Decarbonization technologies in merchant shipping

Pathways for fast implementation and scaling

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Executive summary

In the context of the International Maritime Organization's (IMO) revised greenhouse gas (GHG) strategy for international shipping, this paper explores the pathways to fast implementation and scaling of decarbonization technologies in merchant marine shipping. The IMO's strategy consists of four key elements, including ambitious emission reduction targets, indicative checkpoints, midterm measures, and a well-to-wake approach to prevent emissions from shifting to other sectors.

The paper assesses the impact of energy-efficiency technologies on merchant marine ships, such as energy-saving devices, wind-assisted propulsion, air lubrication systems, waste heat recovery, and more, to gauge their potential for achieving compliance with the IMO's GHG strategy. It also evaluates various propulsion technologies, including two-stroke engines, fuel cells, and batteries, for different ship types and highlights their yearly CO_2 equivalent abatement potential and associated abatement cost.

Key findings include:
- Ammonia and methanol engines are among the most cost-effective options for decarbonizing merchant marine ships.
- Fuel cells offer significant CO_2 equivalent abatement potential, but come with higher costs and are still at a low technology readiness level for merchant marine implementation.
- Onboard carbon capture may only act as a temporary compliance measure and is insufficient for achieving net-zero emissions by 2050.
- Dual-fuel engines combined with energy-saving technologies should be considered for newbuildings, and this trend is expected to solidify as 2050 approaches.
- Existing ships may require dual-fuel engine conversions or energy-efficiency retrofits depending on their age and operational patterns.

The maritime industry has begun transitioning toward decarbonization technologies, with the sector scaling up its efforts to meet the IMO's emissions reduction targets. The paper underscores the need for ongoing innovation and collaboration across sectors to achieve more ambitious climate goals in the future.

A new direction from the IMO calls for a renewed focus on the implementation of decarbonization technologies

In the summer of 2023, the International Maritime Organization (IMO) revised and adopted its greenhouse gas (GHG) strategy, governing emissions of international seagoing transport. There are four main elements:

First, the levels of ambition. GHG emissions from international shipping are to peak as soon as possible and reach net zero by or around 2050, i.e. close to 2050, taking into account different national circumstances and being consistent with the long-term temperature goal set out in Article 2 of the Paris Agreement. Uptake of zero or near-zero GHG emission technologies, fuels, and/or energy sources are to represent at least 5%, striving for 10%, of the energy used by international shipping by 2030. Concerning carbon intensity, the goal is to reduce CO_2 emissions per transport work, as an average across international shipping, by at least 40% by 2030, compared to 2008.

Second, indicative checkpoints. The revised GHG strategy sets the absolute reduction targets for total annual GHG emissions from international shipping, compared to 2008, to at least 20%, striving for 30% by 2030 and at least 70%, striving for 80% by 2040.

Third, midterm measures. There is general support for a low GHG fuel standard (similar to FuelEU Maritime), and a GHG levy is still on the table. Midterm measures should take into account well-to-wake GHG emissions of marine fuels. The details of the midterm measures are to be developed, and they are expected to enter into force in the first half of 2027.

Fourth, a well-to-wake approach. The levels of ambition, indicative checkpoints, and midterm measures should take into account well-to-wake GHG emissions with the objective of preventing a shift of emissions to other sectors. To support this approach, the first version of IMO's life-cycle assessment guidelines was adopted.

With the revised GHG strategy comes a renewed focus on the decarbonization of international shipping for compliance and beyond. In this paper, we assess the GHG effect of energy-saving technologies on merchant marine ships and how far the technologies can take the ship types toward compliance. We also assess various propulsion technologies for use in three merchant marine ship types to make transparent the inherent differences in abatement of absolute yearly CO_2 equivalents[1] (CO_2e) and the associated abatement cost per tonne abated CO_2e. The purpose of the paper is to contribute to decarbonization discussions concerning propulsion technologies for the merchant marine to accelerate the implementation of decarbonization measures.

[1] CO_2 equivalents include carbon dioxide, methane, as well as nitrous oxide, all at Greenhouse Warming Potential 100

Energy-efficiency improvements can take us some of the way to compliance with IMO's revised GHG strategy, but not all the way

To assess and compare the possible GHG reduction effects of technologies, we draw on the IMO Data Collection System (DCS) and EU Monitoring, Reporting and Verification (MRV) data. The two data sets are combined to establish CO_2 emissions from the predominant merchant marine ship segments, i.e. container vessels, tankers, bulk carriers, and LNG carriers. Common for these two databases is that they include the actual fuel consumption of ships, which is particularly interesting in a decarbonization perspective because it gives an indication of the saving potential compared to the actual fleet. This basic data is supplemented with predictions[2] until 2050 to enable an assessment of future CO_2 emissions of the ship segments.

Various technologies can be implemented on the ships to reduce CO_2 emissions by increasing energy efficiency:
- Energy-saving devices can take many forms, for example, high-efficiency propellers in combination with a rudder bulb have been shown to yield around 8% savings – the assessment in Fig. 1 considers these savings already applied on container vessels[3]
- Wind-assisted propulsion can lead to around 5% savings on ship types where mounting sails is possible
- Air lubrication systems can lead to around 5% savings for large, flat-bottomed ships where air bubbles reduce the hull's frictional resistance
- Waste heat recovery on the propulsion plant can lead to around 5% savings
- EcoEGR can lead to around 2% savings
- Installing a power take-off system on the propulsion plant, leading to ship-type-specific savings
- Speed optimization, leading to ship-type-specific savings
- Finally, alternative fuels can lead to different savings, depending on the type of fuel, see Table 1.

Feedstock	Fuel type	Well-to-tank	Tank-to-wake	Well-to-wake	Greenhouse warming potential relative to HFO (%)
Fossil	Hydrogen (natural gas)[a]	132.0	0.0	132.0	144
Fossil	Ammonia (natural gas)[a]	121.0	0.0	121.0	132
Fossil	Methanol (natural gas)[a]	31.3	69.1	100.4	110
Fossil	HFO[a]	13.5	78.1	91.6	100
Fossil	LNG (medium Otto cycle)[a]	18.5	72.6	91.1	99
Fossil	LNG (large Otto cycle)[a]	18.5	65.4	83.9	92
Fossil	LNG (large Diesel cycle)[a]	18.5	57.7	76.2	83
Fossil	LPG[a]	7.8	65.5	73.3	80
Liquid biofuels	Bio-diesel (waste mix)[b]	-26.1	77.5	51.4	56
Liquid biofuels	Bio-LNG[b]	-38.9	57.7	18.8	21
e-fuels	e-methane (large Diesel cycle)[c]	-52.1	57.7	5.6	6
e-fuels	e-methanol[b]	-67.1	71.6	4.5	5
e-fuels	e-hydrogen[a]	3.6	0.0	3.6	4
Liquid biofuels	Bio-methanol[c]	-69.1	71.6	2.5	3
e-fuels	e-ammonia[a]	0.0	0.0	0.0	0

Table 1: CO_2 emission factors in gCO_2e/MJ for merchant marine fuels and their greenhouse warming potential relative to heavy fuel oil ([a]FuelEU Maritime, [b]IMO[4] , [c]Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping)

[2] Predictions until 2024-5 are based on World Seaborne Trade from Clarkson Shipping Intelligence Network whereas predictions beyond 2024-5 are based on DNV's Maritime Forecast to 2050 in the Energy Transition Outlook 2022 report
[3] Nielsen, Jens Ring, Shin K.W., Lundgren, E., Faghani, F.; Combined Kappel propeller and rudder bulb system for improved propulsion efficiency, Motorship Conference 2012, Hamburg, Germany
[4] IMO, "Development of draft lifecycle GHG and carbon intensity guidelines for maritime fuels (draft LCA guidelines) ISWG-GHG 11/2/3," 2022. [Online]. Available: https://www.ics-shipping.org/wp-content/uploads/2020/08/ draft-life-cycle-ghg-and-carbon-intensity-guidelines-for-maritime-fuels-1.pdf [accessed 13 Oct. 2022].

The predicted total CO_2 emissions per ship segment, the required energy-efficiency reduction, and the possible reductions by means of energy-saving devices are shown in Fig. 1. The required energy-efficiency reductions are associated with Energy Efficiency Design Index (EEDI) Phase III, which will enter into force in 2025 for new ships. It is assumed that compliance with EEDI phase III is attained by a reduction of the installed power. Compared to the average ship in the fleet, EEDI phase III requires savings of 5% for container vessels, 27% for bulk carriers, 32% for tankers, and 34% for LNG carriers.

On top of the required reductions, additional reductions can be achieved with energy-saving technologies. The savings from energy-efficiency technologies on top of the EEDI-required savings are determined to 25% for container vessels, 18% for bulk carriers, 18% for tankers, and 26% for LNG carriers – all for the average ship in each segment. Therefore, by considering EEDI Phase III compliance attained by a power reduction and energy-efficiency increasing technologies, the assessment shows that energy savings can lead to a CO_2 reduction of approx. 30% for container vessels, approx. 45% for bulk carriers, approx. 50% for tankers, and approx. 60% for LNG carriers compared to the present average fleet.

The reductions are achieved by implementing all relevant energy-saving technologies to the respective ship segments and reducing speed to an optimum, considering onboard power consumption, a relative increase of added wave resistance, and more ships required to perform the same transport work. The variance in reduction potential between ship segments arises mainly from a different potential of speed reductions, considering the above-mentioned factors.

The average lifetime of a ship in the merchant marine is approx. 25 years, and therefore, a ship contracted today must be able to reach net-zero operation by or around 2050. Alternatively, on the way to 2050, a ship on fossil fuels could possibly pay a currently unknown carbon levy, but in 2050 and beyond, net-zero operation is required, and on top of this there will be risks concerning other penalties or geographical prohibitions for fossil-fueled ships on the way to 2050. This leads to the conclusion that some alternative fuel capability is required for newbuildings already today. Based on Fig. 1 and Table 1, it is clear that all fuels based on fossil feedstock combined with all relevant energy-saving devices are not sufficient to reach net zero. Bio-LNG, bio-methanol, and bio fuel oils can be used in the transition towards carbon neutrality, but e-fuels will be needed to obtain carbon-neutral or carbon-free transportation. Owing to the current scarcity of synthetic fuels, the energy-saving technologies are required for accelerating and scaling the decarbonization implementation in shipping as well as ensuring reductions until e-fuels are available at the required scale.

Existing ships will need evaluations of their options for compliance, which depends on their lifetime, as regulations are foreseen to tighten through currently unknown intermediate measures as the year 2050 approaches. For some ships, energy savings may be sufficient for compliance in intermediate periods, however, some will require retrofitting to a fuel that leads to compliance, while others will rely on advanced bio-fuels. Of course, this should be compared to the alternative – paying the levy – which may be relevant for some ship types and ships of a certain age, as opposed to a retrofit. Ship-by-ship business cases are required to make an evaluation.

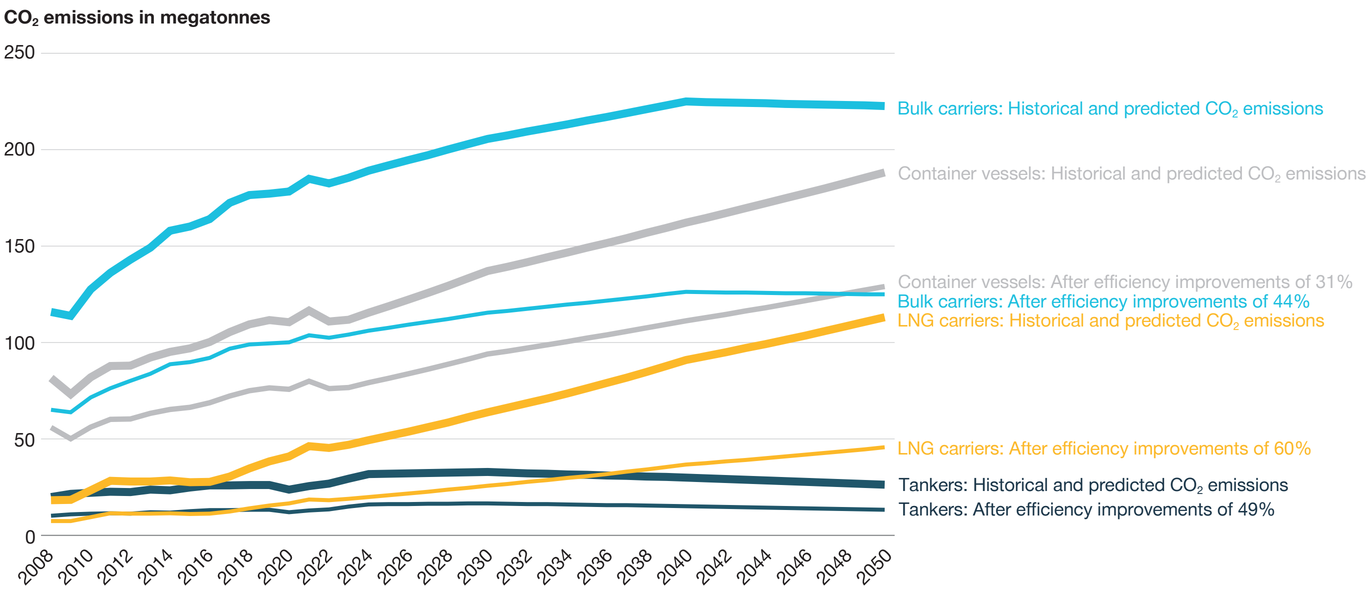

Fig. 1: Predicted total CO_2 emissions (not equivalents) and emissions after possible efficiency improvements of ship segments in the merchant marine

Absolute yearly abatement and the associated abatement cost

Whereas the previous section focused on energy-saving technologies, this section focuses on propulsion technologies. There are inherent differences in (1) the absolute yearly abatement potential and (2) the cost per tonne abated CO_2e across technologies as well as across ship types. In the following, we assess these two dimensions for three high-volume ship types in the merchant marine: a New Panamax container vessel, a 2,000 teu feeder vessel, and a Kamsarmax bulk carrier (see Fig. 2). For each ship type, we show variations in yearly abatement potential as well as the abatement cost of the following propulsion technologies, using a two-stroke engine running on heavy fuel oil (very-low-sulphur fuel oil for 630 $ per tonne) as benchmark (abbreviated 2S VLSFO on Figs. 3-5). In the assessment, we have combined the propulsion technologies with fuels that reduce CO_2 emissions compared to HFO.

Two-stroke engines
The assessment includes dual-fuel two-stroke engines running on, respectively, synthetic methanol (2S e-MeOH), synthetic methane (2S e-methane), and synthetic ammonia (2S e-NH_3). The two-stroke dual-fuel technology for methanol and methane is at technology readiness level (TRL) 9 – actual system proven in operational environment – whereas ammonia is currently at TRL4 – technology validated in lab – with a view to TRL9 in or around the year 2025, based on successful full-scale two-stroke tests. To maximize the CO_2 abatement, these three engines can be supplemented with power take-off, waste heat recovery, and synthetic pilot oil injection (PTO WHR e-PO). Also included is a dual-fuel two-stroke engine running on LNG (2S LNG), and an LNG engine with power take-off, waste heat recovery, and synthetic pilot oil injection (2S LNG PTO WHR e-PO) with the purpose of increasing the efficiency of the engine while gaining the approx. 17% CO_2 emissions advantage from LNG over HFO on a well-to-wake basis for a diesel-cycle engine. The TRL for all LNG propulsion system elements included is 9.

Two-stroke engines with onboard carbon capture
An onboard carbon capture and storage system could be combined with a two-stroke engine running on, for example, LNG (2S LNG CCS) or ultra-low-sulphur fuel oil (2S ULSFO CCS) – ULSFO is considered as minimizing amine degradation in the CCS plant. The onboard carbon capture technology is currently at TRL5-6 and has been validated on board a ship, and a technology pilot is being or has been demonstrated. The onboard carbon capture technology for the merchant marine that is currently pervading is amine-based. The technology itself has been assessed, not the disposal of captured/stored carbon. Offloading and documenting the onboard-captured and stored carbon can be foreseen to add considerable complexity to a ship, but has not been taken into consideration in the following financial assessments of abatement costs. A higher TRL is required for further assessment.

Fuel cells
Two fuel cell technologies have been assessed: solid oxide fuel cells, and polymer exchange membrane fuel cells. Although fuel cells can be used for other purposes in the lifecycle of marine fuels, such as synthetic fuel production, we only consider them for propulsion purposes here, supplying

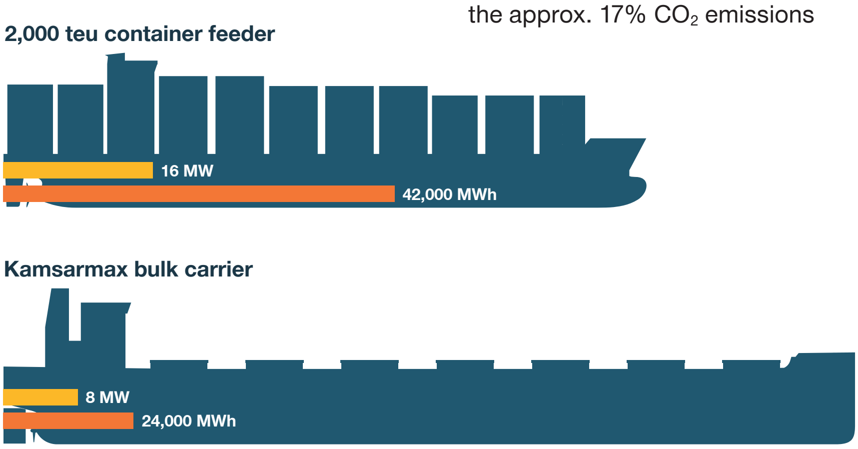

Fig. 2: Comparison of ship sizes, installed effect, and energy consumption

energy to an electric motor driving a propeller. In our assessment, we consider the fuel cell technologies scalable/stackable to the power needed for the three ship types. Solid oxide fuel cells running on LNG, synthetic methanol, and synthetic ammonia are included (SOFC LNG, SOFC e-MeOH, SOFC e-NH_3, respectively), and polymer exchange membrane fuel cells running on synthetic methanol and synthetic ammonia (PEM e-MeOH, PEM e-NH_3, respectively) are included.
Fuel-cell-based propulsion for large ships is at different technology readiness levels, depending on the fuel used: SOFC on LNG and ammonia both at TRL7, on methanol at TRL3; and PEM on methanol and ammonia both at TRL3. Further, the lifetime of a fuel cell for propulsion is currently unknown, and therefore, in the assessment below, we have defined that the fuel cell stack lasts the full lifetime of the vessel. It is likely, however, that it will need to be serviced/exchanged during the vessel's lifetime, significantly increasing the cost of abatement. It is furthermore assumed that fuel cells can operate on the same qualities of fuels as other energy converters considered here. If a higher purity of the fuel is needed to avoid poisoning the fuel cell, it may deteriorate the operational cost.

Batteries
We did an initial assessment of batteries but found that the abatement cost is prohibitive for the three ship types selected for this paper, due to the required power consumption. The cargo displacement was too large to be commercially relevant on merchant marine ships. The current strength of batteries in shipping is in near-coastal shipping, not propulsion of merchant marine shipping. Batteries may be relevant to integrate in the onboard electric grid for large ocean-going vessels[5].

Factors considered

The assessment includes factors such as cost of the technology and assorted onboard supply and storage systems, cost of lost cargo space (where relevant), cost of capital, cost of fuel, efficiency of the technologies, etc. Naturally, the cost of fuel has a great impact on the abatement cost, and the prices used[6] are 11 $ per GJ HFO, 8 for fossil LNG, 61 for synthetic methanol, and 48 for synthetic ammonia.

New Panamax container vessel

According to Fig. 3, the absolute abatement potential of a dual-fuel two-stroke engine running on synthetic ammonia is approx. 92 kilotonnes (kt) CO_2e per year with an abatement cost of 460 € per tonne. By adding a combination of PTO, WHR and e-PO to the ammonia two-stroke engine, the yearly abatement can be as much as 102 kt CO_2e at a cost of 450 € per tonne, however at the cost of increased complexity in the propulsion solution. For some engine operators, a standard ammonia engine, as opposed to one with several add-on technologies, is preferable. The absolute abatement with a methanol two-stroke engine is also approx. 93 kt per year at a cost of around 640 € per tonne, whereas the figures for e-methane are 93 kt per year at a cost of 500 € per tonne. With the same energy-saving technologies, the absolute abatement can be slightly

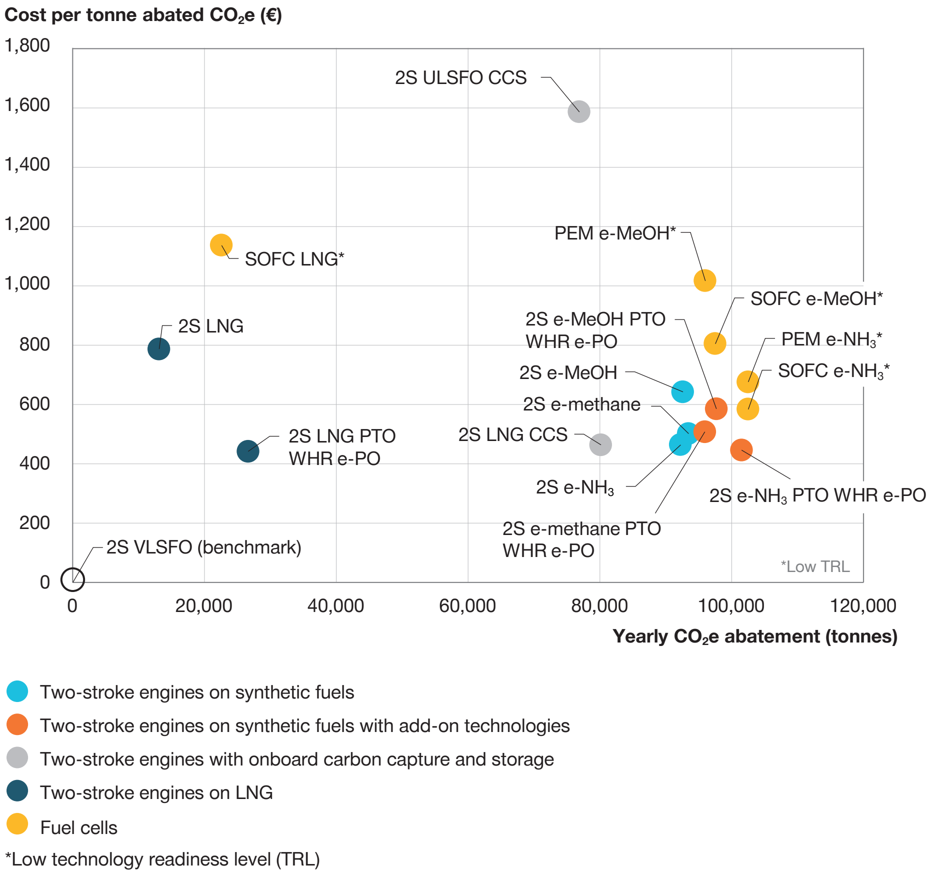

Fig. 3: CO_2e abatement through various propulsion technologies on a New Panamax container vessel

[5] Batteries on board ocean-going vessels, MAN Energy Solutions https://www.man-es.com/docs/default-source/marine/tools/batteries-on-board-ocean-going-vessels.pdf?sfvrsn=deaa76b8_14 [accessed 25 September 2023]
[6] Mærsk Mc-Kinney Møller Center for Zero Carbon Shipping, NavigatE model

increased (98 kt for methanol and 96 kt for e-methane) at a slightly lower cost (590 €/tonne for methanol and 510 €/tonne for e-methane).

Fuel cells using methanol and ammonia have a relatively high absolute yearly abatement, ranging between 96-103 kt at an abatement cost in the range of 580-1,020 €/tonne, so that the higher absolute abatement compared to a two-stroke engine comes at the expense of up to twice the cost.

A two-stroke engine with onboard carbon capture abates approx. 80 kt CO_2e per year at the cost of 460 €/tonne when running on LNG, compared to 77 kt per year at a cost of 1,590 €/tonne when running on ULSFO. Note that the system and its associated cost do not include off-loading the captured/stored carbon, nor the possible gain in the carbon economy, which is currently uncertain and therefore poses a risk to onboard carbon capture.

A two-stroke engine running on LNG can abate approximately 13 kt CO_2e per year at a cost of 790 €/tonne whereas the comparable figures are 27 kt at a cost of 440 €/tonne when PTO, WHR, and e-PO are added, where PTO demonstrates a great impact by shifting the onboard electric power production to the two-stroke combustion engine, thus gaining a methane slip advantage compared to using four-stroke auxiliary GenSets. Biogas and synthetic methane can be applied to further increase the absolute abatement, especially in a transition period, though increasing the cost per tonne.

Finally, a solid oxide fuel cell running on LNG can abate 23 kt CO_2e per year at a relatively high cost of 1,140 €/tonne.

2,000 teu feeder vessel

The pattern in absolute abatement and abatement cost is similar for a 2,000 teu feeder vessel as for a New Panamax container vessel, naturally adapted to the smaller ship and lower energy consumption: The absolute abatement potential of all technologies is lower as the annual emissions of a 2,000 teu feeder vessel are lower than for a New Panamax container vessel. However, the relative placement of the propulsion technologies on the chart is similar, with a few exceptions: The lower energy consumption, from approx. 126 GWh for the New Panamax to approx. 42 GWh for the feeder vessel, exacerbates the cost of running on LNG on a two-stroke engine, and the abatement cost is more than 1,030 € per tonne because the capital expenditure of the LNG system is high compared to the relatively low energy consumption. Also, the cost of a solid oxide fuel cell on LNG has been reduced by 220 €/tonne: This is due to the difference in installed effect on a large container vessel versus a feeder vessel, where there is a tendency to install large engines with much spare capacity on large container vessels and a better match between installed effect and actual effect used on smaller ones. So the size and therefore the cost of the fuel cell solution is relatively smaller for the feeder vessel, resulting in an abatement cost of 920 €/tonne compared to almost 1,140 €/tonne on the New Panamax. Our calculations show that a dual-fuel two-stroke engine with LNG in combination with onboard carbon capture could theoretically deliver medium-high absolute abatement, assuming that LNG comes at a lower cost than the other fuels included here. However, at TRL5-6, a realistic cost cannot currently be determined, and financial and practical risks associated with offloading and certification/documentation persist, along with risks of increased system complexity.

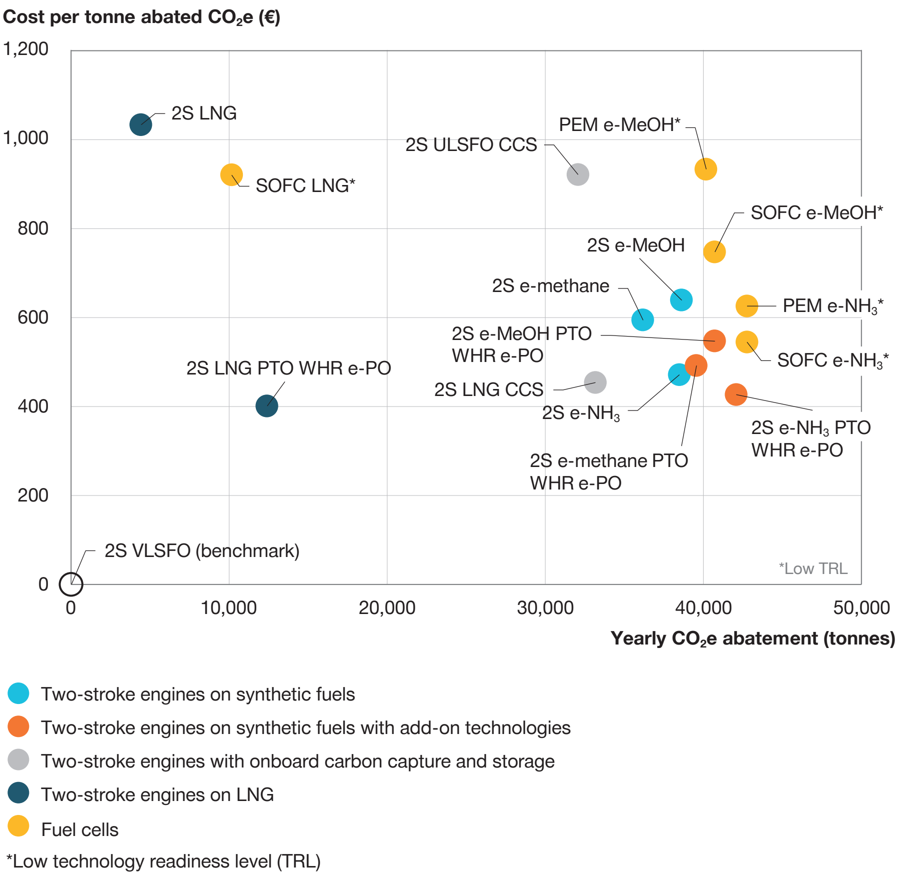

Fig. 4: CO_2 abatement through various propulsion technologies on a 2,000 teu feeder vessel

Kamsarmax bulk carrier

The same pattern of absolute abatement potential and abatement cost is also found for a Kamsarmax bulk carrier, but adapted to the lowest energy consumption of the three ship types included here, i.e. 24 GWh; therefore, the absolute abatement potential is also lower. Here, a dual-fuel two-stroke engine on LNG becomes even more expensive as the capital expenditure of the LNG system is proportionally larger than the energy consumption, compared to larger ships, at an abatement cost of 1,470 €/tonne, which can be reduced to 940 €/tonne if combined with PTO and WHR.

In summary, the cheapest and simplest way to decarbonize a large merchant marine ship or a ship with a high energy demand is with an ammonia engine, closely followed by a methanol engine and an e-methane engine, whereas methanol has an advantage over ammonia for smaller merchant marine ships and ships with lower energy consumption, as the capital expenditure increase is limited. By adding various add-on technologies, both the absolute yearly abatement as well as the abatement cost can be slightly reduced, but at the expense of a more complex engine room. Fuel cells offer high absolute yearly abatement, but at higher costs than a two-stroke engine – and currently, the technology is under development. Onboard carbon capture is also under development and may act as an intermediate buffer for temporary compliance, however, it is not enough for achieving compliance with net zero in 2050 – additional technologies are required. Therefore, it is possible that fuel cells as well as carbon capture find their main contribution to decarbonization of shipping in on-shore applications, for example in fuel production where both efficiency and cost can be optimized compared to an onboard application.

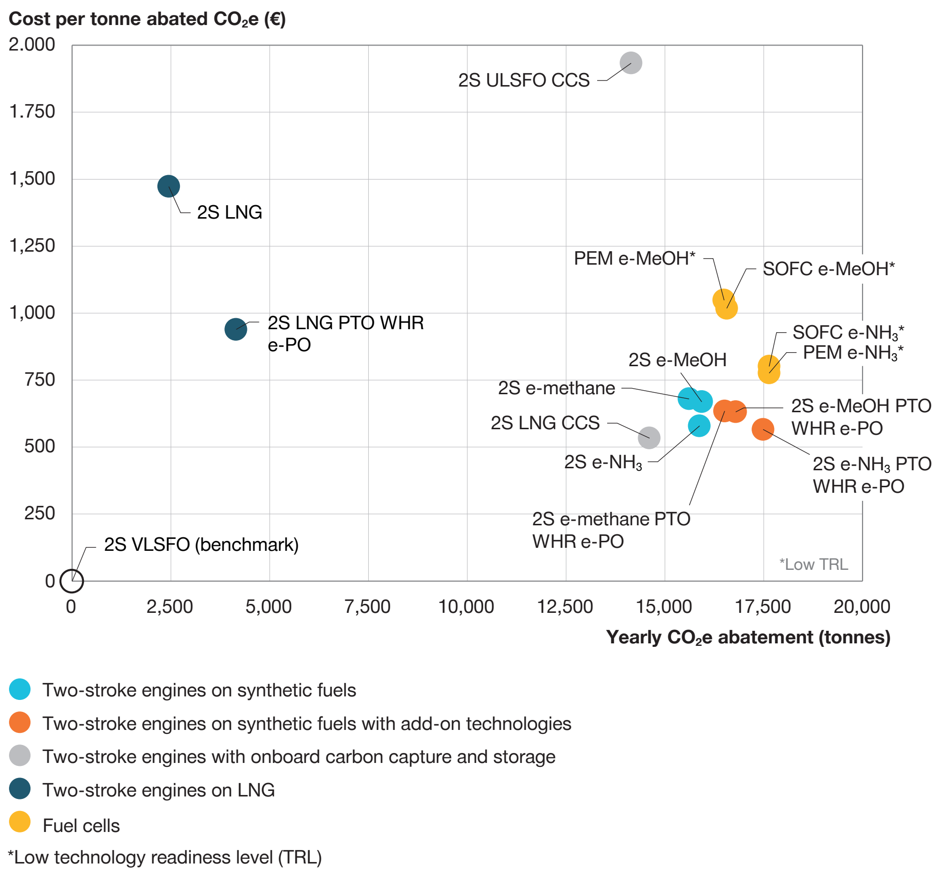

Fig. 5: CO_2 abatement through various propulsion technologies on a Kamsarmax bulk carrier

Looking ahead

The revised GHG strategy of the IMO is now aligned with a 2°C pathway to net-zero shipping[7], following Article 2 in the Paris Agreement. After the MEPC80 meeting in the summer of 2023, critical voices expressed disappointment that the GHG strategy does not align with a 1.5°C pathway. However, setting targets for one sector and not others effectively penalizes that sector. Therefore, once the shipping sector has shown its ability to implement and scale up decarbonization technologies in operation, it will be possible to make yet another revision of the GHG strategy. But before such a decision can be passed, shipping as a sector requires a commitment that other sectors will move in the same direction, i.e. alignment with 1.5 instead of 2°C. Such a commitment can, for example, be formalized at a COP meeting. Once countries having ratified The United Nations Framework Convention on Climate Change sign up to a new pathway, shipping will be ready to follow, so that all sectors have equal commercial conditions.

While we are waiting for the midterm measures of the IMO, a tentative conclusion is that dual-fuel engines, possibly in combination with energy-saving technologies, can advantageously be selected for newbuildings already now. The trend will solidify and amplify as we move closer to the year 2050. For existing ships, large ships, or ships with a high energy consumption, a dual-fuel conversion of their fuel oil engine can be advantageous, or in some cases energy-efficiency retrofits may be sufficient for compliance, which depends on the ship's age and operational pattern.

Planning for a retrofit at the time of ordering a new ship may be risky with regard to securing yard capacity for the conversion some years later if there is a strong demand for retrofit. By ordering a dual-fuel engine for the newbuilding, the yard capacity for the dual-fuel build is secured.

To drive maritime decarbonization, net-zero fuels must be available in quantities matching the propulsion technologies. This calls for investments in the energy value chain and prioritization of the shipping sector. The "chicken or the egg" dilemma – which comes first: installed technology or availability of synthetic fuels? – is not a dilemma here. Both are needed. So while shipowners already now need to select an abatement technology for newbuildings, energy suppliers need to ensure the availability of synthetic fuels, matching the installed base of the merchant marine fleet. In practice, there will be a need for both e-methanol, e-ammonia, and e-methane. This requires scaling up green hydrogen production, as part of the net-zero fuels value chain. Capital from a carbon levy can advantageously be used for scaling green hydrogen production.

The maritime energy transition has started, and the sector is now scaling and implementing decarbonization technologies.

[7] IMO's newly revised GHG strategy: What it means for shipping and the Paris Agreement, https://theicct.org/marine-imo-updated-ghg-strategy-jul23/ [accessed 29 September 2023]

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