91% from the HFO baseline.

If, on the other hand, the CO_2 emissions credits are claimed by Ship A, Ship B does not benefit from using the e-methanol produced with CO_2 that was captured onboard Ship A. In this case, the TtW GHG emissions for Ship B are not different from its emissions if it used fossil methanol. At 40% gross capture, the GHG emissions savings of Ship A is 28.5%. Ship B has higher GHG emissions due onboard combustion of methanol (69.1 gCO_2eq/MJ), though its WtT GHG emissions of e-MeOH are lower than those of fossil HFO and fossil methanol, assuming renewable energy is used to produce it. The calculated net GHG emissions savings is around 17% from the HFO baseline.

Equally sharing the carbon credits (50-50%) allows ships A and B to lower their GHG emissions compared to the HFO baseline with net GHG emissions savings of 11% and 54%, respectively.

If the emissions from combusting such e-methanol are recaptured on a methanol-fuelled ship with OCCS for a subsequent round of e-methanol production, a circular economy of carbon can potentially be realised, though properly accounting and assigning the carbon credit can be complex.

Table 3 – GHG emissions and savings for scenario 3, following different CO_2 credits claiming scenarios, compared to HFO baseline: 93.3 gCO_2eq/MJ

	Ship A (HFO+OCCS 40% gross capture)			Ship B (e-MeOH)		
CO_2 credits claiming scenario	Captured CO_2 credits [X value] (gCO_2eq/MJ)	Net WtW GHG emissions (gCO_2eq/MJ)	GHG emissions savings (%)	Onboard TtW emissions [Y value] (gCO_2eq/MJ)	Net WtW GHG emissions (gCO_2eq/MJ)	GHG emissions savings (%)
Fully claimed by Ship B (e-MeOH)	0.0	99.5	-6.6%	0.0	8.4	91.0%
Fully claimed by Ship A (OCCS)	32.8	66.7	28.5%	69.1	77.5	16.9%
Shared between ships A and B (50-50%)	16.4	83.1	10.9%	34.6	42.7	54.2%

Viability of OCCS to help shipowners reduce GHG emissions

While the recently articulated GHG Fuel Intensity (GFI) framework does not explicitly specify how emissions reduction from OCCS is taken into consideration, the study offers a structured basis for assessing the solution’s potential in helping shipowners and operators manage their emissions portfolio.

By calculating the abatement from OCCS based on the amount of CO_2 it removes per unit of energy (in gCO_2eq/MJ) on a WtW approach, an “equivalent” GFI can be derived. Extending this concept, the study shows an HFO-fuelled ship adopting MEA-based OCCS at 40% gross capture can, on a WtW basis, maintain an equivalent GFI below the direct compliance target until 2032. Similarly, LNG-fuelled ships equipped with the same OCCS can maintain an equivalent GFI below the direct compliance target until 2035. Further, when fossil fuels are completely replaced by their bio-counterparts, OCCS can lower the GFI enough for the ship to be compliant with the more stringent 2040 targets.

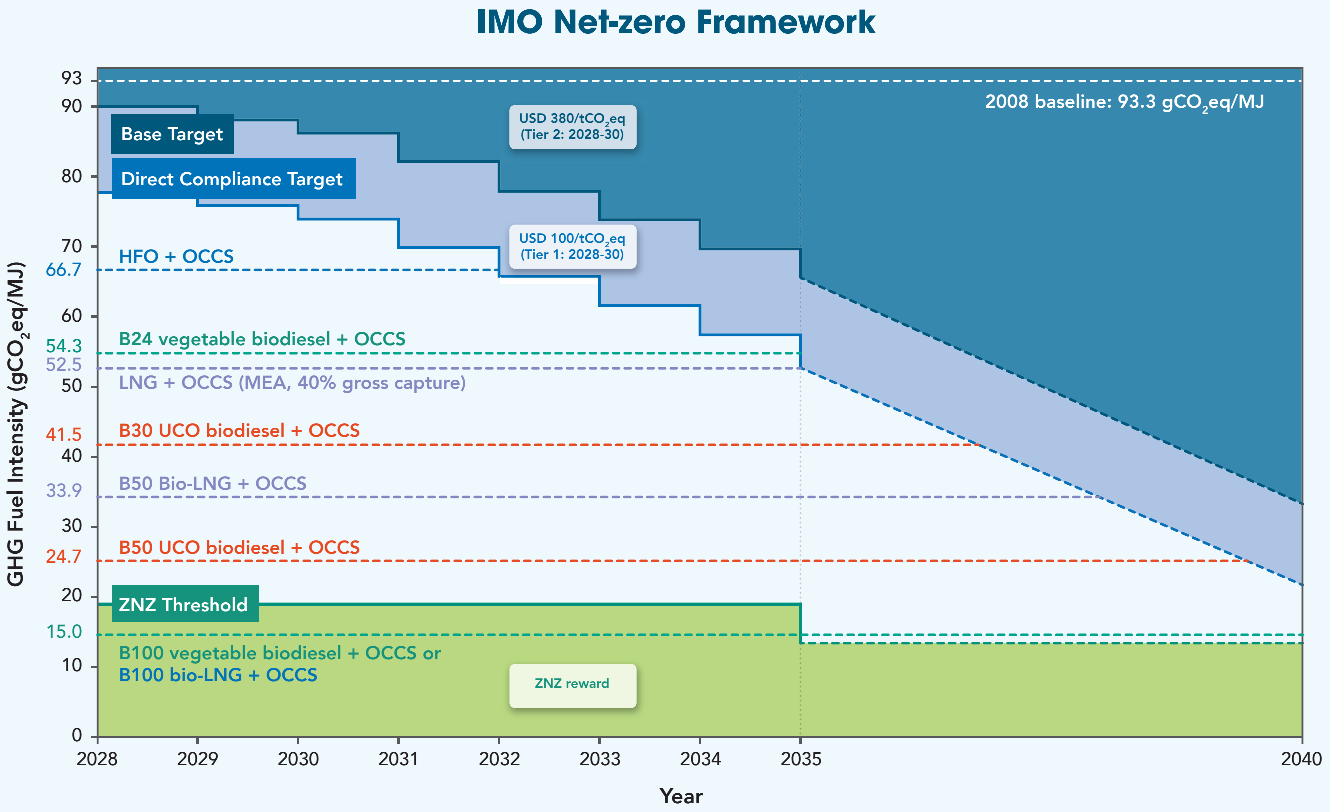


Figure 10 – GFI target compliance strategies for ships adopting OCCS and biofuels. OCCS technology is based on MEA capture and 40% gross capture rate, on a WtW basis. The values of GHG fuel intensity for biofuels are averaged based on different biomass sources and biofuel production processes. ZNZ (zero or near-zero) threshold is the GFI value below which ships are eligible for financial rewards.

Evaluating the cost of capture and avoidance

The capture cost of MEA-based OCCS across the carbon value chain was estimated at USD 207-312/tCO$_2$ and USD 210-277/tCO$_2$ for the permanent storage and utilisation pathways, respectively (Figure 11). The onboard capture cost is based on the results of the Project REMARCCABLE feasibility study (GCMD, OGCI, *Stena Bulk* et al. 2024) of a 40% gross capture rate of an OCCS installed on an MR tanker, considering a full-scale, Nth-of-a-kind system with full heat recovery. The cargo loss related to the reduction of available space onboard for OCCS was not included in the calculations.

For each tonne of CO$_2$ captured onboard and sequestered in a reservoir, only 0.77 tonnes of CO$_2$ is avoided. This considers the GHG emissions across the carbon value chain, i.e., OCCS, CO$_2$ transport and final injection into the reservoir. This leads to an overall avoidance cost of USD 269-405/tCO$_2$ for the permanent storage pathway.

The overall summary of the LCA of the GHG emissions savings and avoidance cost is shown in Table 4.

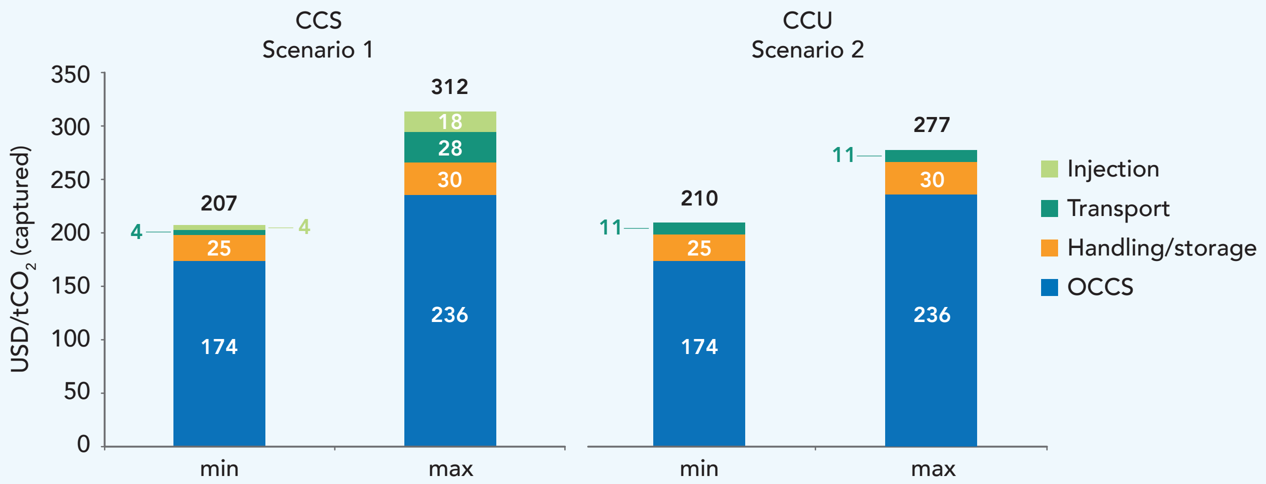


Figure 11 – Cost of captured carbon with OCCS across the carbon value chain for CCS and CCU pathways. Average cost of OCCS is based on Project REMARCCABLE estimations for 40% gross capture, full-scale, Nth-of-a-kind installation of commercial system with full heat recovery (error window ±15%).

Table 4 – Summary of LCA GHG emissions savings and cost analysis for OCCS with 40% gross capture rate

	OCCS technologies (Fuel: HFO)				
	MEA capture	Advanced amine capture	MEA offloading	Alkaline capture	Calcium looping
Technology description	• Solvent: MEA • Solvent regeneration: onboard • CO$_2$ liquefaction: onboard • Data from Project REMARCCABLE (full-scale OCCS with full heat recovery on an MR tanker) and industry survey	• Solvent: advanced amine (higher CO$_2$ extraction) • Solvent regeneration: onboard • CO$_2$ liquefaction: onboard	• Solvent: MEA • Solvent regeneration: onshore • CO$_2$ liquefaction: onshore • Onshore energy mix: high carbon-renewable	• Sorbent: CaO (solid) • Sorbent regeneration: none • Sea discharge of CaCO$_3$ product	• Sorbent: CaO (solid) • Sorbent regeneration: onshore • Sea discharge of CaCO$_3$ product • Onshore energy mix: high carbon-renewable
WtW GHG emissions savings	28.5%	29.8%	31.6%	-19.0%	31.8%
Including onshore GHG emissions	-	-	21.2-31.3%	-	17.3-31.3%

	Fuel types (OCCS technology: MEA capture)								
	HFO	LNG	MeOH	Biodiesel vegetable oil (B30)	Biodiesel vegetable oil (B100)	Biodiesel used cooking oil (B30)	Biodiesel used cooking oil (B100)	Bio-LNG	Bio-methanol
WtW GHG emissions savings	28.5%	43.7%	17.3%	44-47%	79-89%	55-56%	116-121%	69-98%	91-119%

	Carbon value chain scenarios (Fuel: HFO; OCCS technology: MEA capture)			
	1a	1b	2	3
CO_2 final disposition	Permanent storage (CCS) ARAMIS reservoir (NL)	Permanent storage (CCS) Northern Lights reservoir (NO)	Use in concrete production (CCU)	Use in e-methanol production (CCU)
Scenario description	• MEA capture, HFO fuel • CO_2 offloaded in Rotterdam • 200 km CO_2 by pipeline to reservoir	• MEA capture, HFO fuel • CO_2 offloaded in Rotterdam • 1,000 km CO_2 shipping to Øygarden • 100 km CO_2 by pipeline to reservoir	• MEA capture, HFO fuel • CO_2 offloaded in Zhoushan • 100 km CO_2 by truck to concrete plant • CO_2-curing process with displacement of cement production	• Ship A: HFO with OCCS • Ship B: e-methanol • MEA capture (Ship A) • CO_2 offloaded in Zhoushan • 200 km transport by truck roundtrip to/from e-fuel plant • e-methanol production with wind energy • e-methanol used in another ship (B)
Carbon value chain GHG emissions savings	28.2% (post-capture GHG emissions are negligible)	27.2%	28.5% (ship) 59.8% (ship + CO_2 use)	**Credits claimed by Ship B** Ship A: -6.6% ; Ship B: 91.0%
				Credits claimed by Ship A Ship A: 28.5% ; Ship B: 16.9%
				Credits shared (50-50%) Ship A: 10.9% ; Ship B: 54.2%

	Scenario 1a + 1b
Cost analysis assumptions	• OCCS: USD 174-236/tCO_2 • Handling: USD 25-30/tCO_2 • Transport: USD 4-28/tCO_2 • Permanent storage: USD 4-18/tCO_2 • Cargo loss due to OCCS: not included • Project REMARCCABLE (full-scale, Nth-of-a-kind OCCS with full heat recovery on an MR tanker)
Avoidance cost (USD/tCO_2)	269-405

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List of Abbreviations

ASU	Air Separation Unit
AU	Australia
BECCS	Biofuel Energy with Carbon Capture and Storage
BECCU	Biofuel Energy with Carbon Capture and Utilisation
BOG	Boil-off gas
CC	Carbon Capture
CCS	Carbon Capture and Storage
CCU	Carbon Capture and Utilisation
CN	China
DAC	Direct Air Capture
e-MeOH	Renewable Methanol
EET	Energy-efficient Technology
EOR	Enhanced Oil Recovery
EU ETS	European Union Emissions Trading System
GFI	GHG Fuel Intensity
GHG	Greenhouse Gas
HFO	Heavy Fuel Oil
IEA	International Energy Agency
IMO	International Maritime Organization
IPCC	Intergovernmental Panel on Climate Change
ISO	International Organization for Standardization
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCO_2	Liquefied CO_2
LNG	Liquefied Natural Gas
MEA	Monoethanolamine
MeOH	Methanol
MEPC	Marine Environment Protection Committee
MGO	Marine Gas Oil
MP	Medium pressure
NL	Netherlands
OCC	Onboard Carbon Capture
OCCS	Onboard Carbon Capture and Storage
OPC	Ordinary Portland Cement
PEM	Polymer Electrolyte Membrane
SP	Supercritical Pressure
TtW	Tank-to-wake
UCO	Used Cooking Oil
WHRU	Waste Heat Recovery Unit
WtT	Well-to-tank
WtW	Well-to-wake
ZNZ	Zero or Near-Zero

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1. Goal and scope of the study

The ambitious decarbonisation goals set by the International Maritime Organization's (IMO) Maritime Environment Protection Committee (MEPC) Session 81 in July 2023 have upped the ante on finding solutions to meet these targets. It is generally accepted that, with the shortage of green alternative fuels, fossil fuels will still dominate the maritime fuel landscape[1]. Even on the back of operational energy efficiency improvements, deployment of energy-efficient technologies (EETs), and tighter energy efficiency design indices, achieving zero-emission shipping is difficult. OCCS systems are now on the IMO MEPC discussion table to potentially complement and synergistically act with technical and operational measures to close the gap towards zero emissions (Figure 1.1).

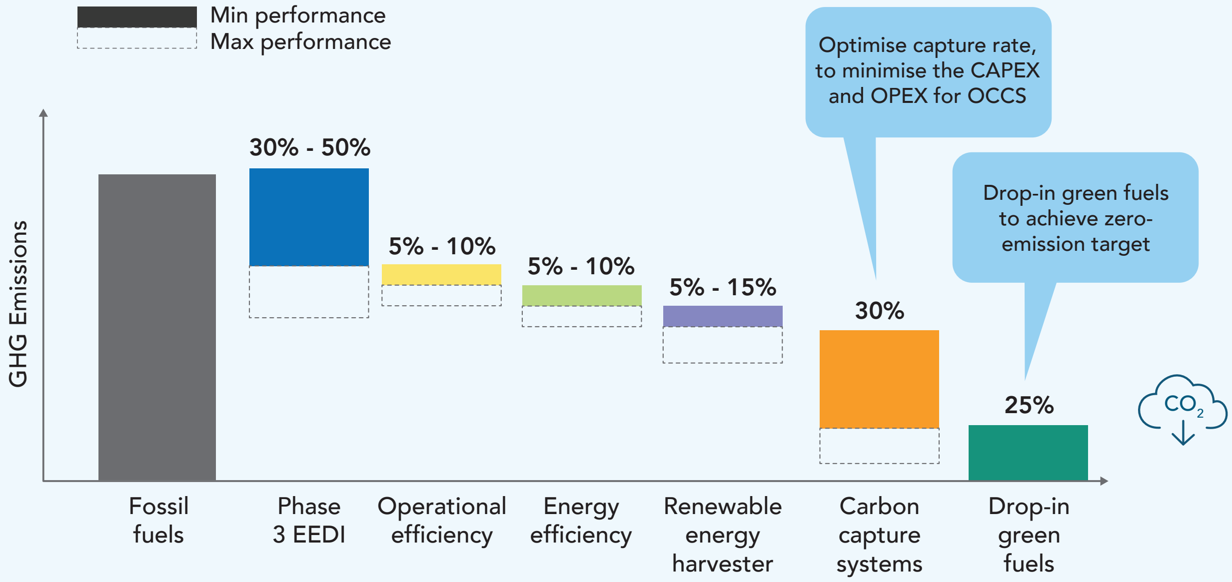


Figure 1.1 – Estimated impact of decarbonisation measures in shipping (Source: GCMD)

With application to all carbon-containing fossil, electro and biofuels, OCCS system has the potential to play a vital role in maritime decarbonisation depending on regulatory requirements, alternative fuel availability and their prices, and OCCS technology development and its commercial viability. OCCS could assume the role of a bridging technology capable of recycling captured CO_2 to produce materials and alternative fuels. A proper accounting of GHG emissions across post-capture pathways for the carbon captured from the vessel's emissions is key to justifying the sustainability of the adopted OCCS solution. Although there is a lot of literature on life cycle assessment (LCA) studies for onshore carbon capture technology, limited work is done in the context of OCCS systems[2].

OCCS system contributes to vessel decarbonisation by capturing shipboard carbon emissions, which is then offloaded at ports to be directed to permanent storage facilities or utilisation pathways by the industrial sector. The OCCS system solution does not differentiate carbon emissions from fossil, low-carbon and carbon-neutral fuels and can potentially enhance the net carbon emission reduction associated with using the fuel. Furthermore, with the emergence of various utilisation pathways, e.g., e-fuels, green concrete or formic acid, that have different energy requirements for its manufacture, the net carbon avoidance impact of the entire OCCS system-linked carbon value chain must be evaluated to justify the investments across the chain in relation to its overall net carbon avoidance.

In the case of e-fuels, the captured carbon, whilst ultimately re-released upon combustion, will need to be accounted for due to its fossil origin. Thus, the effectiveness of OCCS in removing carbon from the environment can be correctly evaluated against other decarbonisation measures, i.e., alternative fuels, technical and operational, direct air capture (DAC) systems.

In the recent IMO MEPC 76, 79 – 81 submissions, several papers have called for onboard carbon capture (OCC) systems to be included in the IMO GHG regulatory framework and integrated into existing LCA guidelines for marine fuels[3]. The challenge and importance of accounting for GHG emissions for OCC and sustainable renewable marine fuels were highlighted. In the case of EU ETS, which allows the OCC system to reduce the allowances that companies must surrender, it is important to demonstrate the final disposition through permanent storage and utilisation in accordance with the legislation requirements.

With this perspective in mind, the study aims to provide a comprehensive LCA of the GHG emissions associated with the use of the OCCS system against a baseline, i.e., without an installed system. A value of 93.3 gCO_2eq/MJ is used as the HFO baseline to be aligned with the GHG fuel intensity (GFI) of fossil fuel in 2008 level on a WtW basis, as defined during the 83rd session of MEPC in April 2025. The project collected data and information from the latest body of literature and industry partners. This was used to build a life cycle emissions analysis model with SimaPro software. The software provides realistic estimations, with different assumptions, of the emission reduction potential of the OCCS system-linked carbon value chain.

The LCA analysis considered multiple scenarios based on different fuels, i.e., HFO, LNG, methanol and biofuels, different OCCS technologies, i.e., onboard monoethanolamine (MEA) and advanced amine capture with CO_2 liquefaction, onboard alkaline carbon capture (CC) and calcium looping, and different value chain configurations towards the final disposition, i.e., utilisation and long-term storage. Final net GHG emissions also accounted for additional fuel consumption, materials and energy required to capture, store and transport CO_2 to either storage or utilisation pathways.

As the captured CO_2 needs to be sequestered and/or utilised on land, a complete LCA for the OCCS system must also include emissions from post-capture onshore operations such as onshore storage, e-fuel or material/chemical production and permanent storage (Figure 1.2). The emissions derived from onshore activities need to be added to the emissions from the onboard operations to get a complete and coherent view of the net decarbonisation potential of a deployed OCCS system.

The final utilisation of the captured CO_2 could include the production of concrete, brick, e-fuel, and other materials. An evaluation of the cost of e-fuels produced with post-combustion CO_2 required an assessment of the current (and expected) costs of OCCS system and the current and future cost of e-fuel production.

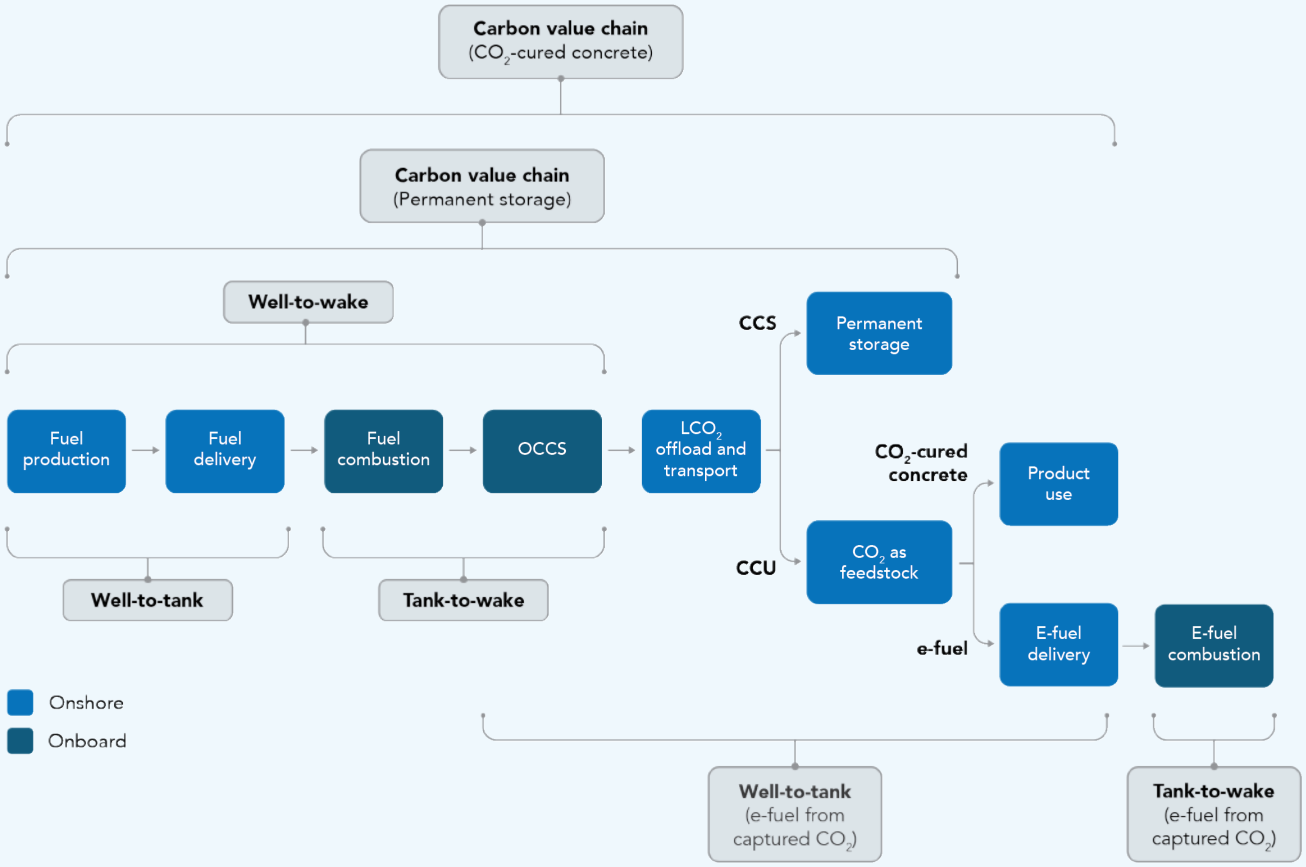
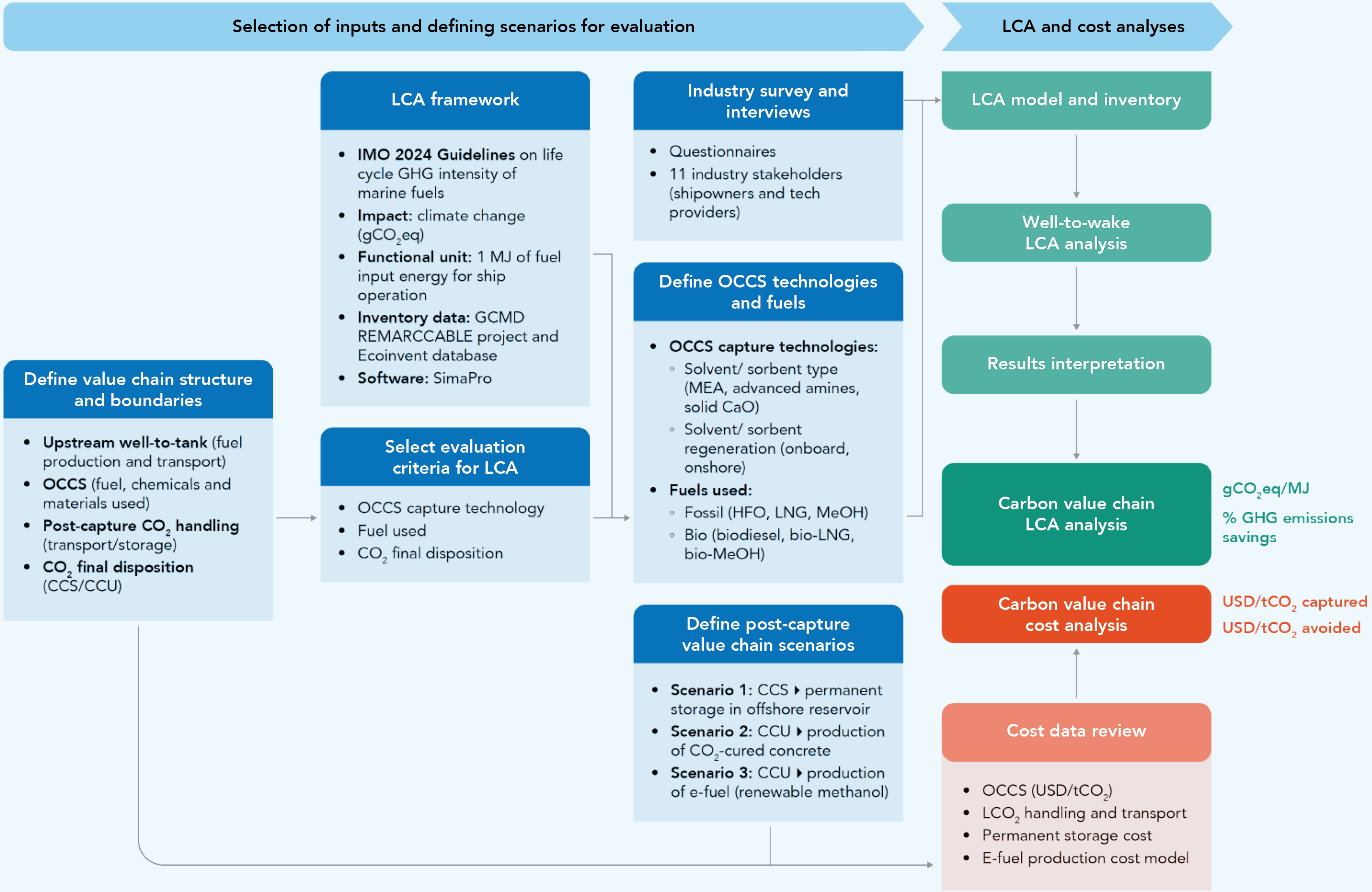


Figure 1.2 – Carbon value chain of onboard carbon capture and storage

The workflow adopted for this study is shown in Figure 1.3. After defining the boundaries of the system, which includes upstream fuel production and downstream post-capture processes, the main evaluation criteria of OCCS were defined. First, a comparative study of the WtW GHG emissions of an HFO-fuelled ship adopting different OCCS capture technologies was performed, to identify the most effective. The second step involved the analysis of the well-to-wake GHG emissions of OCCS with different marine fuels, considering the capture technology singled out in the first step. Hence, the boundary of the analysis was expanded to integrate the fate of the CO_2 captured onboard, exploring different scenarios based on its final disposition, i.e., permanent storage (CCS) or utilisation (CCU).

An industry survey was carried out to collect useful data for the LCA model. Several stakeholders involved in the carbon capture value chain were contacted, including ship owners, OCCS technology providers, LCO_2 storage and transport operators and CO_2 users. The gathered information served to reinforce the data collected for the LCA analysis.



Selection of inputs and defining scenarios for evaluation

LCA and cost analyses

Define value chain structure and boundaries

- **Upstream well-to-tank** (fuel production and transport)
- **OCCS** (fuel, chemicals and materials used)
- **Post-capture CO_2 handling** (transport/storage)
- **CO_2 final disposition** (CCS/CCU)

LCA framework

- **IMO 2024 Guidelines** on life cycle GHG intensity of marine fuels
- **Impact:** climate change (gCO_2eq)
- **Functional unit:** 1 MJ of fuel input energy for ship operation
- **Inventory data:** GCMD REMARCCABLE project and Ecoinvent database
- **Software:** SimaPro

Select evaluation criteria for LCA

- OCCS capture technology
- Fuel used
- CO_2 final disposition

Industry survey and interviews

- Questionnaires
- 11 industry stakeholders (shipowners and tech providers)

Define OCCS technologies and fuels

- **OCCS capture technologies:**
    - Solvent/ sorbent type (MEA, advanced amines, solid CaO)
    - Solvent/ sorbent regeneration (onboard, onshore)
- **Fuels used:**
    - Fossil (HFO, LNG, MeOH)
    - Bio (biodiesel, bio-LNG, bio-MeOH)

Define post-capture value chain scenarios

- **Scenario 1:** CCS ▸ permanent storage in offshore reservoir
- **Scenario 2:** CCU ▸ production of CO_2-cured concrete
- **Scenario 3:** CCU ▸ production of e-fuel (renewable methanol)

LCA model and inventory

Well-to-wake LCA analysis

Results interpretation

Carbon value chain LCA analysis

gCO_2eq/MJ

% GHG emissions savings

Carbon value chain cost analysis

USD/tCO_2 captured

USD/tCO_2 avoided

Cost data review

- OCCS (USD/tCO_2)
- LCO_2 handling and transport
- Permanent storage cost
- E-fuel production cost model

Figure 1.3 – Workflow of the LCA GHG emissions and cost analysis of OCCS across carbon value chain

The GHG emissions of a ship that uses OCCS technology can be defined in different ways, depending on the system boundaries considered in the analysis. Figure 1.4 shows the fluxes of GHG (emitted and captured) associated with a ship that operates OCCS technology onboard. The choice of the system boundaries defines the extent to which GHG emissions can be calculated.

Onboard or TtW GHG emissions refer to the combustion of fuel in the engine, which produces both CO_2 and other non-CO_2 GHG gases such as methane (CH_4) and nitrous oxide (N_2O). When the OCCS system is operating, additional fuel is burned in the auxiliary engine(s) and in the auxiliary boiler(s) to provide heat and electricity for the capture and liquefaction of CO_2. This means that an additional flux of CO_2 is generated, part of which is captured by the system itself, depending on the amount of exhaust gas processed and on the capture rate (Figure 1.4a). Net TtW GHG emissions are calculated by subtracting the gross amount of CO_2 captured from the total emissions of CO_2, CH_4 and N_2O in the exhaust, expressed in gCO_2 equivalent (gCO_2eq). If the WtT emissions due to fuel production, transport and bunkering are added to the balance, the resulting net GHG emissions are defined as WtW and refer only to the fuel used onboard. To assess the total WtW GHG emissions related to the ship operation, the GHG emissions associated with the production and disposal of chemicals and materials other than the fuel itself must be included in the calculations (i.e., amine solvent for the capture). However, WtW GHG emissions alone do not represent the full picture of the impact of adopting OCCS technology in shipping, as the CO_2 must be offloaded and disposed of in some way after onboard capture. Transporting and storing the CO_2 causes additional emissions to the atmosphere and varies depending on the pathway taken, i.e., storage or utilisation. If the captured CO_2 is used to manufacture a product, carbon credits may be available for the displacement of another more carbon-intensive product: in this case, such credits must be included in the overall carbon value chain balance as a deduction. The formulae used for the calculations are reported in Figure 1.4b.

Whilst international guidelines for carbon accounting on ships are yet to be established, some guidelines and principles were included in the latter MEPC documents (MEPC 80/INF.31). It was stated in “The challenge and importance of accounting for GHG emissions from shipping for sustainable renewable marine fuels and onboard carbon capture” that a clear framework for the use of OCCS is still missing. Subsequently, a report on the draft work plan was submitted by the assigned Correspondence Group in MEPC 83 (MEPC 83/6/1), clearly laying out the objectives, boundaries and tasks to develop the regulatory framework for the use of OCCS in order to reduce net GHG emissions from ships without negatively affecting the environment. The exception are matters related to accounting of CO_2 captured onboard ships that will be addressed by the workstream on further development of the LCA framework undertaken by GESAMP-LCA working group which has also submitted their first interim report in MEPC 83 (MEPC 83/7/1). The need to clearly understand the flow of carbon from source to sinks and recycled usage was highlighted.

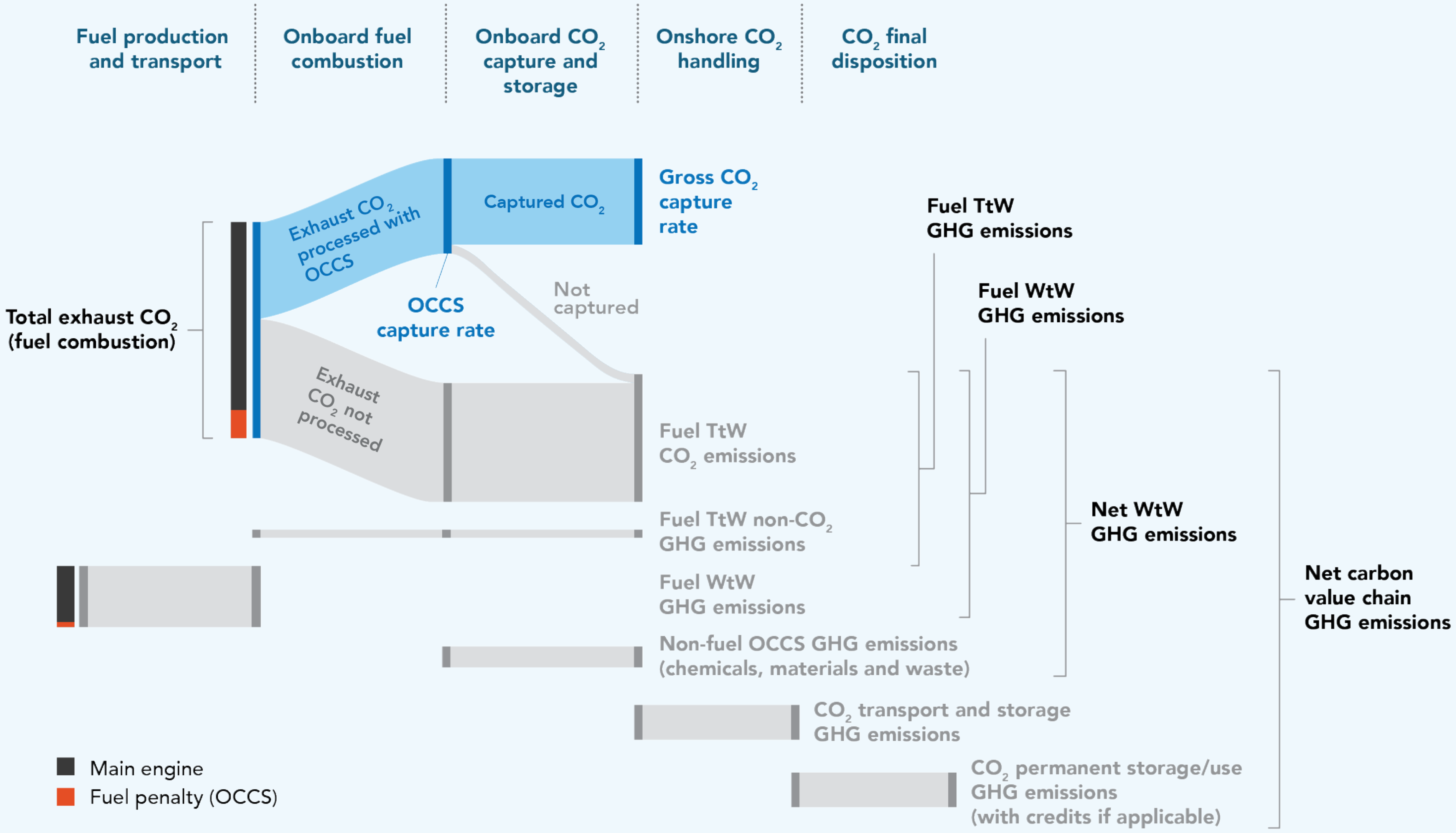


Figure 1.4a – CO_2 and GHG emissions flows of a ship equipped with OCCS that illustrates the gross CO_2 capture rate, which is the sum of processed exhaust CO_2 captured by the OCCS. The net WtW GHG emissions are the sum of fuel baseline emissions (WtT and TtW), the emissions due to the additional fuel consumption for OCCS (fuel penalty) and non-fuel chemicals and materials OCCS used in the process. The net carbon value chain GHG emissions includes the GHG emissions from net WtW, CO_2 transport and storage and CO_2 permanent storage/use.

$$(1) \quad OCCS\ capture\ rate\ (\%) = \frac{Captured\ CO_2}{Exhaust\ CO_2\ processed\ with\ OCCS} \bullet 100$$

$$(2) \quad Gross\ CO_2\ capture\ rate\ (\%) = \frac{Captured\ CO_2}{Total\ exhaust\ CO_2} \bullet 100$$

$$(3) \quad Fuel\ TtW\ GHG \left[{}^{gCO_2eq}/_{MJ}\right] = \frac{Total\ exhaust\ CO_2 - Captured\ CO_2 + fuel\ TtW\ non\,CO_2\ GHG[gCO_2eq]}{Total\ fuel\ burned\ [kg] \bullet LHV\ fuel \left[{}^{MJ}/_{kg}\right]}$$

$$(4) \quad Fuel\ WtW\ GHG = Fuel\ WtT\ GHG + Fuel\ TtW\ GHG$$

$$(5) \quad Net\ WtW\ GHG = Fuel\ WtW\ GHG + Nonfuel\ OCCS\ GHG$$

$$(6) \quad Net\ carbon\ value\ chain\ GHG = Net\ WtW\ GHG + CO_2\ transport, storage\ GHG + CO_2\ permanent\ storage/use\ GHG - CO_2\ credits_{CO_2\ use}$$

Figure 1.4b – Equations to calculate onboard capture rates, net GHG emissions and savings across the carbon value chain (refer to Figure 1.3a)

2. CO_2 value chain

Current EU Emissions Trading System (ETS) dictates that the application of OCCS requires onboard captured CO_2 to be permanently stored or utilised in accordance with the legislation requirements. This being the case, a fully developed infrastructure for the entire logistics chain to store and transport the CO_2 from the ship, where such CO_2 is captured during operations, to the final destination of the molecule, i.e., permanent storage site or utilisation plant is needed. The two main pathways for captured CO_2 are carbon capture and storage (CCS) and carbon capture and utilisation (CCU).

In CCS, CO_2 is permanently stored in underground depleted oil and gas reservoirs and aquifers for long periods of time, on a scale of centuries. CCU, on the other hand, involves the use of CO_2 as input material for other processes to generate products and services. CCS is considered the most viable pathway to manage the large amounts of CO_2 captured from fossil fuel-burning sources such as power plants, cement, steel, petrochemicals, and potentially from ships when aggregated in CO_2 hubs. CCU industry capacity to manage these captured CO_2 is comparatively limited (Figure 2.1).

However, examples from both pathways were considered and included in this LCA study, especially since the captured volumes are expected to be smaller in the early stages of transition, and much work remains to bridge emitters to sinks[4].

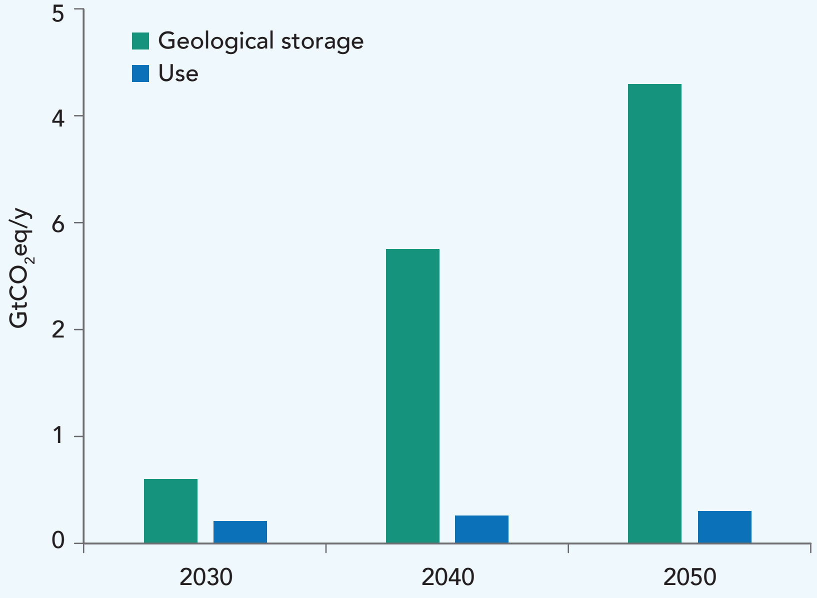


Figure 2.1 – Forecasted annual CO_2 destination volumes, Clean Technology Scenario of IEA (adapted from IEA, 2019)[5]

Several transformation pathways of CO_2 are emerging with growing interest, though many technologies are still in development. CO_2 can be used to produce a wide range of goods, including fuels, intermediate chemicals and building materials. Furthermore, CO_2 can be used directly in combination with CCS to improve the extraction of oil (Enhanced Oil Recovery – EOR) or to boost plant growth in greenhouses. Figure 2.2 summarises the main pathways for the utilisation of CO_2 in the global market.

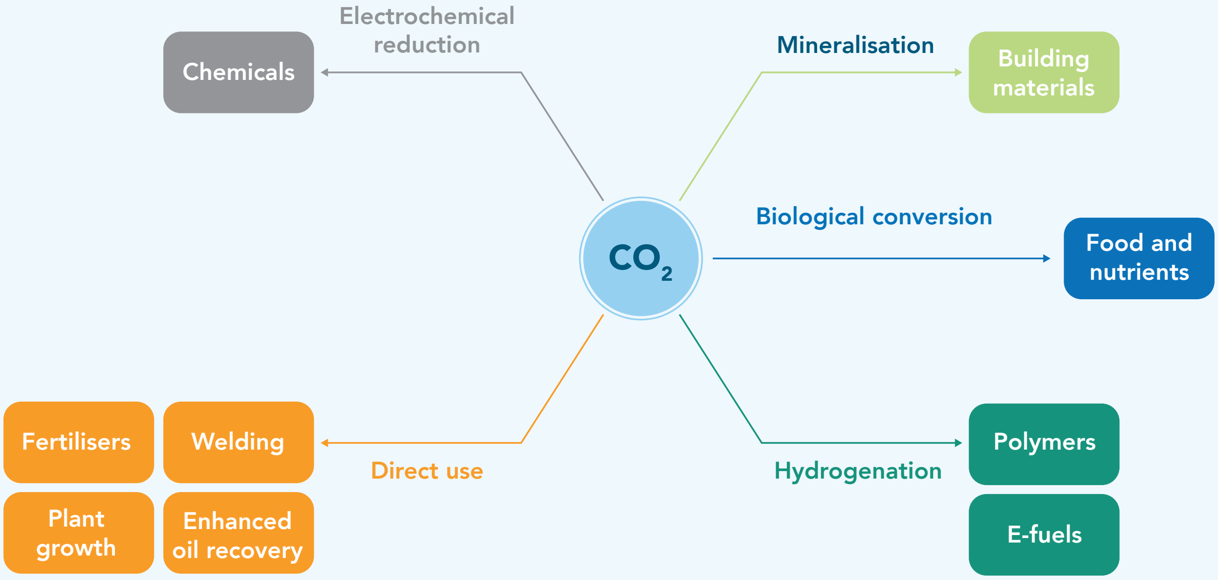


Figure 2.2 – Pathways for CO_2 uses[6,7]

Mineral carbonation is the conversion of alkaline materials, i.e., calcium oxide (CaO or quicklime), to produce solid carbonates. This process is the only exception among all CO_2 conversion paths in terms of energy requirements, as the carbonation reaction is exothermic and does not require the input of external energy, except from the energy required to move and transport the materials and to power the equipment. One of the main carbonation pathways is the production of CO_2-cured concrete, where CO_2 is used in small quantities (2-3 wt%) to strengthen concrete.

Biological conversion uses autotrophic organisms that fix CO_2 into bioproducts and require energy in the form of light or reducing agents.

Hydrogenation is a thermal and catalytic process in which CO_2 reacts with hydrogen to form hydrocarbons or alcohols. This process occurs at high temperatures and low pressures, as well as the presence of a metal-based catalyst.

When CO_2 is reduced through electrochemical reactions in an electrolyser, it can produce value-added chemicals such as methane, alcohols and formic acid, which are key intermediate chemicals to produce a wide variety of substances in the chemical industry.

Today, the most mature conversion pathways are thermal-catalytic hydrogenation and mineralisation, with many existing demonstration projects and plants operating at large scale. Biological and electrochemical conversions are instead at a lower technology readiness level, and large-scale demonstration is still lacking.

It is also possible to use CO_2 directly without converting it into other molecules. One possibility is to inject it into existing oil reservoirs to enhance oil production and store it permanently underground. This represents a sort of mix between CCS and CCU pathways. CO_2 can also be used as a shielding gas for welding, to enhance plant growth in greenhouses or to make fertilisers that increase the carbon stock in the soil (urea).

For the scope of this study, the analyses focus on the most promising uses for captured CO_2 from onboard ship operations. While CO_2 storage in depleted reservoirs and saline aquifers permanently stores CO_2 for long periods of time and effectively removes it from the atmosphere, the utilisation of CO_2 as material to produce goods does not necessarily reduce GHG emissions from a global life cycle perspective. The climate benefits associated with captured fossil CO_2 use depend on several factors, such as:

i) product displacement potential of the CO_2-based product
ii) amount of energy used in the conversion process
iii) lifetime of CO_2 inside the product
iv) scale of the product market

Major emissions savings can be achieved if CO_2 utilisation prevents GHG emissions during the production of other services and products. However, it is important to remember that such positive effects will decline over time as the global economy decarbonises and fossil CO_2 becomes less attractive in the markets. Moreover, higher and more reliable carbon removal is only achieved when the captured CO_2 used in the process does not return quickly to the atmosphere, as this could lead to issues with the quantification and allocation of carbon credits along the value chain. The carbon retention time varies depending on the product, as shown in Table 2.1.

Direct uses of CO_2 must also be carefully evaluated. Enhanced Oil Recovery (EOR) is the practice of extracting oil from a well that has already gone through the primary and secondary stages of oil recovery. It is basically a permanent storage of CO_2 in a reservoir, with the additional commercial benefit of improved oil extraction. It is estimated that each barrel of CO_2-EOR oil can provide up to 37% GHG emissions savings compared to conventional oil[8]. However, this assumes that EOR-supplied oil displaces the existing supply of conventional oil, thus reducing the overall emissions of the oil industry. While this may be considered an environmental benefit, from a global perspective, the coupling of a decarbonising technology such as carbon capture and the fossil fuel industry is controversial as it may eventually promote the continued production and consumption of fossil fuels. Recent studies have also found that carbon emissions savings are available only in a short period (6-18 years), after which the carbon balance becomes positive[9]. Moreover, if captured carbon comes from fossil point sources, the stored CO_2 credits can only be counted once as reduced emissions from the point source or the production of extra oil at the extraction site[10]. For these reasons, EOR was not included in the scenarios of this study.

CO_2 is also used as shielding gas for welding operations in automotive, aerospace and construction industries. It is commonly sourced from industrial plants such as natural gas and coal processing plants or cement production plants. The destination of the molecule after the welding process is the atmosphere; therefore, the use of onboard captured CO_2 for this purpose makes sense only if it displaces the originally more carbon-intensive CO_2 sourced elsewhere. However, if the CO_2 for welding is already sourced from onshore capture plants, it is unlikely that welding will be an attractive pathway for OCCS for both economic and environmental reasons, and thus, it was not covered in the analysis.

The use of CO_2 to produce fertilising agents to improve carbon soil content and foster plant growth in greenhouses is another promising direct use of CO_2. While it is widely accepted that enhancing the soil organic carbon content can improve soil health and increase crop yields, GHG flows from agricultural soils are very large, complex and highly heterogeneous[11]. Under certain soil conditions, the increase in soil organic carbon and organic nitrogen levels could even increase carbon dioxide, methane and nitrogen emissions from the soil. It is also relevant to highlight that agronomic management has to be changed permanently to maintain a new soil carbon equilibrium, while the contribution to climate change mitigation only occurs in the first decades when the soil carbon stock is increasing[12]. Eventually, most of the carbon is likely to return to the atmosphere in a shorter timescale than the one required to effectively mitigate climate change. As an appropriate evaluation of the problem in a life cycle approach is still lacking, this pathway was not considered in this study.

The most promising pathways for the use of CO_2 are the ones that can ensure an effective and long-term storage of carbon dioxide, preventing its return to the atmosphere in a short time span, such as the production of building materials for which CO_2 is stored inside the material, i.e., CO_2-cured concrete. Climate benefits must also be evaluated considering the market scale of the product, as larger markets can provide more emission reductions globally compared to niche applications. According to IEA, the highest relative climate benefits can be achieved by using CO_2 to produce building materials and fuels (Figure 2.3).

Table 2.1 – Lifetime of CO_2 inside materials

CO_2-based product category	CO_2 lifetime in product
Fuels, food, nutrients, welding gas and fertilisers	<1 year
Intermediate chemicals	<10 years
Building materials, polymers, EOR	≈100 years or more

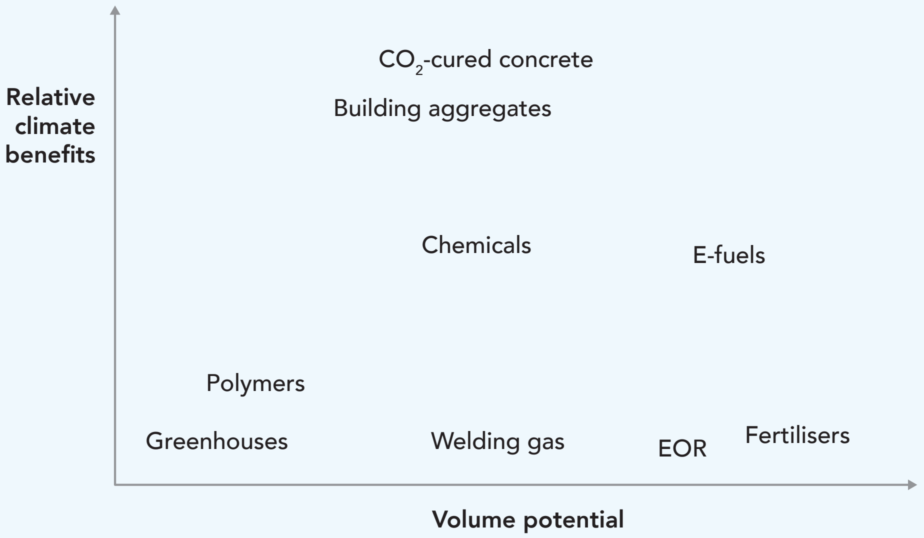


Figure 2.3 – Theoretical potential and climate benefits of CO_2-derived products and services (adapted from IEA[6])

3. LCA model

In order to compare OCCS with other decarbonisation technologies, it is necessary to evaluate the GHG emissions related to the overall value chain of CO_2, including fuel WtT, capture, storage, transport and final use. As such, this LCA study was conducted with the goal of evaluating the GHG emissions of a ship equipped with OCCS system across the entire value chain and comparing it to the GHG emissions baseline of an HFO-fuelled ship without onboard carbon capture. The analysis was performed with the LCA software SimaPro. This chapter will first introduce LCA and its methodology, with selected boundaries and functional unit. Followed by explanation and discussion of the model and inventory data used to calculate the overall GHG balance for the scenarios, along with the main assumptions and limitations.

3.1 Life cycle assessment

LCA is a tool to assess the environmental impact over the course of the entire life cycle of a product, material or process. LCA is regulated by international standards (ISO 14044:2006), which specify requirements and provide guidelines for LCA.

LCA is carried out by evaluating each step of the process chain with a cradle-to-grave approach and consists of four main phases:

1. Goal and scope definition
2. Life cycle inventory (LCI)
3. Impact assessment
4. Interpretation

The first step includes defining the LCA objective, the final product with its life cycle and a description of the system boundaries, which is necessary to simplify the complexity of interconnected real processes and systems. This step includes the definition of the functional unit, which serves as the quantified performance of a product system for use as a reference unit. The second step (inventory) involves the collection of all relevant data for the analysis, including the materials and energy used in each step of the process. This can be performed by harvesting data from literature and industry with specific software tools and existing LCA databases. The environmental outputs are also considered, i.e., any product that the life cycle releases out of the boundaries and into the environment (pollutants, by-products and waste streams). The impact assessment is then carried out, calculating the functional unit's value for different assumptions and scenarios defined in the LCA study. Several impact categories can be evaluated, and each one analyses a specific type of effect on the environment. Examples of impacts are climate change, acidification of soils and water, eutrophication of waters (nutrient enrichment), land use, ecotoxicity, and depletion of natural resources. The last step is the interpretation of the analysis outcomes, which concludes the assessment by reviewing the data, providing conclusions, and stating the strengths and limitations of the analysis.

In this study, the SimaPro software was used, which is based on the ecoinvent database that collects a wide range of data on industrial processes specifically arranged for life cycle inventory, regularly updated with data from industry and literature studies. For additional information regarding the LCA framework adopted for this study, refer to the Appendix.

3.2 Analysis boundaries and functional unit

OCCS is an emerging application, and it is important to assess its environmental impact to compare it with other decarbonisation measures. The impact category of interest is "climate change", expressed in grams of CO_2 GHG equivalent (gCO_2eq) emitted into the atmosphere per functional unit, which is usually defined as the fuel energy burned in the engine or the energy at the shaft. Most of the published studies and reports on this topic only assess the GHG emissions savings considering what happens onboard the ship, i.e., the net emissions in the exhaust after the capture. However, this study aims to assess the impact of OCCS by expanding the boundaries to the entire CO_2 value chain, including the production of materials required by the capture system, the transport of CO_2 after capture and its final disposition, as indicated by the IMO 2024 Guidelines on Life Cycle GHG Intensity of Marine Fuels[3].

The selected functional unit is 1 MJ of marine fuel burned. In this way, the LCA outcome is the g of CO_2-equivalent emitted for each MJ burned in the main engine(s), auxiliary engine(s) and in the auxiliary boiler during the ship operation (including CO_2 capture and onboard liquefaction and storage). When the OCCS system is on, the engines require more fuel compared to normal operation without carbon capture. To properly assess the impact of OCCS and compare it with the baseline ship, the results were calculated considering the same amount of fuel energy required by main engines and auxiliaries to operate the ship. In this way, it is possible to compare the impact of OCCS, defining a fixed operational profile of the ship (same route and speed).

As mentioned previously, operating the OCCS system requires additional energy and materials, which carry a GHG burden as CO_2 is emitted in their production. Moreover, the degraded solvent constitutes a waste that needs to be disposed of, adding to the total GHG balance. Therefore, the overall onboard GHG net emissions are the sum of the CO_2 emitted in the exhaust (total CO_2 from the engines minus the captured CO_2) plus the CO_2 emissions due to materials and fuel production and waste management (Figure 3.1).

The expansion of LCA system boundaries outside the ship is important to avoid neglecting the impact of extra-fuel production before capture and CO_2 transport and storage/use after capture (Figure 3.2). Energy is required for loading/unloading operations and for reliquefaction of CO_2 boil-off gas (BOG) during temporary storage at the port. The CO_2 needs to be transported to its final disposition site, a step that involves additional GHG emissions related to the energy consumption for transport operations. Indeed, if the CO_2 is transported by pipeline, electrical energy is needed for compression, while if the transport occurs by truck or ship, the emissions due to the combustion of fuel need to be considered. Permanent storage of carbon dioxide in depleted gas and oil reservoirs or saline aquifers requires electrical energy to reach the necessary injection pressure. If CO_2 is used as input material to generate a product, then the energy and material balance of the product must be evaluated together with any displacement of other materials due to the new CO_2-based product. For example, if the CO_2 is used to produce concrete, a different process will be applied compared to the conventional process. This leads to different material and energy demands, which ultimately leads to a distinct carbon footprint. The difference between the CO_2-based and conventional processes constitutes an additional element of the overall value chain GHG balance.

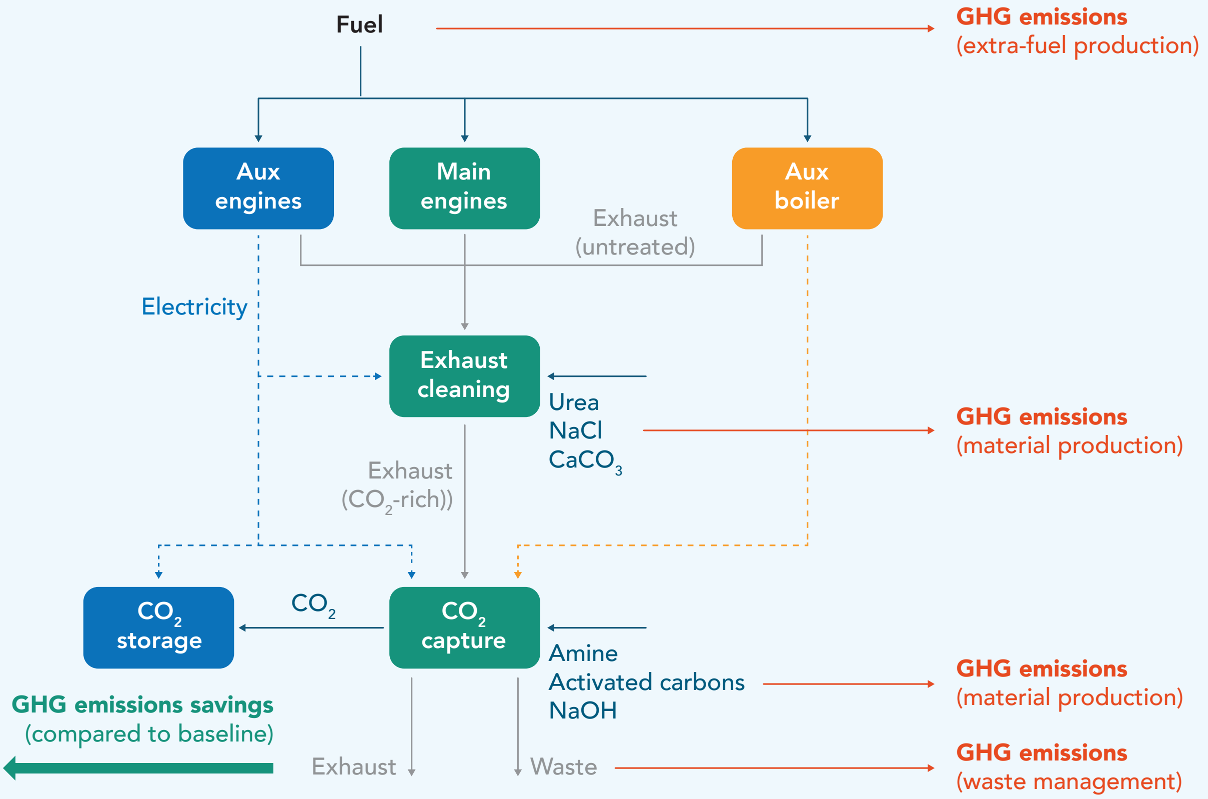


Figure 3.1 – GHG additional emissions and savings of the OCCS system

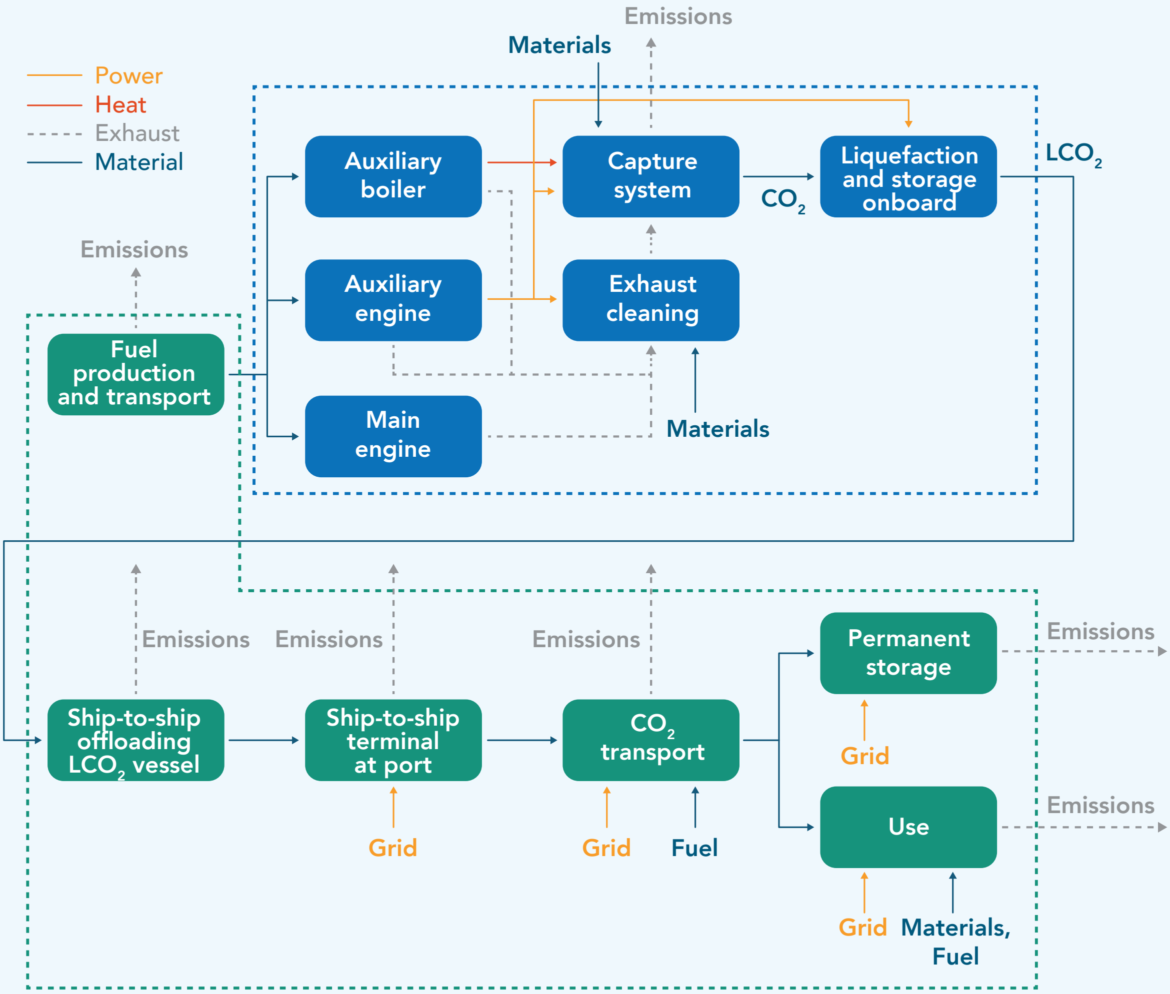


Figure 3.2 – LCA boundaries of captured CO_2 value chain that liquefy CO_2 onboard vessel with a cradle-to-grave approach

As the results of the LCA depend on the assumptions made for the considered systems, this study assessed the GHG impact of OCCS considering different scenarios for some of the most important parameters, more specifically:

- The OCCS technology
- The fuel used by the ship
- The final disposition of the CO_2 and its value chain

The next chapters describe the main assumptions made in the LCA to evaluate the overall GHG emissions of OCCS technology.

3.3 Scenarios and Life Cycle Inventory (LCI)

3.3.1 OCCS technologies

The capture of carbon dioxide onboard ships can be performed with different technologies, depending on the capture method (absorption, adsorption, separation). Absorption-based methods use liquid solvents that bind to CO_2 through chemical reactions. CO_2-saturated solvents are subsequently treated by raising the temperature and reducing the pressure to separate the carbon dioxide and regenerate the liquid solvent, which is then reused in the capture process. Amines such as MEA are the most commonly used chemical solvents, as they have a high CO_2 capture rate. However, the process requires high amounts of heat to regenerate the amine for reuse. Amine-based absorption is currently the most commercialised type of capture and is, therefore, considered the most viable option for onboard ship applications. Solid absorption involves instead the chemical binding of CO_2 to a solid material to obtain stable and low-toxicity materials such as carbonates. While this technology is less mature compared to amine-based absorption, it was nevertheless included in the analysis due to increased interest towards this alternative capture method for marine applications.

Five different technology pathways were considered (Figure 3.3):

1. MEA capture with CO_2 liquefaction onboard
2. Advanced amine capture with CO_2 liquefaction onboard
3. MEA capture with CO_2-rich amine offloading and onshore regeneration
4. Alkaline CC with storage in calcium carbonate ($CaCO_3$) and discharge in the sea
5. Calcium looping with onshore regeneration of quicklime (CaO) for reuse onboard

The baseline fuel considered for the OCCS technology is HFO; therefore, a seawater scrubbing system had to be considered in all the scenarios in order to minimise sulphur and other pollutants, which decreased the capture efficiency. The only energy source onboard is the fuel; hence, the extra energy required for capturing and liquefying the CO_2 must come from burning additional fuel in the auxiliary engine and the auxiliary boiler. From an LCA perspective, it is crucial to identify some key parameters of the capture system, such as energy and material flows required to capture and liquefy the CO_2. Inventory data for LCA of onboard amine capture were based on Project REMARCCABLE, which included the design of a capture system onboard a tanker ship[13] (see Appendix). The capture was modelled considering a fixed 90% efficiency of separation of CO_2 from the treated flow. Different gross capture rates are achieved by acting on the fraction of the exhaust gas sent to the capture system with the corresponding sizing. It is important to note that this is an instantaneous condition of a design operation (steady state) for which the engine is running at a constant speed, with the OCCS system treating a fixed amount of exhaust gas, capturing a fixed gross amount of CO_2. This is different from Project REMARCCABLE, which considers an annualised operational profile (dynamic state). Data for alkaline CC and calcium looping were based on recent projects and literature studies. For the purpose of comparing capture technologies, the energy used for offloading was not considered because of the variability in the offloading methods, which are not standardised.

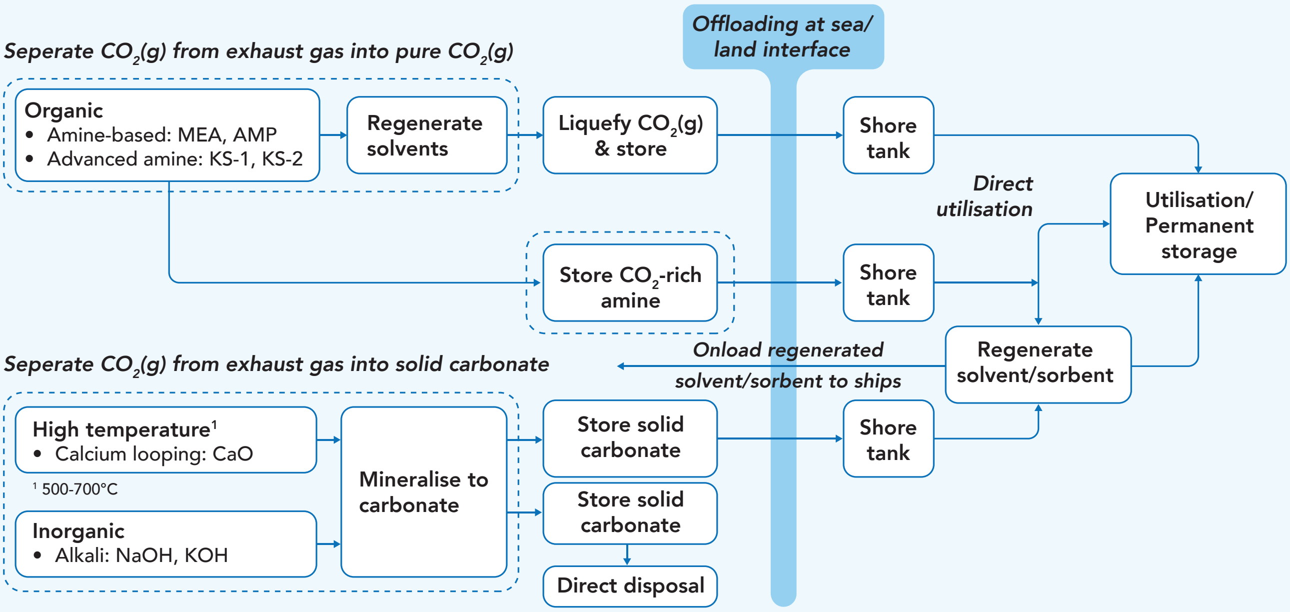


Figure 3.3 – OCCS pathways (Source: GCMD)

MEA capture with CO_2 liquefaction onboard

The MEA-based CO_2 capture was modelled with data available from Project REMARCCABLE (see Appendix), which considers the application of this capture method on an MR tanker that runs on HFO for the main engine and marine gas oil (MGO) for the auxiliary engines (Figure 3.4). The exhaust gas coming from the engine is first treated with a seawater SOx scrubber to remove pollutants that could deactivate the solvent. Subsequently, the exhaust gas is conveyed through the carbon capture system that removes the CO_2, which is then liquefied onboard with a refrigeration system based on the ammonia cycle. Finally, CO_2 is stored in onboard tanks and then offloaded at the port hub.

From a GHG life cycle perspective, it is important to define the energy requirements of each subsystem and the input/output material flows, as shown in Table 3.1 and Figure 3.5. The GHG burden of the materials used to build the plant was also included in the analysis (Table 3.2). The energy input required to run the carbon capture is related to the power consumption of the electrical equipment (i.e., pumps and compressors) and the heat provided to the reboiler (in the form of steam produced by the auxiliary boiler), which is necessary to strip the CO_2 out of the amine. Since the energy source onboard the ship is mainly fuels, the energy input of the OCCS system translates into extra-fuel consumption, which must be evaluated in the overall GHG balance. The overall heat requirement of the reboiler is 3.5 GJ/tCO_2 captured, which is reduced by 34.5% thanks to the heat recovery system installed onboard. Scrubbing requires generally 1-2% of the engine power[14].

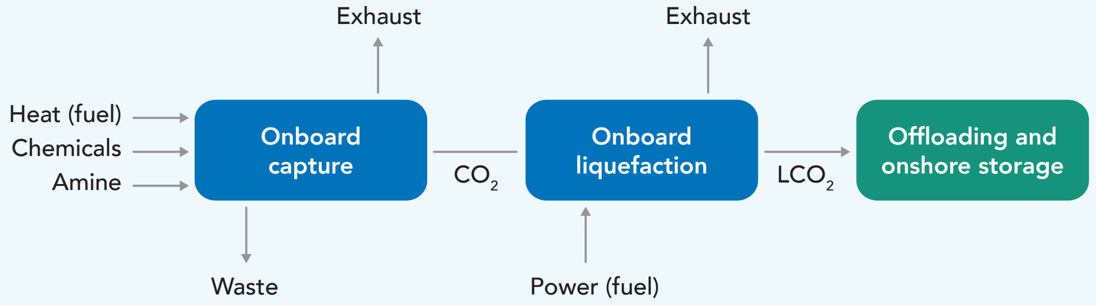


Figure 3.4 – MEA-based onboard CO_2 capture process (MEA capture scenario)

Table 3.1 – Main energy and materials flow of the OCCS system

Input	Amount	Unit
Electricity for scrubbing	29	kWh/tCO_2
Electricity for CC	39	kWh/tCO_2
Electricity for liquefaction	117	kWh/tCO_2
Net heat at the reboiler	2.3	GJ/tCO_2
MEA	1.5	kg/tCO_2
NaOH	0.16	kg/tCO_2
Activated carbons	0.06	kg/tCO_2
Output	**Amount**	**Unit**
Reclaimer waste	2.9	kg/tCO_2

The chemicals used in the process include the make-up of the amine, which is required due to its progressive degradation from contaminants in the exhaust. The system contains around 9 m^3 of amine/water solution at 30% amine concentration, which is replaced every six months of ship operation. Data from Project REMARCCABLE were compared with available literature data and inputs from the industry survey[15–18], and an average value of 1.5 kg MEA make-up for each tonne of CO_2 captured was defined. Additional material requirements include activated carbons to absorb degradation products of MEA and caustic soda (NaOH) to promote the regeneration of MEA from heat-stable salts in the reclaimer[16]. The process generates waste, which is mainly degradation products (thermal and oxidative) from the capture. Amine waste is hazardous and requires proper treatment[15,19]. The process of incineration of hazardous waste was selected from the ecoinvent database. Efficiency of onboard power generation and boiler efficiency were set at 49% and 80%, respectively. The materials required to build the plant usually have a negligible impact on the overall life cycle of captured CO_2[20]. However, the values were calculated based on available literature in order to verify the relative impact[21,22]. The ecoinvent database and literature data were used to determine the GHG burden related to the different results, as shown in Table 3.3.

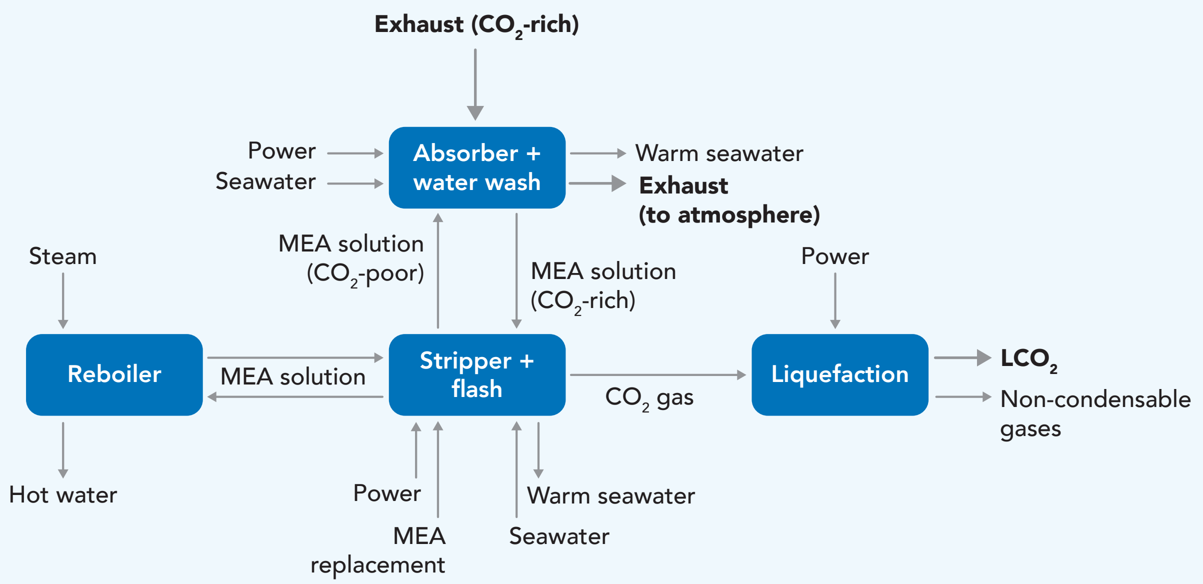


Figure 3.5 – LCA model structure for onboard capture and liquefaction systems

Table 3.2 – Input materials for scrubbing and CC equipment

System	Material input (t)
Scrubber	
Steel	0.5
Black steel	28
Stainless steel	11
Glass reinforced epoxy (GRE)	13
Copper	1.2
Carbon Capture (CC) system	
Stainless steel	254
Polyethylene	138
Concrete	3

Table 3.3 – GHG burdens of chemicals and materials

Input	Amount	Unit
MEA solution 30%	0.608	$kgCO_2/kg$
Sodium hydroxide	1.29	$kgCO_2/kg$
Activated carbons	3.33	$kgCO_2/kg$
Reclaimer waste (treatment)	2.7	$kgCO_2/kg$ waste
Scrubber plant	0.811	$kgCO_2/tCO_2$
Carbon capture plant	7.7	$kgCO_2/tCO_2$
Fuel WtT (HFO)	0.599	$kgCO_2/kg$ fuel
Fuel TtW (HFO)	3.114	$kgCO_2/kg$ fuel

Advanced amine capture with CO_2 liquefaction onboard

MEA scrubbing is the state-of-the-art technology used to remove CO_2 from flue gas. However, MEA-based capture systems have high energy requirements. Significant research has been implemented to improve amine chemicals, and novel solvents are available on the market[23]. Advanced amine processes use novel solvent formulations and plant configurations that can significantly reduce the energy required by the capture process, which ultimately leads to higher efficiency in terms of energy consumption and lower waste production. The advanced amine system was modelled based on the MEA CC system, with improved performances, as shown in Table 3.4.

Table 3.4 – Advanced amine parameters[24]

Parameter	MEA	Advanced	Unit
Solvent loss	1.5	0.3	kg/tCO_2
Reboiler heat	3.5	2.6	GJ/tCO_2

MEA capture with CO_2-rich amine offloading and onshore solvent regeneration

Another available option is to store the CO_2-rich amine onboard and offload it at the port (Figure 3.6). In this way, the CO_2 stripping and liquefaction steps can be carried out onshore with the advantage of reducing the GHG impact of energy use if low-carbon energy sources are available. Indeed, while onboard, the only available energy source is the fossil fuel burned in the engines; onshore, the energy can be sourced from different origins, including the use of renewable electricity and heat. This solution can likely be applied only for short trips and low-power ships due to the higher volume required to store CO_2 in the form of an amine solution. The energy sources used for onshore operations and their carbon factor are summarised in Table 3.5.

Table 3.5 – Carbon factor of different onshore energy sources (Source: ecoinvent; 2023 data for Singapore grid emission factor)

Energy source	Carbon factor
Electricity	
Singapore grid	0.412 $kgCO_2/kWh$
Norway grid	0.027 $kgCO_2/kWh$
Heat	
Sugarcane bagasse	2.2 $kgCO_2/MJ$
Natural gas	74 $kgCO_2/MJ$

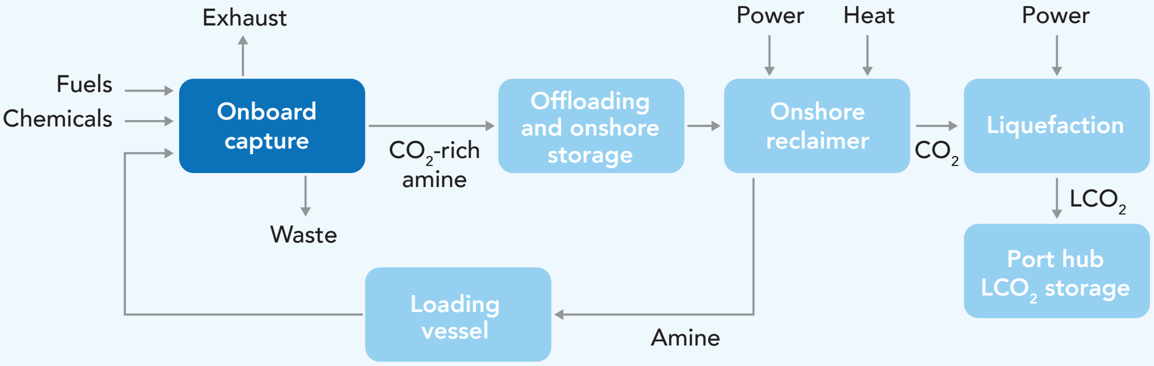


Figure 3.6 – MEA-based onboard CO_2 capture with onshore solvent regeneration (amine offloading scenario)

Alkaline CC with storage in calcium carbonate ($CaCO_3$) and discharge in the sea

This system is based on CO_2 reaction with quicklime (CaO) in a carbonator reactor to produce limestone carbonate material, followed by the discharge of $CaCO_3$ into the sea (Figure 3.7). The reaction occurs at high temperatures (600°C) and is exothermic; therefore, does not require additional heat. The power consumption is also relatively low as there are no compressors and pumps involved, and the only electricity required is due to the handling and movement of the materials. However, there is a high material consumption since the carbonate is discharged at sea, and new CaO must be continuously fed to the system. Sodium hydroxide (NaOH) is also required for the reactions. However, it can be recycled with a makeup set at 5%. The overall material and energy requirements are summarised in Table 3.6. The effects of alkalinity improvement of seawater were not included in the analysis[25,26]. Heat recovery options onboard were not considered in this analysis. Based on ecoinvent data, the GHG burden related to the production of CaO and NaOH is 1.19 $kgCO_2/kg$ and 1.27 $kgCO_2/kg$, respectively.

Table 3.6 – Material and energy flows for onboard alkaline CC system[24,27,28]

Input	Amount	Unit
Electricity	7.3	kWh/tCO_2
Quicklime (CaO)	1.27	kg/kgCO_2
Caustic soda (NaOH)	0.014	kg/kgCO_2
Output	3.33	kgCO_2/kg
Limestone ($CaCO_3$)	2.27	kg/kgCO_2

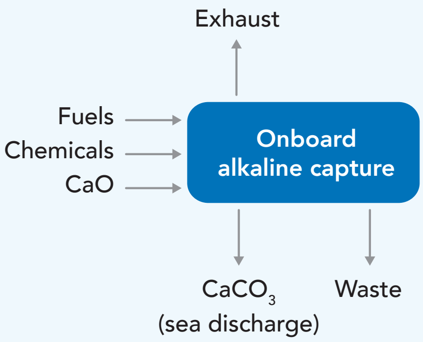


Figure 3.7 – Alkaline-based onboard CO_2 capture with storage in $CaCO_3$ and sea discharge (alkaline capture scenario)

Calcium looping with onshore regeneration of quicklime (CaO) for reuse onboard

Carbon capture with a calcium looping system involves the alkaline reaction of CO_2 in the flue gas with CaO to produce $CaCO_3$ (Figure 3.8). Unlike the alkaline CC system with sea discharge, the carbonate is stored onboard and offloaded at port. The $CaCO_3$ is later processed into an onshore calciner, which requires high-temperature heat to extract CO_2 and regenerate CaO for reuse onboard ships.

The onboard process is modelled as per the previous scenario, while the onshore process energy and material requirements are taken from the literature. The makeup flow of fresh $CaCO_3$ must be continuously fed into the calciner to compensate for sorbent deactivation. Oxygen is required for the reaction and is obtained with an Air Separation Unit (ASU). Liquefaction of CO_2 also occurs onshore. The overall material and energy requirements are summarised in Table 3.7.

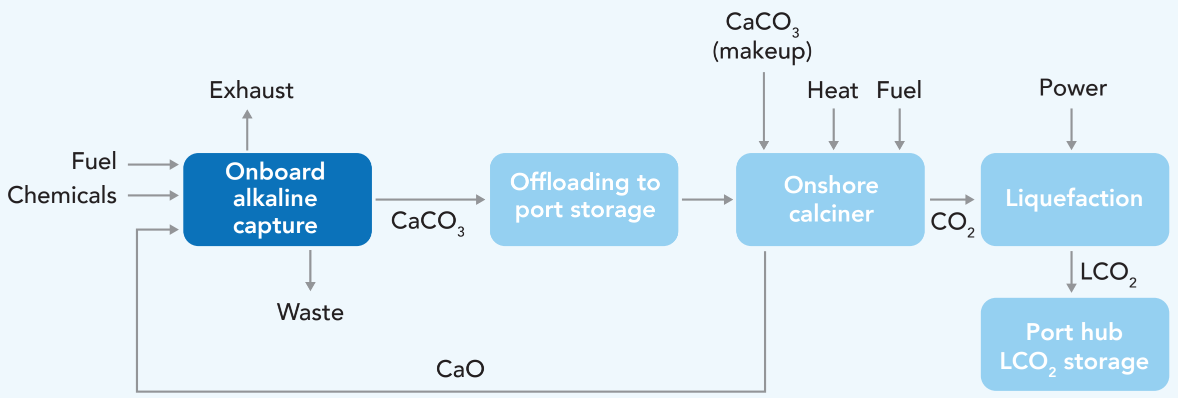


Figure 3.8 – Onboard CO_2 capture with calcium looping and onshore CaO regeneration (calcium looping scenario)

Table 3.7 – Material and energy flows for onshore calciner and CO_2 liquefaction[24,29–31]

Input	Amount	Unit
Electricity (ASU)	68	kWh/tCO_2
Electricity (liquefaction)	93	kWh/tCO_2
Heat	5	GJ/tCO_2
$CaCO_3$ (makeup)	0.1	$kg/kgCO_2$
Output	3.33	$kgCO_2/kg$
$CaCO_3$	2.27	$kg/kgCO_2$

3.3.2 Fuels

The post-combustion OCCS systems act on exhaust gas, therefore, it can be applied to a variety of ships that run on different marine fuels. In order to provide a broad evaluation of overall GHG emission reduction that can be achieved in shipping by adopting CO_2 capture technology, the analysis included the comparison of the emissions savings related to the use of different fuels with respect to the conventional diesel baseline. Four different fuel scenarios were considered in the LCA, for an MEA capture system: HFO with scrubbing; fossil LNG; fossil methanol; biofuels (biodiesel, bio-LNG, biomethanol). Because amine solvents are susceptible to sulphur poisoning, the flue gas that enters the OCCS system must be scrubbed to reduce sulphur content down to single-digit ppm levels. Therefore, the combustion of HFO requires scrubbing to clean the exhaust, while flue gas from cleaner fuels such as LNG and methanol can, in principle, be treated with carbon capture without pre-treatment.

HFO

This scenario is the baseline CO_2 capture scenario evaluated in the previous chapter (Figure 3.5), based on the Project REMARCCABLE OCCS system, which includes seawater scrubbing of the exhaust, amine absorber and stripper, onboard CO_2 liquefaction and storage of CO_2 in insulated tanks at 20 bar pressure.

Fossil LNG

From a technical perspective, LNG-fuelled ships offer high compatibility with carbon capture systems due to a few advantages over HFO-fuelled vessels. The presence of a free heat sink related to the regasification of LNG provides a reduced energy requirement for the reboiler (Figure 3.9). Up to 50% capture rate from heat recovery could, in principle, be achieved with efficient system design onboard LNG ships[32]. Moreover, LNG contains very low amounts of sulphur, and the exhausts are relatively clean and low in impurities such as SOx and particulate, which could degrade the amine solvent. Thus, no exhaust pre-treatment is required, further reducing space and energy demands. In addition, the use of LNG alone (without CC) already provides more than 20% GHG emissions savings compared to HFO and adding CO_2 capture can only increase the environmental benefits[33]. Studies have shown that the cost of captured carbon on LNG ships is about 20% lower compared to HFO, with almost half of the CAPEX cost[34,35]. Considering an 82% capture rate, LNG design leads to a lower fuel penalty compared to HFO, depending on ship type and route profile. For a large crude carrier, CO_2 capture of LNG exhaust requires 20% additional fuel consumption, compared to 41% of fuel oil case[36]. The LCA model of LNG configuration was based on the HFO configuration, with reduced energy requirements based on existing studies, as shown in Table 3.8.

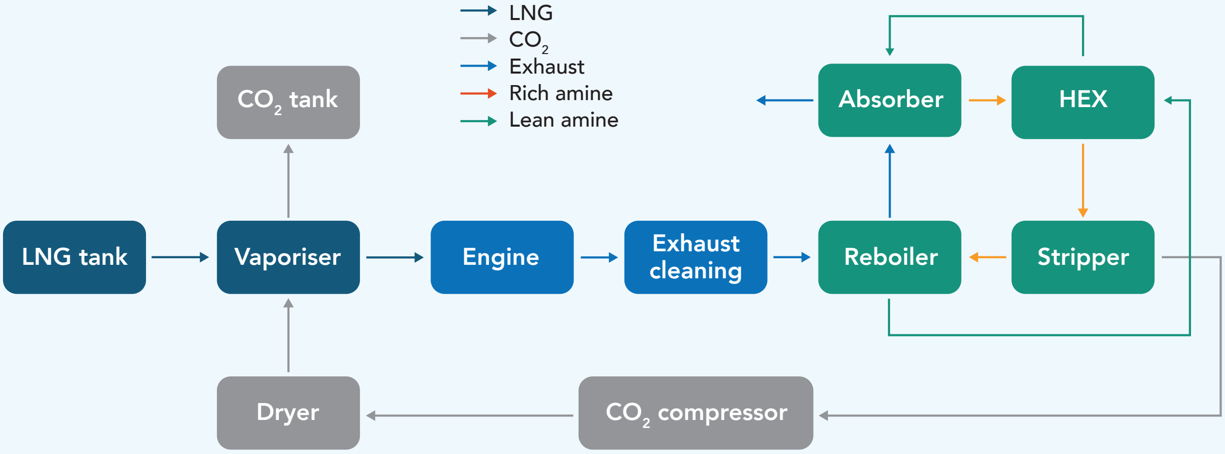


Figure 3.9 – Example of OCCS system onboard an LNG ship (adapted from[37])

Table 3.8 – Parameters for OCCS on LNG ships[37,38]

Input	Variation from HFO + OCCS system	Amount	Unit
Electricity (scrubber)	-100%	0	kWh/tCO_2
Electricity (liquefaction)	-40%	70.2	kWh/tCO_2
Reboiler heat	-20%	1.84	GJ/tCO_2
Heat recovered from exhaust	-5%	30	% of reboiler duty

Fossil methanol

Methanol contains no sulphur, and its combustion produces limited nitrous oxides. Similarly to LNG, its flue gas is relatively clean and ready for CC without needing a scrubber. However, since there are no heat sinks in a methanol-fuelled ship, a carbon capture system will require a complete CO_2 liquefaction onboard. Moreover, methanol is a refined fuel that has slightly higher WtT GHG emissions than HFO. The resulting WtW CO_2 emission of methanol is higher when compared to conventional diesel production, with an average of 100 gCO_2eq/MJ compared to the HFO baseline of 93.3 gCO_2eq/MJ[3] (Figure 3.10). CO_2 avoidance cost is expected to be slightly lower than for HFO-fuelled ships[35].

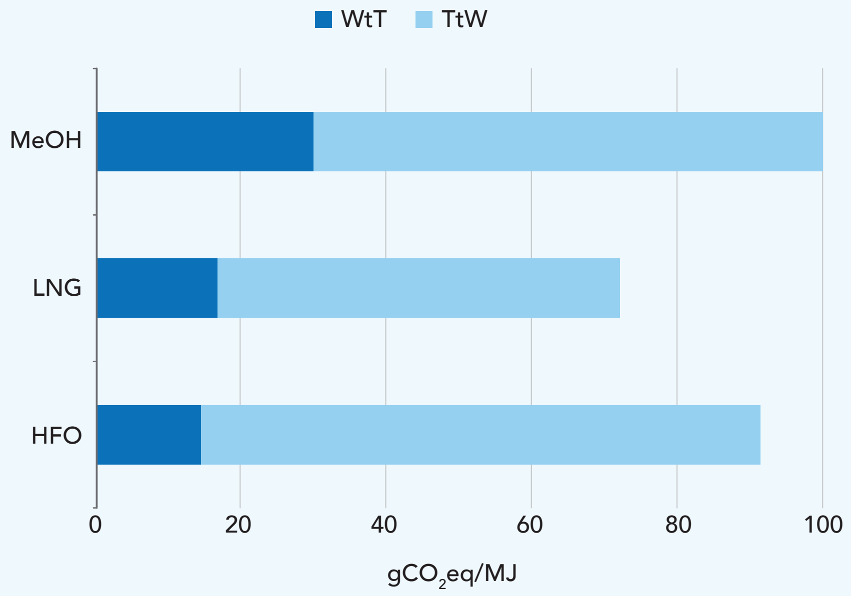


Figure 3.10 – WtW GHG emissions of analysed fossil marine fuels[3]

Biofuels

The use of biofuels in marine engines provides significant GHG emissions savings, depending on the biomass source and fuel production method (Figure 3.11). The combination of biofuel and carbon capture can achieve major GHG reduction and even negative emissions (if the capture rate is sufficiently high). Biodiesel is available and can be blended with fossil diesel to achieve sufficient GHG emissions savings and meet IMO targets with low capture rates. This study includes the evaluation of the overall GHG emissions of OCCS applied with different biodiesel blends (B24, B30, B50 and B100), bio-LNG and biomethanol, adapting the LCA model used for fossil fuels with different WtW GHG emission values of biofuels.

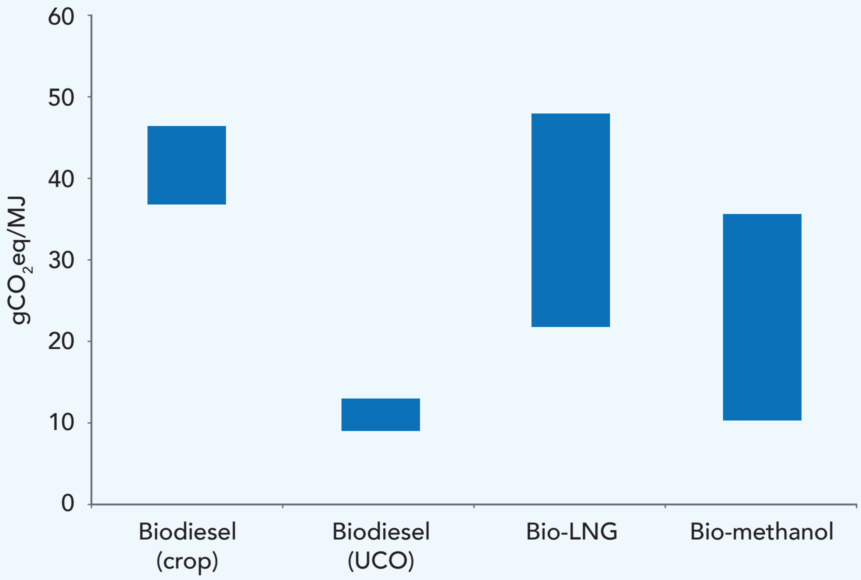


Figure 3.11 – WtW GHG emissions of analysed biofuels (values for biodiesel are taken from RED II)[39–41]

3.3.3 CO_2 transport and permanent storage

Transportation of LCO_2 is required to move the captured CO_2 to either permanent storage or to the manufacturing plants as part of the utilisation pathway. Among the typical transportation options are pipeline, ship, railway or truck. Figure 3.12 shows two possible pathways from GCMD's concept study on LCO_2 offloading[42]. From the study, "Concept 2" considers Ship-to-floating CO_2 storage via an intermediate LCO_2 receiving vessel, while "Concept 3" considers Ship-to-liquid bulk terminal via an intermediate LCO_2 receiving vessel. It is envisaged that the onboard captured CO_2 will be unloaded to a receiving vessel, which will then be directly offloaded to the closest storage terminal or shipped via an LCO_2 carrier to a storage facility at a port farther off. From this intermediate storage step, the carbon dioxide can then be transported through a pipeline to a permanent storage site (reservoir) or trucked to a manufacturing plant where it is used for fuel/material production. The GHG emissions associated with the transport of CO_2 are mainly from the energy required to move and pump the liquefied gas and to re-liquefy the boil-off. Transport by large pipelines is by far the most efficient way of moving CO_2 from one place to the other for short distances (<500 km)[43], with very low fugitive emissions and low-pressure drops.

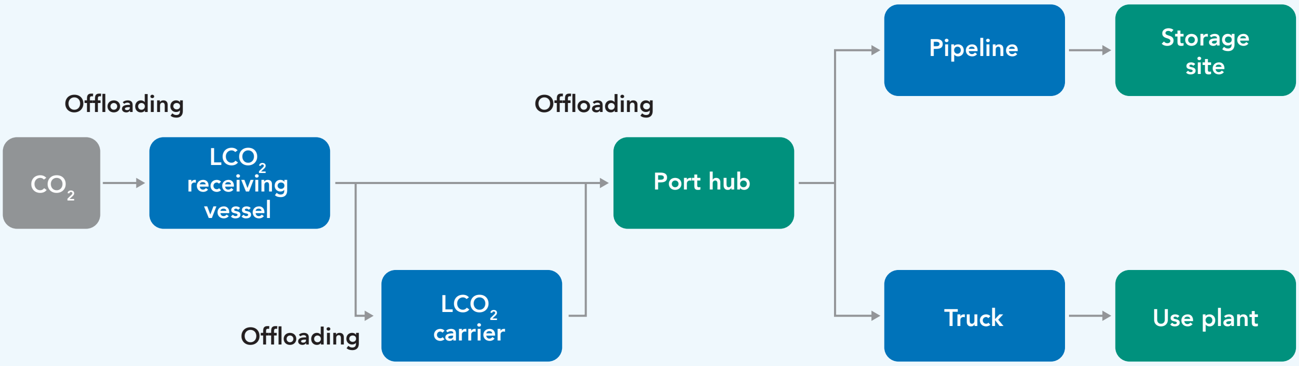


Figure 3.12 – LCO_2 transportation scheme (adopting concepts 2 and 3 of GCMD study on onboard captured CO_2 offloading)[42]

The main source of emissions for pipelines is related to the energy required for pumping to raise the pressure of LCO_2 from intermediate transport and storage pressures to supercritical conditions, i.e., above 74 bar for injection into the reservoir. For offshore pipelines, CO_2 transport pressure range is 120-180 bar[44]. Transporting pressurised liquid CO_2 by cargo ship is a viable option for longer distances (>500 km)[45] but will have higher GHG emissions due to fuel consumption and energy required to balance the boil-off. In the case of volumes ranging from 10-35 kt, CO_2 is preferably kept liquefied at medium pressures (15-20 bar) and moderately low temperatures (-29°C to -20°C)[13,46], and the constant heat exchange with the environment causes some carbon dioxide to evaporate, increasing the pressure inside the storage tank of the vessel. BOG must then be re-liquefied along the journey. Daily boil-off rates for LCO_2 carriers are typically around 0.12-0.15% for 15 bar pressure[47], which means that during a 30-day intercontinental journey, around 4-6% of the total transported CO_2 evaporates, depending on the storage pressure[48]. Truck transport has the highest GHG impact of all transport methods and, thus, should be used only for short distances (Figure 3.13).

The SimaPro model transport-related assumptions are:

i. Ship: A 10,000 DWT vessel with an empty return trip. Reliquefaction of BOG is powered by onboard diesel generators and onshore grid power. The average boil-off rate was set at 0.15%/day.
ii. Truck: Large tank (>20 t); fully loaded and with an empty return trip.

iii. Offloading: Liquid CO_2 pumps; the energy consumption was estimated based on existing equipment and literature data, as shown in Table 3.9.
iv. Pressure management: It is assumed that CO_2 is kept at medium pressure along the journey, with an increase to supercritical pressure when using pipeline with subsequent injection into reservoir for permanent storage.
v. Purity management: The purity level of captured CO_2 was considered compliant with requirements for transportation and its final storage or end-use manufacturing. Therefore, no additional GHG emissions are accounted for since no purification step is required along the value chain.
vi. Fugitive emissions: Deemed to be quite low along the value chain as they are usually linked to valves, tank purges and transport operations. Based on IPCC guidelines, less than 0.1% of the CO_2 is lost as fugitive emissions[18,49].

Table 3.9 – Liquid CO_2 pumping energy requirements and pressure stages[18,50–53]

Input	Variation	Unit
Medium pressure (MP)	20	bar
Supercritical pressure (SP)	120	bar
Offloading energy at MP	0.1	kWh/tCO_2
Pumping from MP to SP	7	kWh/tCO_2

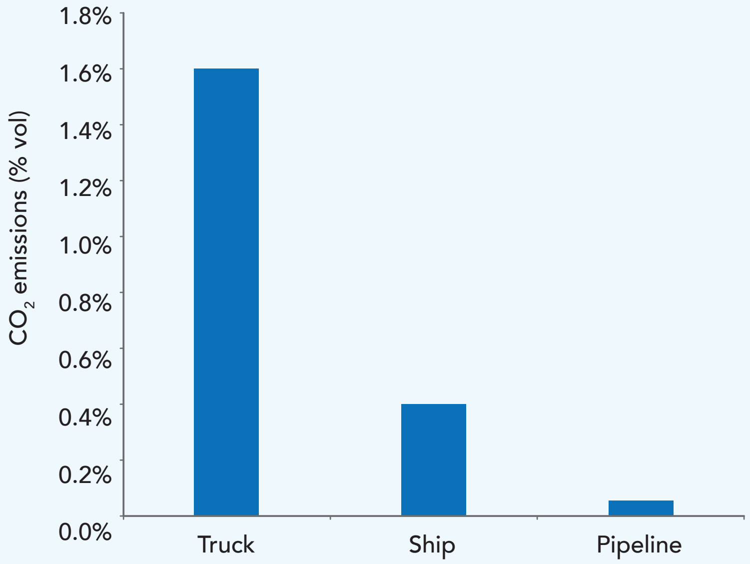


Figure 3.13 – Estimated CO_2 emissions due to the transport of CO_2 for 200 km by different transport methods, expressed as % of transported volumes[48]

3.3.4 CO_2 final disposition

Considering applicability, level of interest, market volume of products, and CO_2-storing potential, this study focused on three disposition pathways for CO_2:

i. Scenario 1: Permanent storage in underground reservoir (CCS)
ii. Scenario 2: Production of CO_2-cured concrete (CCU)
iii. Scenario 3: Production of e-fuel (CCU)

Scenario 1 - Permanent storage in reservoir (CCS)

In this scenario, the CO_2 is transported from the hub terminal to the injection wells offshore through a dedicated pipeline. There are several CCS demonstration projects worldwide; among them, the ARAMIS and Northern Lights projects were considered as case studies (Figure 3.14). Both scenarios consider the capture of CO_2 produced by a container vessel during a route from Port of Zhoushan (CN) to Port of Rotterdam (NL). For the ARAMIS project scenario, the CO_2 is collected in an intermediate hub located in Rotterdam port and subsequently transported by pipeline for 200 km to an offshore reservoir, where it is injected and sequestered. Northern Lights is a CO_2 long-term storage project for which the reservoir is located offshore in Øygarden port, Norway. In this scenario, the CO_2 is transported by an LCO_2 carrier for 1,000 km from Rotterdam to Øygarden and unloaded to the intermediate storage terminal, which is connected through a 100 km pipeline to the injection wells, where the CO_2 is offloaded into the reservoir at 200-300 bar pressure.

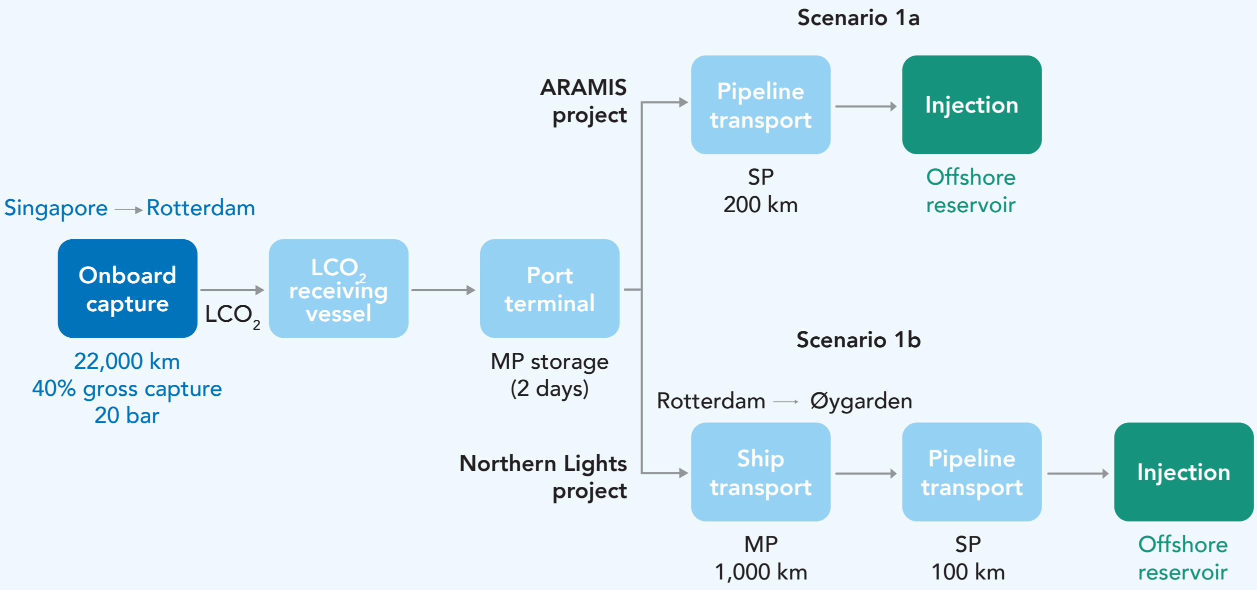


Figure 3.14 – CO_2 final disposition scenario 1 (CCS), with the pathways corresponding to different CO_2 injection sites

Life cycle emissions were evaluated based on the ecoinvent database, literature data, and the LCA of the Northern Lights project (Table 3.10), which assessed the CO_2 transport and storage operations over an estimated project lifetime of 25 years. It was estimated that for 128 Mt of total CO_2 stored, about 300 kt of CO_2 will be emitted due to storage operations, including power consumption for injection, auxiliary operations and plant construction (excluding shipping). This is equivalent to 2.3 kgCO_2/tCO_2 stored (0.2%). Life cycle emissions for scenario 1 were based on Northern Lights estimations, considering a calculated energy consumption for injection of 15 kWh/tCO_2. In the case of injection sites located in different areas of the world, the emissions are adjusted according to the local grid carbon emission factor.

Table 3.10 – LCA GHG emissions of Northern Lights CCS operations

Emissions category	kgCO_2/tCO_2(stored)
Electricity consumption (injection)	0.4
Site construction	1.2
Decommissioning and other processes	0.7

Scenario 2 – Production of CO_2-cured concrete (CCU)

In this scenario, the CO_2 is captured onboard a ship that travels from Port Hedland (AU) to Zhoushan (CN) and is then offloaded at the destination port, where it is transported through a 200 m pipeline to an intermediate storage. From here, the CO_2 is loaded and transported by truck to the concrete production plant, located 100 km from the port hub (Figure 3.15).

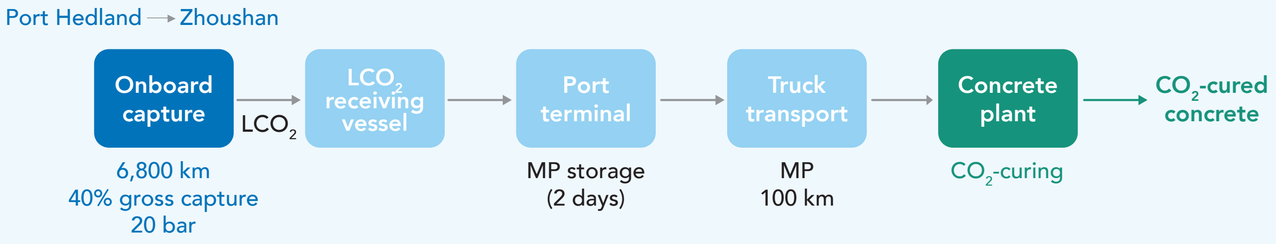


Figure 3.15 – CO_2 final disposition scenario 2 (CCU with concrete production)

CO_2 can be utilised as a curing agent to accelerate precast concrete fabrication. Curing is an important process in concrete construction that controls moisture loss and increases material strength. Carbon dioxide reacts in a carbonation reaction with calcium or magnesium to form carbonate compounds that make up the concrete. This represents one of the most mature pathways to convert CO_2 into a stable and marketable product. This process can reduce manufacturing costs as well as help to reduce the carbon footprint of concrete production, which is a carbon-intensive process. Although there are several companies that are investing in this technology, the lack of publicly available data leads to a difficult assessment of the emissions reduction benefits from the reduced input of cement required to produce concrete. However, some detailed LCA studies of cured-concrete production have been published, estimating the GHG emissions saved compared to the conventional process for different types of concrete. Typically, around 20-60 kg of CO_2 is stored in 1 m^3 of concrete[54]. Depending on the process parameters and the type of concrete, up to 10-30% GHG emissions savings can be achieved, as cement is responsible for about 90% of the GHG emissions of concrete production[55]. Table 3.11 shows the amount of GHG emissions savings achieved with CO_2-curing processes compared to conventional steam-cured concrete production. CO_2 savings vary with different cement types, i.e., binding material, as they have a distinct GHG footprint. Ordinary Portland Cement (OPC) type was selected as a reference case for this analysis, for which each kg of CO_2 stored in the final cured product provides 0.9 kg of GHG emissions savings compared to the conventional process that uses steam as a curing agent instead of CO_2.

It is important to note that many studies assume that CO_2-cured concrete has similar properties to conventional concrete. However, more recent studies highlight that a decrease in the compressive strength of the material is often the result of the CO_2-based carbonation process in concrete production; therefore, when taking this factor into account, the net CO_2 balance of the concrete can be positive, i.e., leads to increased emissions compared to the conventional process[54,56]. When compressive strength of the material is used as a criterion for comparison (i.e., 1 MPa), the CO_2-curing process may also increase the overall GHG emissions compared to conventional concrete production since a greater mass of binder (cement) is required to achieve the same compressive strength. Companies often claim to achieve carbon uptake with the same strength as conventional cement. However, process data are lacking, and it is difficult to substantiate these claims. While performance-based standards and regulations have not yet been developed, non-structural applications of concrete for which mechanical strength is not a critical requirement (i.e., road construction) should be considered as the main market for the initial development of this technology.

Table 3.11 – Amount of CO_2 avoided in the production process of different CO_2-cured concrete products compared to conventional steam-cured concrete, depending on the cement binder material. Values were calculated for the production of 1 m^3 of concrete[57].

Concrete type by binder	Curing agent	Acronym	$kgCO_2$(avoided)/ $kgCO_2$(stored)
Portland Cement Block (conventional process)	Steam	OPC	-
Portland Cement Block	CO_2	OPC	0.9
Wollastonite-Portland Cement Block	CO_2	WPC	1.9
MgO-Portland Cement Block	CO_2	MPC	0.2
Slag-Portland Cement Block (SPC)	CO_2	SPC	2.8
Calcium Silicate Cement Block	CO_2	CSC	1.5

Scenario 3 – Production of e-fuel (CCU)

Electrofuels (e-fuels) are synthetic fuels produced by combining hydrogen and carbon dioxide to obtain a wide variety of compounds, among which are methanol and methane. These fuels are attractive as they are considered low-carbon fuels with a higher energy density compared to pure hydrogen or ammonia and can be used in several applications, such as marine and aviation transport. Especially the production processes of methanol and methane from CO_2 and H_2 feedstock are mature today, with several commercial plants operating worldwide. With the rise of demand for alternative fuels, these become interesting pathways to convert CO_2 into a valuable product.

To achieve climate benefits, the use of low-carbon energy in the production process of CO_2-based fuels is crucial; however, it is not sufficient alone. While hydrogen can be produced from water by using renewable electricity, the source of CO_2 represents the real issue of this kind of fuel. If sourced from air, by using DAC technology, the resulting fuel can be considered carbon neutral as the cycle of carbon is closed when the fuel is burned and CO_2 returns to the atmosphere. Unfortunately, DAC requires large amounts of energy due to the low concentration of CO_2 in atmospheric air. For this reason, captured CO_2 with a lower cost than DAC-sourced CO_2 becomes attractive for e-fuels generation pathways. If CO_2 is captured from biomass-based power plants (Bioenergy with carbon capture and storage - BECCS), the resulting value chain can be considered carbon neutral as CO_2 was initially absorbed by the plants from the atmosphere during growth. However, if carbon dioxide is captured from fossil point sources, such as power plants or conventional engines, the emission of fossil CO_2 into the atmosphere is not avoided, as the same molecule is used twice by two different users before being released through the exhaust, as outlined in Figure 3.16.

The LCA of scenario 3 was performed considering e-methanol, which is one of the main e-fuels of interest for shipping. Following the scheme of Figure 3.17, the GHG emissions occurring at each step of the value chain are evaluated. The boundary analysis for the LCA is broken into two parts, i.e., the production of the e-methanol and then the use of the e-methanol in a second vessel with a methanol engine without OCCS installed. The e-methanol produced in this way contains fossil carbon; thus, cannot be considered inherently carbon neutral.

Claiming the benefits of the captured CO_2 by different parties, i.e., Ship A with OCCS and Ship B using the resulting e-methanol, is a complex issue. Three different scenarios for the claiming of credits for captured carbon were considered for evaluation:

i. CO_2 credits are claimed by Ship B, therefore Ship A cannot claim any credit for captured carbon.
ii. CO_2 credits are claimed by Ship A, therefore the CO_2 produced by burning e-fuel onboard Ship B is included in its GHG balance as fossil carbon.
iii. The two ships can claim half of the CO_2 credits (shared claiming) calculated on an energy basis, i.e., gCO_2/MJ of fuel burned.
    a. If Ship A captures 1 kg of CO_2 onboard, it can only claim credits for 0.5 kg of CO_2. When Ship B uses e-fuel made from this 1 kg of captured carbon, it is considered to be of '50% fossil' origin.

b. Therefore, Ship B can claim credits equivalent to only 50% to the overall amount of CO_2 produced by combustion of e-fuel in the engines.

The functional unit in this case is the same as for the other scenarios: the grams of CO_2eq emitted per MJ of fuel burned in the engine, which translates into kWh of power to the shaft. The production process of e-MeOH was modelled with a simplified process by considering the methanol synthesis, during which a balanced mixture of CO_2 and H_2 reacts over a catalyst at high pressures (50-100 bar) and moderate temperature (200-300°C) to produce CH_3OH, following the reactions:

$$CO_2 + H_2 \leftrightarrow CO + H_2O$$

$$CO_2 + 3H_2 \leftrightarrow CH_3OH + H_2O$$

$$CO + 2H_2 \leftrightarrow CH_3OH$$

Power is needed to run the equipment, but the process is exothermic; therefore, it does not require external sources of heat. Hydrogen production occurs in a Polymer Electrolyte Membrane (PEM) electrolyser that requires electricity and water. The analysis did not consider the emissions due to plant construction as the most important factor from the LCA perspective is the energy used in the process[40]. Electricity is sourced by wind power and modelled with the ecoinvent database. Hydrogen production occurs at the methanol (MeOH) plant site. MeOH is then transported by truck from the production plant to the port hub. The main parameters used in the LCA are summarised in Table 3.12. The overall emissions are calculated as gCO_2eq/MJ of produced methanol, which represents the GHG burden that it carries when it is burned in Ship B. The combustion of methanol onboard Ship B is modelled considering the same efficiency of diesel engines. This scenario was modeled based on scenario 2, assuming that CO_2 is transported by truck from port to e-fuel production plant, located 100 km from the port hub. The e-MeOH is then transported back to the port hub to be bunkered on the e-fuel ship (Figure 3.18).

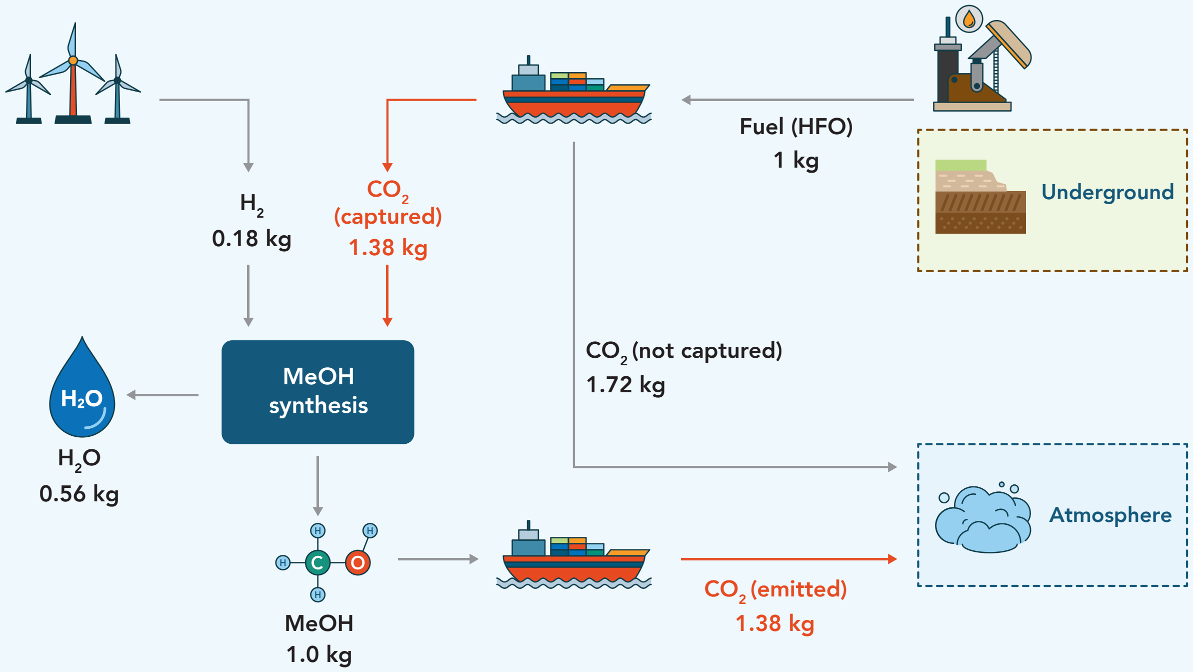


Figure 3.16 – Carbon pathway of onboard captured CO_2 used to produce e-methanol for shipping

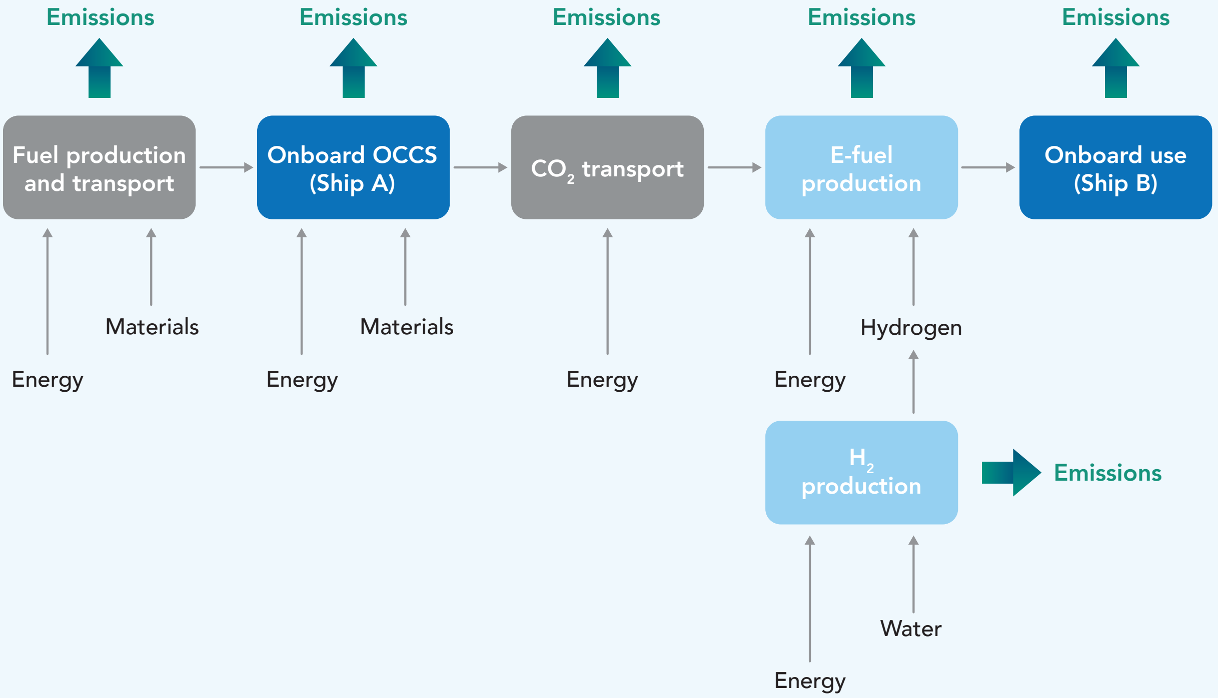


Figure 3.17 – LCA scheme of the e-fuel production and use with CO_2 sourced from OCCS

Table 3.12 – LCA parameters for H_2 and MeOH production and transport[58–60]

Input	Amount	Unit
H_2 production plant size	50	TPD
Electrolyser efficiency	65%	-
MeOH synthesis efficiency	94%	-
H_2 input for MeOH synthesis	0.19	kg/kgMeOH
CO_2 input for MeOH synthesis	1.45	kg/kgMeOH
Electricity input for MeOH synthesis	0.169	kWh/kgMeOH
Fuel LHV	19.9	MJ/kg
MeOH transport distance	100	km
TtW GHG emissions (MeOH)	69.4	gCO_2eq/MJ
Engine efficiency	49%	-

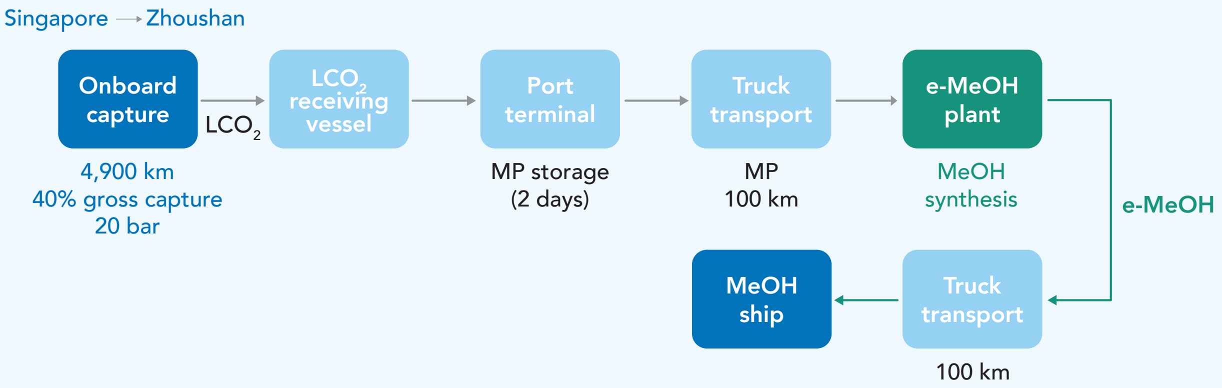


Figure 3.18 – CO_2 final disposition scenario 3 (CCU with e-methanol production)

4. LCA results

4.1 Net WtW emissions of OCCS

This section presents the analysis of the net WtW GHG emissions of OCCS technology, focusing on the often-overlooked emissions due to the production of fuel, chemicals and materials required to build and run the system. While a practical target for onboard gross capture rate is 40%[61], the results shown here are for the maximum theoretical limit of 90% gross capture, which is achievable only by treating all the exhaust gas with OCCS and without considering onboard space constraints. This sensitivity analysis highlights the contribution of the above-mentioned factors to the overall GHG emissions balance.

4.1.1 Onboard TtW vs WtW emissions due to OCCS

The GHG emissions of the OCCS system are due to the additional fuel consumption, the chemicals required for exhaust pre-treatment, carbon capture and the materials used to build the system. The environmental performance of the amine capture system is based on Project REMARCCABLE data, and industry data for a diesel-fuelled ship was evaluated in order to assess the amount of GHG emitted into the atmosphere for each kg of captured CO_2 and to estimate the net emission savings of the system. The results presented in this section refer to the capture and liquefaction of CO_2 onboard without considering the rest of the value chain from CO_2 transport to its final destination (storage or use). The emissions are calculated in grams of CO_2 equivalent emitted into the atmosphere per unit energy of the fuel burned. The values were calculated assuming the same output energy to the shaft.

In the overall emerging discussion on carbon capture onboard ships, the emissions savings are usually presented considering the onboard emissions (TtW), namely the net CO_2 flux in kg/h that is emitted by the main engine and the auxiliary engines and boilers after capture. While this is important as a first assessment of this decarbonisation option, in order to properly compare it with other measures, it is key to expand the boundaries of the analysis outside the ship, including the upstream emissions (WtT). This is especially important as OCCS requires energy to operate and, thus, additional fuel. Therefore, it implies additional energy depletion and GHG emissions that add to the balance. Only the onboard emissions due to the combustion of the fuel can be captured, while the upstream emissions of fuel production remain.

Figure 4.1 shows the amount of net GHG emission savings achieved with OCCS, assuming a 90% gross capture rate, which corresponds to a 41% fuel penalty based on the model of MEA-based carbon capture described in section 3.3.1, compared with baseline emissions considering onboard TtW and WtW GHG emissions. The actual net GHG emission savings for WtW is ~61%, considerably lower than TtW emission savings of ~83% that accounts for upstream emissions as outlined by IMO guidelines on the evaluation of the life cycle GHG intensity of marine fuels[3].

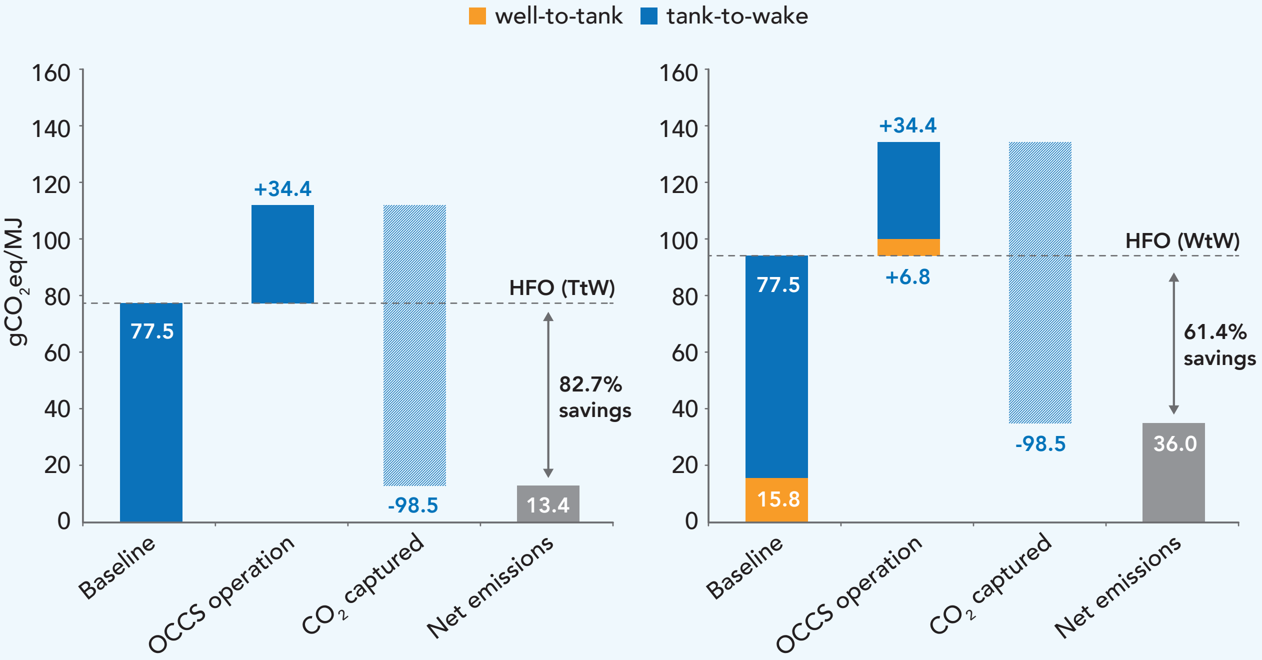


Figure 4.1 – Net onboard TtW and WtW GHG emissions of an HFO-fuelled ship equipped with OCCS (90% gross capture rate, 41% fuel penalty) with a heat recovery system. OCCS emissions include the extra fuel consumption due to the onboard capture and liquefaction of the CO_2, chemicals and materials required for OCCS operation. Baseline represents the GHG emissions due to the vessel operation without OCCS.

4.1.2 Net WtW GHG emissions

The results of the LCA analysis are summarised in Figure 4.2. Baseline emissions are due to the use of fuel for the normal operation of the ship, excluding carbon capture. The emissions due to additional fuel consumed for the CC system are the sum of upstream fuel production and transport emissions as well as the portion of onboard CO_2 emissions, which is not captured. The consumption of amine and other chemicals and the materials required to build the system only have a minor impact on the overall GHG balance, reducing the net GHG emissions savings from 63% to approximately 61%.

Figure 4.2 also highlights the importance of heat recovery for OCCS. The net WtW GHG emissions savings of an OCCS design to capture 90% of the CO_2 in the exhaust drops from ~61% to ~54% without heat recovery. From a fuel penalty perspective, an increase of 41% to more than 60% in additional fuel is required to operate the OCCS system without a heat recovery system, which is unacceptable. The fuel penalty is mainly due to the heat duty of the reboiler needed to strip the CO_2 from the amine.

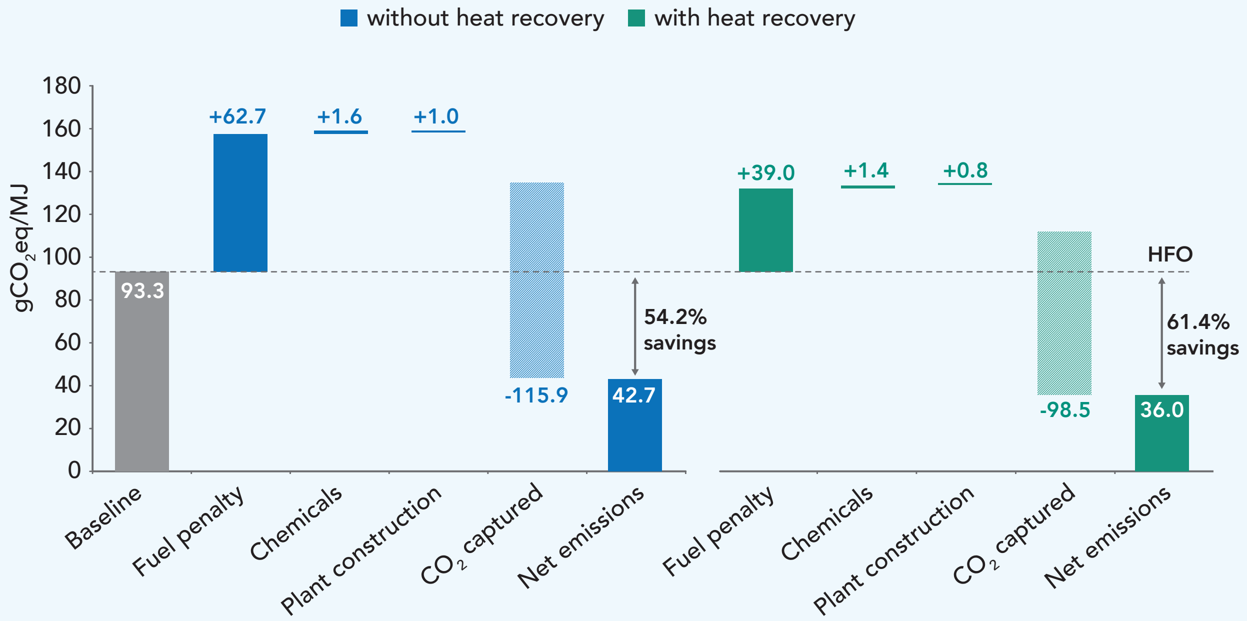


Figure 4.2 – Net WtW GHG emissions of OCCS with and without heat recovery, by category. Gross capture rate is 90%, with all exhaust treated with CC. Baseline represents the GHG emissions due to the HFO-fuelled vessel operation without OCCS.

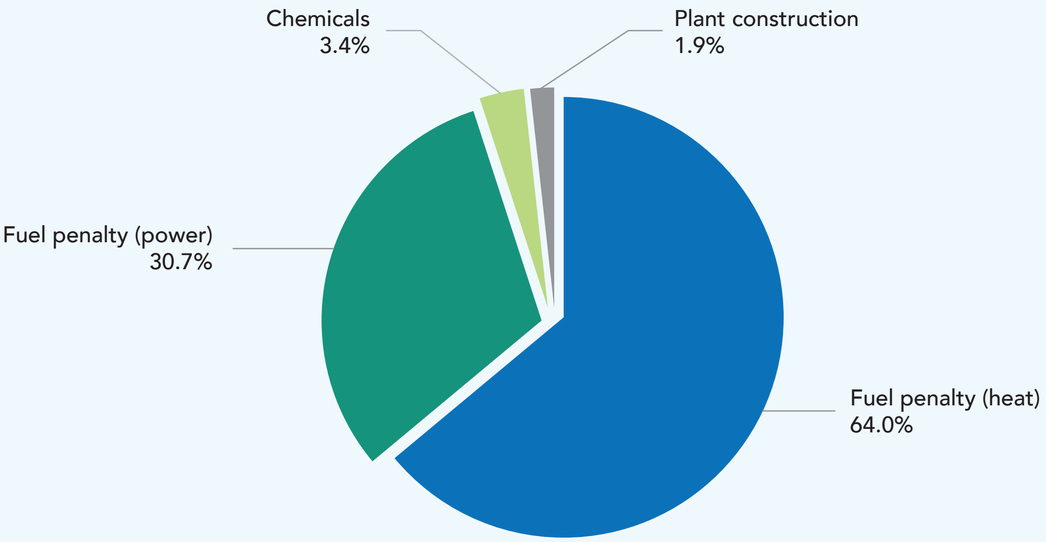


Figure 4.3 – Relative GHG impact of MEA-based OCCS with heat recovery by category

The results highlight the importance of system design and energy efficiency of the capture process in order to minimise fuel penalty and maximise net emission savings. For this reason, the following analysis results are presented considering the heat recovery system that was put in place. In the case study of Project REMARCCABLE, the amount of exhaust gas directed to the capture system is varied and the corresponding overall capture rate decreases.

The CC system keeps working at its design set point of 90% capture of treated exhaust and a variable fraction of the exhaust is sent directly to the atmosphere bypassing the capture system, depending on the operating conditions. In this way, it is possible to reduce material and energy consumption if high capture rates are not required.

In summary, almost 95% of the OCCS system's overall GHG emissions are due to the additional fuel required to run the exhaust cleaning and the CO_2 capture (Figure 4.3). The highest contribution comes from the steam used for the reboiler, which is produced by burning diesel in the auxiliary boiler. Any additional fuel that needs to be produced upstream (WtW emissions) also adds to the fraction of the total CO_2 emissions of the ship, which is not captured, depending on the selected gross capture rate, which is here defined as the amount of CO_2 captured over the total CO_2 released by the engine. A relevant contribution is also due to the production of amine makeup and the treatment of waste. Infrastructure materials used to build the plant make up a smaller, though not negligible, contribution to the overall GHG balance. The results highlight the importance of system design and energy efficiency of the capture process to minimise fuel penalty and maximise net emission savings.

For this reason, the following analysis results consider the full availability of heat from the onboard system using the Nth-of-a-kind model in Project REMARCCABLE. Figure 4.4 shows the fuel penalty and the GHG emission savings related to different overall capture rates. The selected capture rate determines the net GHG emissions savings and the ship's fuel penalty.

While 90% onboard gross capture is theoretically achievable considering the effectiveness of the separation technology, OCCS is constrained by the practical challenges of storing large amounts of captured CO_2 onboard ships. Recent work by members of EGCSA has suggested a practical limit of an average of 40% carbon capture and storage onboard ship[61], which is taken as a reference for the calculations in the following sections.

With a 40% onboard gross capture rate, 28.5% net WtW GHG emissions savings are obtained with a fuel penalty just below 6%. In this case, 44.4% of the exhaust must be treated with the capture system (which is designed for a 90% capture rate of the treated CO_2 flow).

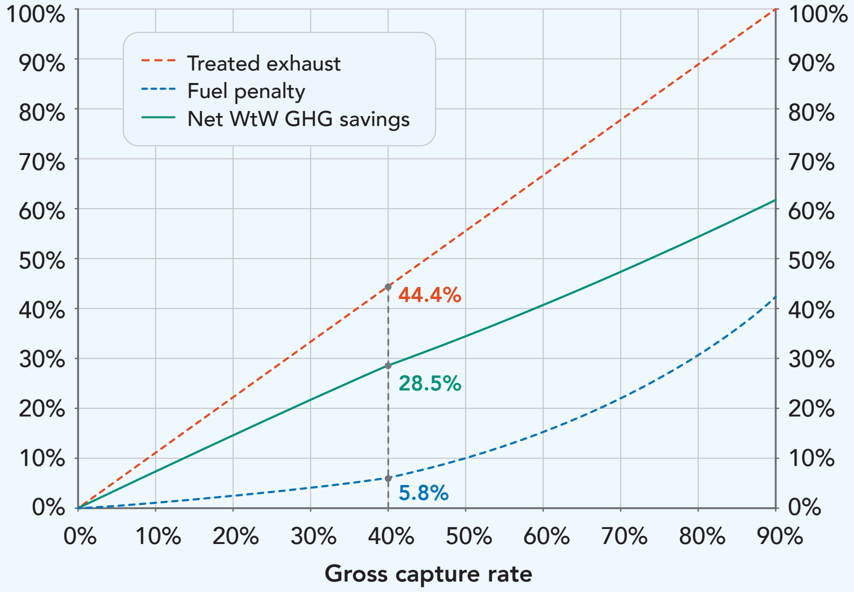


Figure 4.4 – Net WtW GHG emissions savings and fuel penalty with MEA-based OCCS for different gross capture rates, with full availability of heat via recovery system (chemicals and materials required for OCCS operation are included). 40% gross capture rate was selected as the practical limit for OCCS with the corresponding fuel penalty and net GHG emissions savings.

4.2 OCCS technologies

The most mature technology for onboard capture is based on chemical absorption by a solvent. MEA is the most common solvent used today in industry. However, a few advanced patented alternatives have made their appearance in the market. Such advanced amine solvents are more resistant to degradation and allow the capture of CO_2 more efficiently, with reduced material input and energy consumption. Considering an HFO-fuelled ship equipped with an onboard CC system designed to capture 40% of the gross CO_2 in the exhaust, advanced amine has a slightly better environmental performance than MEA-based process (Table 4.1).

The main sources of energy expense for the onboard amine-based capture systems are the heat required to produce the steam for the reboiler and the power for the liquefaction of CO_2. The required energy is produced by burning fuel oil in the auxiliary boiler and engines, producing additional CO_2. One of the ways to overcome the high onboard fuel penalty is to store the CO_2-rich amine solution onboard and offload it at the port, reducing the onboard fuel penalty to regenerate the amine. Low-carbon energy sources can then be used for amine stripping and CO_2 compression and liquefaction in an onshore facility. If low carbon energy is available at the port facility, higher emissions savings can be achieved compared to onboard CO_2 stripping with MEA (31.3% against 28.5% savings). However, if natural gas and grid electricity with high carbon factor are used for onshore MEA regeneration and CO_2

liquefaction, the resulting GHG emissions savings are lower (21.2%) compared to the baseline system with the reboiler onboard (28.5%).

Table 4.1 – Net WtW GHG emissions (in gCO_2 eq/MJ) with onshore emissions related to different onboard capture technologies (40% gross capture rate) compared to HFO baseline (93.3 gCO_2 eq/MJ)

Category	MEA capture	Advanced amine	MEA offloading	Alkaline	Calcium looping
Main engine emissions for ship propulsion (after capture)	62.3	62.3	62.3	62.3	62.3
Fuel penalty for OCC(S) (aux engine + aux boiler)	3.6	2.8	1.0	0.5	0.5
Chemicals	0.5	0.1	0.2	47.9	0.5
Plant construction	0.3	0.3	0.3	0.3	0.3
Onshore energy consumption	-	-	0.3-9.7	-	0.5-13.6
Total GHG emissions	66.7	65.5	64.1-73.5	111.0	64.1-77.2
			% of HFO baseline		
Net WtW GHG emissions	**71.5%**	**70.2%**	**68.4%**	**119.0%**	**68.2%**
Onshore GHG emissions	**-**	**-**	**0.3-10.4%**	**-**	**0.5-14.6%**
Net GHG emissions savings	**28.5%**	**29.8%**	**31.3-21.2%**	**-19.0%**	**31.3-17.3%**

The alkaline CC system is among the most efficient in terms of energy consumption onboard and fuel penalty since the carbonation reaction does not require external heat, and only a small amount of power is required for material conveying. However, large amounts of CaO are required, which is produced by crushing and heating limestone at high temperatures. In this scenario, the product of the carbonation reaction ($CaCO_3$) is dumped in the sea. Therefore, the process is not circular. The material that binds itself with CO_2 has not been recovered, and fresh CaO input must be supplied to the system for each kg of CO_2 captured.

As shown in Figure 4.5, $CaCO_3$ is mined and treated to produce CaO through the calcination process, which releases large amounts of CO_2 into the atmosphere both from the combustion of fuel and from the carbon stored in the rock itself. CaO is then hydrated and used as input in a variety of industry applications, including petrochemical, iron and steel and water treatment. If CaO is used to capture CO_2 from onboard flue gas returning to its original carbonated state, the entire value chain is unfavourable from a life cycle perspective. This is because, for each kg of CO_2 captured, the same amount was released into the atmosphere to produce the CaO necessary for the reaction. Since each process step in the chain requires energy for processing and transporting the materials, the overall GHG balance is negative (-19%), and this leads to an increase in the overall emissions compared to the baseline. Novel promising methods are under development, which involve the reaction of CO_2 directly with limestone to obtain bicarbonate ions to be discharged at sea[62], avoiding the use of carbon-intensive CaO. However, no process data are available to perform an LCA and, therefore, it was not included in this study.

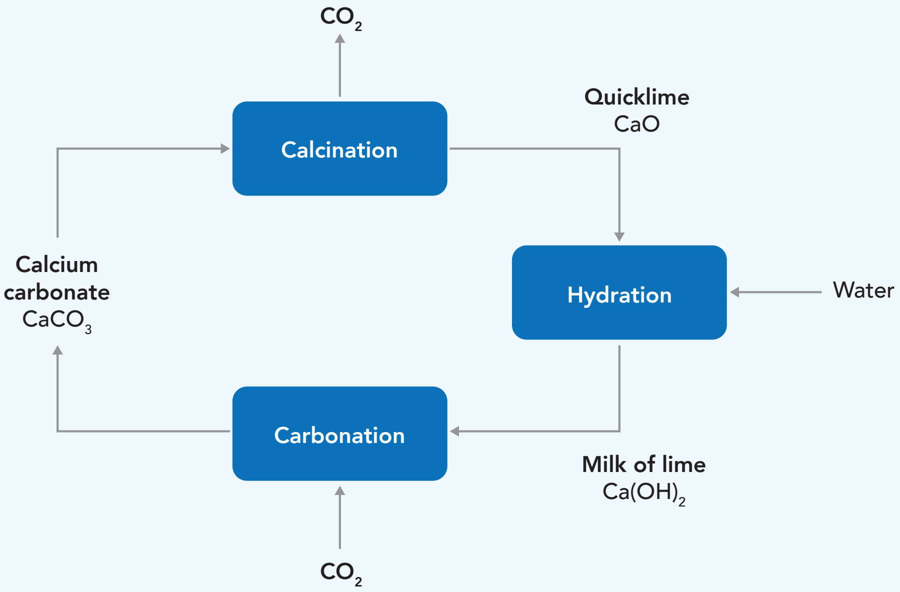


Figure 4.5 – Life cycle of quicklime (CaO)

An alternative to overcome this issue is to store the calcium carbonate produced after capture and offload it onshore, where it can be treated in a calciner to recover the CaO and be used again for onboard capture (calcium looping). While this approach eliminates the need for onboard steam production, compression and liquefaction of CO_2, making it on par with the alkaline CC system in terms of energy consumption and fuel penalty, it still requires a large amount of energy supplied to the onshore calciner. As for the MEA offloading scenario, the onshore energy mix determines the overall GHG emissions of CO_2 capture. Indeed, the two scenarios have similar GHG balances since most of the energy demand for capture is shifted from onboard systems to onshore facilities. However, the uncertainty of availability of large amounts of low carbon energy, particularly heat, at key port locations in the near future make onshore regeneration less viable currently compared to MEA and advanced amine capture.

4.3 Fuel types

As carbon capture onboard can be applied to marine fuels other than HFO, WtW emissions were calculated for LNG, methanol and biofuels. LNG offers beneficial synergies with OCCS thanks to the virtual absence of sulphur in the exhaust and the availability of a heat sink to partially cover the liquefaction energy duty of the CC system. Fossil methanol is also characterised by clean flue gas, though no cold energy recovery is available to liquefy the CO_2. To capture 40% of the total CO_2 emitted onboard, the HFO-fuelled ship emits an additional 6.2 gCO_2eq/MJ, while the emissions of OCCS for LNG and methanol ships are 2.7 and 5.9 gCO_2eq/MJ, respectively. The results of the analysis are shown in Figure 4.6.

For a 40% gross capture rate, the WtW GHG emissions of OCCS with LNG and methanol achieve ~44% and ~17% savings compared to the HFO baseline without OCCS. WtT GHG emissions of LNG constitute 23% of the overall WtW emissions, compared to 17% of HFO. Since extra fuel is needed for carbon capture, the increase of WtT emissions of LNG burned in the engine counterweighs the benefits of onboard energy savings due to lower liquefaction energy and the absence of exhaust pre-cleaning. Fuel production plays an even more important role for methanol, for which the WtT GHG emissions reach 31% of the total WtW. For this reason, the overall net GHG emissions savings are lower compared to HFO, even considering the excellent onboard performance due to the absence of exhaust cleaning (see Table 4.2). Overall, from a WtW penalty perspective, LNG is the best fuel to be combined with OCCS, followed by HFO. The best choice for a newbuild ship in terms of total life cycle GHG emissions savings compared to IMO guidelines baseline (93.3 gCO_2eq/MJ) is the LNG-fuelled ship with OCCS, for which the benefits related to the cleaner fuel add to the carbon capture.

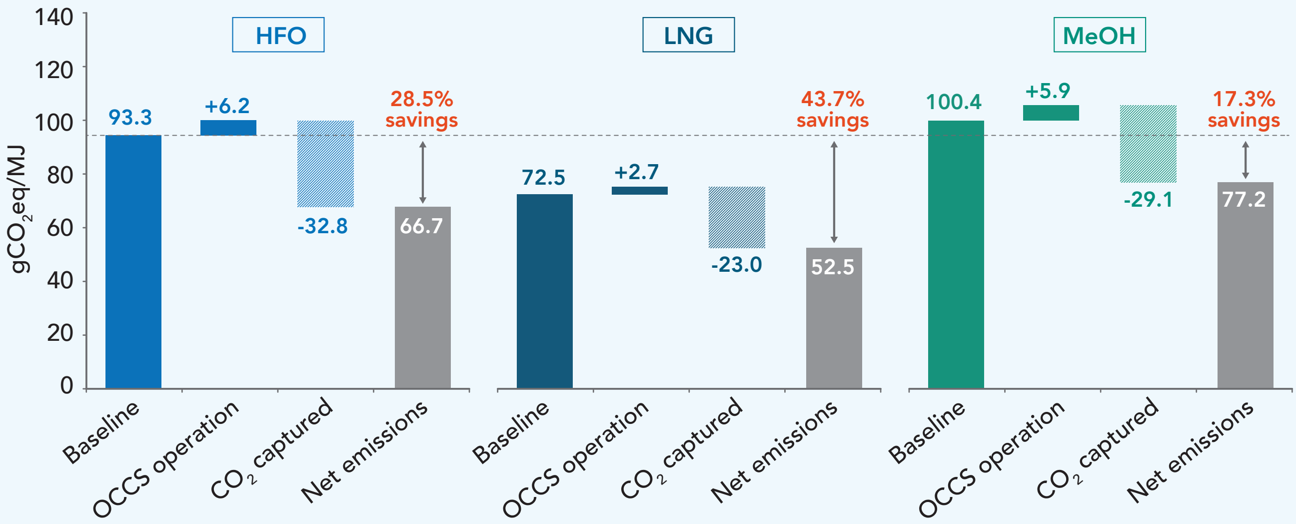


Figure 4.6 – Net WtW GHG emissions of OCCS for different fossil fuels, with MEA capture process (40% gross capture rate). Baseline represents the GHG emissions due to the vessel operation without OCCS.

Table 4.2 – Net WtW GHG emissions savings and fuel penalty of OCCS with different fossil fuels (40% gross capture rate) compared to HFO baseline (93.3 and 77.5 gCO_2eq/MJ, for WtW and TtW emissions, respectively)

Parameter	HFO	LNG	MeOH
TtW GHG emissions savings	35.8%	55.0%	43.1%
WtW GHG emissions savings	28.5%	43.7%	17.3%
Fuel penalty	5.8%	3.0%	5.3%

Biofuels contain biogenic carbon and, therefore, are generally considered carbon neutral[63,64]. When CO_2 from biomass energy sources is captured, it is possible to achieve negative emissions, which means that carbon dioxide is removed from the atmosphere. Baseline emissions shown in Figure 4.7 are due to the production of biofuel (WtT), and the additional emissions of the capture system are mainly related to the fuel penalty. The captured CO_2 instead comes from the combustion of biogenic carbon; therefore, if the capture rate is sufficiently high, the overall net GHG balance is negative.

The upstream emissions of biofuel production depend on several factors such as the conversion route, biomass source and its distance from the processing plant and carbon footprint of the energy used in the production process. The LCA impact of OCCS was calculated based on WtW GHG emission ranges of different types of biofuels, the results of which are summarised in Figure 4.8. The use of onboard carbon capture with the adoption of biofuels provides excellent environmental performance as CO_2 is actively removed from the carbon cycle, i.e., negative emissions could be achieved. Biodiesel from used cooking oil (UCO) has the best performance (up to 121%). Biomethanol shows the second-highest WtW GHG emissions savings (up to 119%), followed by bio-LNG (up to 98%) and conventional second-generation biofuels (vegetable oil). In the case of the bio-LNG scenario, 1.5% methane slip (defined as the ratio of the unburned fuel to the fuel injected in the engine) was included in the analysis, as CH_4 acts as a potent GHG regardless of whether its carbon atom is of biogenic or fossil origin.

In general, the best performance from an LCA perspective is to source biomass from waste streams (second-generation biofuels), for which no additional land use change emissions are generated for growing the biomass. In the case of biodiesel, common blends today (B24 and B30) do not provide high emissions reduction. However, the use of OCCS technology in conjunction with biodiesel boosts GHG emissions savings considerably, especially for higher blends (B50 and B100) as illustrated in Figure 4.9.

The analysis results show that the use of OCCS with the adoption of biofuels provides excellent environmental performance as CO_2 is actively removed from the carbon cycle, i.e., negative emissions could be achieved.

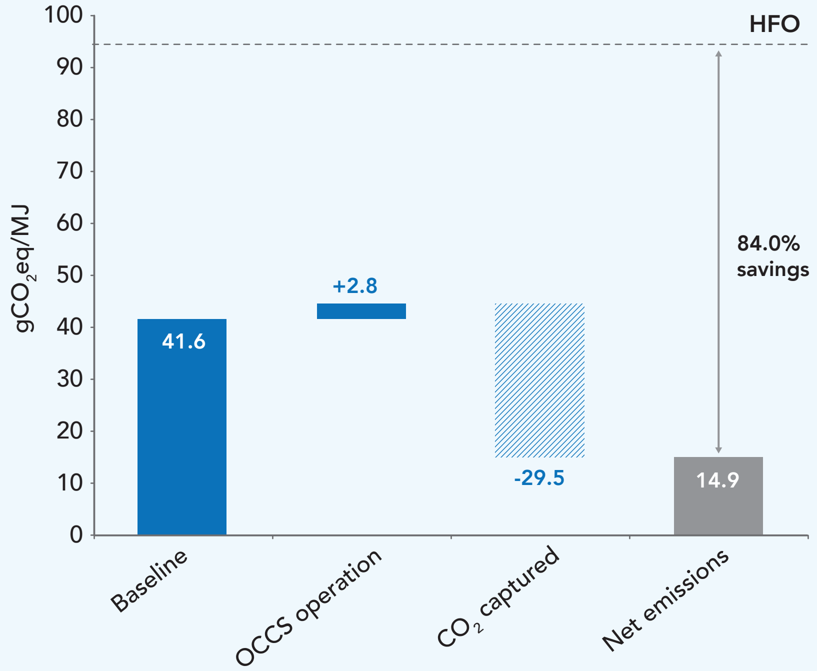


Figure 4.7 – Average net WtW GHG emissions of OCCS with B100 biodiesel from vegetable oil (40% gross capture rate). Baseline represents the GHG emissions due to the HFO-fuelled vessel operation without OCCS.

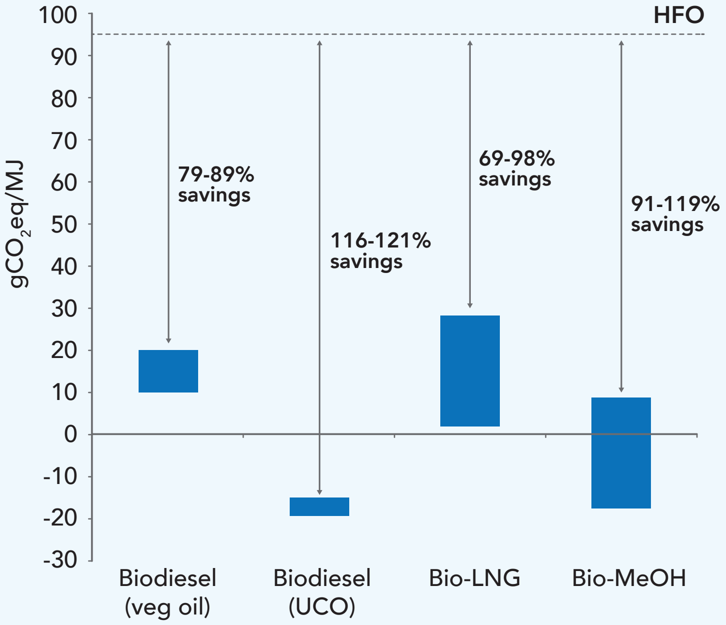


Figure 4.8 – Ranges of net WtW GHG emissions and savings of carbon capture with different biofuels (B100) (40% gross capture rate) compared to HFO baseline

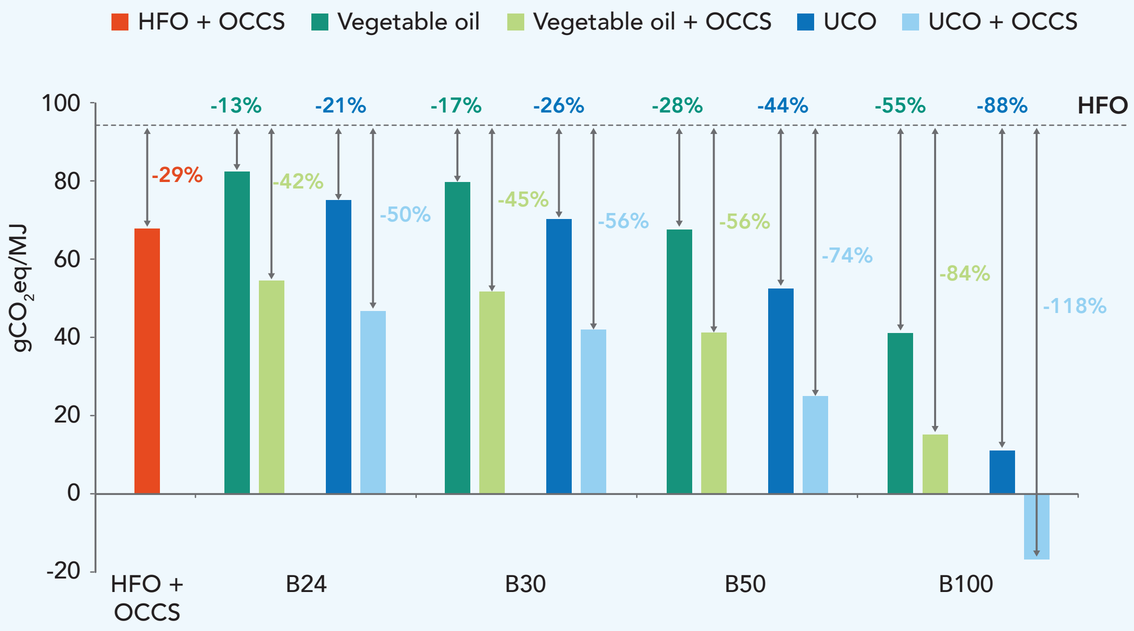


Figure 4.9 – Average net WtW GHG emissions and savings achieved with different biodiesel blends and OCCS with a 40% gross capture rate, compared with the HFO baseline emissions without OCCS. Transport and storage/use of CO_2 are not included. Default WtW GHG emissions values of pure biodiesel are 41.6 and 11.2 gCO_2eq/MJ for vegetable oil biodiesel and UCO biodiesel, respectively.

The WtW GHG emissions of a blend can be estimated by calculating its emission factor, which is based on the weighted average of the emission factors of the blended fuels, based on their energy content, using the following equation:

$$E_{f\ blend} = E_{f\ biofuel} \cdot \%_{blend} + E_{f_{HFO}} \cdot (1 - \%_{blend})$$

where E_f is the WtW fuel emission factor in gCO_2eq/MJ and $\%_{blend}$ is the amount of biofuel in the mix (i.e., 0.3 for B30). If OCCS is active, the emission factors will be lower and must be calculated, considering the GHG emissions savings related to the captured CO_2 and the additional GHG emissions due to the capture. In such a case, $E_{f\ biofuel}$ is calculated by performing the LCA of the system with pure biodiesel as fuel (B100) and with a fixed capture rate.

4.4 Carbon value chain

The results discussed above refer to the life cycle of fuel burned in the engine, from its production to the net mechanical energy at the shaft. However, to properly evaluate OCCS, the eventual fate of the captured CO_2 cannot be neglected, as its use determines the final GHG emissions savings from a total life cycle perspective. Therefore, the boundary of the analysis was expanded to include the transport and the final destination of CO_2, considering three main scenarios involving permanent storage, the use in building material production and e-fuel production, as described in Chapter 3.3.4. The reference ship is HFO-fuelled and equipped with an MEA capture system that captures 40% of the total CO_2 in the exhaust.

4.4.1 Scenario 1 – Permanent storage (CCS)

In this scenario, LCO_2 is unloaded at Rotterdam port and then transported to an offshore reservoir for injection. In scenario 1a (ARAMIS), the offshore reservoir is located near the Netherlands coast, and CO_2 is transported through an undersea pipeline. In this case, the emissions associated to post-capture operations are negligible. Scenario 1b (Northern Lights) describes the transport of liquefied CO_2 with a carrier to Øygarden port in Norway and then sent through an undersea pipeline to the offshore reservoir. As shown in Figure 4.10, loading/unloading steps along the value chain, BOG reliquefaction and transport through the pipeline have minimal impact on the overall value chain emissions, with shipping by the LCO_2 receiving vessel contributing the most GHG emissions for this leg. Onboard capture and liquefaction account for the largest contribution to the value chain emissions, between 85-95%. The transport and permanent storage of LCO_2 after onboard capture and liquefaction add around 9-34 gCO_2eq for each kg of CO_2 captured and stored. Overall, 201-227 gCO_2eq are emitted across the carbon value chain for each kg of CO_2 captured and stored in a reservoir, depending on the transport distance and location of the permanent storage site. The carbon footprint of local electricity is a relevant factor since power is needed to compress the CO_2 at supercritical pressure before injection into the reservoir. Even though renewable electricity from Norwegian hydropower plants is used for compressing CO_2 in scenario 1b, the overall emissions are higher due to the impact of transporting LCO_2 from Rotterdam to Øygarden. The results show that to minimise the life cycle emissions of captured CO_2, the storage site should be located close to the port where CO_2 is offloaded, opting for pipeline transport if possible.

With a 40% gross capture rate, the net GHG emissions savings of the ship equipped with OCCS considering the entire carbon value chain are ~27% for the CCS scenario where the captured CO_2 is shipped from Rotterdam to Øygarden (Figure 4.11). The ratio between the amount of CO_2 avoided, which is the savings, and the amount of CO_2 captured is 0.77, which means that for each tonne of CO_2 captured onboard and permanently stored in reservoir, the emissions of only 0.77 tonnes are avoided due to the GHG emissions across the entire value chain.

$$\frac{CO_2\ avoided}{CO_2\ captured} = \frac{Baseline\ GHG - net\ carbon\ value\ chain\ GHG}{CO_2\ captured} = \frac{93.3 - 67.9\ gCO_2eq/MJ}{32.8\ gCO_2eq/MJ} = 0.77$$

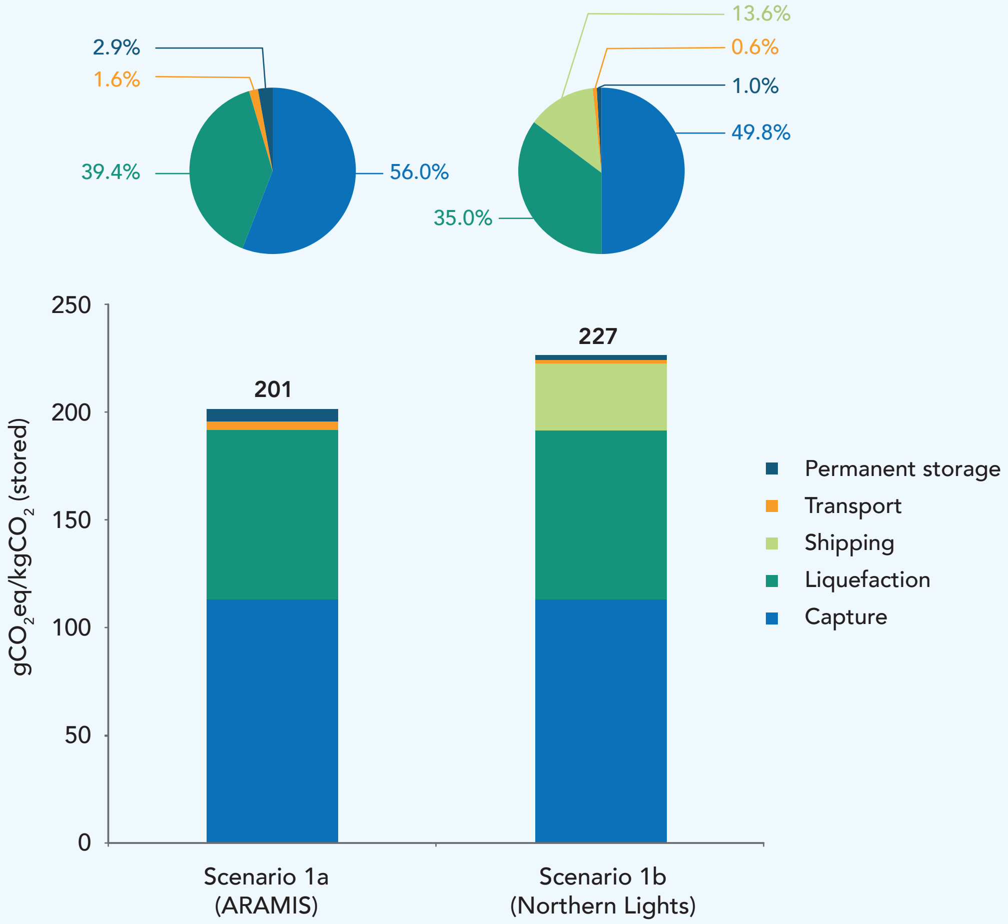


Figure 4.10 – Absolute and relative GHG emissions contributions of the carbon value chain for scenario 1. Transport refers to the energy consumed for CO_2 loading/unloading, pipeline transport and boil-off gas reliquefaction. For scenario 1b, CO_2 is shipped for 1,000 km from Rotterdam to Øygarden on a LCO_2 carrier vessel. Permanent storage emissions are related to the energy consumption for CO_2 injection and plant construction/decommissioning.

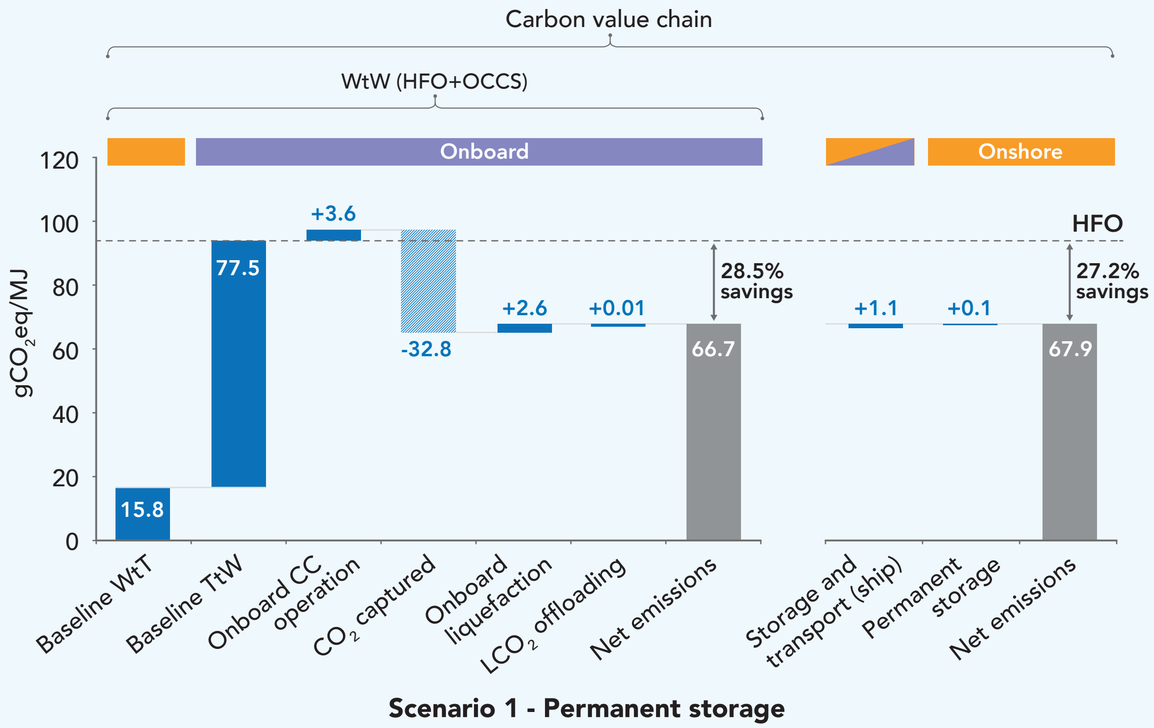


Figure 4.11 – Net carbon value chain GHG emissions and savings for OCCS with permanent storage of captured CO_2 under scenario 1b, Rotterdam to Northern Lights reservoir in Norway (40% gross capture rate). Baseline represents the GHG emissions due to the HFO-fuelled vessel operation without OCCS.

4.4.2 Scenario 2 – Use in concrete production (CCU)

In this scenario, the CO_2 produced during a trip from Port Hedland (AU) to Zhoushan (CN) is captured and unloaded at the destination port, where it is conveyed to an intermediate storage tank through a pipeline. From here, LCO_2 is loaded on a truck and then transported for 100 km to the conversion plant, where it is used in the curing process for concrete production. CO_2 is permanently stored in the material, with the additional benefit of displacing the production of cement, which is a carbon-intensive material. For each kg of CO_2 used in the curing process, 0.9 kg of CO_2 from cement production is avoided and, therefore, can be considered as savings. Figure 4.12 shows the results of the LCA analysis considering that the CO_2 saved, due to the lower quantity of cement used, is fully accrued to the ship owner with OCCS installed.

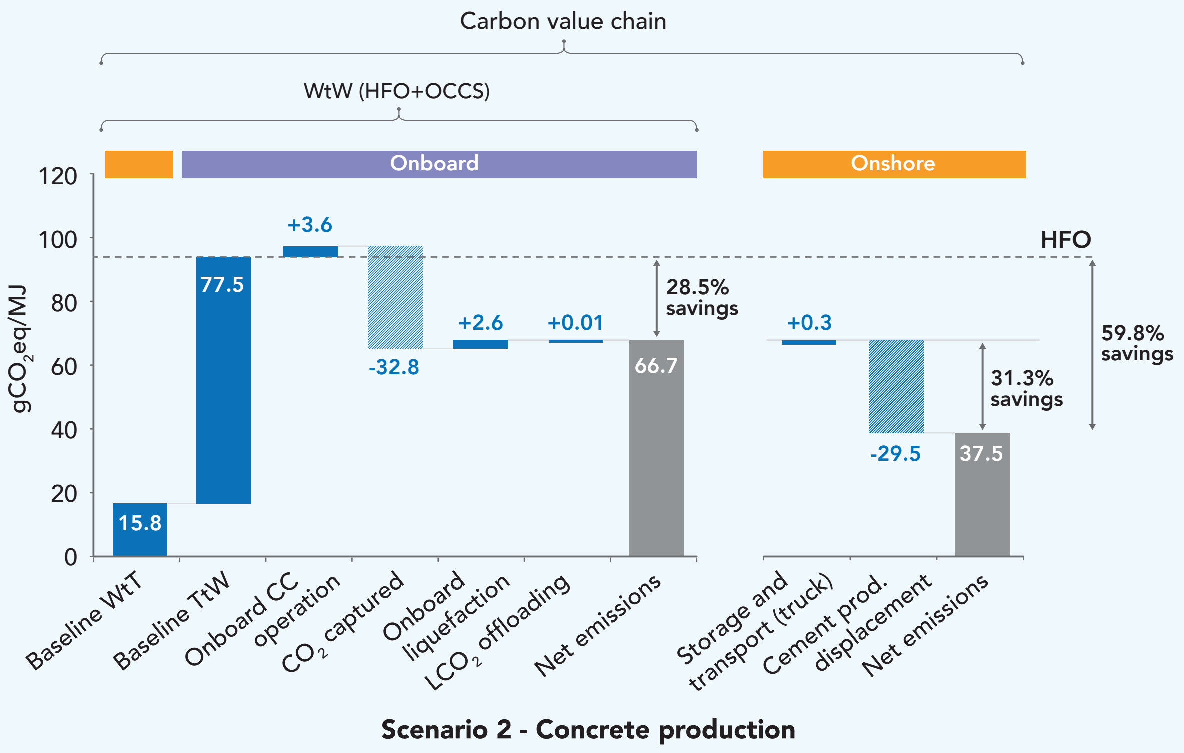


Figure 4.12 – Net carbon value chain GHG emissions and savings for scenario 2, Port Hedland to Zhoushan (40% gross capture rate), considering the emission credits generated by onboard capture and onshore CO_2-cured concrete production. This process displaces the production of carbon-intensive cement required by conventional concrete process. Baseline represents the GHG emissions due to the HFO-fuelled vessel operation without OCCS.

Similarly to the previous analysed scenario, the onboard capture and liquefaction processes are responsible for most of the emissions. With a 40% capture rate, the overall net GHG emissions savings of the carbon value chain reach ~60% when the savings related to CO_2 use are accounted to OCCS ship. However, in this case, the concrete producer does not have an incentive to use CO_2 for curing if emissions credit due to the displacement of cement production cannot be claimed. If such credits are claimed by the concrete producer, the carbon value chain GHG emissions savings of OCCS are 28.5%.

It is important to consider that the decarbonisation of the global economy will eventually reduce the benefits of using CO_2 in concrete production. Cement-related emissions will gradually decrease when cleaner energy sources are used in the production process. If cement is produced with low-carbon energy, no savings can be attributed to CO_2-curing, consequently there would be no environmental benefits to using this process for the concrete producers other than fixing the captured CO_2 for the shipowners.

4.4.3 Scenario 3 – Use for e-fuel production (CCU)

The last scenario of the analysis considers the captured CO_2 as input for the synthesis of e-methanol by combining it with hydrogen from electrolysis. In this case, scenario 2 is taken as the reference for the value chain structure and e-fuel production plant distance from the offloading port. The benefits of using the captured CO_2 to produce e-methanol are related to the displacement of fossil fuel when e-MeOH is burned in another marine engine. The emissions related to the consumption of energy in hydrogen production and methanol synthesis and transport are 7.8 gCO_2eq/MJ of methanol produced. Since the production of hydrogen requires large amounts of electricity to feed the electrolysis process, the only viable way to a low-carbon process is to use renewable energy. For this reason, wind energy was assumed as the energy source for the e-fuel production plant. If grid electricity is used for fuel synthesis instead of renewable wind energy, the emissions due to the synthesis process may increase by up to 50% in if there is high fossil energy share in the mix, as seen in the current Singaporean grid.

In this case the GHG emissions due to fuel synthesis and transport are 12 gCO_2eq/MJ. There is a substantial difference between using CO_2 by storing it inside a long-lasting material such as concrete and using CO_2 to produce e-fuel. In the latter case, the captured CO_2 is emitted into the atmosphere when the e-fuel is burned in a marine engine. This leads to the non-trivial problem of how to distribute the GHG emissions savings (or carbon credits) generated by recycling the CO_2 molecule through e-fuel production. Indeed, since the CO_2 molecule is eventually emitted into the atmosphere, its emission must be accounted for somewhere along the value chain.

Figure 4.13 shows the net carbon value chain GHG emissions and savings related to the operation of two ships, the first running on HFO and capturing 40% of onboard CO_2 (Ship A) and the second (Ship B) running on e-methanol produced by using the CO_2 captured by the first ship. The net GHG emissions of both ships depend on who claims the carbon credits.

If the OCCS ship (Ship A) claims all the credits corresponding to the amount of CO_2 captured onboard, then all the onboard carbon emissions due to the combustion must be accounted by the e-fuel ship (Ship B), exactly as if it were burning fossil fuel.

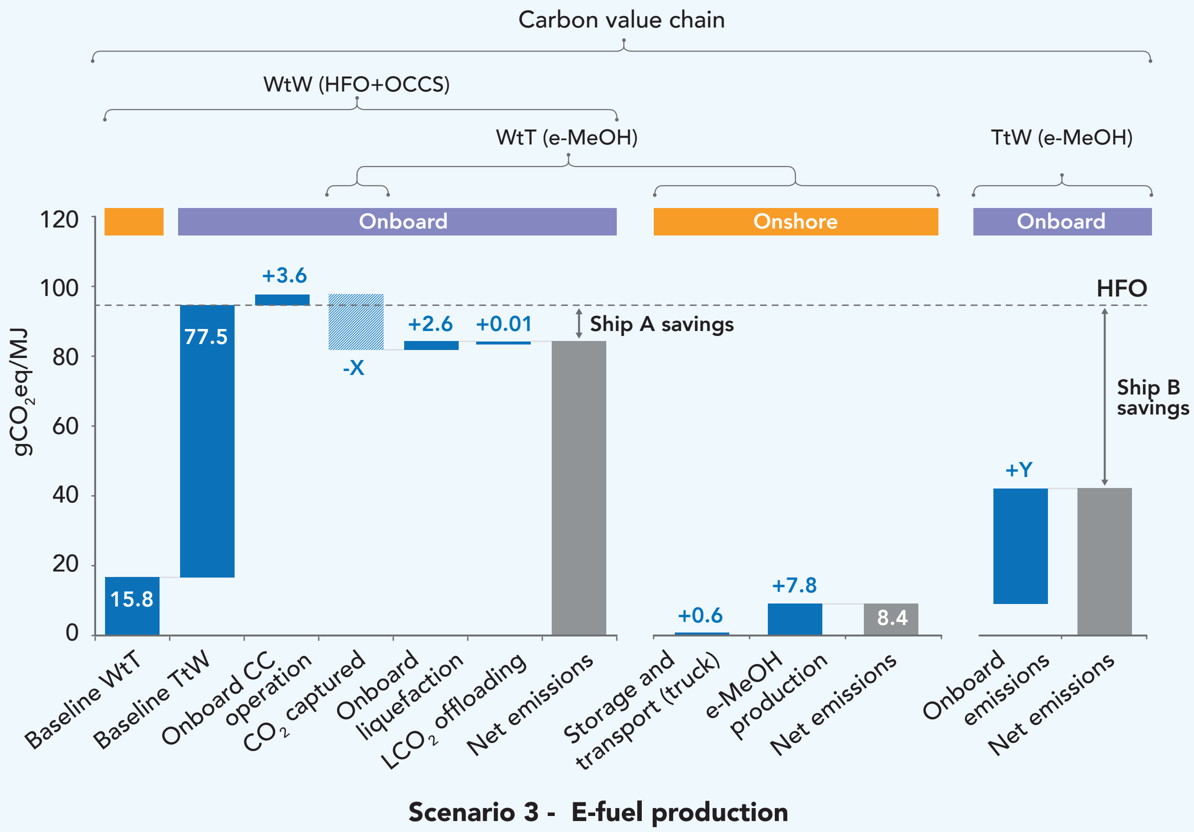


Figure 4.13 – Net carbon value chain GHG emissions and savings for scenario 3 (40% gross capture), considering the emission credits generated by carbon captured onboard an OCCS-installed HFO-fuelled vessel (Ship A) and CO_2 from the combustion of e-methanol made from such captured carbon in an e-MeOH-fuelled vessel (Ship B). Baseline represents the GHG emissions due to the HFO-fuelled vessel operation without OCCS.

On the contrary, if the carbon credits are claimed by the e-fuel ship, the OCCS ship cannot claim any credit for the captured carbon to avoid double accounting. This will lead to an increase in the overall GHG emissions due to the additional GHG emissions of the OCCS system resulting from the impact of fuel, chemicals and materials used to run the onboard capture system. This approach was recently proposed by China during the 17th session of the IMO Intersessional Working Group on the Reduction of Greenhouse Gas Emissions from Ships (ISWG-GHG 17)[65]. Following this proposal, the OCCS ship owner may decide not to claim the emission credits due to capture and instead benefit from selling the captured CO_2 to e-fuel producers. Such CO_2 would be considered "marine circular carbon", which can be utilised to produce green e-fuel to be used within the shipping sector only. The CO_2 produced from the combustion of e-fuel made from circular carbon is not accounted for in the TtW GHG emissions balance of the ship, and the only emissions are the WtT GHG emissions due to e-fuel production (hydrogen production and fuel synthesis).

A third option is to share the credits between both ships equally: in this case, the OCCS ship can claim only half of the amount of captured CO_2 as credits, while the e-fuel ship, having claimed half the captured CO_2 credits, must include 50% of the total amount of CO_2 produced by e-fuel combustion in its overall GHG emissions balance. Since guidelines on carbon accounting for e-fuels made from onboard captured CO_2 are not available at present, this study presents different estimations of GHG emissions savings related to the accounting approaches discussed above.

Referring to Table 4.3, when the credits of captured CO_2 are fully claimed by the e-MeOH ship B, no credits can be claimed for such captured carbon by Ship A, and therefore, its net GHG emissions are higher than the HFO baseline (+6.6%). The e-MeOH-fuelled Ship B benefits from using onboard captured CO_2, the emissions of which were already accounted for by Ship A. Therefore, the onboard emissions due to combustion are considered as equal to zero in the overall GHG balance. The only emissions of ship B are due to the upstream production of e-MeOH, assuming renewable energy is used, which is considered a WtT component of the fuel GHG emissions. The net GHG emission is 8.4 gCO_2eq/MJ, a GHG emissions savings of 91% from the HFO baseline for Ship B.

Table 4.3 – GHG emissions and savings for scenario 3, following different CO_2 credits claiming scenarios, compared to HFO baseline: 93.3 gCO_2eq/MJ

	Ship A (HFO+OCCS 40% gross capture)			Ship B (e-MeOH)		
CO_2 credits claiming scenario	Captured CO_2 credits [X value] (gCO_2eq/MJ)	Net WtW GHG emissions (gCO_2eq/MJ)	GHG emissions savings (%)	Onboard TtW emissions [Y value] (gCO_2eq/MJ)	Net WtW GHG emissions (gCO_2eq/MJ)	GHG emissions savings (%)
Full claiming by e-MeOH Ship B	0.0	99.5	-6.6%	0.0	8.4	91.0%
Full claiming by OCCS Ship A	32.8	66.7	28.5%	69.1	77.5	16.9%
Shared claiming (50-50%)	16.4	83.1	10.9%	34.6	42.7	54.2%

If the emission of CO_2 molecules into the atmosphere is accounted fully to ship B, ship A can claim all the credits generated by OCCS. In this case, for a 40% gross capture rate, the GHG emissions savings of ship A amount to 28.5%. Ship B has higher GHG emissions due to the onboard combustion of methanol (69.1 gCO_2eq/MJ). There are still some GHG emissions savings since the WtT GHG emissions of e-MeOH are lower compared to fossil HFO and fossil methanol, assuming only renewable energy is used to produce it. The net GHG emissions savings are 16.9% from the HFO baseline for ship B. The shared claim of emissions credits allows ship A to lower its GHG emissions compared to the HFO baseline (net GHG emissions savings of 10.9%) while still providing ship B with 54.2% net GHG emissions savings.

Marine carbon circular economy

Carbon capture and utilisation (CCU) enables the re-use of captured CO_2 and, therefore, is seen as a potential solution to mitigate GHG emissions by reducing the dependency on virgin resources needed for the manufacture of the said product. CCU could be a useful way to gradually shift the current industry from a linear carbon pathway (from underground reservoirs to the atmosphere, i.e., long carbon cycle) to a circular carbon pathway where CO_2 is extracted from the short carbon cycle. In the first phase, the CCU industry will capture fossil CO_2 from other processes to make carbon-based products and gradually move to capture from bio-resources (BECCU) or atmospheric air (DAC), ultimately leading to a circular economy of carbon.

In shipping, carbon captured from OCCS can be utilised to produce marine e-fuels, which can then be used onboard vessels, and if these are equipped with OCCS, their emissions can be recaptured to restart the carbon cycle (Figure 4.14). This would enable the creation of a marine carbon circular economy. While this approach could, in principle, provide GHG emissions savings and help shipping with its transition to a low-carbon fuel landscape, it raises the question of how to quantify and allocate the carbon credits related to such emissions reduction among the multiple users of e-fuels made with circular captured carbon. Indeed, with each round of onboard re-capture, only a fraction of the CO_2 is captured, while the rest is emitted into the atmosphere. The amount of captured carbon that can be used for e-fuel production rapidly decreases after a few capture cycles: considering a 40% gross capture rate, after only three rounds of recapture, more than 93% of the CO_2 initially captured is emitted into the atmosphere. Moreover, additional GHG emissions due to OCCS capture and e-fuel production steps must be taken into account. Therefore, the adoption of a marine circular economy framework for captured carbon must be carefully evaluated, considering scenario modelling with different carbon credits allocations to fuel users.

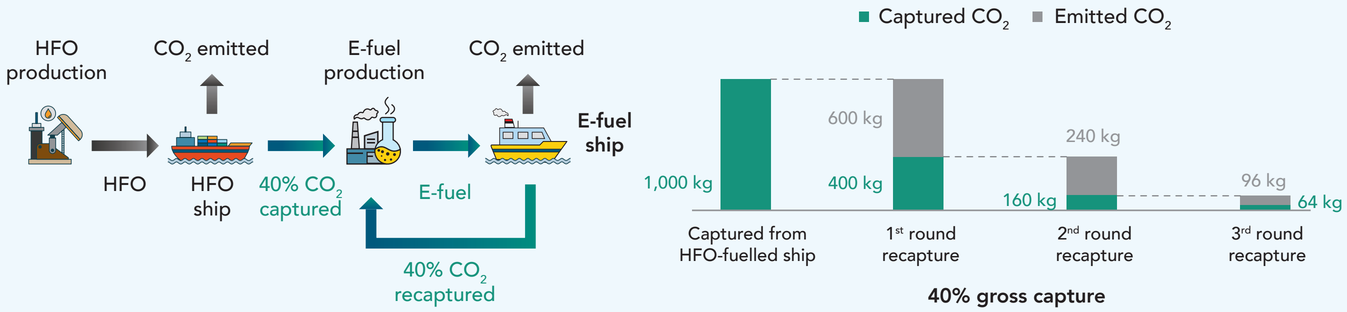


Figure 4.14 – Circular framework for onboard captured carbon, with e-methanol production from onboard captured CO_2 (left) and mass balance of captured and emitted CO_2 after three rounds of recapture (right)

Other important barriers to the development of fossil-based e-fuels are: i) the availability of renewable energy and ii) the regulatory complexity for carbon accounting.

E-fuels must be produced with renewable power in order to reduce GHG emissions compared to fossil fuels. However, renewable electricity can be used in different ways, i.e., for clean hydrogen production or for directly "greening" the power grid. New renewable power capacity should be used in the most direct possible way to maximise the GHG emissions savings. In the medium term, there will be strong competition among users to buy renewable energy for their processes and more efficient pathways will be rewarded while less efficient pathways (i.e., e-fuel production from captured carbon) may be discouraged.

The use of fossil CO_2 for CCU application implies that the same molecule is used by several distinct actors, all of which need to claim GHG emissions savings (carbon credits). This brings up the issue of properly tracing the CO_2 pathway along the value chain and allocating the costs and emissions savings related to the capture phase and the use phase.

4.5 OCCS as useful tool for ships to comply with IMO targets on GHG emissions

The 83rd session of the MEPC held from 7 to 11 April 2025 approved draft regulations on the mid-term measures in line with IMO Strategy on Reduction of GHG Emissions from Ships released in 2023. For ships of 5,000 GT and above engaged in international voyages, the GHG fuel intensity (GFI) of the fuel used, i.e. the GHG emissions per unit of energy from the fuel used, will be regulated. Progressively stringent compliance targets for GFI were set for 2028-2035 period. Two tiers of GHG fuel intensity targets were defined, namely the "base target" aimed for achieving the level of ambition for 2050 and the "direct compliance target" that every ship should further try to reach:

- **GFI ≥ Base target:** two deficits are generated, one corresponding to the GHG emission exceeding the "base target", considering USD 380/tCO_2 (Tier 2), and another corresponding to the GHG emission between the "base target" and the "direct compliance target", considering USD 100/tCO_2 (Tier 1).
- **Base target ≤ GFI ≤ Direct compliance target:** a deficit corresponding to the GHG emission exceeding the "direct compliance target" USD 100/tCO_2 (Tier 1).
- **GFI ≤ Direct compliance target:** compliance surplus units are gained by the ship and can be transferred to another ship to balance its "base target" compliance deficit or banked for use within two subsequent calendar years.

Compliance deficit shall be calculated with respect to the corresponding tiers and must be paid to the IMO Net-Zero Fund. A ship with a GFI lower than the Direct Compliance target will gain Surplus Units (SUs) which can be transferred to other ships or retained for use within subsequent accounting years.

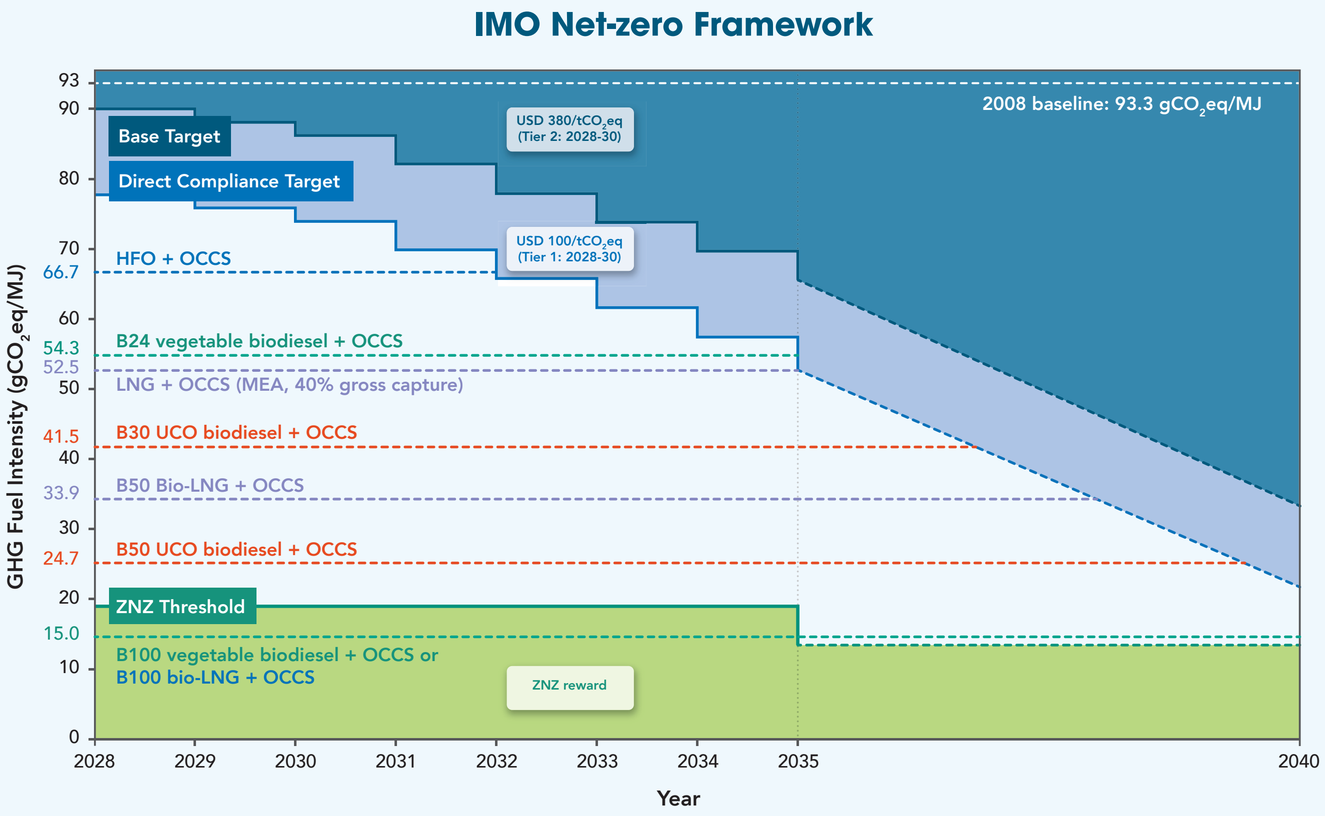


Figure 4.15 – GFI target compliance strategies for ships adopting OCCS and biofuels. OCCS technology is based on MEA capture and 40% gross capture rate, on a WtW basis. The values of GHG fuel intensity for biofuels are averaged based on different biomass sources and biofuel production processes. ZNZ (zero or near-zero) threshold is the GFI value below which ships are eligible for financial rewards.

Although the recently articulated framework does not specify how OCCS contributes to GFI reduction, it nonetheless offers a structured basis for assessing OCCS's potential in helping shipowners and operators manage their emissions portfolio.

By calculating the abatement from OCCS based on the amount of CO_2 it removes per unit of fuel energy (in gCO_2eq/MJ), using a WtW approach, an "equivalent" GFI can be derived. This assumes OCCS to be an alternative technology or an "equivalent" under regulation 4 of MARPOL Annex VI which supports ships in meeting environmental compliance. Extending this concept, the study shows that the GFI of an HFO-fuelled ship adopting OCCS with MEA capture and a 40% gross capture rate stays below the direct compliance targets from 2028 to 2032. In order to reach compliance until 2035, biodiesel can be progressively blended with HFO. LNG-fuelled ships equipped with OCCS can maintain an equivalent GFI below the direct compliance target until 2035, highlighting the positive synergy between LNG and OCCS. When fossil fuels are completely replaced by their bio-counterparts (biodiesel for HFO and bio-LNG for fossil LNG), OCCS can lower the GFI enough for the ship to be compliant with the more stringent 2040 targets.

5. Cost analysis

5.1 Onboard capture cost

The technology to capture CO_2 onboard ships is based on onshore applications, where flue gas from industry and power plants is treated with amine. The cost of onshore captured carbon, in most cases, is in the range of USD 60-140/tCO_2[66]. While the capture of industrial flue gas is a mature and well-established technology, its application onboard ships is still at the demonstration stage. Moreover, the onboard plant scale is, at best, one order of magnitude lower than land applications. The same applies to the liquefaction step. This leads inevitably to higher investment and operational costs, which ultimately increase the final cost of captured CO_2, as highlighted in Figure 5.1.

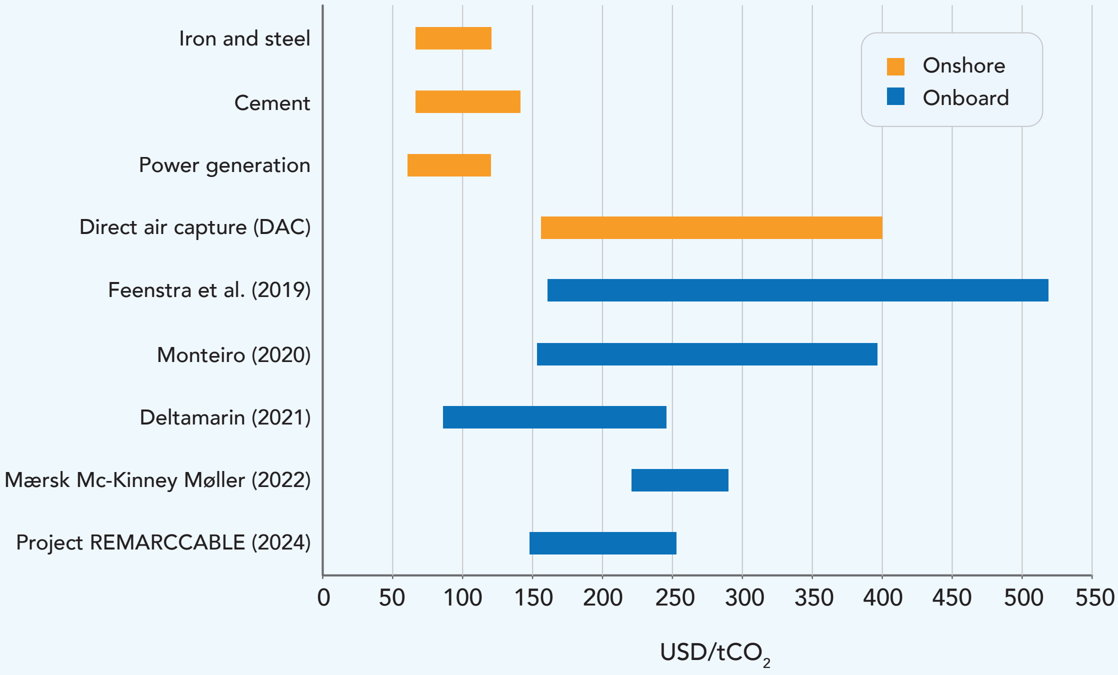


Figure 5.1 – Cost of captured CO_2 for onshore and onboard applications. Onboard capture data from recent studies. Project REMARCCABLE data refer to Nth-of-a-kind installation of commercial OCCS system, for gross capture rates in the range 30-60% (including ±15% error margin). Onshore capture data are taken from IEA (2020)[34,35,37,67,68].

Capturing carbon dioxide onboard ships costs generally 2-3 times more than capturing CO_2 onshore. However, most recent estimates indicate that, with a proper design, OCCS is generally more cost effective than DAC. This is due to the high energy consumption required to harvest CO_2 from atmospheric air, in which it appears in extremely low concentrations. The cost of capture varies greatly depending on the ship type, system design and capture rate. Higher capture rates imply that the OCCS system is used at a higher capacity over its lifetime, thus reducing the levelised cost to capture one single tonne of CO_2. Figure 5.2 shows the cost estimations of capturing CO_2 with N^{th}-of-a-kind OCCS system installed on a tanker ship, under Project REMARCCABLE. Specific capture cost for 40% gross capture rate was selected for the analysis, considering full heat recovery onboard and the ±15% error margin included in Project REMARCCABLE study calculations. Therefore, the assumed cost of capturing CO_2 with OCCS for this study is USD 174-236/tCO_2.

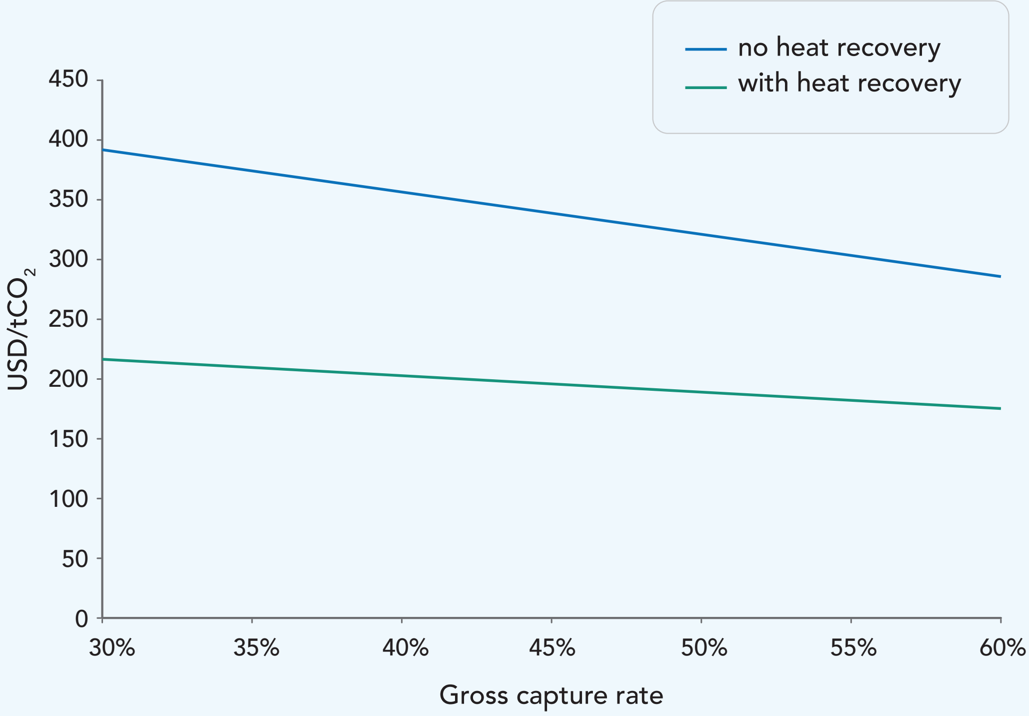


Figure 5.2 – Estimated cost of capturing and liquefying CO_2 onboard an MR tanker by gross CO_2 capture rate, with and without heat recovery from exhaust, for an N^{th}-of-a-kind installation of commercial OCCS system (data from Project REMARCCABLE, average)

5.2 Transport and handling cost

The cost of transporting CO_2 is influenced by the transport method and the distance. The most common methods of transporting liquid CO_2 are by pipeline, ship and truck (Table 5.1). Over short distances, pipeline transport is the most cost-effective option, while for long distances (>500 km), the economical option is shipping (Figure 5.3). Trucks are used for land transport over short distances where pipeline is not available. The cost of handling infrastructure, such as handling equipment, intermediate storage hubs, and onshore platforms for loading/unloading operations, is added to the transport cost.

The additional cost of handling CO_2 was estimated at around USD 25-30/t, consisting of storage and port fees (USD 10-15/tCO_2) and platforms for loading/unloading operations (USD 15/tCO_2)[69–71]. Value chains should be designed for high transport capacities (>3 MtCO_2/year) to keep costs in this range.

Table 5.1 – Average cost of transporting CO_2[72–75]

Transport method	Distance (km)	Cost (USD/t)
Pipeline	0-1,000	3-15
Ship	500-12,000	15-50
Truck	0-100	2-10

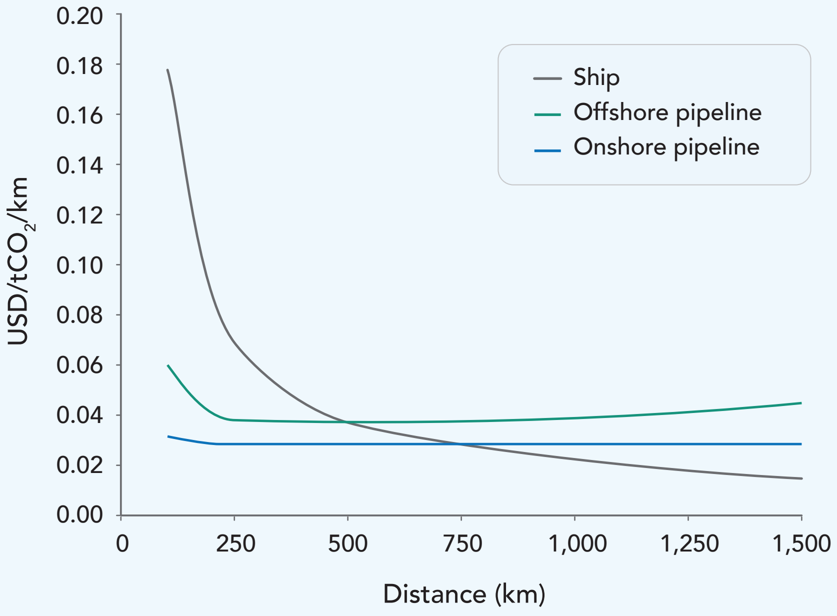


Figure 5.3 – CO_2 transport cost by distance with pipeline and ship[45]

5.3 Permanent storage cost

The cost to permanently store the captured CO_2 in underground sites depends on several variables, such as the site location, characteristics and the availability of existing infrastructure. Most of the current operating CCS projects have selected onshore saline formations. However, more and more projects are using offshore sites, including depleted oil and gas fields. High injection rates and site capacities decrease the overall cost of storage, which is related to the installation and operation of the injection platform, including the energy for CO_2 compression to injection pressures. Table 5.2 shows the ranges of storage costs for different scenarios.

Storing CO_2 in offshore sites is more expensive due to the higher costs of installing and operating an injection platform in the middle of the sea. If previous oil and gas infrastructure can be re-used, part of the costs can be offset. It is important to consider that the costs always depend on the specific project, as each one has its specific cost of capital, equipment, energy and maintenance. In the case of the Northern Lights project, the expected storage cost in the offshore saline aquifer is higher than the average value reported in the table below: EUR 35-50/tCO_2 (including pipeline transport)[66]. The estimates of project ARAMIS for transport and permanent storage costs are even higher, at EUR 40-60/tCO_2[76].

However, these also consider the cost of port infrastructure and CO_2 transport via pipeline, which was already evaluated in the previous section.

Table 5.2 – Storage cost ranges for different CO_2 permanent storage scenarios[66]

Location	Site	Infrastructure	Cost (USD/tCO_2)		
			min	max	avg
Onshore	Depleted oil/gas field	Re-used	1	10	4
Onshore	Depleted oil/gas field	New	1	14	5
Onshore	Saline formation	New	3	16	7
Offshore	Depleted oil/gas field	Re-used	3	12	8
Offshore	Depleted oil/gas field	New	4	19	14
Offshore	Saline formation	New	8	27	19

5.4 E-fuel production cost

The cost of producing e-methanol depends on the installation and operating costs of the electrolysis plant to produce the hydrogen and the methanol synthesis plant. The production cost of e-fuels is calculated according to the below equation[77] :

$$Total\ Cost = I_{electrolyser} + O\&M_{electrolyser} + C_{stack} + C_{electricity} + I_{synthesis} + O\&M_{synthesis} + C_{CO2} + I_{\mathrm{BoP}}$$

where I is the plant investment cost, $O\&M$ is the operation and management cost, and C is the cost of energy, materials and equipment replacement. Table 5.3 shows the main parameters for evaluating the production cost of methanol from renewable hydrogen and CO_2 from OCCS.

The cost of CO_2 was calculated based on the value chain of scenario 3, considering the estimates reported in the previous sections. Cost estimates for PEM electrolyser and wind energy used for hydrogen production and methanol synthesis were based on 2030 forecasts. The total cost of methanol as marine fuel includes the additional cost of transport and bunkering.

Table 5.3 – Main parameters for e-methanol production cost evaluation, 2030 and 2050 forecast

Component	Amount		Unit	Reference
	(2030)	(2050)		
Plant size	50	100	TPD	-
Plant lifetime	25	25	year	-
Capacity factor	90%	90%	-	-
Discount rate	5%	5%	-	-
PEM electrolyser CAPEX	800	500	USD/kWh	[59,77–81]
O&M electrolyser	3%	2%	CAPEX	[59,77–81]
Stack replacement cost	40%	30%	CAPEX	[59,77–81]
Electrolyser efficiency	65%	70%	-	[59,77–81]
Synthesis CAPEX	0.3M	0.3M	USD/TPD	[77,82–84]
O&M synthesis	5%	5%	CAPEX	[77,82–84]
Synthesis energy demand	0.169	0.169	kWh/kgMeOH	[58]
Electricity cost (wind)	30	20	USD/MWh	[85]
Transport and storage cost	40	40	USD/tMeOH	[86,87]
Bunkering and port fees	30	30	USD/tMeOH	[88]

5.5 CO_2 capture and avoidance cost

The overall cost for the CO_2 value chain is presented in Figure 5.4. The cost of CO_2 at the end of the value chain is the sum of the capture cost (which includes liquefaction), storage and transport of LCO_2 to its final destined site. CCS pathway shows a slightly higher cost due to the cost of injection in the reservoir (USD 207-312/tCO_2 captured). The range is large due to the cost variability of onboard capture and the impact of LCO_2 shipping, considered in the maximum cost scenario. Capture and liquefaction onboard ship is responsible for 80% of the final CO_2 cost on average. Injection in the CCS scenario takes about 2-6% of the share.

For both CCS and CCU pathways, CO_2 storage and its transportation constitute 14-19% of the final cost. The added cost to capture and liquefaction onboard, from the ship tank to its final destination, is between USD 33-76/tCO_2. The final cost at the end of the CCU value chain (before use) is USD 210-277/tCO_2 captured.

It is important to remember that the captured CO_2 and avoided CO_2 are not the same. Indeed, for each tonne of CO_2 captured onboard (based on a 40% gross onboard capture rate) and stored in a reservoir, only 0.77 tonnes of CO_2 is avoided, as we account for the GHG emissions across the total value chain, i.e., OCCS, CO_2 transport and final injection into the reservoir.

The cost of avoidance with OCCS and permanent storage scenario was estimated as USD 269-405/tCO_2 avoided. The cost of OCCS was based on the results of a feasibility study on an MR tanker, considering a full-scale, Nth-of-a-kind system with full heat recovery[13]. It is important to note that the reduction of available space onboard due to the OCCS system was not included in the cost calculations, nevertheless it needs to be considered when comparing OCCS with other decarbonisation measures onboard a specific ship.

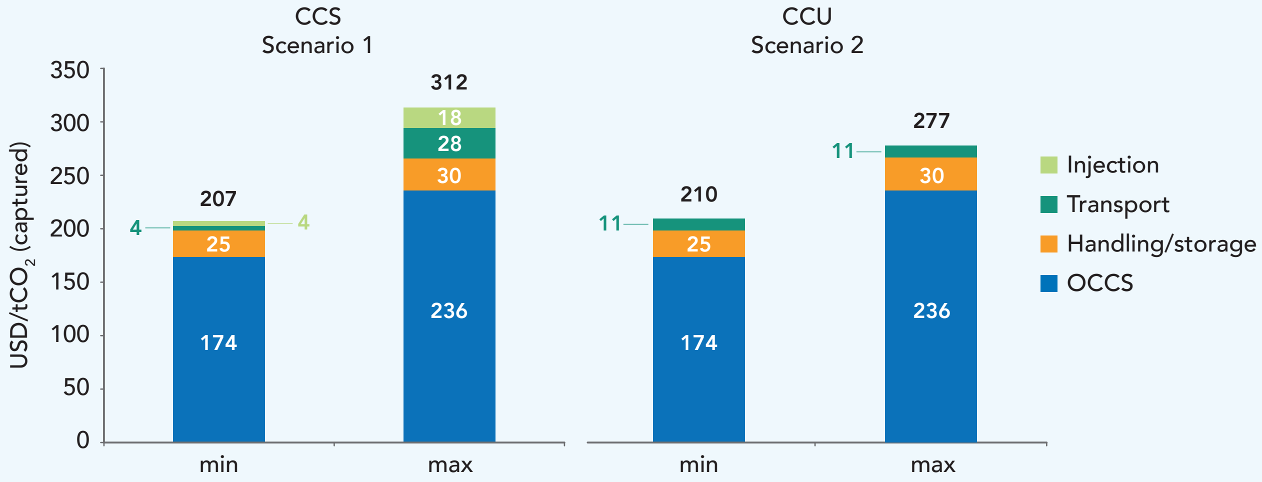


Figure 5.4 – Value chain cost of captured carbon with OCCS for CCS and CCU pathways. Average cost of OCCS is based on Project REMARCCABLE estimations for 40% gross capture, Nth-of-a-kind installation of commercial system with full heat recovery (±15% error).

In the case for e-fuels, the cost of CO_2 at the end of its value chain is the material cost for the synthesis of e-methanol, which determines the final production cost of the fuel. The CO_2 constitutes 26-44% of the final production cost of synthetic methanol. The cost of onboard captured CO_2 is higher than the cost of CO_2 captured from industrial applications onshore, and this leads to higher e-methanol costs, about 25% more (Figure 5.5).

It is important to consider that e-methanol produced from fossil CO_2 cannot be considered the same as methanol with CO_2 obtained from biogenic sources or DAC. The contribution of the CO_2 emitted from the combustion of e-methanol varies depending on the accounting scenario.

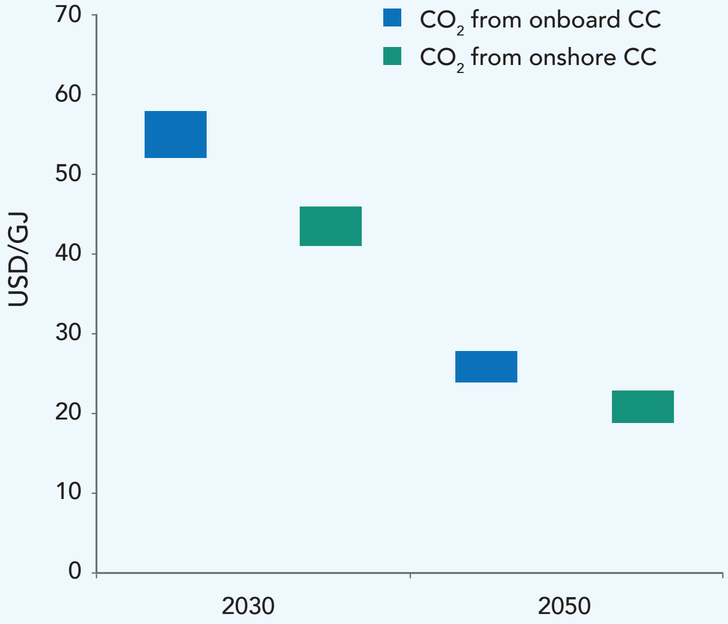


Figure 5.5 – Cost of e-MeOH produced from CO_2 captured onboard and onshore, projections to 2030 and 2050

6. Conclusions

This study provides an estimation of the life cycle emissions and value chain costs related to the capture of carbon dioxide onboard ships as decarbonisation measure for global shipping (see Table 4 in the Executive Summary). OCCS is considered as a promising way to decarbonise shipping in the medium term, as fossil fuels will still play a major role in the global fuel mix for the next few decades. OCCS is expected to reach commercial maturity by 2030, and several demonstration projects are currently being developed. To properly assess the effectiveness of OCCS in removing carbon from the environment, it is essential to analyse the emissions of the entire post-capture carbon value chain, expanding the scope beyond the ship to include transport, storage and utilisation of CO_2.

WtW GHG emissions of OCCS are considerably higher than TtW (onboard) emissions, and around 95% of the total is due to fuel penalty required to provide energy to capture and liquefy onboard. Indeed, the emissions from the production of the extra fuel consumed (WtT) are not captured onboard. The materials used to build the system and to operate it have a lower but relevant impact that should not be neglected. Heat recovery onboard is crucial to reduce the energy demand and can provide up to 30% capture and above 20% net GHG emissions savings with a minimum fuel penalty (below 5%). With 40% gross onboard capture rate, 28.5% GHG net savings can be achieved from a WtW perspective.

Among the possible CC technologies and configurations, MEA-based capture with onboard CO_2 liquefaction is the most promising from a techno-economic perspective. Onshore amine regeneration and alkaline-based capture with material recovery onshore could, in principle, provide extra GHG emissions savings, however they require a more complex arrangement and large quantities of renewable energy for onshore regeneration. OCCS can also be applied to a variety of marine fuels, with LNG being the best match among fossil fuels due to system-fuel synergies that halve the fuel penalty. The combination of OCCS operating at high capture rate with biofuel blends can achieve net negative GHG emissions, thus effectively removing carbon from the atmosphere, with biomethanol and biodiesel from UCO being the most advantageous fuels.

In a CCS scenario, the transport and permanent storage of CO_2 after onboard capture add around 9-34 gCO_2eq for each kg of CO_2 depending on the transport distance and location of the permanent storage site. With a 40% gross onboard capture rate applied to an HFO-fuelled ship, about 27% GHG emissions savings can be expected per unit of MJ fuel. Among CCU pathways, utilising CO_2 in building material production, specifically CO_2-cured concrete, offers additional GHG emissions savings. This is due to the permanent binding of CO_2 within the material, which displaces carbon-intensive products and removes additional carbon. With a 40% gross onboard capture rate, nearly 60% savings can be achieved when considering both onboard and onshore emission credits.

If CO_2 is used instead to produce e-fuel for shipping (i.e., methanol), the GHG emissions of both the OCCS ship and the ship using e-methanol will vary depending on the carbon accounting scenario. If the emissions of captured CO_2 are fully accounted to the OCCS ship, its net GHG emissions are around 7% higher than HFO baseline (due to OCCS) while the e-MeOH ship reaches GHG emissions savings higher than 90% since onboard emissions from fuel combustion are not included in the GHG balance. If the captured CO_2 emissions are accounted entirely to the e-MeOH ship, the OCCS ship can claim all the credits generated by the onboard carbon capture. The GHG emissions savings in this case are 28.5% and ~17% for OCCS ship and e-MeOH ship, respectively. If the emissions are equally shared among users, the OCCS ship has minor emissions reduction (11%) compared to HFO baseline, while the e-MeOH ship has ~54% GHG emissions savings. The availability of renewable energy is key for e-fuel CCU scenarios since large amounts of energy are required to produce the hydrogen and to synthesise the e-fuel; however, such availability is highly dependent on local context due to the competition with renewable power users such as industry and tertiary sectors.

The cost of avoided carbon from onboard capture is higher compared to land-based capture applications due to stricter constraints and smaller scale related to the marine environment. The cost of onboard captured CO_2 falls in between the capture cost from industrial flue gas and DAC. The higher the capture rate, the lower the cost of captured CO_2 due to the higher utilisation factor of the plant. The estimated cost of onboard capture and liquefaction is in the range of USD 174-236/tCO_2 captured, for a 40% gross capture rate, based on the estimations of Project REMARCCABLE for the full-scale, N^{th}-of-a-kind installation of OCCS on a tanker ship. Transport and handling of the CO_2 add another USD 29-41/tCO_2 to the cost at the end of the value chain (and before use). The overall cost of avoided carbon for the CCS scenario with permanent storage in depleted reservoir, which considers the CO_2 emitted along the entire value chain (including injection into the reservoir), is expected to lie between USD 269-405/tCO_2. E-methanol produced from carbon which was captured onboard will have a higher cost compared to e-methanol from onshore industrial fossil CO_2 (+25%) and, therefore, would require a higher carbon tax to be competitive with HFO. The combustion of e-MeOH from fossil-sourced CO_2 still produces emissions and could be subjected to carbon taxation. The accounting of the carbon molecule used twice by two different actors is a complex issue, which needs to be addressed from a regulatory perspective if the use of e-fuels from fossil CO_2 is to be fostered.

The results of the study show that OCCS can provide substantial net GHG emissions savings for shipping decarbonisation from a life cycle perspective. The captured CO_2 can be permanently stored or used to generate products that can displace other carbon-intensive processes, such as building materials or fuels. However, CO_2 captured from onboard operations remain more expensive than CO_2 captured from the flue gas of power generation and industry. Therefore, its economic attractiveness for use as input CO_2 material for any valuable product highly depends on specific conditions and local context.

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Appendix

LCA model framework

The following table presents the details of the life cycle analysis steps conducted for this study, as defined in the ISO standards 14040 and 14044 (Table A.1). The ultimate goal of this LCA study is to assess the potential of OCCS technology to reduce the GHG emissions of ships compared to conventional ships that use HFO as fuel without any onboard carbon capture. SimaPro software was used to build the LCA model.

Table A.1 – LCA framework used for the study

LCA step	*Item*	*Description*
Goal	Objective of the study	To evaluate the GHG emissions of ships adopting OCCS technology across the entire value chain, depending on different scenarios of capture technology, fuel used, CO_2 final disposition and to compare it to a defined baseline
	Intended audience	Relevant stakeholders in the onboard captured CO_2 value chain i.e., shipowners, policy makers, marine service providers, utilisation and sink operators
	LCA type	Attributional
Scope	Analysed product/ function	The operation of the ship with OCCS system, including not only the onboard fuel consumption for capture and liquefaction of CO_2 but also chemicals and materials used in the process
	System boundaries	Two main boundaries were selected for this analysis: WtW and carbon value chain. WtW includes: • WtT (fuel production, transport and bunkering) • TtW (onboard fuel combustion) • OCCS chemicals and materials production and transport • OCCS waste management Carbon value chain expands the WtW boundary including: • CO_2 handling, transport and temporary storage after onboard capture • Final disposition of CO_2: permanent storage in reservoir or use to produce materials
	Benchmark (baseline)	HFO-fuelled ship without OCCS
	Functional unit	1 MJ of fuel input, considered as energy required to run the main engine and the auxiliaries of the ship (excluding OCCS)
	Guidelines	• ISO 14044:2006 - Life cycle assessment • IMO Guidelines on life cycle GHG intensity of marine fuels (MEPC 81)

LCA step	Item	Description
Inventory	Data sources	• Primary data (industry survey) • Secondary data (ecoinvent 3.10 LCI database) • Secondary data (literature sources as peer reviewed journal articles and reports published by research centers and international associations)
Impact Assessment	Assessment method	IPCC 2021 – Global Warming Potential (GWP) with 100 years timeframe
	Impact category	Climate change (gCO_2eq)
	Main input/output data considered	• Energy • Raw materials • Chemicals (including fuel)
Interpretation	Limitations of the study	• Analysis is applied to a stationary system (fixed OCCS gross capture rate) and therefore cannot be used as reference for the real operation of a ship • Low reliability of data for OCCS technologies other than MEA-based capture due to lower maturity • Large range of biofuels GHG footprint • Uncertainties related to the impact of products displacement due to the use of CO_2-based products

Onboard vs onshore carbon capture

Capture of carbon dioxide from exhaust gases with amine solvent is a mature technology widely used in industry applications[66]. The adoption of this technology onboard ships is still in development, as many challenges need to be addressed to apply a technology designed and proven for large processing plants on land to ships (Table A.2). Point source capture onshore is more cost-efficient, with lower avoidance costs and less impact than capturing carbon dioxide onboard vessels due to the constraints of operating a system on a vessel in the middle of the sea.

Onboard space availability and weight of OCCS lead to cargo loss and potential stability problems, as well as energy consumption and exhaust pre-treatment, which increase system complexity and require specific equipment arrangement, design and integration[35]. With fewer constraints for land applications, carbon capture systems can be designed more efficiently with a higher cost-reduction potential. OCCS systems, on the other hand, are smaller and harder to operate; thus, the resulting cost is considerably higher than current industrial carbon capture.

The only energy source onboard is the fuel; therefore, the extra energy required for capturing and liquefying the CO_2 must come from burning more fuel in the engine. Considering that hydrocarbon-based fuels of fossil and non-fossil origins (e.g., MGO, HFO, methanol, LNG and biofuels) will play a major role in global shipping fleet operations for the next decades, adoption of the OCCS system is one of the decarbonisation levers to reach international targets. Therefore, a significant amount of research has been carried out to study the technical, economic, and environmental performance and feasibility of OCCS. It is expected that the OCCS lever could reach full maturity by 2030 when the integrated system of capture, liquefaction and onboard storage will be fully developed and tested in the marine environment for several ship types and operational profiles[35]. To analyse the life cycle of the technology, this study made use of data from existing research projects, which were reviewed through feedback from shipping and onshore operators.

Table A.2 – Summary of major OCCS challenges and current areas of research.

Topic	Challenges/barriers	Areas of research
Space and weight constraints	OCCS has large volume and weight requirement due to capture, liquefaction and storage system	Engine room system integration, height of absorption and reclaimer towers
Marine environment	• Large motion and vibration may influence the system performance • Salinity of water increase degradation of materials	Vibration countermeasures Handling of amine
Contaminants in the engine exhaust	Sulphur and dust in the exhaust can degrade the amine solution fast	Novel solvents with lower degradation rate
Capture rate and operations	Onboard proven capture rate achievable is lower compared to onshore	System intelligent design and measurement
Energy consumption	OCCS has high energy requirements for both capture and liquefaction of CO_2	System design and optimisation Heat recovery solutions
Cost	OCCS is expensive and CAPEX is large compared to newbuild cost, depending on vessel's design	Optimisation of capture rate Cost reduction strategies
Infrastructure	CO_2 unloading and handling infrastructure is lacking	Port equipment design and safety
Regulatory framework	Currently there is no framework for assessing and evaluating CO_2 credits from onboard capture in a holistic approach	Accounting strategies LCA of OCCS Inclusion into future international regulations

Project REMARCCABLE

Project REMARCCABLE (Realising Marine Carbon Capture to demonstrate the Ability to Lower Emissions) is a collaborative demonstration project launched in July 2022 between *Stena Bulk*, Global Centre for Maritime Decarbonisation (GCMD), the Oil and Gas Climate Initiative (OGCI), Alfa Laval, Deltamarin, American Bureau of Shipping (ABS), Nederlandse Organisatie voor Toegepast Natuurwetenschappelijk Onderzoek (TNO), Lloyd's Register (LR) and Seatrium. The project aims to design, build and demonstrate carbon capture technology adapted to an MR tanker, *Stena Impero.* A concept and front-end engineering design (FEED) study was carried out for phase 1, investigating the technical and economic aspects of integrating an OCCS system based on MEA absorption on an existing vessel, as well as a newbuild installation.

Stena Impero is an MR Tanker (Figure. A.1), equipped with:

- 1 main engine: 2-stroke MAN 6S50ME-C9.5 (fuel oil, 10 MW rated power)
- 4 auxiliary engines: 2x MAN 6L23/30H (1,050 kW) and 2x MAN 5L23/30H (710 kW)
- 2 auxiliary boilers: 12,500 kg/h steam capacity
- 1 SOx open-loop seawater scrubber: max flow 61,200 kg/h

The conceptual design was derived from stationary carbon capture applications and assumes that the system begins downstream of a retrofitted waste heat recovery unit connected to the engines. The main steps of the capture process are listed as follows in Figure A.2:

1. Exhaust heat recovery: a retrofitted Waste Heat Recovery Unit (WHRU) produces steam for ship utilities and for the reboiler of the capture system
2. Quenching: Seawater is used to scrub the cooled exhaust to remove contaminants and lower the temperature of the exhaust gas to approximately 40°C, a temperature at which carbon dioxide is absorbed in the next stage by MEA.
3. Blowing: A blower compensates for back-pressure induced by the overall system to avoid negative performance impacts on the two-stroke propulsion engine.
4. Absorption: The cooled exhaust gas then enters the absorber column, where it is exposed to the amine sorbent, and carbon dioxide is absorbed into the solution.
5. Water wash: Most of the volatile amine carried out of the absorber is removed from the exhaust gas by the water wash and returned to the column.
6. Heat recovery: The carbon dioxide-enriched amine is then pumped out from the bottom and sent through a heat exchanger to scavenge energy from the carbon dioxide-lean amine returning from the stripper.
7. Stripping: At the bottom of the stripper, the temperature of the amine solution is increased to around 120°C at 2 bar pressure. The reboiler raises part of the amine solution to the boiling point in order to introduce sufficient vapour to strip the carbon dioxide from the solvent.

8. Flashing & cooling (CO_2 extraction): Concentrated CO_2 and water vapour exit the top of the stripper and are then cooled and flashed to remove residual water and amine, which is returned to the main loop. The almost pure gaseous carbon dioxide is then sent to a final quench station where the remaining impurities are removed.
9. Liquefaction & storage: Finally, the CO_2 is sent to a liquefaction system where it is compressed, liquefied and pumped into holding tanks at a pressure of 20 bar.

Figure A.1 – *Stena Impero* (Project REMARCCABLE)

The system was designed with a fixed flow rate, targeting 30% capture, processing the same amount of exhaust gas and removing the same absolute amount of CO_2 across different operating points. The main parameters of the OCCS system are listed in Table A.3. The data of Project REMARCCABLE were taken as a reference for the LCA, with the fuel penalty from the full-scale technology deployment, N^{th}-of-a-kind scenario adopted and validated based on the feedback received from industry partners.

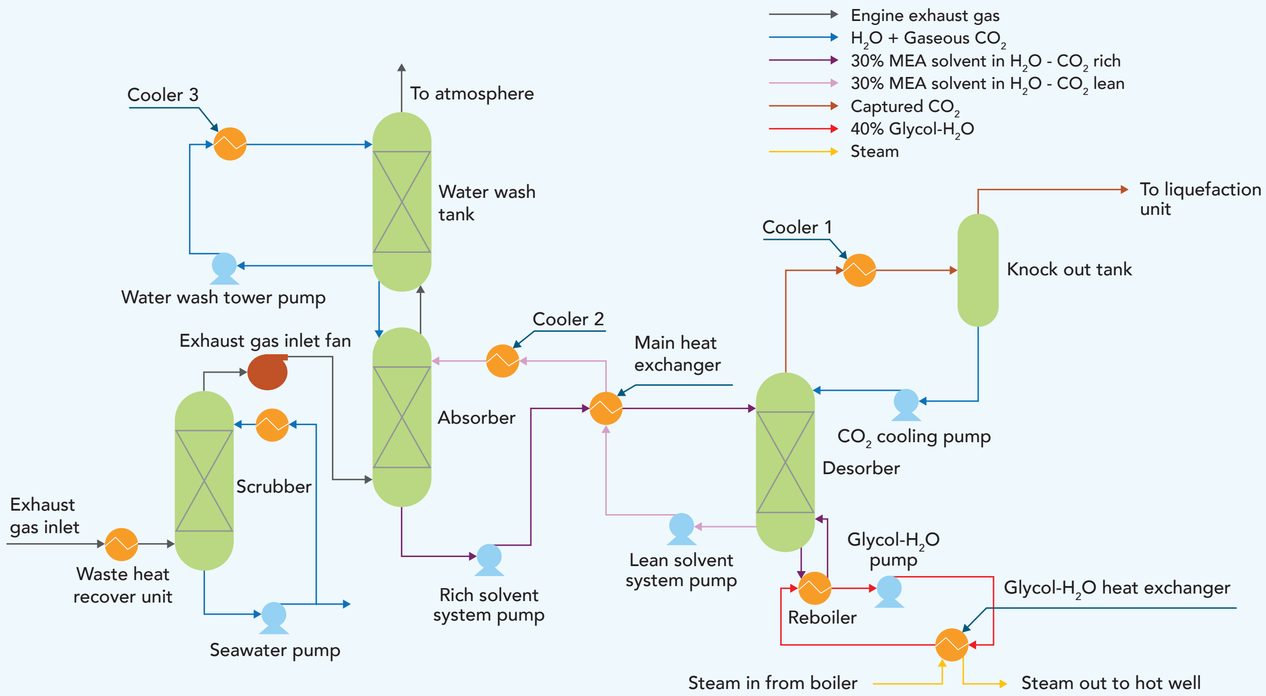

Figure A.2 – Scheme of onboard carbon capture system (Project REMARCCABLE)

Table A.3 – Main parameters of *Stena Impero* OCCS system (Project REMARCCABLE)

Parameter	Amount	Unit
Exhaust flowrate	17,266	kg/h
Exhaust temperature at OCCS inlet	34	°C
Total CO_2 flowrate entering OCCS	1,439	kg/h
Captured CO_2	1,286	kg/h
Capture rate	90%	-
Reboiler temperature	121.7	°C
Heat duty required by reboiler	1,202	kWth
Specific reboiler heat duty	3.5	GJ/tCO_2
Net heat supplied by the boiler	2.3	GJ/tCO_2
Average heat recovery	34.5%	-
Specific electricity demand of capture	39	kWh/tCO_2
Specific electricity demand of liquefaction	117	kWh/tCO_2
Total electricity demand	156	kWh/tCO_2
Total MEA in the system	1.8	t
MEA continuous make-up	1.5	kg/tCO_2
MEA replacement rate	6	months

Acknowledgements

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ABOUT THE GLOBAL CENTRE FOR MARITIME DECARBONISATION (GCMD)

The Global Centre for Maritime Decarbonisation (GCMD) was established as a non-profit organisation on 1 August 2021 with a mission to support the decarbonisation of the maritime industry by shaping standards, deploying solutions, financing projects, and fostering collaboration across sectors.

Founded by six industry partners namely BHP, BW Group, Eastern Pacific Shipping, Foundation Det Norske Veritas, Ocean Network Express and Seatrium, GCMD also receives funding from the Maritime and Port Authority of Singapore (MPA) for qualifying research and development programmes and projects. Since its founding, bp, Hanwha Ocean, Hapag-Lloyd and NYK Line have joined as Strategic partners. To-date, over 130 centre- and project-level partners have joined GCMD, contributing funds, expertise and in-kind support to accelerate the deployment of scalable low-carbon technologies and lowering adoption barriers.

Since its establishment, GCMD has launched four key initiatives to close technical and operational gaps in: deploying ammonia as a marine fuel, developing an assurance framework for drop-in green fuels, unlocking the carbon value chain through shipboard carbon capture and articulating the value chain of captured carbon dioxide as well as closing the data-financing gap to widen the adoption of energy efficiency technologies.

GCMD is strategically located in Singapore, the world's largest bunkering hub and busiest transshipment port. For more information, go to www.gcformd.org

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