MULTI-CRITERIA PATHWAY EVALUATION FOR SUSTAINABLE FUELS IN THE MARITIME SECTOR

Wolfgang Gruber-Glatzl, Christoph Höfer, Jana Reiter, Ian Calixto
AEE INTEC
Feldgasse 19, Gleisdorf, Austria
w.gruber-glatzl@aee.at

1 SUMMARY

This comprehensive study examines the urgent need for cleaner, sustainable maritime fuels to combat the significant contribution of the maritime sector to global greenhouse gas emissions. Through a meticulous comparative analysis of Hydrogen, Ammonia, and Methanol pathways technologies, the research reveals varying levels of technological readiness, economic viability, and environmental implications. To achieve an eco-friendlier maritime future, the study emphasizes the importance of an interdisciplinary approach, considering factors such as energy demand, logistics, and regional conditions. Hydrogen emerges as a promising option, while Ammonia and Methanol require further research, offering a roadmap for sustainable maritime energy solutions and reducing emissions in international shipping.

Keywords: sustainable fuels, energy efficiency for maritime applications, fuel cells, hydrogen, methanol, ammonia

2 ABSTRACT

The maritime sector's substantial contribution to global greenhouse gas emissions underscores the urgent need for cleaner, more sustainable fuel sources. This comprehensive study delves into an exhaustive and meticulous comparative analysis of three emerging maritime fuel technologies, namely Hydrogen production through Proton Exchange Membrane (PEM) Electrolysis, Ammonia production via N2-Air Separation and Haber-Bosch synthesis, and Methanol production by means of Biogas Upgrading. The research employs a multifaceted approach, deftly integrating both qualitative case studies and quantitative Key Performance Indicators (KPIs), reaching far beyond conventional metrics to encompass crucial aspects such as hydrogen fuel demand, electricity requisites, water consumption, and emission profiles. The insights derived from this comprehensive evaluation lay bare the varying levels of technological maturity, economic feasibility, and environmental ramifications associated with these alternative fuels, thereby providing invaluable guidance for the maritime sector's shift towards a more sustainable and eco-friendly future.

The maritime industry is a significant contributor to global greenhouse gas emissions, accounting for nearly 2.9% of all emissions attributed to human activities in 2018 (Munim et al., 2023). To reduce GHG emissions in international shipping, the International Maritime Organization (IMO) has set ambitious goals, making it imperative to identify and adopt sustainable maritime fuels (Harahap et al., 2023). The study's findings not only highlight the performance and potential of Hydrogen, Ammonia, and Methanol but also serve to underline the intricate and multifaceted challenges that accompany the transition to these alternative fuels. An additional layer of complexity emerges when considering the logistical aspects of transporting these fuels, including the inevitable loss of some fuel during transit, necessitating innovative solutions to optimize transportation efficiency.

In the broader context of mitigating carbon emissions, the study underscores the need for an interdisciplinary approach that bridges gaps between technology, environmental science, socio-economic studies, and public policy. The maritime sector is distinguished by a diversity of shipping routes, varying infrastructural capabilities, and regional conditions, necessitating a nuanced approach tailored to the specific circumstances and requirements of each region.

The maritime industry can navigate the intricate landscape of sustainable maritime energy solutions by adopting a balanced strategy that combines technological enhancements, systemic optimization, and comprehensive environmental impact assessments (Trivyza et al., 2022). By integrating these elements, the maritime industry can pave the way for a new era characterized by the harmonious coexistence of operational efficiency and long-term sustainability.

In essence, this study contributes not only to the growing body of knowledge on alternative maritime fuels but also to the urgent and overarching mission of mitigating climate change. It brings the vision of a sustainable future for the maritime sector within closer reach, reinforcing the possibility of a global maritime industry that is not only more environmentally responsible but also economically viable and technologically advanced.

The study's findings shed light on the potential of these fuel alternatives in the maritime sector. Hydrogen, produced via PEM Electrolysis, is on the brink of commercial viability with a Technology Readiness Level (TRL) of 8. While its initial capital requirements are relatively high, Hydrogen exhibits promise for lower operational costs, boasting a well-to-wheel efficiency of 28%.

Ammonia, synthesized through the Haber-Bosch process, presents a TRL of 7 with costs considered moderate. Its well-to-wheel efficiency stands at 26%. Ammonia emerges as a well-rounded alternative, balancing energy efficiency and environmental considerations.

In contrast, Methanol, derived from Biogas Upgrading, is the least mature option with a TRL of 6. Although its initial costs are relatively low, operational expenses are high, leading to a well-to-wheel efficiency of 21%. Methanol's environmental footprint and efficiency are key challenges.

The study posits that Hydrogen is a viable solution for the maritime sector due to the existing storage and transportation infrastructures (Hren et al., 2023; Pomaska & Acciaro, 2022; van Biert et al., 2016; Veldhuis et al., 2007). However, Ammonia and Methanol, which have higher energy density and efficiency, require additional research in the domains of storage and transportation to be seamlessly integrated into maritime applications(Danebergs & Deledda, 2023). The use of hydrogen as a source of energy requires four main technologies: production, storage, transportation, and application (Veldhuis et al., 2007).

As the International Maritime Organization (IMO) is working to reduce greenhouse gas emissions in international shipping, and a recent study offers a roadmap for sustainable fuel alternatives (Al-Aboosi et al., 2021; Inal et al., 2022; McKinlay et al., 2021). The study recommends targeted research and development investments, especially in Hydrogen and Ammonia, both of which show significant promise in terms of technological readiness and energy efficiency (Al-Aboosi et al., 2021; Inal et al., 2022; Machaj et al., 2022). For Methanol, a comprehensive environmental assessment is recommended to illuminate its environmental trade-offs and identify mitigation strategies (Djermouni & Ouadha, 2023; McKinlay et al., 2021). Technological advancements have the potential to optimize costs and enhance well-to-wheel efficiencies across the board, thereby contributing to global efforts to combat climate change (Al-Aboosi et al., 2021; Inal et al., 2022; McKinlay et al., 2021).

In conclusion, this research offers a nuanced perspective on alternative maritime fuels, each with its unique advantages and challenges. Achieving a sustainable maritime sector requires a concerted effort, encompassing technological innovation, infrastructural adaptability, and consistent regulation. This study serves as a cornerstone for future discussions and decisions among stakeholders as the maritime sector approaches an ecological turning point.

As global shipping emissions represented a considerable 1,076 million tonnes of CO2 in 2018, accounting for approximately 2.9% of global emissions from human activities, the need to reduce greenhouse gas emissions in the maritime industry is more pressing than ever. The International Maritime Organization (IMO) has set ambitious goals to reduce GHG emissions from international shipping, further intensifying the urgency of finding sustainable alternatives to traditional maritime fuels.

The study not only provides valuable insights into the performance and potential of Hydrogen, Ammonia, and Methanol but also underscores the complexity of the challenges associated with transitioning to these alternative fuels. Shipping these fuels introduces logistical issues, such as fuel loss during transportation, adding an additional layer of complexity that requires innovative solutions.

In the context of reducing carbon emissions, the study emphasizes the importance of not only technology but also an interdisciplinary strategy that bridges gaps between technology, environmental science, socio-economic studies, and public policy. The complexity of the maritime sector, characterized by diverse shipping routes, varying infrastructure, and regional conditions, calls for a nuanced approach tailored to each region's specific circumstances and needs.

To navigate the intricate landscape of sustainable maritime energy solutions, the study advocates for a balanced approach that combines technological improvements, systemic optimization, and comprehensive environmental impact assessments. By integrating these elements, the maritime industry can steer itself into a new era that harmonizes operational efficiency with long-term sustainability.

In essence, the study contributes not only to the growing body of knowledge on alternative maritime fuels but also to the urgent mission of mitigating climate change, making a sustainable future for the maritime sector more achievable and attainable.

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4 CONFERENCE TOPIC

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Coupling of Energy Sectors, Life Cycle Assessment, Centres for circularity, Approaches towards net-zero/negative emissions in the industry including CCU