COMPREHENSIVE ASSESSMENT AND TARGETED STRATEGIES FOR GREENHOUSE GAS EMISSION REDUCTION IN MARITIME SHIPPING

MEPC D8

1. Background

The IMO Fourth GHG Study (2020) estimates that the international shipping industry contributes around 2.9 percent to the global greenhouse gas emissions. As the IMO GHG Strategy is being revised in 2023, with the goal of a net-zero situation by or around 2050, the need to embrace transitional fuel solutions that are both environmental and economically viable is increasing. The upcoming MEPC 83 discussions on mid-term GHG reduction measures and life-cycle emission guidelines (MEPC.391(81)) emphasize the need for balanced strategies.

As developed economies move towards mass-based hydrogen and e-fuel developments, developing countries are still burdened with numerous constraints capped by low research and development, high capital formation, and reliance on external fossil fuel sources. The economic responsiveness of these countries to fuel taxes and technological switching calls on solutions that are both technically viable and economically viable solutions.

In this context, the paper proposes an Integrated Methanol Ammonia Hybrid Fuel System (IMAHFS) along with AI-based Waste Heat to Fuel (WH2F) recovery. By streamlining fuel production and waste heat conversion via digital twin control systems, the proposed model would reduce expenses. It is crafted so that all can take part in decarbonization worldwide by exploiting current dual-fuel technologies, carbon capture in ports and hydrogen infrastructure. The proposal is a move in the right direction towards meeting a long term climate goal of IMO and sustaining economic stability of emerging maritime states.

2. Idea

2.1**.** System Overview

The Integrated Methanol-Ammonia Hybrid Fuel System (IMAHFS) combines three mutually complimentary technologies into a single architecturally consistent system: capture and reuse of CO_2, microchannel methanol synthesis, and hybrid combustion of methanol and ammonia. Ship exhaust gases are scrubbed with amine-based absorbers to produce over 95% pure CO_2 that is liquefied and kept of port. This capturated carbon is then reacted with green hydrogen through microchannel reactors at about 250-300 ºC and 50-80 bar, following the reaction:

$$CO_2 + 3H_2 \rightarrow CH_3\text{OH} + H_2\text{O}$$

This results in synthetic methanol, to be fueled together as a dual-fuel mixture with bunkered green ammonia. Methanol is used to pilot and stabilize ammonia burning improving the quality of ignition and suppressing NOx generation by 40%. The system can operate within the framework of existing dual-fuel engine platforms such as the MAN B&W ME-LGIM and Wärtsilä X52DF-M engines, while ammonia-compatible designs like the MAN 2T50ME-AAmine and Wärtsilä 4-stroke prototypes are in advanced development.

2.2. Carbon Capture and Utilization

The IMAHFS employs amine-based post-combustion carbon capture, governed by the reversible reaction:

$$CO^{2} + 2RNH^{2} \rightleftharpoons RNH^{3+} + RNHCOO^{-}$$

Captured CO_2 is liquefied at approximately 6 bar and –30 °C, stored in insulated tanks, and subsequently delivered to port-based synthesis units. Each tonne of CO_2 captured yields roughly 0.73 tonnes of methanol, effectively converting emissions into reusable fuel. The continuous recycling of CO_2 in this closed carbon loop results in a greater than 90% lifecycle GHG reduction compared with Heavy Fuel Oil (HFO), as verified under MEPC.391(81).

2.3. System Operation

The suggested process is initiated by capture of the CO_2 through ship exhausts and then it is liquefied through absorption and stripping. Once at port, the captured CO_2 is mixed with renewable-produced electrolysis of green hydrogen. Both feed streams flow towards a microchannel methanol reactor, in which waste heat in auxiliary engines or exhaust can be harnessed using the WH_2F loop to keep temperature in the reactions and enhance energy efficiency. The resulting methanol is blended with bunkered green ammonia, blending ratios actively maintained by an AI-based digital twin system based on the needs of the vessel and the availability of fuel. Therefore, it transforms emissions into useful fuel and stays operationally efficient, safe, and compliant with lifecycle emissions.

2.4. Comparative Performance and Lifecycle Impact

The methanol-ammonia hybrid system has considerable environmental and operational benefits compared with HFO. On a net lifecycle basis after capture and reuse, the hybrid system emits 0.25 kg of CO_2 per kg of fuel, compared to 3.11 kg of CO_2 per kg of fuel emitted by the HFO. The heating value of methanol (around 20 MJ/kg) is lower than that of HFO (around 40 MJ/kg), but the mixed operation with ammonia raises the energy density to 27-30 MJ/kg. The Lifecycle GHG Intensity in the hybrid pathway shows a confirmed over 90% cutoff, fulfilling the high-ambition trajectory of the IMO in 2050. Also, the flame stability of methanol provides a smoother ignition to burn ammonia, and decreases NOx and particulate emissions.

2.5. Efficiency and Improvement Potential

The base process of methanol production has a potential of 58% (LHV) efficiency which can be enhanced to 68 percent by incorporation of the WH2F loop to reclaim the exhaust heat to be used in preheating the feed. Another 5-7% of operational energy savings can be added through further optimization with the help of AI and digital twin control, which is already implemented in LNG systems, which increases the overall efficiency to an almost 72%.

2.6. Economic Feasibility

At an average renewable electricity cost of $0.05/kWh, it would cost roughly $2.5/kg to produce hydrogen (50 kWh per kg of H2). On average, one kilogram of methanol needs about 0.19 kg hydrogen, which would contribute to almost $0.48 per each kilogram of methanol when considering the energy price.When CO_2 capture and compression is added (at $50–70 per tonne CO_2), the cost of producing synthetic methanol reaches around $850 to $1,000 per tonne in 2025 and drops below $600 by 2035 as hydrogen prices fall. For an HFO baseline of $550 tonne^{-1} economic parity is reached with carbon levy = 100$/tCO2. Sharing of electrolyzers and waste-heat integration can save capital costs by 25–30%. Therefore, making 5 10 tonnes/day hybrid fuel hub based model viable.

2.7. Application Potential and Equity

The IMAHFS vision gives a tactical advantage to developing countries because it links economic, industrial and environmental concerns. The creation of regional hybrid fuel hubs facilitates common infrastructure and local supply for an overall decrease in imported fuels. These hubs are creating jobs in fuel synthesis, carbon management and digital operations skills that will build economic resilience. It also benefits the development of energy security in a maritime region and contributes to fair participation in decarbonization of the maritime industry.

2.8. Integration and Operational Challenges

Although the integration is technically possible, it needs to be engineered and regulated. Key challenges are heat management between exothermic and endothermic processes, compatibility of the materials with methanol and ammonia as well as safety certification according to the IGF Code. Additionally, AI control systems will need to incorporate redundancy and fail-safe programming as well as interfacing with MRV protocols for transparency and compliance.

3. Conclusion

The IMHF system is a technically innovative, economically balanced and environmentally friendly solution which meets IMO long-term climate strategy. By integrating carbon capture and reuse, waste-heat valorization, and AI-powered optimization, it achieves over 90% reduction of lifecycle GHG compared with HFO. This structure is such that developing countries are able to participate as key players in the global maritime decarbonisation process, without overly onerous impacts on their economies. It is a pragmatic and fair transition model; one which connects the dual-fuel existing-now with zero-carbon next, paving the way for a fair and inclusive clean shipping future.

It is also REQUESTED, that the Marine Environment Protection Committee (MEPC) in consultation with the Sub-Committee pay due attention to the inclusion of the Integrated Methanol-Ammonia Hybrid Fuel System (IMAHFS) in future deliberations on:

1. Under the mid-term GHG programs by the IMO, it is important to note that the Integrated Methanol-Ammonia Hybrid Fuel System (IMAHFS) is a transitional pathway.
2. Pilot projects and IMO-GEF and MTCC IMO-GEF and MTCC frameworks Initiate pilot projects to test modular reactors, waste-heat recovery, and AI-driven optimization.
3. Add methane ammonia blended fuels and port-based hybrid amendments to interim IGF Code.