An end-to-end trial reveals that on-board carbon capture works – and how it can work better

Closing the loop(s)

by Ewa Kochańska

Project CAPTURED, conducted last year by the Global Centre for Maritime Decarbonisation, produced the world's first end-to-end demonstration of a maritime carbon value chain based on real operational data. By capturing CO_2 on a container vessel, then transferring and transporting it across ship and land for utilising in industrial processes, the study attempted to prove the technical and operational viability of linking ship-based carbon capture with downstream utilisation. The project took into account energy penalties and different CO_2 end pathways to produce various life cycle assessment (LCA) scenarios for on-board carbon capture and storage (OCCS) options.

The study's objective was to find out if OCCS can be connected to industrial use on land, cutting emissions from shipping in the mid-term on the path to a long-term zero-carbon maritime future. OCCS' real climate value becomes clear when emissions are measured across the entire carbon chain – from fuel production through capture, transport, and final use or storage of the CO_2 Therefore, an LCA is essential to show whether reductions achieved on board are genuinely beneficial or simply shifted elsewhere.

The study was conducted in June 2025. First, CO_2 was captured on board Evergreen's container carrier *Ever Top* (368-by-51-metre, gross tonnage of 146,700, 13,808-TEU capacity) on her way from Port Klang to Yangshan Deepwater Port, using a full-scale amine-based carbon capture system. In Shanghai, the captured CO_2 was liquefied and ship-to-ship (StS) offloaded to another vessel, *Dejin 26*. Next, the liquefied CO_2 was transferred from ship to truck (StT) in Zhoushan (Zhejiang Province). It was then transported by road for over 2,200 kilometres to Baotou (Inner Mongolia). Finally, at Baorong Environmental's facility, the CO_2 was used as an input to recycle steel slag, producing post-carbonated slag (PCS) and low-carbon precipitated calcium carbonate (PCC). The produced PCC was marketed as a high-value additive for use in paper, coatings, plastics, and construction products, while the PCS was reused as sintering feedstock at a nearby steel plant (beyond steelmaking, PCS could in theory serve as a supplementary material in concrete to reduce cement use, although the underlying chemistry of cement production places practical limits on how far this substitution can go).

Same CO_2 – different math

The study examined several life cycle scenarios to understand what actually happened during the pilot and what could happen if the system was improved and scaled. Each scenario represents a different way the captured CO_2 could be handled and assessed.

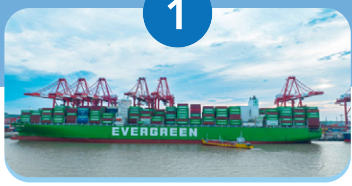
Scenario 1 reflects the real pilot as it was carried out. The CO_2 was captured on *Ever Top* and eventually mineralised at Baorong's plant, where it was turned into PCS and PCC. The former was sent back to the steel plant that originally produced the slag and reused in the sintering process, reducing the need for fresh iron ore, limestone, and dolomite. In turn, the latter replaced the conventional PCC used in construction materials, chosen specifically because this use ensures the CO_2 remains locked away for the long term. To measure the climate impact, the

Fig. 1. Demonstration of the world's first end-to-end carbon value chain for onboard captured CO_2

The sequence of events

The journey

1



Port of Rotterdam

The *Ever Top* began its voyage

2

Port Klang to Yangshan Deepwater Port

SMDERI-QET's OCCS system was activated

- *CO_2 captured and stored enroute from Malaysia to China*

3

Yangshan Deepwater Port

The *Ever Top* moored at berth with the *Dejin 26* for StS transfer

- *25.4 MT of captured CO_2 offloaded*

4

Yangshan Deepwater Port to Zhoushan

The *Dejin 26* in transit

- *CO_2 samples collected for quality testing at all transfer points*

5

Huihao jetty, Zhoushan

Captured CO_2 offloaded from the *Dejin 26* to a tank truck

- *CO_2 reclassified from "hazardous waste" to "hazardous cargo"*

6

Zhoushan to Baotou

The tank truck transported captured CO_2 overland

- *Travelled 2,200 km across several provinces*

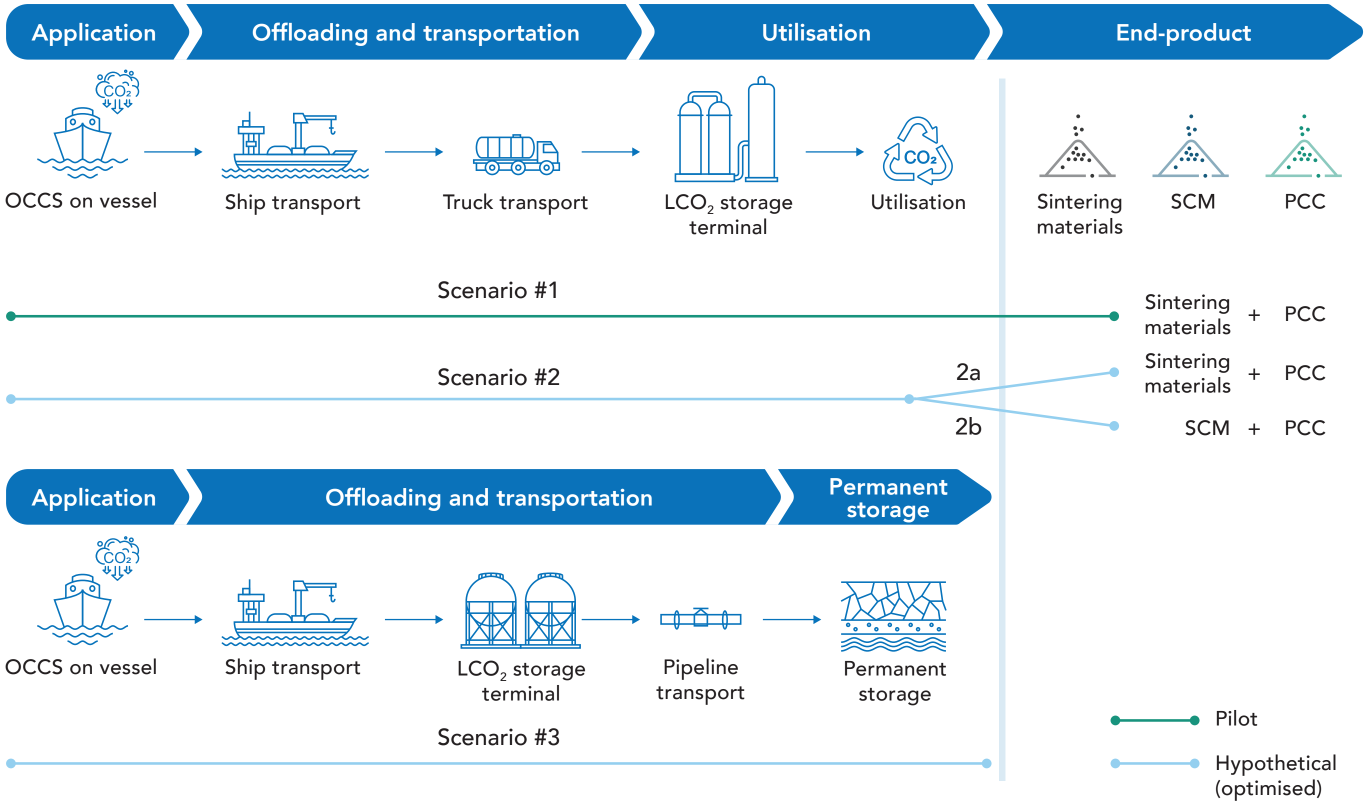
7

Baotou

Baorong used captured CO_2

- *First demonstration of using onboard captured CO_2 as feedstock*

Fig. 2. LCA scenarios considered in the Project CAPTURED study



analysis compared this setup with a reference case where no on-board capture takes place and conventional materials are produced instead. The emissions savings come from avoiding the production of those conventional materials.

Scenario 2 is a 'what-if' case that assumes the whole chain works more efficiently than in the pilot. It removes the operational inefficiencies observed in Scenario 1 and also assumes shorter transport distances for CO_2. This scenario is split into two options. In 2a, the PCS is still used in steel sintering, as in the pilot, but under optimised conditions. In 2b, it is instead used as a supplementary material in concrete, partially replacing cement, which could further reduce emissions from cement production.

Scenario 3 looks at a completely different endpoint. Instead of using the captured CO_2 in production, it is transported and permanently stored in an offshore geological reservoir. Because no products are made in this case, there are no emissions savings from replacing conventional materials. The assessment focuses only on the emissions directly associated with capture, transport, and storage.

In addition, two different LCA approaches were applied depending on the scenario. Consequential LCA was used where products made from captured CO_2 replace conventional ones, as it captures wider system effects and avoids emissions. Attributional LCA was used to examine the carbon footprint of individual parts of the chain, such as the ship or the Baorong plant, and to compare CO_2-based products with their conventional equivalents. For products made at Baorong's facility, emissions were shared between PCC and PCS based on their market value.

Also, the mineralisation process relies on steel slag, which is a by-product of steelmaking and is mostly unused in China, often ending up in stockpiles that can cause environmental problems. To keep the study focused, steelmaking itself was not included in the system boundary. Instead, steel slag was treated as a low-value by-product with an assigned share of the steel plant's emissions, calculated using an economic allocation method.

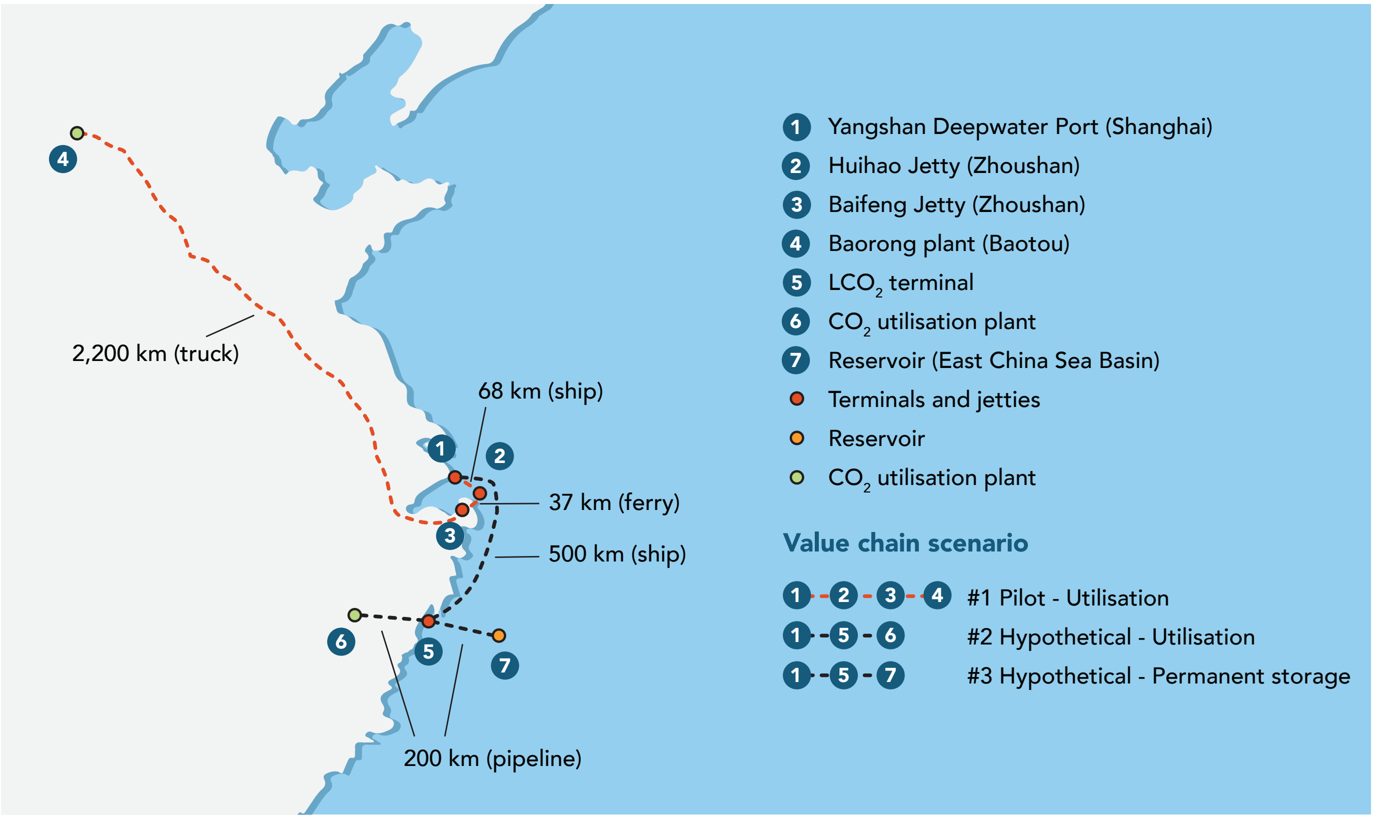
Finally, the analysis was based on real-world operational data wherever possible. Measurements from ship trials, CO_2 offloading, transport, and utilisation during the pilot were combined with recognised life cycle databases and published literature to fill any gaps. Standard Intergovernmental Panel on Climate Change climate factors were used to calculate emissions, and the quality of the data was checked and independently verified.

Slips in the chain

Operational data for the OCCS aboard *Ever Top* were collected during a sea trial to check performance under real conditions. It showed that the system captured about 10.7% of the vessel's CO_2 while operating continuously, using an advanced amine solvent. Steam for solvent regeneration was supplied by an auxiliary boiler burning marine gas oil, while electricity for capture and liquefaction came from generator sets running on heavy fuel oil. As is typical for amine-based systems, solvent degradation required periodic addition of fresh amine, and the process produced two outputs: liquefied CO_2 stored on board and a corrosive waste sludge that had to be landed ashore for incineration.

Transferring the liquefied CO_2 from ship to shore also caused issues. CO_2 was vented during hose purging and after transfers to avoid contamination and dry ice formation, with further emissions arising from fuel and electricity use by ships, trucks, pumps, and the Baorong plant. Although the StS transfer relied on pressure differences rather than pumps, pumping was required for StT transfer and again at the plant. Some CO_2 also remained trapped as liquid heel or vapour in tanks during cooling and transport.

Fig. 3. Value chain scenarios included in the LCA



Even though this CO_2 was not released to the atmosphere, it was treated as lost to the value chain because it never reached the end-user.

At Baorong's facility, the CO_2 was mineralised using steel slag from a nearby steel plant. After vaporisation, the CO_2 reacted with the slag to form PCC and PCS. The assessment considered plant energy use, start-up and shut-down phases, reagents, fuel gas for drying, and supporting operations such as slag grinding and wastewater treatment. Based on mass balance, around 65% of the incoming CO_2 was permanently fixed in the products, while the remaining 35% was released during processing. The low-carbon PCC was compared to a conventional limestone-based one, with laboratory testing confirming comparable quality.

The study also followed the CO_2 mass at each transfer step. Of the 25.4 tonnes offloaded from *Ever Top*, losses during StS and StT transfers reduced the amount reaching Baorong to 15.8t, with only 10.3t ultimately fixed into products. About 2.4t were released during transport and handling, while more than 7.0t remained trapped in tanks along the chain. These results highlight how critical tank conditioning, transfer efficiency, and filling practices are for on-board carbon capture to deliver meaningful climate benefits.

Piloting optimisation

The study looked at how the full CO_2 value chain performed in practice during the pilot and how it could improve if optimised. For the pilot case, the results were independently verified by DNV and reflect what actually happened on board *Ever Top* and downstream.

With the OCCS system capturing 10.7% of the ship's exhaust CO_2, the net greenhouse gas reduction of the entire chain was 7.9% vs normal ship operation. This modest gain was largely due to the capture system having to rely on additional fuel for heat and power (no exhaust heat recovery was installed). As a result, the fuel penalty was around 5.0%, and more than half of the potential emissions savings from captured CO_2 were used up by the energy required to run the system. Almost all of these operational emissions came from extra fuel use, with only a small share linked to solvent production and waste handling. In well-to-wake terms, capturing one tonne of CO_2 avoided about 420 kilograms of emissions.

Offloading and transport turned out to be a major weak point in the pilot. By the time the liquefied CO_2 reached the Baorong plant, emissions from moving it had almost cancelled out the benefits of capturing it. The longest leg – the 2,200+ km truck journey (that's roughly the distance between Gdańsk and Barcelona) – accounted for more than half of all transport-related emissions. Another big issue was venting during transfers, especially from leftover liquid CO_2 in hoses. In addition, the receiving vessel burned a relatively large amount of fuel to transport a small batch of CO_2, which increased emissions per tonne moved (a purpose-built CO_2 carrier would have a payload of roughly 3,500-4,000 tonnes per voyage). At the utilisation stage, turning CO_2 into PCC and PCS also generated emissions, mainly from reagent supply, electricity use at the plant, and the fraction of CO_2 that was not fixed and escaped during processing.

Even so, the products made from captured CO_2 displaced conventional PCC and sintering materials. According to Project CAPTURED, these avoided emissions more than compensated for the emissions from the mineralisation process itself. PCC delivered the largest benefit because conventional PCC production from limestone is highly carbon-intensive. Overall, when capture, transport, and utilisation were all considered together, each tonne of CO_2

Tab. 1. LCA results of the hypothetical value chain[1, 2, 3]

Optimised section of the value chain	Optimised parameter	Default value/ condition	Optimised value/ condition	Unit	Description	GHG emissions ($kgCO_2eq/tCO_2$)				
						OCCS	Offloading and transport	Utilisation	Total value chain	Variation relative to pilot
Total value chain (pilot)	No parameter is optimised	-	-		Pilot value chain (Scenario 1)	582	375	951	**1,908**	**0%**
OCCS	Reboiler heat demand	2.8	0	GJ/tCO_2	At 10.7% gross capture rate, reboiler heat is supplied by WHRS	187	375	951	**1,512**	**-21%**
Offloading and transport	Venting losses	• Liquid phase in the pipes • Two StT transfers	• Vapor phase in the pipes • One StT transfer	-	• Considering whether liquid- or vapor-phase CO_2 is left in the liquid line after offloading • Considering one StT offloading instead of two	582	277	951	**1,810**	**-5%**
	Ship transport (CO_2 offloaded mass)	25.4	525.0	MT	Corresponding loading factor in the *Dejin 26* tank: 95%.	582	342	951	**1,875**	**-2%**
	Ship transport (distance)	67	500	km	Considering an offloading port close to utilisation plant					
	Land transport (method)	Truck	Pipeline	-	Pipeline is the most common way to transport CO_2 in a well-established value chain	582	182	951	**1,715**	**-10%**
	Land transport (distance)	2,200	200	km	Assuming CO_2 utilisation plant is located in the same region of the offloading port					
	Hypothetical transport value chain	All the above, for offloading and transport		-	Considering all the sensitivity variations above for offloading and transport value chain	582	50	951	**1,583**	**-17%**
Utilisation	Electricity grid carbon factor	0.565	0.191	$kgCO_2eq$/ kWh	Low-carbon/ high-efficiency grid electricity in China (Chen *et al.*, 2023)	582	375	756	**1,713**	**-10%**
	CO_2 losses in the process	35%	10%	-	Considering 90% CO_2 mineralisation efficiency (Lee *et al.*, 2023)	582	375	795	**1,752**	**-8%**
	Hypothetical CO_2 use	All the above, for utilisation		-	Considering both electricity and CO_2 losses for CO_2 utilisation	582	375	601	**1,558**	**-18%**
Total value chain (hypothetical)	All parameters are optimised	All the above, for the total value chain		-	Hypothetical value chain (Scenario 2)	187	50	601	**837**	**-56%**

[1] *Orange denotes the changes in GHG emissions with the application of hypothetical values.*
[2] *GHG emissions are expressed per MT of CO_2 captured and offloaded from the Ever Top.*
[3] *Credits for captured CO_2 and avoided emissions from displaced products are not included.*

captured resulted in about 840 kg of emissions being avoided, giving the net 7.9% reduction observed for the pilot.

The study then explored what would happen if the value chain elements were properly optimised. A key improvement would be recovering waste heat from the ship's exhaust and engine jacket water to supply the capture system. In theory, this heat could fully cover the reboiler demand, sharply cutting the fuel penalty and the associated emissions. Road transport is another area for improvement, as replacing long-distance trucking with a shorter pipeline connection would almost eliminate emissions from CO_2 overland transport. Better hose draining, single-step transfers, and improved tank pre-conditioning would also reduce venting losses to insignificant levels. Moving larger CO_2 volumes that match the capacity of the transport vessel would further improve efficiency and lower emissions per tonne transported.

On the utilisation side, higher mineralisation efficiency and cleaner electricity at the plant would further improve performance. When all these measures are combined, emissions from offloading and transport drop dramatically, and the overall value chain emissions decrease by over 50% compared with the pilot. Under these optimised conditions, net greenhouse gas savings increase from 7.9% to nearly 18% at the same capture rate.

The analysis finds that using captured CO_2 to make PCC and PCS reduces emissions more than just storing the CO_2 permanently. With a 40% capture rate, permanent storage can cut emissions by about 21% compared to a ship without OCCS. But using CO_2 in production can achieve even greater reductions – up to 70% with an optimised value chain (depending on whether PCS is used in steel sintering or as a cement substitute). This shows that system design, waste heat recovery, and downstream logistics are key to making on-board carbon capture effective.

Carbon accounting

The Project CAPTURED report underscores some challenges when it comes to emission reporting under current laws and regulations. From a regulatory point of view, greenhouse gas accounting in shipping is still mostly attributional, which means that emissions are assigned step by step rather than after considering wider system effects. When on-board carbon capture is added, this accounting boundary has to extend beyond the ship to include what happens to the captured CO_2 afterwards. If the CO_2 is permanently stored, it can be treated as a waste stream from fuel combustion, and the shipowner simply accounts for the emissions from transporting and storing it. Utilisation is more complicated because the CO_2 becomes a raw material for another industry, making it harder to decide whether the ship burning the fuel or the plant using the CO_2 is the 'owner' of the emissions and/or any emission savings.

Looking at the results from the shipowner's perspective helps illustrate this problem. Using attributional LCA and real pilot data, on-board capture with utilisation actually increases reported emissions, because the emissions from CO_2 processing are counted – but the avoided emissions from displaced products are not. Even with an optimised value chain, the savings are marginal. If the system boundary is narrowed to ship operations plus CO_2 offloading and transport, the picture improves, and the emissions reduction is similar to that of a permanent

Fig. 4. Accounting for GHG emissions from OCCS along the carbon value chain

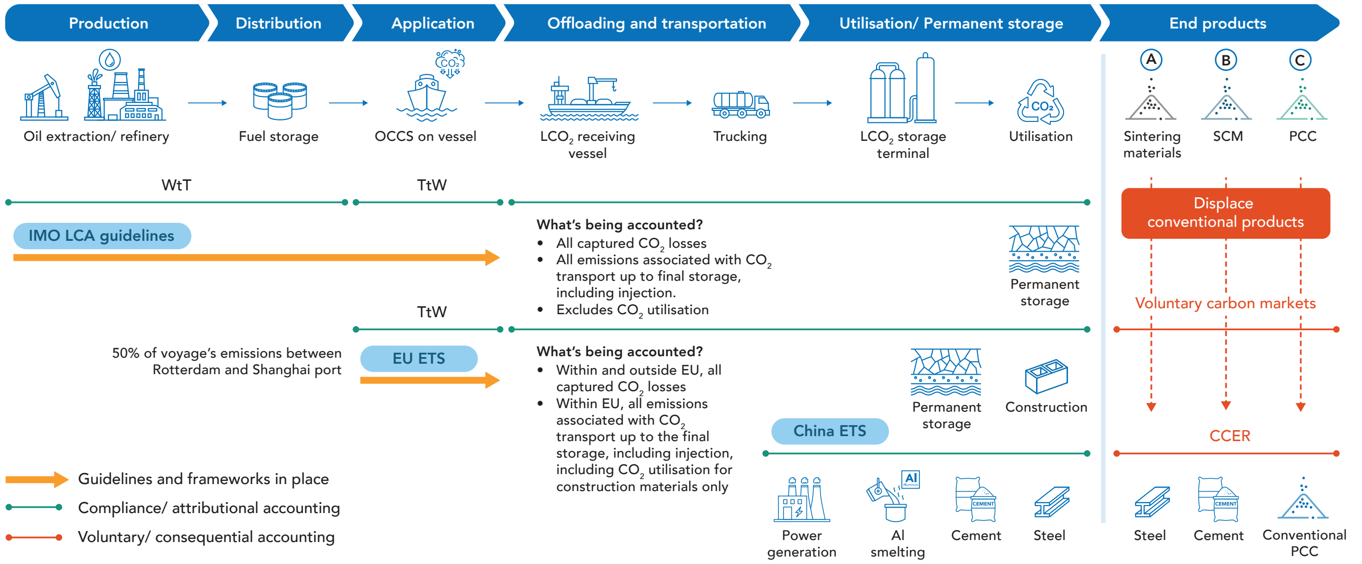
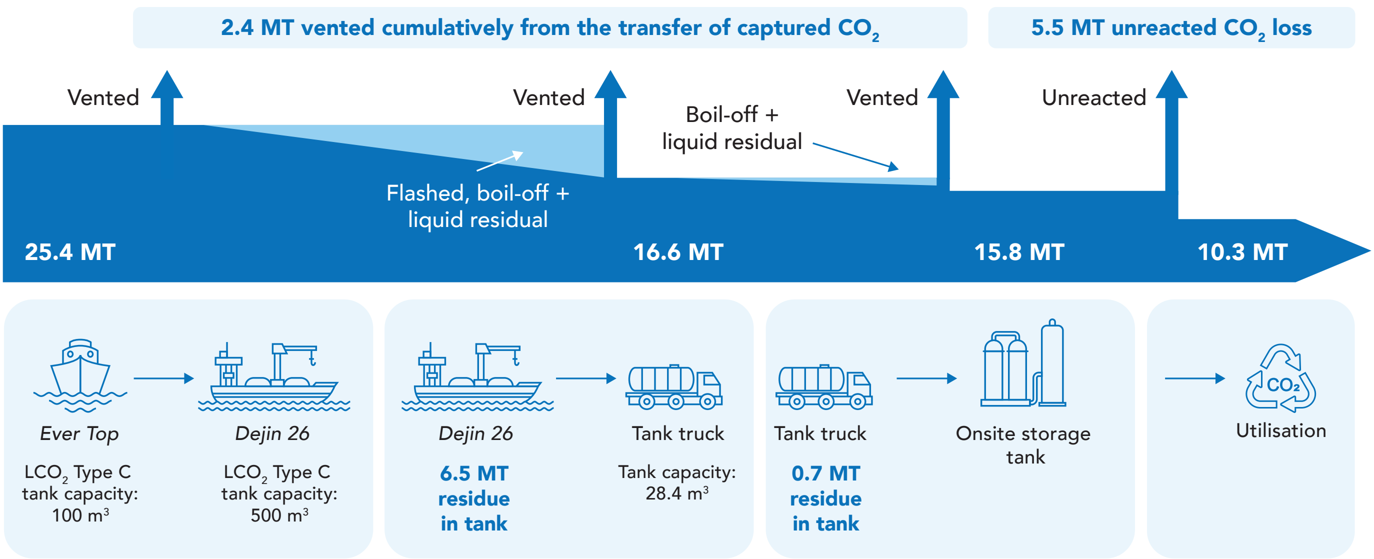


Fig. 5. Mass balance of offloading, transport and utilisation of LCO_2



storage pathway. When capture rates are higher, this contrast becomes even more obvious. Permanent storage consistently reduces reported emissions, all the while utilisation pathways appear to increase them under attributional rules, even though they deliver real-world benefits when assessed consequentially. This points to a mismatch between current International Maritime Organization-style accounting and how CO_2 utilisation actually works in practice.

From the CO_2 user's perspective, attributional LCA is more familiar and is used to compare product footprints. At Baorong, PCC made from captured CO_2 has a significantly lower carbon footprint than conventional PCC, and this advantage becomes much larger if credits for captured CO_2 are included. PCS, on the other hand, has a higher attributed footprint than the materials it replaces, even when CO_2 credits are applied, largely because of the energy and materials needed for mineralisation.

In the end, assigning emissions and credits across the CO_2 value chain involves multiple parties, from shipowners to end-users, and how these impacts are shared will depend on future regulations and contractual arrangements designed to prevent double-counting.

Room for improvement

Project CAPTURED supplied real-world data that combining OCCS with CO_2 utilisation delivers greater emissions benefits than permanent storage. Although emissions from capture, offloading, and transport are substantial, they are offset by avoided emissions from replacing very-high-carbon-footprint conventional PCC and sintering materials.

The pilot analysis shows opportunities to improve performance, particularly by recovering waste heat on board, reducing CO_2 losses during transfer, moving larger CO_2 volumes over shorter distances, and improving utilisation efficiency. According to the Global Centre for Maritime Decarbonisation's project, when these improvements are combined and capture rates rise to 40%, total emissions savings could reach around 68-71% compared with a conventional ship powered by heavy fuel oil. □