# Decarbonizing Maritime Shipping: Emissions, Feasibility, and Environmental Impacts of Alternative Fuels

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22.081 Introduction to Sustainable Energy

November 16th, 2022

# I. Abstract

The maritime sector currently contributes to ~3% of global greenhouse gas emissions (Mallouppas et al., 2021). Maritime shipping primarily uses heavy fuel oil (HFO) due to its high fuel density that allows ships to travel long distances without refueling. To achieve International Maritime Organization's (IMO) goals of reducing greenhouse gas (GHG) emissions by 50% by 2050 compared to 2008 levels, alternative fuels will play a key role, in addition to energy efficiency measures such as employing wind and solar and improving ship design. Alternative fuels that show the most promise include Liquefied Natural Gas (LNG), bio- and synthetic fuels, hydrogen ammonia, and methanol and will be compared for decarbonization potential, cost, feasibility, and socioenvironmental impact. LNG and drop-in bio and synthetic fuels are limited in their decarbonization potential but cost-competitive and may be used as transition fuels while new shipping infrastructure is developed. Biofuels also pose sustainability and supply availability issues. Hydrogen and ammonia are currently more expensive but ideal for achieving net-zero goals in the long-term with increased availability of renewables in the grid, investments in ship infrastructure, and technological innovations.

# II. Introduction

Hard-to-decarbonize sectors are not addressed by the majority of discussions which focus on just decarbonizing electricity in the grid. In 2020, 24% of GHG emissions in the U.S. came from the industrial sector and 27% from the transportation sector, 36% of which came from medium- and heavy-duty trucks, shipping, and aviation, which will all require alternative fuels (Environmental Protection Agency). The International Energy Agency (IEA) finds that globally, shipping contributed 0.84 Gt $CO_2$ in 2021, the second biggest emitting

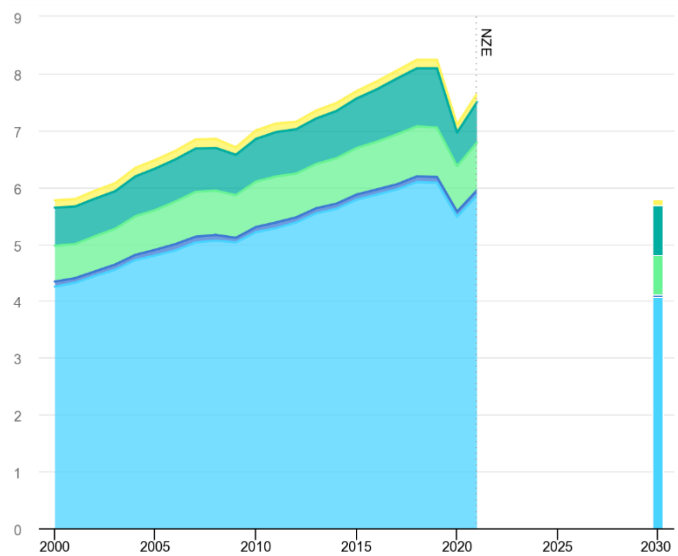


***Figure 1:*** *Global $CO_2$ emissions from transport by sub-sector in the Net Zero Scenario. From top to bottom: pipeline transport (yellow), aviation (turquoise), shipping (light green), rail (dark blue), and road (light blue).*
*Source: [https://www.iea.org/reports/transport](https://www.iea.org/reports/transport)*

transport sub-sector next to road transport (Figure 1). The IEA finds that we are not on track for decarbonizing transport unless we begin a rapid scale-up of low-carbon fuels in the maritime and aviation sectors.

Decarbonizing the maritime shipping sector means using alternative fuels. Marine diesel engines conventionally use heavy diesel oil (HFO), marine diesel oil (MDO) and increasingly, liquefied natural gas (LNG). HFO has a high viscosity and sulfuric fuel that emits $SO_x$. It is highly unlikely that a battery could be developed that has enough capacity to carry upwards of 200,000 tonnes across the ocean without recharging. Alternative fuels, such as biofuels, hydrogen, ammonia, methanol, and nuclear, as well as renewable sources, energy efficiency measures, and carbon capture and storage (CCS) will be needed to transition the maritime industry. A diversity of fuels will need to be adopted strategically and in tandem to meet ambitious decarbonization goals in a reasonable timeline. All of these fuels come with an array of cost and feasibility concerns. The energy density of the fuel, maturity of the technology, and production scale will influence price and the amount of energy that will need to be consumed. These fuels will also rely on infrastructure within the design of the ships themselves and the grid capacity and infrastructure. As we create a world dependent on these new carbon-neutral fuels, there will be new socio-environmental implications, including jobs, safety, ecological, and environmental justice impacts.

## III. Decarbonization Goals and Challenges in the Maritime Industry

The maritime sector currently contributes to ~3% of global greenhouse gas emissions (Mallouppas et al., 2021). The International Maritime Organization (IMO), which is a United Nations agency, set goals to achieve an at least 50% reduction in annual global GHG shipping emissions by 2050 in alignment with the Paris Agreement. They hope to reduce average $CO_2$ per transport work by 40% by 2030, 70% by 2050 reduction compared to 2008 levels, and achieve net-zero as soon as possible by 2100. Various efficiency improvement standards are in place for the short-medium term. The European Green New Deal sets more ambitious goals, opting for 90% carbon-neutrality by 2050, with 55-60% reductions by 2030.

A challenge of the energy transition is the decreased energy efficiency of renewable sources. A 100% renewable shipping sector would increase energy consumption by 163% (García-Olivares et al., 2018). To achieve the IMO's 2030 goals, it would cost $40 billion per year, and to fully decarbonize shipping, it would cost $1-1.8 trillion, 87% of which would go toward hydrogen infrastructure on land. With uncertainty for what alternative fuel the future holds, the conundrum for the shipping industry is deciding what to invest in now—"Do I build a cheaper asset now with the anticipation of retrofitting it in five years' time to ammonia or do I build a more expensive asset now, with that premium at risk because I might be betting on the wrong fuel?" (Gerretsen, 2022).

## IV. Alternative Fuel Types

### Liquefied Natural Gas (LNG)

LNG is natural gas cooled to a liquid form for storage and transport. It may be derived from extracted natural gas, or derived from farm or urban waste (bio-LNG), hydrogen, and $CO_2$ in the Sabatier Process. LNG may serve as a readily available transition fuel to decarbonizing the shipping industry. While its use has surged recently, many of these ships will become stranded assets because it is not a carbon neutral fuel. This could result in financial losses of $850 billion by 2030, or if LNG-fueled vehicles were retrofitted to run on zero-emission fuels, $129-210 billion (Gerretsen, 2022).

LNG is cryogenically stores at very low temperatures of −162 °C. This allows it to take up to 600 times less space for storage and transport compared to its gaseous form. It is the cleanest available fuel for shipping currently that can be produced in meaningful volumes, and complies with emissions standards for $SO_x$, $NO_x$,, and PM while reducing $CO_2$ emissions by 20-30%. However, there are significant, uncertain levels of methane slip throughout the lifecycle of LNG, and current engines experience methane slips of 2-5% (Mallouppas et al., 2021).

### Biofuels and Synthetic Fuels

Biofuels are produced from organic waste, mainly from plant-based sugars and oils such as palm, soybean, and rapeseed. A common production method is using anaerobic digesters to generate biogas, which is then processed to remove impurities. Biogas can be used to create Liquified Bio-Methane (LBM), Liquified Synthetic Methane (LSM), or hydrogen. It may replace conventional fuels, or be blended with gasoline to produce bioethanol or diesel to produce biodiesel. Carbon neutrality may only be achieved if the absorption of $CO_2$ makes up for the processing, transport, and combustion of the fuel, which is difficult to achieve.

Implementing biofuels may come with some friction. The industry has work to do in handling and applying biofuels in the fuel supply chain. There is also more research to be done in maintaining oxidation stability during the storage of biofuels.

The production of biofuels comes with a set of social and environmental impacts. The crops used in feedstock production may expand dependency on monoculture feedstocks, which displaces food production, is linked to deforestation, and degrades resources and biodiversity. Food crops compete with agriculture and cellulosic ethanol draws nutrients from crop soil (García-Olivares et al., 2018). By limiting arable land, feedstock production may incur supply squeeze in food prices, natural resources, and perpetuate land-grabbing injustice, especially among indigenous communities and the Global South. Biofuels from soybeans and palm oil may also have a higher carbon intensity than conventional fossil diesel due to their resource-intensive production (Gonzalez, 2016).

## Hydrogen

Hydrogen is favorable for its high gravitational energy density, low volumetric energy density and availability. It releases no emissions except for water vapor when it is used as the primary fuel in fuel cells, except for high $NO_x$ under certain temperatures due to the nitrogen content of air. It may also be used as a drop-in fuel in existing diesel engines or gas turbines, blended with fuel such as HFO at low levels to avoid damage. Retrofitting ships to run on fuel cells will be necessary to achieve carbon neutrality, and fuel cells are also more efficient, with max efficiencies of 60-65% compared to 40% for internal combustion engines (ICE) (McKinlay, 2020).

The bulk of the carbon associated with hydrogen comes from its emissions-intensive production process. Hydrogen is primarily produced by steam methane reforming (SMR) natural gas, which involves reacting natural gas with high-temperature steam to generate synthesis gas—a mixture of hydrogen, carbon monoxide, and carbon dioxide. Over 95% of global hydrogen currently produced through SMR, which emits ~12 kg-$CO_2$/kg-$H_2$ and it is the cheapest method (Atilhan et al., 2021; Tao et al., 2022). Natural gas or methane in hydrogen production is known as grey hydrogen, whereas brown hydrogen is produced from coal. Blue hydrogen integrates CCS with natural gas. To achieve full decarbonization, green hydrogen will be necessary. The primary process for producing green hydrogen is electrolysis, which utilizes electrical currents to split water into hydrogen and oxygen.  This is ideal in the long-term as solar and wind, which are cheaper than conventional fossil energy, become more available. In the future, green hydrogen may also be produced through methods such as biomass fermentation and thermochemical water splitting driven by solar concentrators or nuclear reactors. While hydrogen production often happens on land, reversible fuel cells could be used to produce green hydrogen onboard a ship, with the only inputs being water and electricity, which can come from renewables. This would reduce the need for storage infrastructure on land, so long as the process is not too time consuming or inefficient, and a very high electrical demand can be satisfied (McKinlay et al., 2020). Compared to the fuels used in the maritime industry, most hydrogen supply chain pathways (even grey hydrogen) will reduce $CO_2$ significantly (Mallouppas et al., 2021).

Today's water electrolyzers come in different forms—alkaline electrolyzers, proton-exchange-membrane (PEM) electrolyzers, and solid oxide electrolyzers—and they consume more than 55 kWh/kg-$H_2$. Electric grid-powered water electrolysis would emit less $CO_2$ than the SMR process when the carbon intensity for grid power falls below 0.22 kg-$CO_2$/kWh. Solar and wind-powered electrolyzers can reduce $CO_2$ emissions by over 80% (Tao et al., 2022). However, electrolysis is three times more expensive than the equivalent from natural gas or coal, at costs of \$140/MWh compares to \$44-68/MWh (Mallouppas et al., 2021). Prices will fall with economies of scale, technological improvement, and renewable deployment. The cost for green hydrogen has dropped 50% since 2015 and could be reduced further by 30% by 2025 (Mallouppas et al., 2021).

The complexities of ship storage is a challenge for the implementation of hydrogen. It can be stored as compressed hydrogen, liquid hydrogen at very low temperatures of −252.9 °C, or chemical storage. Chemical storage may involve using ammonia as a storage medium or fuel, producing synthetic fuels using hydrogen, or using Aromatic Liquid Organic Hydrogen Carriers (LOHCs) with a catalyst to store hydrogen (Mallouppas et al., 2021). At ambient conditions, the gravitational energy density of hydrogen is particularly high, at 0.033 MWh/kg, but the volumetric energy density is very low, at 0.003 MWh/$m^3$. Volumetric energy density may be improved using additional complex infrastructure such as a highly pressurized container up to 700 bar, which can increase energy density to 1.4 to 2.1 MWh/$m^3$. As a liquid, energy densities can reach 2.2 and 2.8 MWh/$m^3$ (McKinlay, 2020).

While liquid hydrogen is nontoxic, unlike fuels such as ammonia and methanol, its high energy density and very low flashpoint of −231 °C can pose flammability and explosion risk

(Atilhan et al., 2021). There is also risk of asphyxiation. Safety challenges, complexities, high costs, and unavailability globally create barriers to the adoption of hydrogen. There is also a chicken-and-egg problem that comes with the concerted effort of developing infrastructure for its sustainable production and consumption. Ship modernization efforts are needed to provide extreme cryogenics and minimize boil-off product loss, and investment in R&D is needed to improve the safety and efficiency of on-board storage (Atilhan et al., 2021).

## Ammonia

Ammonia ($NH_3$) is produced via Haber-Bosch (H-B), which combines hydrogen and nitrogen at high temperatures of around 500 °C and high pressure of 20 MPa, along with a catalyst (McKinlay, 2020). This ubiquitous fertilizer is the most energy intensive chemical commodity and accounts for 2% of global energy consumption and 1% of CO2 emissions. Around half of global hydrogen, primarily derived from fossil fuels, is consumed as feedstocks for ammonia (Al-Aboosi et a., 2021). Its use on ships would be similar to hydrogen. It has a high octane rating, so it can be used in combustion, either as a drop-in fuel in diesel engines, gas turbines or a primary fuel in fuel cells.

Ammonia may achieve zero-emissions through combustion with a post-combustion device (such as a selective catalytic converter [SCR]) to prevent the release of $NO_x$ and $N_2O$ (a highly potent greenhouse gas) or a fuel cell. To mitigate $NO_x$ and $N_2O$, ammonia cracking has also been suggested, which is a process that converts ammonia back into hydrogen, though it is uncertain if the energy cost would be better or worse than storing pure hydrogen (McKinlay, 2020). At the production stage, “green ammonia” can be produced using renewable sources such as solar, wind, or hydropower, but this is not yet cost-competitive. “Grey ammonia” uses fossil fuel in feedstock production and energy in the H-B process. “Blue ammonia” involves a combination of the two, along with the use of CCS, and can be used in the transitional phase to green ammonia. 90% of ammonia relies on fossil fuels such as natural gas but this will change in the future as new green ammonia projects are developed (Kirstein et al., 2018). Green hydrogen and nitrogen feedstocks will be necessary. Nitrogen can be produced carbon-free through cryogenic distillation column, pressure swing adsorption, and membrane separation, as well as renewable energy in an air separation unit (ASU) (Al-Aboosi et al., 2021).

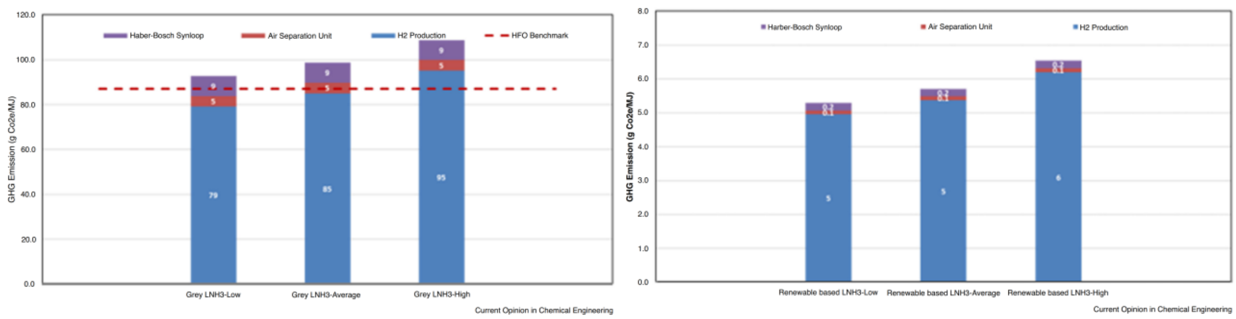


***Figure 2:*** *GHG emission breakdown for grey ammonia production (left) and green ammonia production (right). Hydrogen feedstock production contributes to most of the total emissions, but green ammonia is more than 10 times less GHG intensive (Al-Aboosi et al., 2021)*

Compared to hydrogen, ammonia has a higher volumetric energy density and does not require cryogenic storage, with temperatures of −33.4 °C needed for ammonia compared to −252.9 °C for hydrogen (Kirstein et al., 2018). Ammonia may also be stored under pressure at 0.8 MPa at ambient temperatures. Still, its need for high pressure, low temperature storage makes it more expensive and complicated than methanol. It is not flammable in air, although a secondary ignition fuel (natural gas or hydrogen) would be required for combustion. Most safety concerns come from ammonia's corrosiveness and high toxicity. Small levels of exposure can lead to loss of consciousness. $NO_x$ emissions, which are capped at 3.4 g/kWh by the IMO, can lead to acid rain, smog, ozone damage, and threaten human health (McKinlay, 2020). In terms of rapid adoption, ammonia is favorable because production, storage, and distribution infrastructure already exist.

## **Methanol**

Methanol ($CH_3OH$) is an alcohol that has similar carbon emissions at point of use as LNG for energy equivalent (McKinlay, 2020). Like LNG, methanol allows for a ~25% reduction in GHG emissions compared to HFO. There is no nitrogen or sulphur content, so it reduces SOx, NOx and PM by 99%, 60% and 95% respectively (Kirstein et al., 2018). It can be used in fuel cells, such as Direct Methanol fuel cells (DMFC), but requires CCS in order to be emission free. Methanol could potentially be used as a hydrogen carrier, but the hindering energy cost of conversion at high temperatures makes a DMFC most efficient. Methanol is produced thorough the catalytic conversion of synthesis gas ("syngas"), which is a mixture of carbon monoxide and hydrogen. The syngas is most commonly derived from natural gas or coal, and is a very energy intensive process.

Alternatively, lower carbon methanol can be produced from methane from carbon capture, industrial waste, municipal waste, agricultural waste, or biomass (highly available), which companies like Maersk are betting on. Hence, the feedstocks used for methanol pose similar socioenvironmental issues to biofuels. Biomass feedstock must undergo pretreatment, gasification, and reforming processes before they are introduced to hydrogen and converted to syngas. Novel purification methods will need to be commercialized to clean the syngas, but maritime methanol can be of lower quality (90% purity). Bio-methanol is produced at 60% energy conversion efficiency, compared to natural gas-derived methanol at 67-68% efficiency. Fossil-based plants also produce 5-10 time more tons per day of methanol than bio-methanol plants, though economic barriers and supply chains for bio-methanol adoption are minor (Svanberg el al., 2018). Steel-work off-gasses may also be used as feedstocks for methanol production. Methanol can also be produced from the catalytic synthesis of $CO_2$ and (green) hydrogen using electrolysis (Svanberg el al., 2018). This is a very low efficiency process and requires a large amount of renewable energy (McKinlay, 2020).

Methanol is a convenient fuel to rapidly deploy in terms of its cost and simplicity. With a boiling point of 65 °C, it may be stored as a liquid at ambient temperatures (McKinlay, 2020). The technology is mature and existing ships can be retrofitted, making it a viable short-term solution. However, methanol has a relatively low flash point of 12 °C, and higher explosion range than LNG, HFO, and ammonia (McKinlay, 2020). It is also highly toxic to humans, and the IMO suggests ample monitoring systems, which is a mature technology.

## V. Comparison analysis

There are limitations in the decarbonization potential of LNG, fuel cells, wind, and solar. Hydrogen, ammonia, nuclear, and advanced biofuels offer up to 100% reductions in GHG emissions (Mallouppas et al., 2021). Hydrogen, ammonia, and methanol are favorable because of their ability to produce energy with a fuel cell rather than combustion, mitigating any direct emissions from vessels. However, carbon neutrality will only be realized if the production of the fuel is carbon neutral (in the case of electro-fuels) or carbon negative (in the case of biofuels). Hybrid systems, such as those combining PV, diesel, and batteries, may be useful in the transition (García-Olivares et al., 2018).

| Measures | Possible $CO_2$ Emissions Reductions |
|---|---|
| Advanced biofuels | 25–100% |
| Liquefied Natural Gas (LNG) | 0–20% |
| Hydrogen | 0–100% |
| Ammonia | 0–100% |
| Fuel cells | 2–20% |
| Electricity | 0–100% |
| Wind | 1–32% |
| Solar | 0–12% |
| Nuclear | 0–100% |

***Table 1:*** *Possible $CO_2$ emission reductions for various alternative fuels. 100% is only achieved with renewable energy throughout the full lifecycle (Mallouppas et al., 2021).*

| Propulsion type | Currently used | Carbon free | Emission-free through combustion | Emission-free through combustion + SCR | Emission-free with fuel cell | Potential hydrogen carrier |
|---|---|---|---|---|---|---|
| Coal | N | N | N | N | N/A | N |
| HFO | Y | N | N | N | N/A | N |
| MDO | Y | N | N | N | N/A | N |
| LNG | Y | N | N | N | N/A[a] | N |
| LPG | N | N | N | N | N/A | N |
| Hydrogen | N | Y | Y[b] | N/R | Y | N/A |
| Ammonia | N | Y | N | Y | Y | Y |
| Methanol | N | N | N | N | Y[c] | Y |
| Batteries | N | Y | N/A | N/A | N/A | N |
| Nuclear | Y | Y | N/A | N/A | N/A | N |
| Biofuels | N | N[d] | N[d] | N[d] | N/A | N |

Key: Y = Yes; N = No; N/A = not applicable; N/R = not required.

***Table 2:*** *(McKinlay, 2021)*

In terms of energy density, biodiesel is the only fuel similar to diesel in energy density. LNG/LPG is 40% lower energy density than diesel, and hydrogen, ammonia, and methanol are 40-50% lower than LNG (Mallouppas et al., 2021). Figure 3 shows the energy density of various fuels. However, when the energy density of storage systems is also accounted for, energy density decreases significantly. Hydrogen then has about a quarter of the energy density of LNG and

HFO, and slightly lower energy density than ammonia and methanol. Methanol exceeded ammonia in both types of energy density for fuel and storage. Metal hydride and batteries are consistently too bulky. Despite its low volumetric energy density, hydrogen is still viable for powering large-scale vessels, especially with cryogenic storage (McKinlay, 2020).

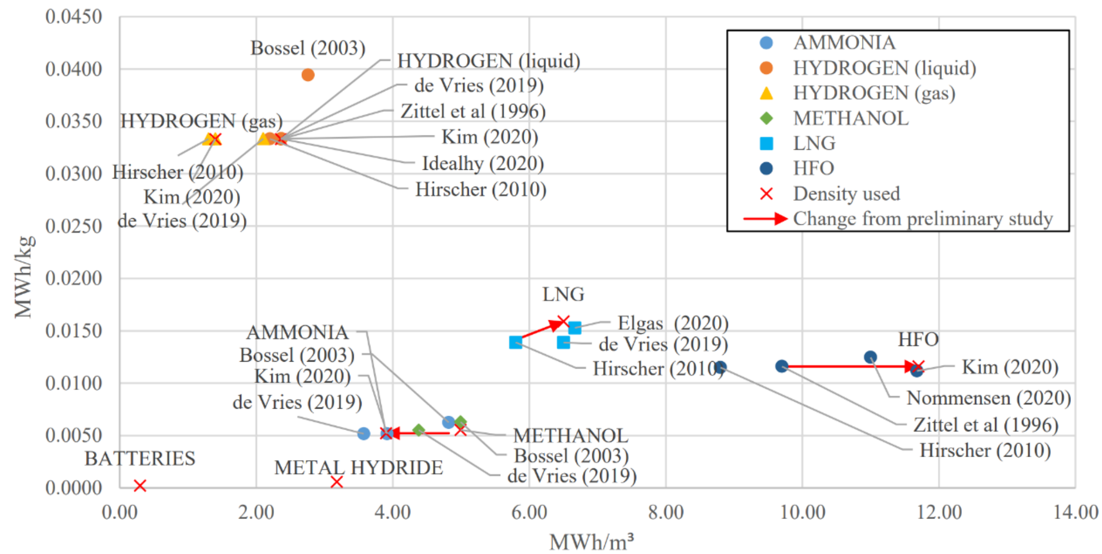


***Figure 3:*** *A comparison of energy densities across literature for various fuels (McKinlay, 2021)*

The feasibility of adopting alternative fuel technologies is based on supply chains, grid capacity and infrastructure, and retrofitting maritime vessels. It is important to note that despite having the lowest current production, hydrogen requires the lowest increase in production to meet global demand.

Due to current low availability of hydrogen, SMR can help meet demand during transition period but is not carbon neutral. Electrolysis is now commercially viable. In 2015, the electricity required to produce hydrogen was 51 kWh/kg although this is projected to drop to 44.7 kWh/kg by 2025 (McKinlay, 2020). However, hydrogen is most complex in terms of providing proper infrastructure for its storage requirements.

There is a well-established existing global supply chain for ammonia, primarily in the fertilizer sector, but it is highly energy intensive to produce, requiring multiple steps. The Haber-Bosch process is not expected to improve in efficiency to any significant extent (McKinlay, 2020). Unless green ammonia is adopted, emissions will just be displaced to the fuel production part of the supply chain. However, producing green ammonia is currently not very cost-competitive. It also relies on a scale-up of renewable energy supply for manufacturing, which we should bet on anyway. Supply of land is also a tradeoff—"it was estimated that 1482 km2 of land would be required for green hydrogen, or 1620 km2 for green ammonia" (14, McKinlay).

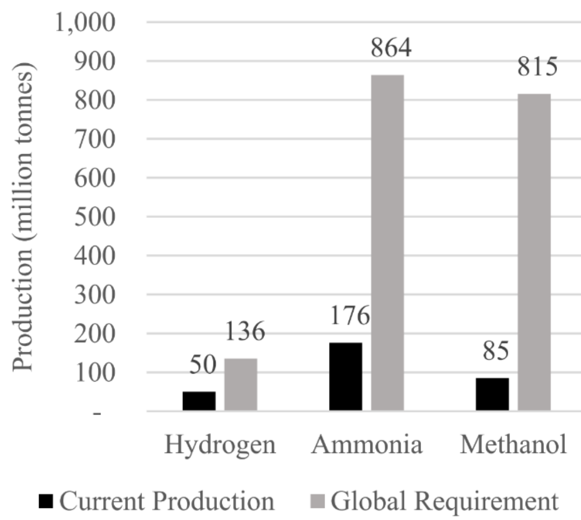


***Figure 4:*** *Current annual production compared to estimated annual demand for global fleet of 50,000 ships. Hydrogen production requires the least increase in production to meet global demand at 171% compared to 391% for ammonia and 859% for methanol (McKinlay, 2020).*

Feedstocks to producing renewable methanol, such as biomass, have well-developed supply chains already, but production capacity would be limited by feedstock transportation costs to plant location. Methanol is one of the most common chemicals and largely produced by fossil fuels. Green production of methanol requires an immense supply of renewables, and additional capital expenditure will be needed for CCS. There are no technical barriers to bunkering methanol for ships.

Ships will need to be retrofitted in the long-term to provide infrastructure for fuel cells. Fuel cells work by creating an electrical current from the chemical energy of a fuel. The fuel is fed into the anode, and protons and electrons are separated from the fuel (typically with a catalyst) and travel to the cathode, forming a current. This would require ships to have an electric drivetrain, which is a developed technology and not uncommon (i.e. duel-fuel diesel electric [DFDE] tankers) (McKinlay et al., 2020).

McKinlay et al., 2020 estimates production efficiency of electro-fuels based on the ratio of energy content in fuels to energy input. They find that the production efficiency of hydrogen, ammonia, and methanol are 76-86%, 60%, and 58% respectively. It should be noted that hydrogen produced from electrolysis are used in ammonia and methanol production.

Transitioning to alternative fuels that are not drop-in nor utilize combustion will require fixed capital investments in retrofitting ships to provide fuel cells, storage, and other needed infrastructure. In terms of variable fuel costs, currently, LNG, methanol, LPG are cost competitive, more mature. Biofuels are more competitive than fuels from renewables or natural gas with CCS (such as hydrogen and ammonia), though they pose sustainability and availability issues (short-term solution) (Mallouppas et al., 2021). Hydrogen and ammonia are more expensive, with some level of uncertainty, though they are expected to become cheaper over time (long-term solution). Renewable hydrogen, ammonia, and methanol are not being produced commercially at scale, but prices should become more competitive with economies of scale, but price of fuel uncertain.

| Fuel | Price $/GJ |
|---|---|
| HFO | 9.41–14.11 (Bengtsson et al., 2014) |
| MGO | 14.11–22.35 (Bengtsson et al., 2014) |
| LNG | 8.23–14.11 (Bengtsson et al., 2014) |
| Hydrogen | 12 (Al-breiki and Bicer, 2020) |
| Ammonia | 28.2 (Al-breiki and Bicer, 2020) |
| Methanol | 16.3 (Al-breiki and Bicer, 2020) |
| Dimethyl Ether | 15.06 (Al-breiki and Bicer, 2020) |

***Table 3:*** *Price comparison of multiple fuels (Al-Enazi et al., 2021)*

## VI. Conclusion

Drop-in bio and synthetic fuels are the best option in the short- and medium-term due to computability with existing infrastructure, while hydrogen or ammonia are best for the long-term (Gray et al., 2021). Hydrogen is a leading candidate due to its decarbonization potential and production efficiency.

## VII. References

Atilhan, S., Park, S., El-Halwagi, M. M., Atilhan, M., Moore, M., & Nielsen, R. B. (2021). Green hydrogen as an alternative fuel for the shipping industry. *Current Opinion in Chemical Engineering*, *31*, 100668. https://doi.org/10.1016/j.coche.2020.100668

Al-Aboosi, F. Y., El-Halwagi, M. M., Moore, M., & Nielsen, R. B. (2021). Renewable ammonia as an alternative fuel for the shipping industry. *Current Opinion in Chemical Engineering*, *31*, 100670. https://doi.org/10.1016/j.coche.2021.100670

Al-Enazi, A., Okonkwo, E. C., Bicer, Y., & Al-Ansari, T. (2021). A review of cleaner alternative fuels for maritime transportation. *Energy Reports*, *7*, 1962–1985. https://doi.org/10.1016/j.egyr.2021.03.036

Claeys, C., says, D. B., Buschgert, D., says, P. M., Mortimer, P., says, N. W., Wilson, N., Nacu, A., Hritsyshyna, M., Bush, J., & Rowland, B. (2020, December 2). *Biofuels vs hydrogen: Which can fuel aviation, shipping, trucks?* Energy Post. Retrieved September 27, 2022, from https://energypost.eu/biofuels-vs-hydrogen-which-can-fuel-aviation-shipping-trucks/

Environmental Protection Agency. (n.d.). *Fast Facts on Transportation Greenhouse Gas Emissions*. EPA. Retrieved November 2, 2022, from https://www.epa.gov/greenvehicles/fast-facts-transportation-greenhouse-gas-emissions

García-Olivares, A., Solé, J., & Osychenko, O. (2018). Transportation in a 100% renewable energy system. *Energy Conversion and Management*, *158*, 266–285. https://doi.org/10.1016/j.enconman.2017.12.053

Gerretsen, I. (2022, November 2). *Who will finance the Green Transition in shipping?* The Maritime Executive. Retrieved November 13, 2022, from https://www.maritime-executive.com/editorials/who-will-finance-the-green-transition-in-shipping

Gonzalez, Carmen G., The Environmental Justice Implications of Biofuels (July 21, 2016). 20 UCLA Journal of International Law and Foreign Affairs 229 (2016)., Seattle University School of Law Research Paper No. 16-19, Available at SSRN: https://ssrn.com/abstract=2813002

Gray, N., McDonagh, S., O'Shea, R., Smyth, B., & Murphy, J. D. (2021). Decarbonising ships, planes and trucks: An analysis of suitable low-carbon fuels for the maritime, aviation and haulage sectors. *Advances in Applied Energy*, *1*, 100008. https://doi.org/10.1016/j.adapen.2021.100008

Kirstein, L., Halim, R., & Merk, O. (2018). Decarbonising Maritime Transport—Pathways to Zero-Carbon Shipping by 2035. In *Paris, France: International Transportation Forum*.

https://www.itf-oecd.org/sites/default/files/docs/decarbonising-maritime-transport-2035.pdf

Svanberg, M., Ellis, J., Lundgren, J., & Landälv, I. (2018). Renewable methanol as a fuel for the shipping industry. *Renewable and Sustainable Energy Reviews*, *94*, 1217–1228. https://doi.org/10.1016/j.rser.2018.06.058

Tao, M., Azzolini, J. A., Stechel, E. B., Ayers, K. E., & Valdez, T. I. (2022). Review—engineering challenges in Green Hydrogen Production Systems. Journal of The Electrochemical Society, 169(5), 054503. https://doi.org/10.1149/1945-7111/ac6983

Mallouppas, G., & Yfantis, E. A. (2021). Decarbonization in shipping industry: A review of Research, technology development, and innovation proposals. *Journal of Marine Science and Engineering*, *9*(4), 415. https://doi.org/10.3390/jmse9040415

Ash, N., Sikora, I., & Richelle, B. (2019). Electrofuels for shipping: How synthetic fuels from renewable electricity could unlock sustainable investment in countries like Chile. *Environmental Defense Fund: London, UK*. https://doi.org/10.1016/j.ijhydene.2021.06.066