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Decarbonizing maritime power systems with hydrogen and ammonia integration

Operators Perspective

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ABSTRACT

The shipping industry is facing increasing pressure to reduce greenhouse gas emissions, with global efforts aiming for net-zero by 2050. Achieving the targets requires a shift toward alternative fuels, with hydrogen (H2) and ammonia (NH3) emerging as promising candidates.

This study evaluates the integration of hydrogen and ammonia into maritime power systems, considering efficiency, fuel requirements, and CO2 reduction potential. It employs the FEEMS modeling framework, specifically designed for marine power and propulsion systems, to assess the performance of hydrogen- and ammonia-based machinery under realistic, time-varying operational conditions. By analyzing logged data over a 280-day period, the model achieves over 95% accuracy in predicting fuel consumption. The study examines how different fuel types and power system configurations affect efficiency, emissions, and overall feasibility. While PEMFC and SOFC enable near-zero emissions, 4-stroke engines remain relevant in the transition, providing a practical pathway toward decarbonization in the near term. The findings also highlight the critical importance of sourcing green hydrogen and ammonia, as fossil-based alternatives could lead to higher GHG emissions than conventional fuels.

1 INTRODUCTION

The International Maritime Organization (IMO) has set ambitious decarbonization targets for the shipping industry, including achieving net-zero greenhouse gas (GHG) emissions by 2050, with interim goals of a 20% reduction by 2030 and 70% by 2040 relative to 2008 levels [1]. These targets highlight the need to tackle the environmental impact of the shipping industry and accelerate the transition toward more sustainable solutions. While operational and technical measures, such as wind-assisted propulsion, can contribute to short-term emissions reductions, long-term decarbonization will require the adoption of advanced technologies and alternative fuels. The maritime transportation sector is often regarded as hard to abate industry. For example, onshore industries can use capture and storage (CCS) to reduce emissions, and road vehicles can rely on batteries for their power. However, ships, especially those involved in regional and deep-sea shipping, encounter difficulties in adopting batteries as a main power source due to the long voyage and requirements for higher power. Moreover, onboard capture and storage (OCCS) have demonstrated potential but scaling them will demand significant investment and integration across the industry [2][3].

As the use of hydrogen and its derivative become important across various industries [4], the maritime sector is no exception. Hydrogen, a potentially versatile and environmentally friendly fuel source, can be obtained from a range of resources and has the capacity to significantly reduce greenhouse gas emissions. Depending on the method of conversion, hydrogen can generate electricity with only water vapor as a byproduct. In a similar vein, ammonia is also emerging as a promising option for greener shipping fuels, particularly when the objective is to create carbon-free alternatives [1].

The environmental impact of using hydrogen or ammonia as fuels depends significantly on the pathways of power production. Emissions from internal combustion engines differ greatly from those of fuel cells, particularly when a pilot percentage is used in a dual-fuel engine [5].

Hydrogen can be produced from various resources, including, fossil fuels, biomass and water electrolysis using electricity. The environmental impact and energy efficiency of hydrogen production depend on the method chosen [6]. For example, producing liquid hydrogen from natural gas can increase CO_2 emissions by 66%, while production through renewable energy can lead to a reduction of up to 100%. Similarly, in the case of ammonia production, emissions change can range from +40% to -94%. However, it is crucial to note that achieving a 100% reduction in NH_3 emissions is not possible due to the presence of nitrogen in ammonia and the potential formation of N_2O.

In the most recent report by DNV [7], focusing on the transition to maritime sustainability by 2050 in 2023, both hydrogen and ammonia are categorized as solutions that can contribute to decarbonizing shipping by up to 100%. While the technology for alternative fuels like LNG is well-established and has a high Technology Readiness Level (TRL), the advancement of technology for utilizing hydrogen and ammonia as fuel is not as highly developed. The level of development and associated risks vary depending on the type of conversion for propulsion power, with hydrogen and ammonia facing notable challenges due to their energy density by weight and volume.

Figure 1 illustrates the energy density of different fuels. While hydrogen has the highest energy content per kilogram (MJ/kg) among these fuels, it comes with a drawback—its density is exceptionally low, resulting in a low energy density (energy per unit volume). On the other hand, ammonia offers a relatively lower specific energy (energy per unit mass), approximately 20% of pure hydrogen. However, it compensates for this by having a higher energy density.

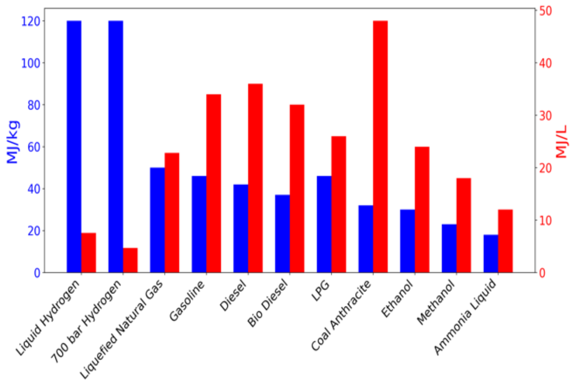

Figure 1. Energy density of different fuels [8]

When it comes to storage, different methods present unique challenges and advantages. Compressed hydrogen storage involves physically storing hydrogen gas in high-pressure tanks. The tank's pressure typically ranges between 350-700 bar, and the fuel has a density of 23-38 kg/m^3 [9]. However, pressures above 350 bar introduce significant challenges for maritime applications, including increased material stress, safety concerns, and complex refueling infrastructure requirements [10]. Liquid hydrogen storage can store about 70 kg/m^3 of liquid hydrogen, making it a more energy-dense option compared to compressed hydrogen. However, it is essential to note that producing liquid hydrogen at temperatures below 22 K requires a significant cryogenic power supply [11]. The theoretical energy needed to liquefy hydrogen is 3.23 kWh/kg, but the actual energy required is approximately 15.2 kWh/kg, which is almost half of the lower heating value of hydrogen. This is roughly twice as much as compressed hydrogen, which requires about 2.6 kWh/kg in theory and up to 8.6 kWh/kg in practice for 700 bar. In addition to physical storage, hydrogen can also be chemically stored using various methods, each with distinct advantages and challenges. Metal hydrides, for instance, allow hydrogen to bond with metals or alloys, forming stable compounds. While they offer safe storage, metal hydrides have their own drawbacks, such as being heavy, having limited filling-discharge capacity, and containing rare elements. They can retain hydrogen equivalent to about 1%-2% by weight, with a maximum of 7% achievable if an active heating system is provided [12]. Liquid Organic Hydrogen Carriers (LOHCs) present another chemical storage option, utilizing organic compounds to reversibly bind and release hydrogen. LOHCs can store approximately 6 wt% hydrogen and are compatible with existing fuel transport infrastructure. However, the dehydrogenation process is highly endothermic, requiring high temperatures and leading to significant energy consumption[13], [14]. For ammonia storage, in a gaseous phase at atmospheric pressure and temperature, it has a boiling point of -33.5°C, but in liquid form it has a density of 682 kg/m^3, and a heat of vaporization of 18.5 kJ/kg. This results in ammonia having an energy density of 12 MJ/L, whereas hydrogen has an energy density of 8.7 MJ/L.

Regardless of the type of storage, propulsion power and onboard energy supply using hydrogen and ammonia can be achieved through internal combustion engines (ICEs), fuel cells (FCs), gas and steam turbines (GT and ST), or hybrid systems s that integrate multiple power sources. These hybrid configurations may include batteries, supercapacitors, or other energy storage technologies.

The primary goal of this paper is to evaluate the impact of various pathways for utilizing hydrogen and ammonia on marine machinery performance, storage requirements, fuel consumption, and emissions, all examined within a specific case study. To achieve this, the potential pathways are first outlined to identify practical and feasible solutions. Subsequently, the case study is introduced, accompanied by the modelling methodology and a comparison between the model data and actual operational data. While hybrid approaches have been discussed as potential solutions, the modeling conducted in this case study does not incorporate any hybrid configurations. Finally, the results and discussion section provide the key findings, giving a detailed analysis of the benefits and challenges associated with these pathways.

2 PATHWAY ANALYSIS

As illustrated in Figure 2, current technologies offer a variety of pathways. When considering hydrogen as the energy source, there are three primary onboard storage options: liquid hydrogen, Liquid Organic Hydrogen Carriers (LOHC), and compressed hydrogen. These storage methods enable the delivery of either liquid or compressed hydrogen to the ship's power system. For Power Generation, while other configurations may also be viable, eight prominent solutions are given here, each representing feasible configurations with distinct advantages and disadvantages. The final output of the Power Generation segment is divided into two categories. If the process has an environmental impact, it must pass through CCS or SCR (Selective Catalytic Reduction) for emission reduction. Otherwise, all outputs proceed to the Output segment, where hydrogen energy is transformed into electrical, mechanical power, or waste heat recovery. The last step, before

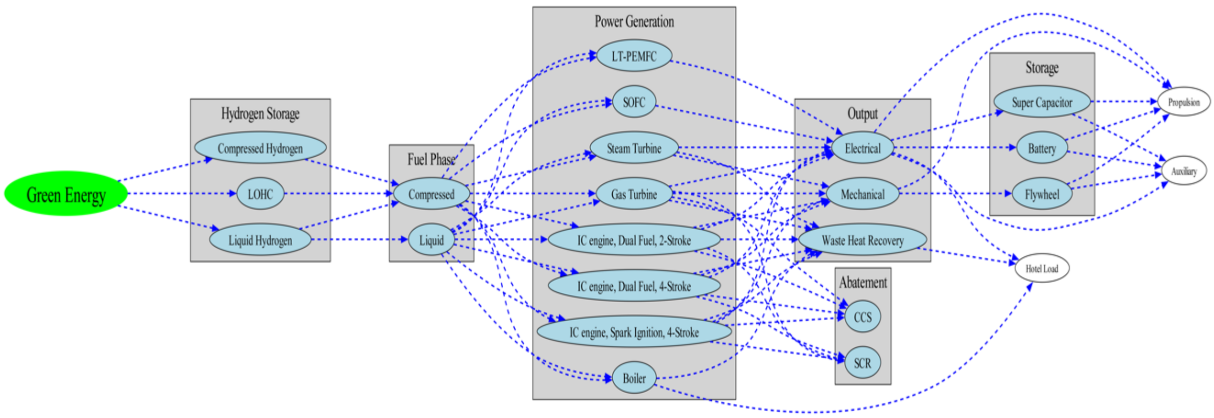

Figure 2. All pathways of using hydrogen onboard ships

specifically defining whether the power is for hotel load, propulsion, or auxiliary purposes, involves Storage. This can be achieved using supercapacitors, batteries, or flywheels to deliver the power output.

Similar pathways can be observed for the application of ammonia. Considering the entire process from fuel production to final energy output is a comprehensive undertaking. This study focuses on the intermediate stages, specifically addressing the fuel phase, power generation, and power conversion leading to the final output. The integration of batteries and other energy storage solutions will be addressed in a subsequent study, once a hybrid configuration is finalized and the battery capacity is defined based on the operational profile. Studying the literature, the pathways that excel in power production, efficiency, and TRL are listed in Figure 3, while safety and installation feasibility were not considered in the selection. The pathways are:

1. H_2-D, ICE-4S: Hydrogen-Diesel, Four-Stroke Internal Combustion Engine
2. H_2-D, ICE-2S: Hydrogen-Diesel, Two-Stroke Internal Combustion Engine
3. H_2, ICE-4S, SI: Hydrogen, Four-Stroke Spark-Ignition Internal Combustion Engine
4. H_2-NG, GT: Hydrogen-Natural Gas, Gas Turbine
5. H_2, LT-PEM-FC: Hydrogen, Low-Temperature Proton Exchange Membrane Fuel Cell
6. NH_3-D, ICE-4S: Ammonia-Diesel, Four-Stroke Internal Combustion Engine
7. NH_3-D, ICE-2S: Ammonia-Diesel, Two-Stroke Internal Combustion Engine
8. NH_3, SOFC: Ammonia, Solid Oxide Fuel Cell
9. NH_3-H_2, ICE-4S, SI: Ammonia-Hydrogen, Four-Stroke Spark-Ignition Internal Combustion Engine
10. NH_3-H_2-D, ICE-4S: Ammonia-Hydrogen-Diesel, Four-Stroke Internal Combustion Engine
11. NH_3-H_2, GT: Ammonia-Hydrogen, Gas Turbine

The green color represents favorable conditions, yellow indicates medium conditions, and red shows poor conditions. It should be noted that the same color does not imply identical values. For instance, a green rating signifies an acceptable range comparable to conventional power plants, whereas red signifies a range significantly outside that of conventional systems. Pathways using gas turbine with an implementation of a combined heat and power system can improve the efficiency to get a yellow color. SOFC and PEMFC showed the highest efficiency, with others falling within an acceptable range compared to conventional power plants. The power to volume ratio column indicates the power density (kW/m^3) of each system. For example, hydrogen-powered diesel engines may not reach 100% of the load capacity. This means that using this pathway, we need higher volume for making the same amount of power. In this list, SOFC, with its lower power density, requires the most space in the machine room to deliver the same amount of power. Emission-wise, SOFC and PEMFC are colored green, indicating lowest emission, while other sources may exhibit high NO_X values or rely heavily on conventional fuel fractions, such as diesel. In certain scenarios, diesel fuel may constitute more than 40% of total energy.

None of the pathways currently have a TRL 9 for maritime use. Gas turbines burning diesel and hydrogen, as well as PEMFC, fall into a category of TRL 8 shown by green color, while others have a lower TRL, particularly gas turbines burning ammonia, with a range of 4-5. In terms of affordability, gas turbines and fuel cells have shown the highest costs shown by red. Assuming cost parity between NH_3-H_2 engines and conventional dual-fuel engines, the other alternatives fall within a similar cost range, all slightly higher than engines running on fossil fuels.

A critical consideration for using hydrogen and ammonia as fuels is whether they can be used alone or require a hybrid system. The last column addresses this with the "System Compatibility" statement to show the compatibility with the marine environment and operation profile. While many pathways have non-hybrid configuration potential, SOFC's slow response time necessitates a hybrid source to compensate for load variations and peak shaving. LT-PEMFCs respond faster, but significant load changes lead to fuel cell degradation and reduced total lifetime. Gas turbines respond quickly to the load changes but exhibit low efficiency when used alone; therefore, hybrid systems are recommended for these systems.

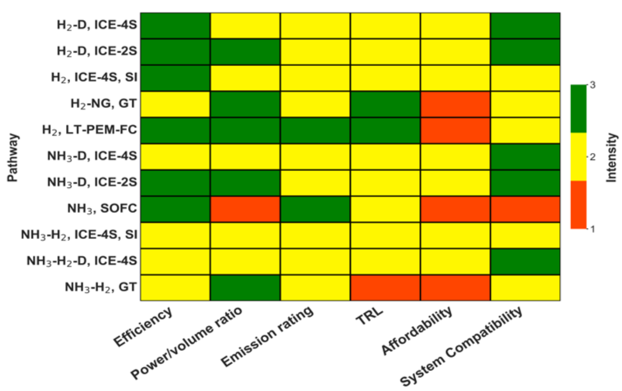

Figure 3. Evaluation of hydrogen and ammonia power sources for maritime applications.

1 CASE STUDY

In order to study the configuration of power system in a real case, BERGEN VIKING, operated by Bergen Tankers AS has been used. The ship, with IMO number 9285213, was initially built in 2007 and underwent a retrofit in 2015. It is used primarily to transport oil and chemicals. Figure 4 shows a picture of the ship in Norway water, and the general specifications of the ship and propulsion system are given in Table 1 and Table 2, respectively.

Figure 4. Bergen Viking, the case study for evaluation of the selected power sources.

Table 1. Ship specification

Attribute	Unit	Value
LOA (length over all)	Metres	95.1
Extreme breadth	Metres	17.0
Draught (fully loaded summer)	Metres	5.89
Net Tonnage	Tonne	1276
Gross Tonnage	Tonne	3960
DWT	Tonne	4168

Table 2. Propulsion system specification

Attribute	Number	Fuel	Unit	Value
Main engine	2	LNG	kW	1240
Auxiliary engine	2	Diesel	kW	515
Propeller	2	-	kW	950

Thanks to Bergen Tankers AS, daily logged data has been provided since March 5th, 2024, totaling 280 days as of the writing of this paper, including periods spent in dry dock. Figure 5 illustrates the power generated by the machinery of the ship. As shown for about 35 hours of the operation, the diesel generators are not at operation. This is happening for about 97% of the time the ship on operation. Due to this fact, we assumed, the auxiliary generators operating by diesel fuel are not part of the power configuration and the marine machinery is operating by its two main gas engines, one in port side and one in starboard. The power production of these two engines (not necessarily the same all the time) feeds the propeller and the auxiliary needs. As shown, most of the generated power is used for the propellers, while approximately 10% of the load is allocated to auxiliary pumps and hotel loads during transit. This percentage increases significantly at port, as indicated by the blue line.

Figure 6 gives the entire of 280 days power output from the engines and input to the propulsion systems in a scatter plot. Analyzing the data reveals that the two engines operate at lower power than the propellers need for only 3.1% of the time. This power is supplied by auxiliary engines. For the majority of the time, the data points align closely with the X=Y line, indicating that propulsion remains the primary load. However, there is a notable region in the data where engine loads are medium while propeller power is near zero. This scenario corresponds to operations near the port, as illustrated in Figure 7 and Figure 8. Figure 7 gives the Violin plot of the propeller actual speed, and Figure 8 gives the Violin plot of the engine power at the port side. As these two plots are showing, the operational profile of the engines and the ship can be defined in two modes, either close to full speed-full load at the transit, or low speed-low load at the port. The Violin plot of engine power shows a different distribution in comparison with the speed. The reason is the need for auxiliary power, where in many hours without sailing, the engine power need to be high to keep the operation of the auxiliary facilities such as pumps, compressors, ventilation systems and the bridge up and running.

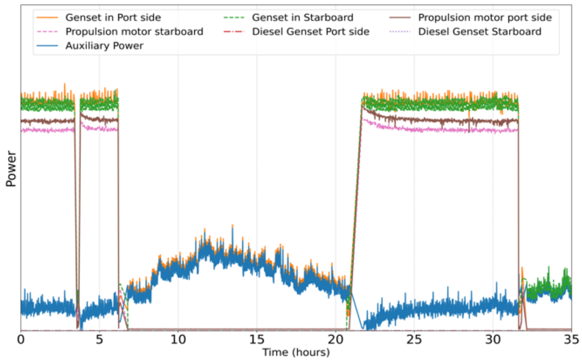

Figure 5. The normalized total power produced by the main engines.

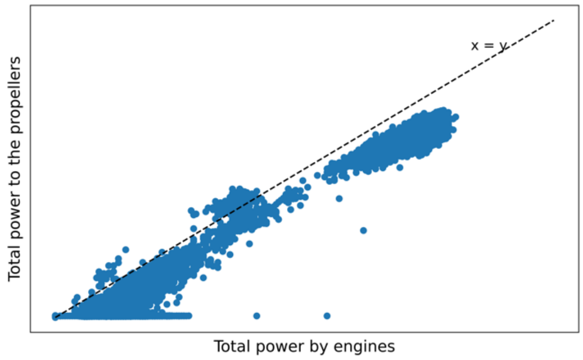

Figure 6. Scatter Plot of Engines Power vs Propellers Power.

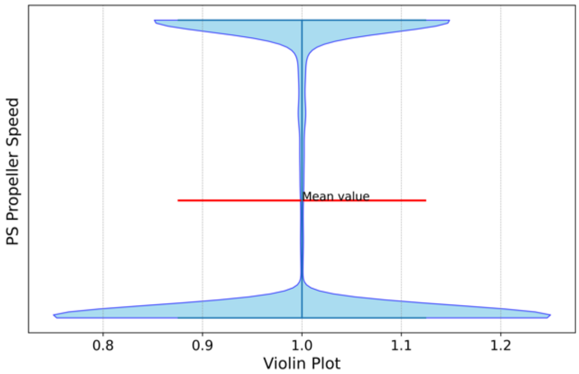

Figure 7. Violin plot of the propeller actual speed (PS stands for port side)

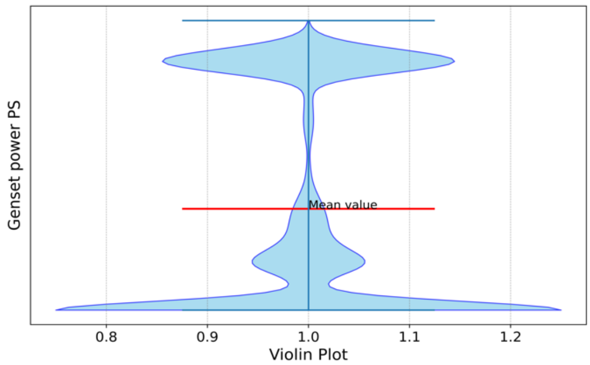

Figure 8. Violin plot of the engine power at the port side

2 METHODOLGY

The main goal of this study is showing the impact of system configuration on fuel consumption for a given load when the fuel and the type of machinery are changing. To explore this, an in-house modelling framework called FEEMS (Fuel Emissions Energy Calculation for Machinery System) was developed. This model enables us to test various fuels, including conventional fossil fuels, hydrogen, and ammonia.

2.1 FEEMS

FEEMS [15] is a modelling framework designed for marine power and propulsion systems. FEEMS calculates fuel consumption, emissions, and energy balance considering various operating modes and external power loads. The framework allows modelers to configure power systems using a component library and a single line diagram. It supports different types of power and propulsion systems, including hybrid/conventional diesel electric propulsion, hybrid propulsion with power take-in/power take-off (PTI/PTO), and mechanical propulsion with a separate electric power system. The unique advantage of using FEEMS is that it will be possible to apply energy management strategy to power sources, such as load-dependent start/stop of power sources, load smoothing/peak shaving operation with batteries, PTI/PTO operation, and choosing optimal power sources depending on the power demand, availability, and criticality of the operation. At the same time, FEEMS is designed to handle a large set of inputs, such as a year-long operational profile, with a short calculation time. Typically, it will give the result of the calculation with more than 100,000 input points in a couple of seconds. In this study, FEEMS was utilized for modeling the power system without hybrid configurations, focusing on conventional setups to evaluate fuel consumption and emissions. More information of the modeling detail is given in [16].

The validation of the model is given in Figure 9. As shown in the analysis for a 280-day voyage, the difference between the logged fuel consumption and the modeled output decreases from 6.0% in the initial days to just 0.4.0-2.4%, highlighting a reduction in the discrepancy as the number of days increases.

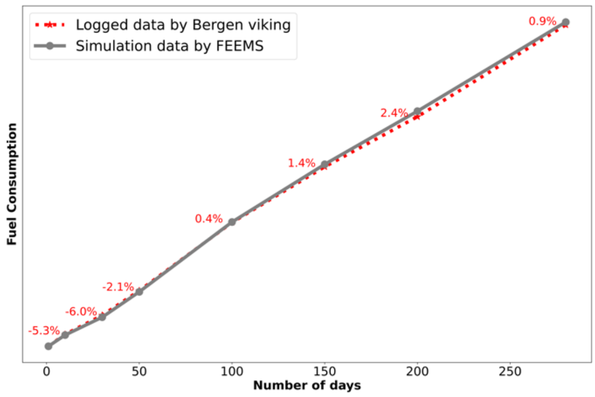

Figure 9. Fuel consumption over the entire days of ship travel (Bullet points indicate days 1, 10, 30, 50, 100, 150, 200 and 280).

1 RESULTS AND DISCUSSION

The results cover the entire 280 days of the ship's voyage. Since the bunkering frequency is not available, the total fuel consumption is used to compare the output of the machinery system. The analysis includes H_2 spark ignition engine; H_2 LT-PEM-FC; NH_3-diesel engine; and NH_3 SOFC. These systems were chosen due to their feasibility for our case study, as the goal is to propose solutions aligned with the current ship's electric propulsion and machinery room design. While using 2-stroke engines could potentially achieve even higher efficiency, the current pathways focus on maintaining compatibility with the existing setup. Additionally, three conventional methods are included for comparison: dual fuel 4-stroke engine, diesel 4-stroke engines, and the ship's current system, which is a lean-burn spark-ignition natural gas engine. Figure 10 illustrates the efficiency of the power systems. Blue and orange bars indicate the maximum allowed load and number of gensets. Limiting the maximum load is crucial for fuel cells where they are more efficient at lower loads. The current power system of the ship, which features lean-burn natural gas engines with spark ignition shown as the last pathway in the figure, serves as the reference value with a dashed red color connected to the blue column, 80% load with 2 gensets. As shown, two of the pathways exhibit higher tank to wake efficiency than the original system, while three show lower efficiency. For example, the first pathway, which involves burning hydrogen in 4-stroke engines with premixed injection, demonstrates efficiency like the reference value. In contrast, PEMFC and SOFC systems exhibit higher efficiencies specially when the maximum power is limited to 40%, achieving efficiencies of approximately 46% and 56%, respectively. Increasing the number of fuel cells to maximize efficiency substantially impacts the total system cost. However, using a larger fuel cell provides more running hours and reduces stress on the fuel cells, potentially extending its lifespan. Further detailed studies are required to evaluate the trade-offs between system sizing, efficiency, cost, and long-term durability

Additionally, the green bar in the graph represents the nominal efficiency of the system without accounting for time-based load impacts. The nominal efficiency of current system with a spark-ignition gas engine, can be higher than 45%. Advanced technologies like SOFC and PEMFC are expected to deliver nominal efficiencies exceeding 60% and around 50%, respectively. The influence of event-based load—where power demand fluctuates over time—significantly affects performance. Neglecting real operational profile and assuming constant loading could result in an overestimated system efficiency by as much as 7%, as indicated in the plot.

Figure 11 shows the fuel consumption in mass across different power systems. Hydrogen-based systems exhibit remarkably lower fuel consumption compared to the reference value, highlighting the reduced fuel mass required for the same voyage. This reduction is especially notable in PEMFC configurations, which leverage the high efficiency of fuel cells and the higher low heating value of hydrogen, approximately three times that of natural gas. As shown, ammonia-based pathways require more fuel due to their lower specific energy. However, ammonia-powered SOFC offers higher conversion efficiency and consumes less fuel than a combustion engine. Comparing the ammonia power systems, it can be seen that while the blue bar, for the 80% load, shows different values due to the efficiency and fuel fraction differences, this difference becomes minor when considering the orange bar, for the 40% load. Although SOFC is expected to have lower fuel consumption, in the case of the engine, the higher fraction of diesel fuel at lower loads resulted in a reduced total fuel mass. This trend is the opposite of what is observed in other pathways with an engine power source, where fuel consumption typically increases at lower loads due to lower efficiency.

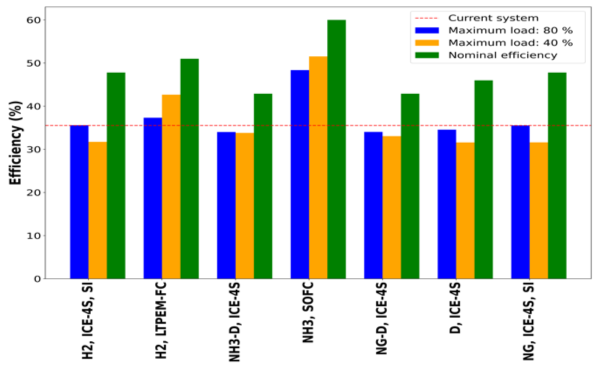

Figure 10. Comparison of the efficiency of the power systems.

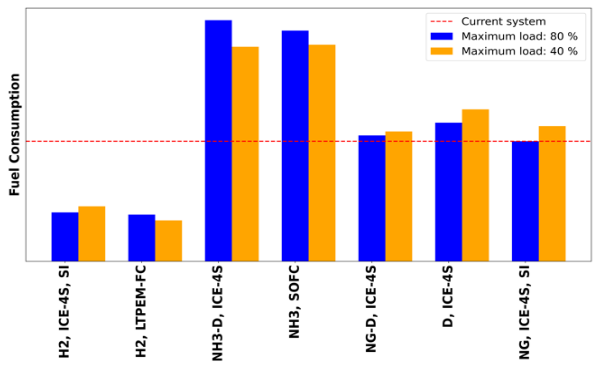

Figure 11. Comparison of total fuel consumption (in mass) across the same voyage.

However, beyond the tonnage of fuel, fuel volume is more critical consideration for the ships. For instance, an LNG-based power system demands nearly double the fuel space compared to a conventional diesel system, creating challenges for shipbuilders in optimizing storage layouts. Figure 12 gives the fuel volume required for various fuel types and power systems, excluding the impact of storage tank design. It should be noted that these pathways assume the direct use of hydrogen and ammonia without employing a cracker. If a cracker were used to convert ammonia to hydrogen, the required storage size would differ. As shown, hydrogen-based power sources demand significantly larger volumes of liquid hydrogen, with PEMFC configurations requiring approximately twice the volume of fuel comparing with the current system. Conversely, SOFC systems maintain similar fuel volume requirements to the original power system due to their higher efficiency and the comparable volumetric energy densities of ammonia and natural gas. However, pathways with lower efficiency or those relying on hydrogen typically exhibit increased fuel storage demands.

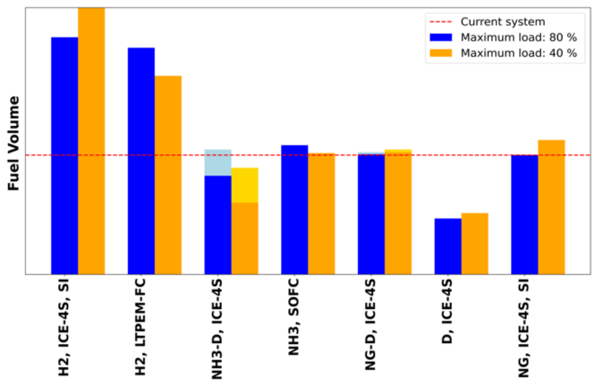

Figure 12. Comparison of the fuel volume without considering the fuel storage impact. Light blue and light orange in ammonia-diesel engine are showing the amount of pilot fuel.

The primary goal of integrating cutting-edge technologies is to achieve cleaner power systems and minimize emissions per unit of cargo or passenger. While CO2 emissions are a key factor for comparison, it is important to also analyze the equivalent CO2 emissions for a more comprehensive assessment. Figure 13 and Figure 14 show the CO_2 of various pathways in tank-to-wake (TTW) and well-to-wake (WTW) scenarios, as well as CO_2 equivalents from methane and N_2O, for a maximum allowed load of 80%, where the engines operate at their most efficient.

In Figure 13, where hydrogen and ammonia are assumed to be green-based fuels, the reduction in CO_2 equivalent emissions is very significant compared to conventional pathways. This is especially true for fuel cells and hydrogen-based power sources. When it comes to using ammonia in a four-stroke engine, the high pilot fuel fraction, especially at lower loads, is a significant source of CO_2 emissions. Additionally, N_2O emissions, with a global warming potential of 298, further increase the total greenhouse gas impact of this pathway. This can be further elevated if the combustion temperature is not sufficiently high to convert the fuel [17]. Assuming fully controlled combustion and considering N_2O emissions caused only by temperature mechanisms, the ammonia and diesel combustion engine pathway can reduce greenhouse gas emissions 30-45%. Otherwise, the total greenhouse gas emissions of this pathway may exceed those of conventional systems. As expected, the hydrogen spark-ignition engine results in zero CO_2 emissions from tank-to-wake, like the PEMFC and SOFC. When comparing the conventional pathways, the natural gas engines show lower CO_2 emissions in tank-to-wake assessments. However, their CO_2 reduction potential diminishes when considering well-to-wake emissions. This is particularly relevant for methane slip, which has a CO_2 equivalent emission factor of 25. On the other hand, as shown in Figure 14, if gray hydrogen and ammonia are used, the results are completely different. In this case, the use of ammonia and hydrogen not only fails to reduce greenhouse gases but can result in higher emissions than conventional machinery. This is specifically shown by the blue column bar of the well-to-tank.

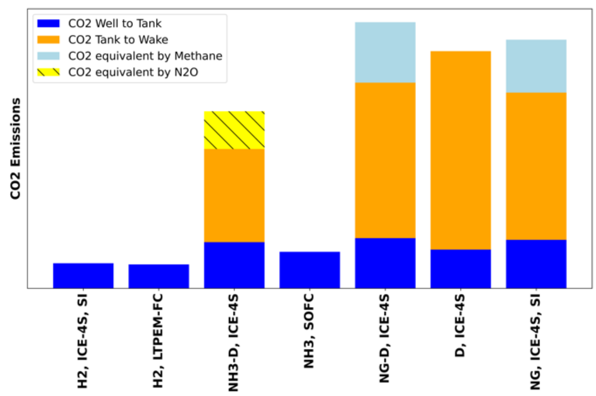

Figure 13. Comparing CO_2-equivalent across different pathways, assuming hydrogen and ammonia green. Values are based on FuelEU targets and in [17], [18], [19], [20]

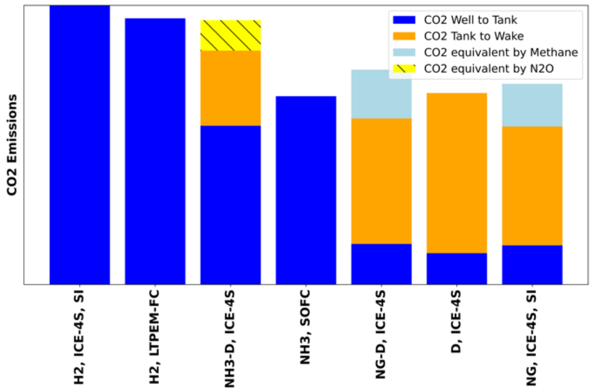

Figure 14. Comparing CO_2-equivalent across different pathways, assuming hydrogen and ammonia fossil-based fuel.

2 CONCLUSION

This study demonstrated the potential of hydrogen and ammonia as alternative fuels for the maritime sector, in line with the IMO decarbonization targets. Through detailed analysis and modeling, we identified key pathways for integrating these fuels into an electric propulsion system. Using the FEEMS modeling framework, we accurately assessed fuel consumption and emissions under real operating conditions. The case study of the BERGEN VIKING vessel further illustrated the practical benefits of adopting hydrogen and ammonia, showing their efficiency and positive environmental impact. In comparison with three conventional methods, we found that using ammonia in dual-fuel engines with conventional fossil fuels as pilot fuels requires more attention. The impact of lower loads, which increases dependency on fossil fuels, reduces the potential for CO_2 emission reduction, making such pathway less effective in achieving CO_2 reduction. Finally, it is shown that if the fuel source is not green but fossil-based, greenhouse gas emissions will significantly increase by using the alternative fuels.

3 ACKNOWLEDGMENTS

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4 REFERENCES AND BIBLIOGRAPHY

[1] "Annex 15, RESOLUTION MEPC.377(80), 2023 IMO STRATEGY ON REDUCTION OF GHG EMISSIONS FROM SHIPS," 2023.

[2] D. - Maritime, "Energy Transition Outlook 2024 – Maritime Forecast to 2050."

[3] S. Tavakoli *et al.*, "Exploring the technical feasibility of carbon capture onboard ships," *J Clean Prod*, vol. 452, May 2024, doi: 10.1016/j.jclepro.2024.142032.

[4] I. Energy Agency, "Global Hydrogen Review 2024," 2024. [Online]. Available: www.iea.org

[5] P. Office of the European Union, "REGULATION (EU) 2023/1805 OF THE EUROPEAN PARLIAMENT AND OF THE COUNCIL of 13 September 2023 on the use of renewable and low-carbon fuels in maritime transport, and amending Directive 2009/16/EC (Text with EEA relevance)", doi: 10.2771/793264.

[6] E. Lindstad, B. Lagemann, A. Rialland, G. M. Gamlem, and A. Valland, "Reduction of maritime GHG emissions and the potential role of E-fuels," *Transp Res D Transp Environ*, vol. 101, Dec. 2021, doi: 10.1016/j.trd.2021.103075.

[7] D. Maritime, "Energy Transition Outlook 2023 – Maritime Forecast to 2050," 2023.

[8] M. Cimenti and J. M. Hill, "Direct utilization of liquid fuels in SOFC for portable applications: Challenges for the selection of alternative anodes," 2009, *MDPI AG*. doi: 10.3390/en20200377.

[9] R. Folkson, "6 - Hydrogen as an energy vector for transportation vehicles**J.W. Sheffield and K.B. Martin, formerly of Missouri University of Science and Technology, United States, contributed to first edition.," in *Alternative Fuels and Advanced Vehicle Technologies for Improved Environmental Performance (Second Edition)*, Second Edition., R. Folkson and S. Sapsford, Eds., in Woodhead Publishing Series in Energy. , Woodhead Publishing, 2022, pp. 151–171. doi: https://doi.org/10.1016/B978-0-323-90979-2.00013-5.

[10] L. Mulky *et al.*, "An overview of hydrogen storage technologies – Key challenges and opportunities," *Mater Chem Phys*, vol. 325, p. 129710, Oct. 2024, doi: 10.1016/J.MATCHEMPHYS.2024.129710.

[11] S. Niaz, T. Manzoor, and A. H. Pandith, "Hydrogen storage: Materials, methods and

perspectives," May 30, 2015, *Elsevier Ltd*. doi: 10.1016/j.rser.2015.05.011.

[12] M. G. Sürer and H. T. Arat, "Advancements and current technologies on hydrogen fuel cell applications for marine vehicles," *Int J Hydrogen Energy*, vol. 47, no. 45, pp. 19865–19875, May 2022, doi: 10.1016/j.ijhydene.2021.12.251.

[13] J. Godinho, R. Hoefnagels, C. G. Braz, A. M. Sousa, and J. F. O. Granjo, "An economic and greenhouse gas footprint assessment of international maritime transportation of hydrogen using liquid organic hydrogen carriers," *Energy*, vol. 278, p. 127673, Sep. 2023, doi: 10.1016/J.ENERGY.2023.127673.

[14] C. Chu, K. Wu, B. Luo, Q. Cao, and H. Zhang, "Hydrogen storage by liquid organic hydrogen carriers: Catalyst, renewable carrier, and technology – A review," *Carbon Resources Conversion*, vol. 6, no. 4, pp. 334–351, Dec. 2023, doi: 10.1016/J.CRCON.2023.03.007.

[15] SINTEF, "FEEMS, Modeling framework for a marine power and propulsion system for calculation of fuel consumption, emissions, and energy balance with the input of operation mode and external power load." Accessed: Jan. 06, 2025. [Online]. Available: https://github.com/SINTEF/FEEMS/

[16] Kevin Kusup Yum, Sadi Tavakoli, Torstein Aarseth Bø, Jørgen Bremnes Nielsen and, and Dag Stenersen, "Design Lab: a simulation-based approach for the design of sustainable maritime energy systems," *International Marine Design Conference*, Jun. 2024, doi: https://proceedings.open.tudelft.nl/imdc24/article/view/844/872.

[17] K. A. Pedersen, M. T. Lewandowski, C. Schulze-Netzer, M. Pasternak, and T. Løvås, "Ammonia in Dual-Fueled Internal Combustion Engines: Impact on NOx, N2O, and Soot Formation," *Energy and Fuels*, vol. 37, no. 22, pp. 17585–17604, Nov. 2023, doi: 10.1021/acs.energyfuels.3c02549.

[18] S. Ushakov, D. Stenersen, and P. M. Einang, "Methane slip from gas fuelled ships: a comprehensive summary based on measurement data," Dec. 01, 2019, *Springer*. doi: 10.1007/s00773-018-00622-z.

[19] EMSA, "Potential of Hydrogen as Fuel for Shipping," 2023. [Online]. Available: www.emsa.europa.eu

[20] R. ; Laursen and D. ; Barcarolo, "Potential of ammonia as fuel in shipping," 2022. [Online]. Available: www.emsa.europa.eu