



# THE FUTURE OF MARITIME DECARBONIZATION

## 1. Introduction

The maritime sector represents an international network of ships and ports powering the global economy that contributes most significantly to greenhouse gas (GHG) emissions within the transportation sector. Large transport, container, and cargo ships move about \$4 trillion worth of goods throughout the world per year, making up approximately 80% of global trade by volume [1]. Meanwhile, global emissions from all vessels make up about 3% of total GHG emissions each year and account for 9% of sulfur oxides (SO<sub>x</sub>) and 18% of nitrogen oxides (NO<sub>x</sub>) emissions annually [2]. Maritime decarbonization refers to the process of reducing GHG emissions through the adoption of green fuels and energy-efficient technology to achieve net-zero emissions. Decarbonization in the maritime sector is especially hard due to a heavy dependence on fossil fuels, longevity and long operational ranges of ships, and difficulty developing and scaling up alternative fuels while keeping costs low. Without transformative changes and adaptations, maritime GHG emissions are expected to grow 16% from 2018 to 2030, and 50% by 2050 [3]. This paper explores the role of alternative green fuels in the decarbonization of maritime transport, with a particular focus on green hydrogen and its key derivatives, e-ammonia and e-methanol.

## 2. Green Hydrogen

Green hydrogen has emerged as a promising solution to decarbonize the marine transportation industry. As shown in Figure 1, hydrogen can be produced by separating the hydrogen from the oxygen in water via electrolysis, summarized by the equation,  $2\text{H}_2\text{O} \leftrightarrow 2\text{H}_2 + \text{O}_2$ . Hydrogen gas is produced at the cathode and oxygen gas is produced at the anode. If the electricity in this process comes from renewable sources like solar and wind, it will produce energy without emitting carbon dioxide into the atmosphere, making it green hydrogen. Furthermore, green hydrogen is a clean energy source that only emits water vapor and leaves no residue in the air, which means that it could stand as a potential foundation for sustainable energy systems in long-term maritime decarbonization strategies. However, one of the most significant barriers to widespread adoption of green hydrogen is its high production cost. Depending on regional energy prices and technological advancements, green hydrogen production costs ranged from \$3 to \$6 per kilogram in 2024, which is substantially higher than grey and blue hydrogen, which both rely on fossil fuels, at \$1 to \$2 per kilogram [4]. This is generally driven up by the high initial costs of electrolyzer systems, the irregularity of renewable power sources,

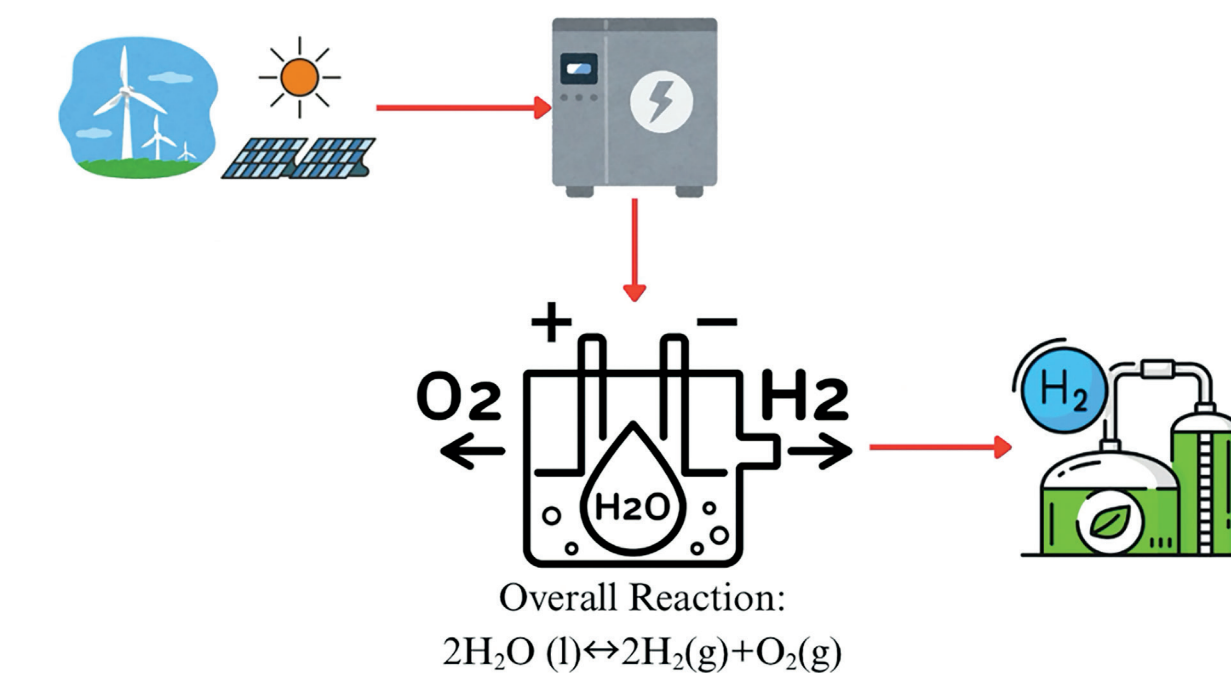


Figure 1. Schematic of green hydrogen production via water electrolysis powered by renewable energy sources.

and underdeveloped infrastructure for hydrogen compression, storage, and transport. Besides reducing costs through mass production of electrolyzers and improving renewable electricity sources, industry and research communities have invested in cost-reduction strategies like next-generation electrolyzers that use non-precious metal catalysts or have higher efficiencies by using waste heat from industrial processes. Furthermore, if the World Hydrogen Council's prediction that production costs will fall by 50% by 2030 holds true, green hydrogen would reshape the economics of maritime transport as a truly viable, scalable, and clean marine fuel [5].

In the short term, hydrogen can be used in combustion engines, where it is blended with conventional fuels for use as a range extender or backup. This would allow the maritime sector to gradually reduce GHG emissions without expensive replacement of existing ship engines or fuel infrastructure, making it lower-risk, cost-effective, and thus, more attractive for the industry. However, the long term goal remains a complete transition to zero-carbon fuels like pure green hydrogen and its derivatives, e-ammonia, and e-methanol. Being able to do so would completely eliminate fossil fuel dependence and drastically reduce emissions from the maritime sector. While green hydrogen is very promising as a zero-emission marine fuel, attempts to use it in its pure form

may not be feasible without an appropriate storage medium since it has a low volumetric energy density. As shown in Table 1, the volumetric energy density of liquid and compressed hydrogen is 8.5 GJ/m<sup>3</sup> and 7.5 GJ/m<sup>3</sup>, respectively, which is much lower than that of conventional marine gas oil at 36.6 GJ/m<sup>3</sup> [6]. This renders hydrogen not suitable for long-distance transportation where onboard storage space is limited. On top of that, hydrogen's low ignition energy and wide flammability range raise serious safety and handling concerns, especially in confined spaces like ships. Consequently, greater emphasis has been put on green hydrogen derivatives such as e-ammonia and e-methanol, which have greater energy densities in liquid form. They are also more conveniently stored and handled under ambient or slightly pressurized conditions, and so, might be better suited to current ship configurations and fuel facilities. The following sections will cover these two fuels in detail, looking at their route of production, advantages, disadvantages, and possible roles in rewriting the future of ship propulsion.

## 3. E-Ammonia

E-ammonia is a synthetic fuel produced by combining green hydrogen with nitrogen extracted from the air through the Haber-

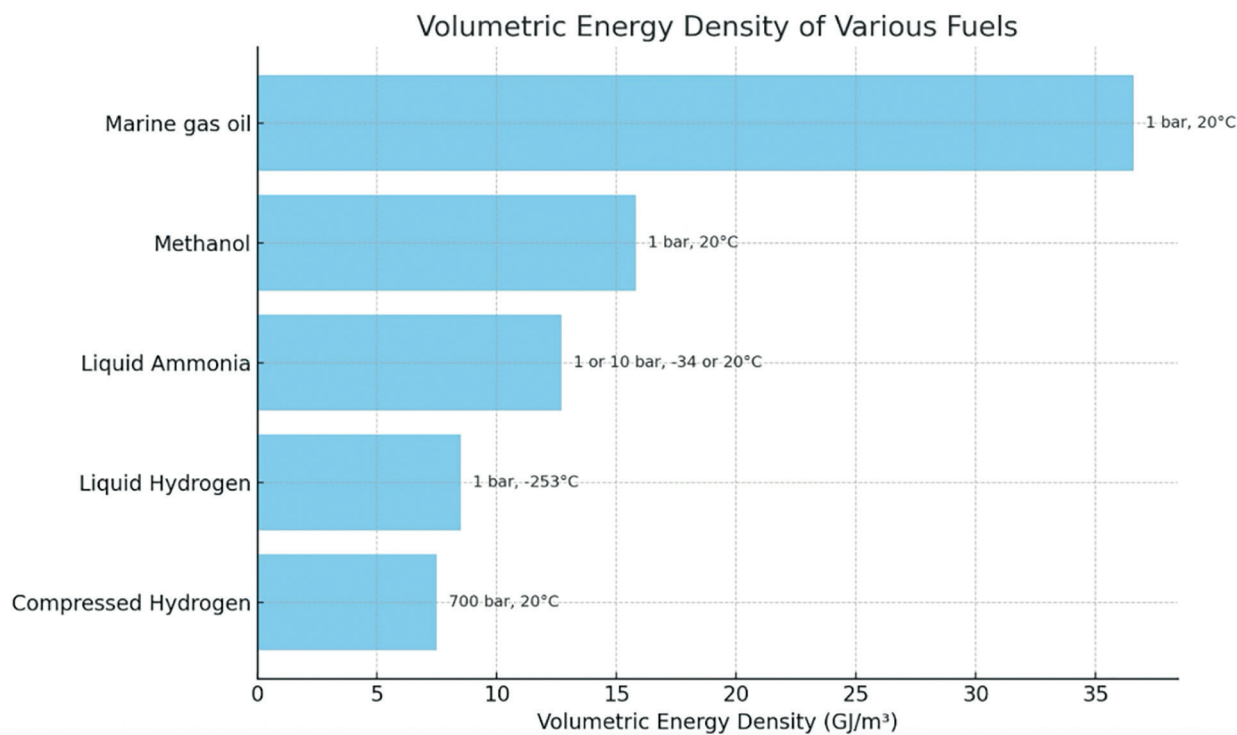


Figure 2. Volumetric energy density and storage conditions of marine fuel options [6].

Bosch process, also powered by sustainable electricity, as shown in Figure 2. Conventionally, the most common method of making ammonia relies on steam methane reforming (SMR) to produce hydrogen. Methane reacts with water vapor under high pressure and temperature to produce carbon monoxide and hydrogen, which is then combined with nitrogen via the Haber-Bosch process to form ammonia. However, approximately 90% of the CO<sub>2</sub> produced comes from methane in the SMR process, making it a major contributor to the carbon footprint of conventional ammonia production [7]. In contrast, e-ammonia is carbon-free at the molecular level, making it a promising candidate for zero-emission marine applications.

One of the most attractive features of e-ammonia is its relatively high volumetric energy density among hydrogen-based fuels. While it has lower volumetric energy density than conventional marine fuels at 12.7 GJ/m<sup>3</sup>, it is still about 50% more than that of liquefied hydrogen and almost 70% more than that of compressed hydrogen [6]. This higher volumetric energy density makes ammonia a more efficient hydrogen carrier that reduces the need for additional storage on vessels. In addition, liquid ammonia can be stored at -34°C or 20°C and 1 or 10 bar. In comparison, liquefied hydrogen has to be stored at -253°C and 1 bar, while compressed hydrogen has to be stored at 20°C and 700 bar [6]. Ammonia storage methods require much more moderate conditions than hydrogen, allowing for improved safety, lower costs, lower energy requirements, and easier integration.

In January 2024, the Clean Air Task Force (CATF) looked at three ammonia-based ship investment scenarios: a new vessel fully powered by ammonia, a retrofitted dual-fuel vessel with full range capacity on ammonia, and a retrofitted dual-fuel vessel with reduced range capacity on ammonia [8]. They found that newly built vessels running entirely on ammonia can achieve a 77% reduction in lifetime GHG emissions compared to conventional heavy fuel oil (HFO) ships. Notably, these ammonia-powered ships would be able to achieve that at the same lifetime cost as a conventional HFO vessel that must pay for its carbon emissions. While the retrofitted vessels achieve a lower reduction in lifetime GHG emissions at 52% for full capacity and 41% for partial capacity, they were still able to comply with or outperform the FuelEU Maritime targets, which aims to reduce the greenhouse gas intensity of maritime fuel usage by 80% by 2050 [9], at a cost equal to or below that of a HFO vessel.

While e-ammonia offers promising advantages as a carbon-free marine fuel, it introduces serious occupational and environmental hazards. Inhalation of ammonia vapors can cause respiratory distress, and exposure to high concentrations may lead to severe health effects or even death. According to OSHA, concentrations above 300 ppm are considered immediately dangerous to life or health [10]. These risks are particularly concerning aboard ships, where confined spaces, variable weather conditions, and limited medical support increase the vulnerability of crew members handling ammonia fuel systems. Particular to the maritime sector, in the event of fuel spills at sea, ammonia is highly soluble in water with concentrations as low as 0.02–0.05 mg/L impairing gill function and reproduction in fish and invertebrates [11]. Given the proximity of fuel tanks to open water and the operating conditions on marine vessels, the unique properties and hazards of ammonia, training, handling, and storage of ammonia must be carefully managed.

Despite these challenges, e-ammonia is gaining traction in the maritime industry due to its high volumetric energy density and ability to remain liquid at moderate pressures and temperatures. These properties offer significant advantages over pure green hydrogen fuels, making it a scalable solution for large-scale implementation in marine applications.

#### 4. E-Methanol

E-methanol is another derivative of green hydrogen created from combining hydrogen with renewably sourced CO<sub>2</sub>, typically captured via direct air capture (DAC) or from industrial emissions, as shown in Figure 4. This also gives the recaptured CO<sub>2</sub> a new purpose other than as industrial waste, allowing methanol to be synthesized without directly contributing to net CO<sub>2</sub> emissions. Given its favorable chemical properties and growing infrastructure, e-methanol is increasingly seen as an attractive option for decarbonizing the maritime industry and reducing its reliance on conventional fossil fuels. The production reaction is catalytically driven, occurring under relatively mild conditions compared to other synthetic fuels. However, CO<sub>2</sub> sources for e-methanol production typically come from waste streams exiting industrial plants, and these plants are often found in places where adjacent infrastructure for CO<sub>2</sub> capture and e-methanol production cannot be built [12].

In comparison with hydrogen and e-ammonia, e-methanol has an even higher volumetric energy density of 23.4 GJ/m<sup>3</sup>, which is substantially higher than that of hydrogen and e-ammonia and only 36% less than marine gas oil. This makes e-methanol even more efficient in terms of fuel volume requirements aboard ships. Although liquid methanol has to be stored at -162°C and 1 bar, which is more extreme than e-ammonia storage, it is still more moderate than liquid hydrogen at -253°C and more than compressed hydrogen at 700 bars [6]. These conditions still allow the incorporation of e-methanol feasible for maritime fuel systems. In addition, storage methods for liquid methanol already exist in the form of liquefied natural gas (LNG) infrastructure [13]. In contrast, hydrogen storage technology for long-distance voyages remains in its infancy.

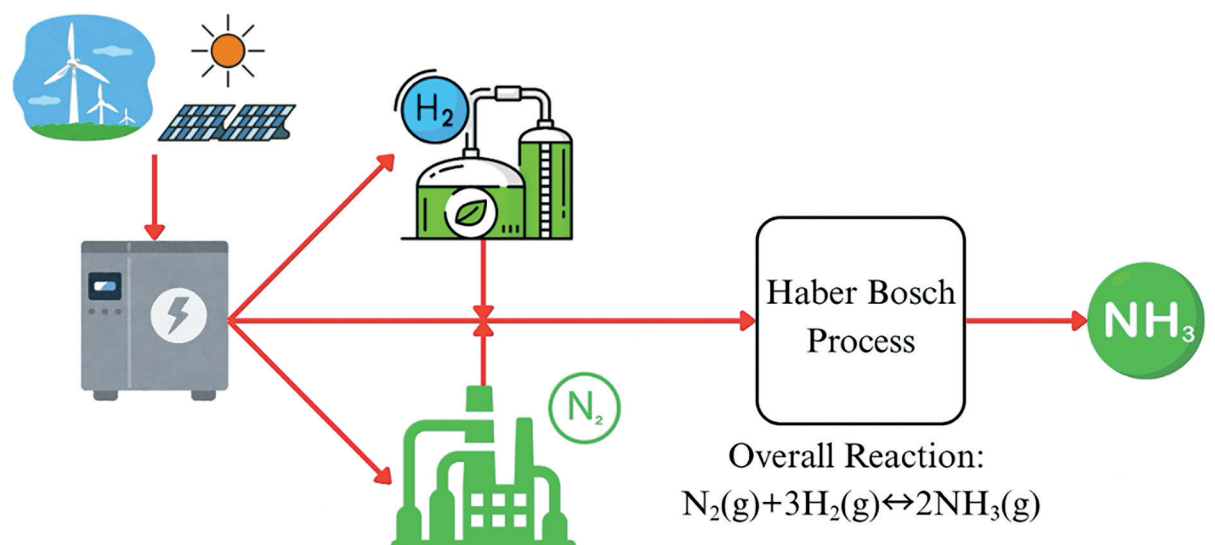


Figure 3. Schematic of e-ammonia production using green hydrogen and renewably powered air separation units and the Haber-Bosch process.

Compared to e-ammonia, e-methanol presents a very different set of hazards when considering its use as a marine fuel. Most important, e-methanol is a highly flammable liquid with a flash point of around 12°C, making it prone to ignition at relatively low temperatures [14]. In confined environments like ships, this poses serious fire and explosion risks. Additionally, e-methanol is toxic with the potential to cause central nervous system depression, blindness, or death in high exposures through the skin, inhalation, or ingestion. Furthermore, it has no strong odor or color, which can delay leak detection and increase the risk of accidental exposure or ignition. Environmentally, methanol is water-soluble and is biodegraded into non-toxic substances within a few days [15]. Despite these hazards, methanol is relatively well understood in industry, and many of its risks can be mitigated with proper training, materials, and ship design.

Scientists at the University of Flensburg in Germany evaluated the impact of adopting e-methanol as a marine fuel in the North and Baltic Seas [16]. They use a scenario-based modelling framework combined with a well-to-wake lifecycle assessment (LCA) to evaluate the emissions of various marine fuel and fleet transition strategies through 2040. The well-to-wake approach captures emissions from the entire fuel supply chain, from production to onboard combustion, providing a more holistic view of a fuel's environmental impact. By modeling a scenario in which the regional shipping fleet transitions to e-methanol, they found that transitioning the existing fleet to e-methanol could reduce CO<sub>2</sub> emissions by up to 90% by 2040. However, this reduction is dependent on the large-scale availability of renewable electricity and CO<sub>2</sub> feedstock to produce e-methanol sustainably. Among the alternative fuel options, e-methanol is both technically feasible and operationally compatible with existing engine technologies, making it more attractive in the short-to-medium term compared to other alternatives like green ammonia or hydrogen that may require more extensive retrofitting and infrastructure development.

In summary, e-methanol presents a compelling option for decarbonizing maritime transport, particularly due to its relatively high volumetric energy density, compatibility with existing liquid fuel systems, and biodegradability, making it a near-term solution for reducing GHG emissions in the maritime sector. While safety hazards such as flammability and toxicity must be carefully managed, these risks are well-characterized and can be mitigated through established industry practices. However, the viability of e-methanol at the industry scale depends heavily on economic and policy support, particularly in overcoming the high costs of green hydrogen production and CO<sub>2</sub> capture. With the right improvements, e-methanol could serve as both a bridge and a long-term solution for achieving net-zero emissions in the maritime sector.

#### 5. Conclusion

As the maritime sector gets put under increasing pressure to decarbonize and meet global climate goals, going toward alternative fuels becomes increasingly more essential. In fact, the 2023 International Maritime Organization (IMO) GHG Strategy aims to reduce the total annual GHG emissions from international shipping by at least 20% by 2030 and at least 70% by 2040 [17]. Green hydrogen provides a clean and flexible basis for zero-emission marine fuels but is still hindered by its prohibitive production costs, low volumetric energy density, and difficult storage. Derived substances including e-ammonia and e-methanol address many of those problems as they possess better storage characteristics, higher energy densities, and compatibility with current infrastructure. E-ammonia seems suitable for long-haul marine shipping due to efficient storage and favorable energy profile, but it does require stringent

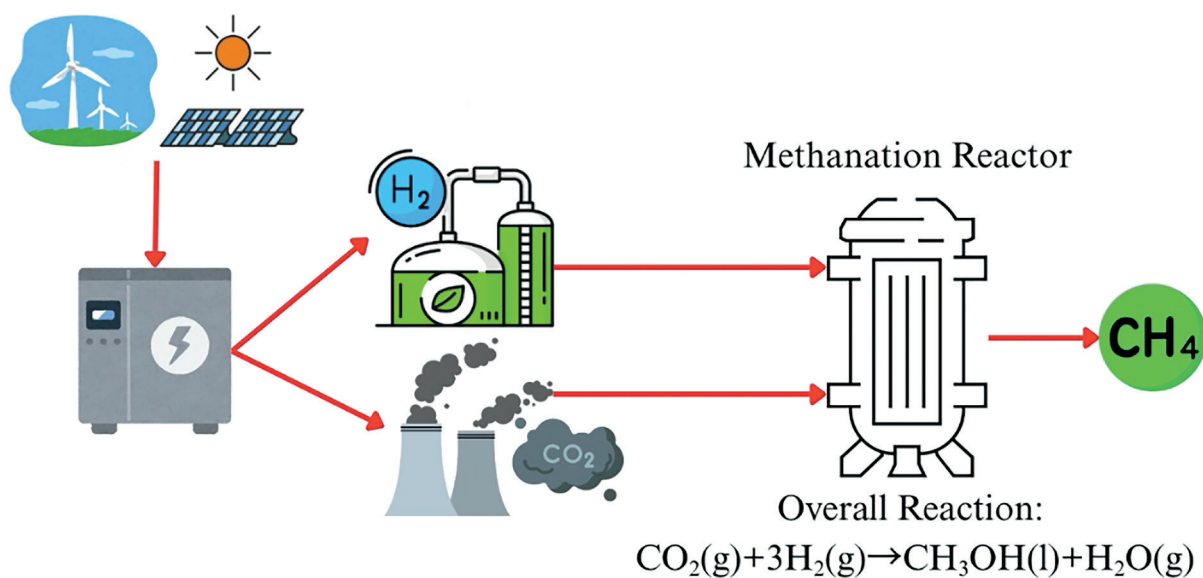


Figure 4. Schematic of e-methanol production combining green hydrogen and recaptured CO<sub>2</sub> via methanation.

safety standards given toxic hazards and environmental risks. E-methanol, on the contrary, offers lower ecological risks and easier implementation compared to the systems having e-ammonia. However, sourcing renewable carbon dioxide and scaling up to industry levels remain big hurdles. Each fuel is a distinct set of trade-offs in cost, infrastructure, safety, and sustainability. The future of maritime decarbonization will most likely necessitate an approach that leverages the complementary strengths of green hydrogen and its derivatives based on specific ship types, routes, and operational demands. Fast-tracking investments into renewables, carbon capture, fuel handling infrastructure, and crew training would act as a catalyst to further unlock fuel potential. Tapping into diversification created by green hydrogen and its derivatives would set the maritime sector on a more sustainable way toward net zero emissions.

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