Hydrogen in shipping

MAN Energy Solutions
Future in the making

Sustainable shipping

with alternative marine fuels

This hydrogen paper aims to provide some guidance and contribute to the ongoing discussion around alternative marine fuels and reducing the (carbon) emission footprint of shipping; in short, how to meet the various regulatory targets and regimes with the help of new shipping fuels and technologies.

Regulations, guidelines and notifications for hydrogen as a shipping fuel – whether IMO, IGF Code or within class societies - are still in development, and the actual use of H_2 in vessels is somewhat in its infancy in terms of widespread adoption. This is especially true for deep-sea, long-distance shipping. At the same time the European Parliament, among others, has announced that renewable hydrogen is "key to Europe's energy transition" and "fossil-based hydrogen should be phased out as soon as possible" – this also includes the shipping sector. So, where is the disconnect and what is the state of play of hydrogen in shipping?

1. Hydrogen fuel supply (chain)

The overall market is presently estimated at roughly 112 million tons or roughly 320 million tons of oil equivalent. Refineries (for reformation of gasoline constituents) and ammonia are the main end use applications for H_2, representing 37% and 28% of 2020 demand respectively, with the remainder used for a variety of purposes including a small amount as fuel. Global H_2 demand grew by 28% over the last decade and 2020 / 2021 has seen exponential growth of investment at the GW scale. Despite the strong growth rate, new applications such as mobility still comprise a minor portion of current global H_2 demand (less than 0.1% of total demand), of which aerospace is the largest part.

About 90% of hydrogen is produced on-site today with limited pipelines dedicated to hydrogen transportation. Globally there are about 4,500 km such pipelines, of which 2,600 km are located in the US (e.g. refinery hubs on the Texas Gulf Coast). One possible solution to increase infrastructure is to retrofit existing natural gas pipelines or mix hydrogen with natural gas for pipeline transportation.

Less than 1% of H_2 is currently produced using renewable methods such as electricity; natural gas is currently the primary source of grey H_2 production, accounting for around 73% of annual production, with the remainder being brown H_2 from coal bed methane. Grey H_2 is the lowest cost option outside of China, averaging $1.27 / kg in 2020. In a mature industry with little room for CAPEX reduction, costs are largely determined by the feedstock price - grey and brown H_2 costs are closely tied to fossil fuel prices, with each expected to rise.

Blue H_2 (grey H_2 + CCS) is still in a relatively nascent stage, mainly due to constraints on Carbon Capture Storage (CCS) technology. Due to limited capacity, Green H_2 constitutes only 0.6% of global production (63% of all green hydrogen is produced in Europe) and is still a long way from being used for commercial applications. It is expected to be more widely adopted as rapidly decreasing renewable energy costs, supportive

policy, regulatory frameworks and increasing interest drive further investment. As of Q2 2020, an additional 15 GW of green H_2 projects have been announced.
Without major CCS cost reductions, blue H_2 will hold a premium, averaging ~50% (i.e. $1.96 / kg in 2020) over grey in the medium term. The cost of green H_2 is currently high, largely due to the relatively higher renewable energy cost and lower utilization hours. According to DNV, green H_2 costs (currently $6.08 / kg, i.e. 2-5 times the cost of grey H_2 and 3-6 times that of marine gas oil (MGO) in 2020) will be around four to eight times the price of very low sulfur fuel oil (VLSFO). Green H_2 is expected to reach widespread competitiveness with grey H_2 by 2030 – 2040 due to the increasing cost of grey H_2 and a simultaneous reduction in renewable energy costs.
Currently there are no H2 bunkering vessels or terminals for seagoing vessels, and only one LH_2 carrier (sailing from Australia to Japan with brown H_2). All marine H_2 supply currently takes place with custom-made supply chain setups via truck/trailer. The issue of bunker infrastructure development (and incentives for H_2 suppliers) depends on price sensitivity in shipping and higher-margin outlets in other customer segments such as Road and Power. As hydrogen can be produced from water using electrolysis, theoretically there are no major limitations to production capacity that could restrict the amount of H_2 available to the shipping industry. This is also underpinned by the fact that production is being ramped up by existing bunker suppliers and energy companies, as well as large utility/ power companies and industrial gas producers that are relatively new to the maritime world.
Certain ports also work on H_2 infrastructure themselves. For example, Rotterdam has plans to supply the steel industry in the German Ruhr area, Hamburg to build large electrolyzers to serve several industry and transport customers in both the port and the city, and Singapore is intending to develop LH_2 infrastructure.

2. Hydrogen as a marine fuel

H_2 is the simplest and most basic renewable fuel generated by electrolysis. It comes in many colors and forms as a transport fuel, including metal hydrides, liquid organic hydrogen carriers (LOHC), compressed H_2 (CH_2), liquefied H_2 (LH_2) or ammonia (NH_3) as a vector. Currently, we believe and see in the market that LH_2 will be the frontrunner for coastal/sea shipping applications due to the high energy requirements. H_2 has a high specific energy value (LHV), LH_2 has around 120 MJ / kg while fuel oil has around 40 MJ / kg (compared to 50 MJ / kg for CH_4). However, because fuel oil is so much denser than hydrogen, one ton of fuel oil contains 1,123 liters, while one ton of liquefied hydrogen equates to 14,125 liters, requiring larger tank volumes.
Hydrogen use is currently concentrated in short-sea and short distance applications (as well as inland waterways) which are in Emission Control Areas, as well as auxiliary engines and/or hotel load. This is mainly due to differences in routes, the availability of hydrogen fuel and local regulations / requirements and funding. Therefore, the fuel is at present more commonly associated with four-stroke (medium/high speed) short-sea applications than with two-stroke deep-sea applications. It is also where most of the projects and government funding currently are.

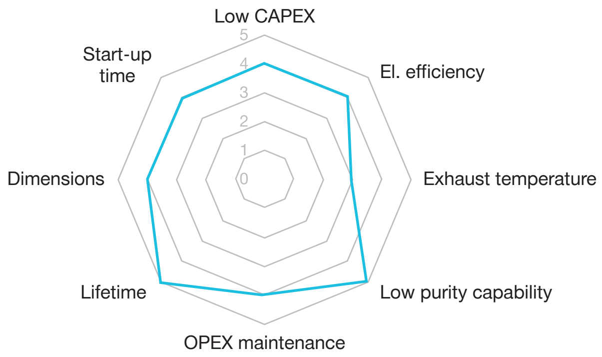
3. H_2 combustion – Internal Combustion Engines (ICE)

Several companies and consortia develop H_2 marine combustion engines. However, MAN has 30 years of experience in the combustion of hydrogen, with early H_2 research on Otto engines beginning in the early 1990s, and H_2 first used in diesel engines for buses in the latter part of that decade. Further development has been somewhat hampered by an adverse policy framework, but this is starting to change.
The general view is that H_2 is less knock-resistant than liquefied natural gas (LNG) or compressed natural gas (CNG), therefore the main challenges are its low methane number, low ignition energy and high flame speed (= high pressure increase). In terms of exhaust after treatment, NO_x emissions are at or below the level of existing Dual Fuel engines, and may be reduced even further to minimal levels with the MAN SCR solution ensuring future emission compliance.
For marine use, two engine concepts are currently being investigated in our R&D facilities. The Stage I marine application is a Dual Fuel (DF) low-pressure engine that operates on a limited H_2 energy share and de-rated power. It ensures flexibility while minimizing the risk of H_2 fuel supply or system problems, with diesel or LNG serving as a fallback solution that could also be financially attractive. It can be adopted for conventional DF engines and will be Tier III compliant without SO_x and CO_2 emissions in the H_2 phase. Depending on market demand, this could be available in 2023.
The Stage II marine application is a Dual Fuel H_2 engine with in-cylinder fuel admission developed with the focus on efficiency and full power in H_2 mode. It will be fully flexible and only requires pilot fuel, which could be sourced from green, synthetic (Fischer-Tropsch) diesel. Depending on market demand, this could be available in 2026 when H_2 supply should be more readily available.
We've compared ICE technologies with gas turbines and proton exchange membrane (PEM) / solid oxide (SOFC) fuel cells across a range of parameters and we believe hydrogen ICEs offer an attractive option compared to fuel cells thanks to cost, power density, fuel flexibility and reliability advantages. Based on historic experience, ICE lifetime over 30 years (with regular maintenance) far exceeds that of a fuel cell stack. We acknowledge a role for fuel cell applications in the lower power range, but not as a main propulsion solution for coastal / sea vessels.

Hydrogen conversion

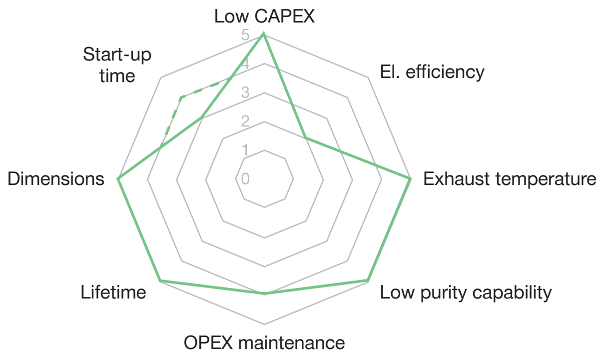
Success factors

Engine (TRL 3-4)



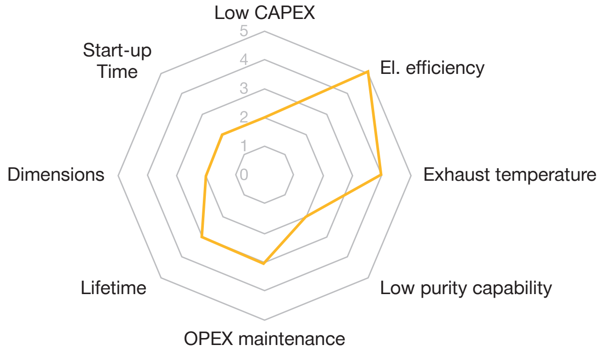
USP: fuel sharing

Turbine (TRL 5)



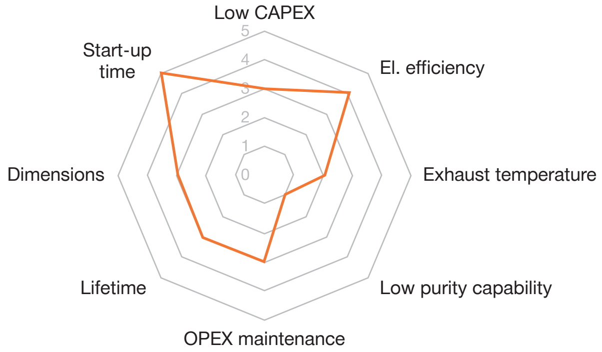
USP: low retrofit cost

SOFC-FC (TRL 7)



USP: el. efficiency

PEM-FC (TRL 8)



USP: start-up time

Hydrogen storage

	Limitation	Energy efficiency	Gravimetric efficiency	Volumetric efficiency	T (°C)	p (bar)
Compressed	Safety - high pressure volume	93%	5-10%	20 H2 kg/m3	RT	800
Liquefied	Safety - low temp., evaporatiwon losses, high energy consumption	70%	8-25%	20 - 50 H2 kg/m3	-252	1
Metal hydride	Weight, cost, time to charge	80%	2-7%	10 H2 kg/m3	RT	30
LOHC	Limited reusability of liquid time to charge	70%	5-10%	30 H2 kg/m3	RT	30

4. LH_2 storage and Fuel Gas Supply System (FGSS)

Cryogenic storage of liquefied hydrogen is very difficult due to the low H_2 boiling point of roughly -253 deg C (at 1 bar) and there are not many companies and manufacturers around that can offer the relevant capability. However, MAN Cryo does have this competence. With 60 years of experience in cryogenic applications such as vacuum insulated tanks, coil-wound vaporizers and piping systems (mainly LNG), in 2020 the company developed an LH_2 fuel gas supply system and vacuum insulated multilayer storage tank for marine applications. It is fully equipped with a tank connection space (TCS), bunker station and re-gasification, and the unit was delivered in May 2021. The design is IGF Code compliant and class approval is in place, with other classes in the pipeline.

The LH_2 FGSS is in the 50 – 300 m^3 range, and the empty tank weight for a 175 m^3 gross volume tank and TCS would be approximately 70 tons.

Currently the maximum filling level is 69% according to IGF, based on a 9 bar design pressure, and MAN does not recommend emptying the tank to below 5%, for cooling purposes. This gives a usable volume of 64%. MAN is in discussion with class societies on how to improve the permissible filling level beyond the current 69%.

Safety measures are of utmost importance to MAN. A double-hull tank (outer hull considered as a secondary barrier), double piping, H_2 detection and automatic controls are in place. The 15 days holding time is in line with the IGF Code. There is no thermal impact for the various supply methods, such as truck-to-ship, ship-to-ship, or terminal-to-ship bunkering.

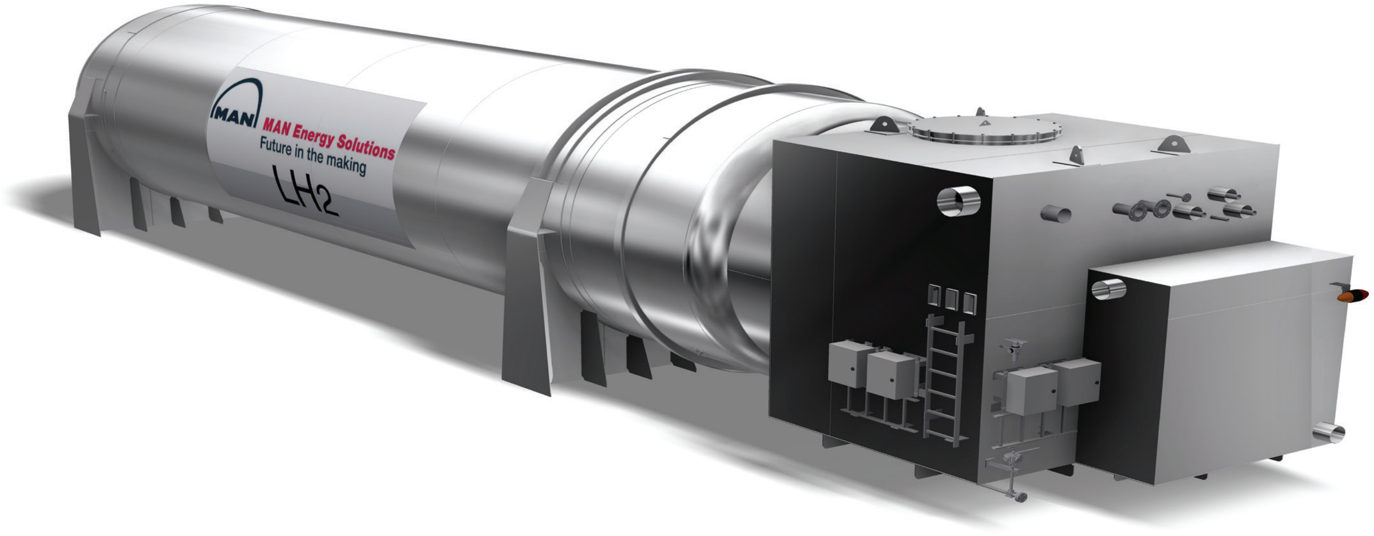
Safety

Introducing a new fuel or energy carrier into shipping, transport or society nowadays poses a variety of challenges and must overcome higher hurdles than the switch from coal-fired steam engines to hydrocarbon-based propulsion back in the day. Safety and sustainability considerations are far greater now. So how does hydrogen compare when it comes to safety? Firstly, let's consider what it does not do as a substance. It does not detonate in open air, decompose, self-ignite, cause cancer (non-carcinogenic). Furthermore, it is non-oxidizing, non-toxic, non-corrosive, non-radio-active, non-contagious and not harmful to water.

Hydrogen is 14 times lighter than air and rapidly disperses upwards, it has a high diffusion coefficient (four times that of methane) and dilutes rapidly in air. It has significantly narrower detonation limits in air than explosion limits – when ignited early, it burns before detonation limits are reached. H_2 burns with an invisible flame with very little heat radiated from the flame. Hydrogen is colorless and odorless; it is technically not possible to add odorant.

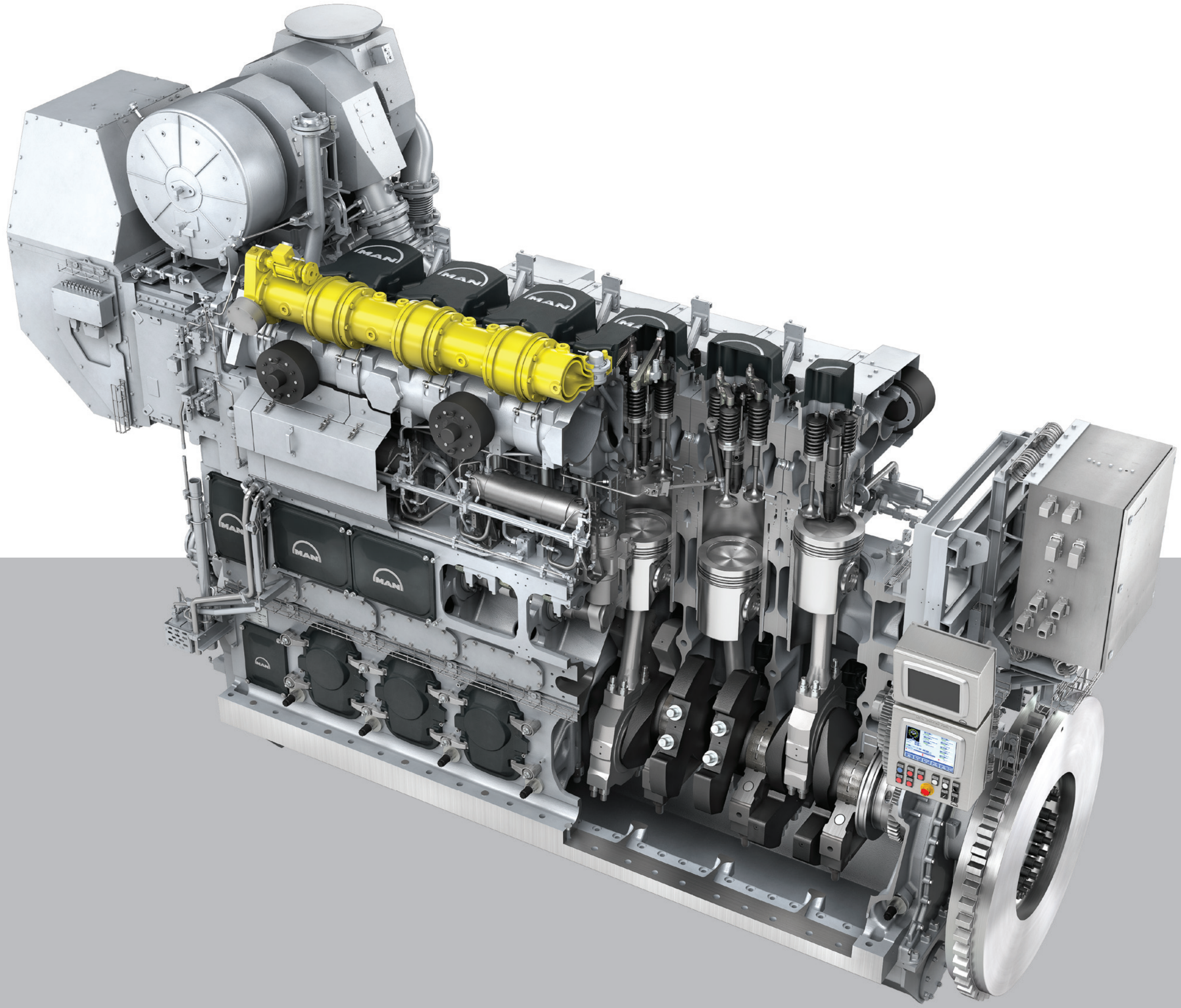
However, H_2 is a very small molecule that is prone to leakage in closed spaces. It can reach flammable concentration or can become an asphyxiate, therefore proper ventilation and detection sensors are required. When stored in a liquid state, H_2 can cause cryogenic burns or lung damage in case of leakage.

All of this can be managed, and MAN Cryo has longstanding experience with different gas fuels such as LNG and, more recently, LH_2, offering a high level of safety.



H2 engine concept

based on the marine-certified dual fuel engine



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