SUSTAINABILITY WHITEPAPER

HYDROGEN AS MARINE FUEL

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OVERVIEW

OBJECTIVE

The International Maritime Organization (IMO) set ambitious targets in April 2018 in the Marine Environmental Protection Committee (MEPC) Resolution MEPC.304(72) to decarbonize the global fleet. The IMO strategy includes initial targets to reduce the average carbon dioxide (CO_2) emissions per transport work from 2008 levels by at least 40 percent by 2030, and 70 percent by 2050. These targets also seek to reduce the total annual greenhouse gas (GHG) emissions from shipping by at least 50 percent by 2050.

Many technologies are being considered to reduce carbon emissions from shipping. The American Bureau of Shipping (ABS) publication *Setting the Course to Low Carbon Shipping: Pathways to Sustainable Shipping* has categorized the available maritime fuel options for decarbonization. Among them, hydrogen (liquefied LH_2, or gaseous H_2) was identified as a low- to zero-carbon fuel that can help meet the IMO GHG reduction target for 2050. Hydrogen offers ship owners and operators a low-carbon and low-emission fuel option for potential use in internal combustion engines and fuel cells.

Through a series of sustainability whitepaper publications, ABS is providing additional information to highlight the fuels being considered by the marine industry to meet the IMO GHG goals. This whitepaper provides information for the consideration of hydrogen as marine fuel in both the near-term and long-term. It is to be noted that the information provided in this document is generic. For specific guidance on hydrogen as marine fuel, contact your local ABS office.

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INTRODUCTION

Hydrogen is typically found naturally as a compound of either water or methane. To acquire pure hydrogen, the element must be separated from these compounds. At standard conditions, hydrogen is a colorless, odorless, tasteless, non-toxic, relatively nonreactive and highly combustible gas with a wide flammability range.

Hydrogen is commonly produced by converting natural gas or coal into hydrogen gas and CO_2, although for the long-term sustainability goals, renewable energy can be used to generate hydrogen through electrolysis. In manufacturing, hydrogen is typically used for chemical production or as an industrial feedstock.

In recent years, industry has recognized hydrogen's potential to generate electricity through fuel cells and combustion technologies. While in many cases hydrogen may be derived locally from fuel reforming of a hydrogen carrier (and hence may have direct GHG emissions), in a hydrogen fuel cell consuming a pure hydrogen fuel supply, greenhouse gases are not emitted. In combustion engines or gas turbines, hydrogen can be used to significantly reduce GHG emissions. Note that gas turbines consuming hydrogen (or hydrogen blends with natural gas) are used primarily for land-based power production and are not considered in this document for power generation on marine vessels.

While hydrogen appears to be an ideal fuel for power generation, it carries various challenges of advanced storage requirements and fire hazard mitigation. To become a competitive alternative marine fuel, hydrogen may also face the challenges of availability and high costs to scale production and transportation infrastructure.

HYDROGEN AS FUEL FOR THE REDUCTION OF GREENHOUSE GAS

Its low density causes any hydrogen to dissipate relative quickly when released in an open environment. Hydrogen in the atmosphere cannot be contained by earth's gravity and eventually escapes into space. Hydrogen leaks are considered non-toxic, although the wide flammability range and potential for combustion can raise concerns of hydrogen safety and risk management. These concerns are addressed in the hydrogen safety and design consideration sections.

Hydrogen has the potential to be a zero-carbon marine fuel when it is consumed in a fuel cell or a mono-fuel internal combustion engine. When consumed in a dual fuel combustion engine, hydrogen can significantly reduce carbon emissions. Hydrogen is characterized by having a very low tank-to-wake (TTW) emissions impact, which considers the emissions produced by an energy source. However, the life cycle of hydrogen production must be considered to evaluate the overall emissions of GHG from hydrogen.

When fossil fuels are used to generate hydrogen, carbon and GHG emissions may not necessarily be reduced. Well-to-tank (WTT) emissions consider all pollutants generated during fuel production, storage and transportation to the end consumer. These can include the emissions generated when coal or natural gas is processed to generate hydrogen, or the fossil fuels combusted to generate grid electricity used to generate hydrogen through electrolysis. To fully eliminate hydrogen emissions prior to fuel delivery, it is critical to focus on carbon-free production, storage and transportation methods. Hydrogen can be produced in renewable or 'green' ways that can eliminate upstream carbon and GHG emissions and result in very low WTT emissions. When both WTT and TTW emissions are eliminated from the fuel life cycle, a zero-carbon well-to-wake (WTW) fuel option is created. Sustainability verification schemes or guarantees of origin (GO) certificates such as the EU CertifHy project can be used, which may be implemented in the hydrogen market to track and quantify the emissions footprint of generated hydrogen. Such schemes may be implemented regionally or nationally but are not yet mandated by the IMO.

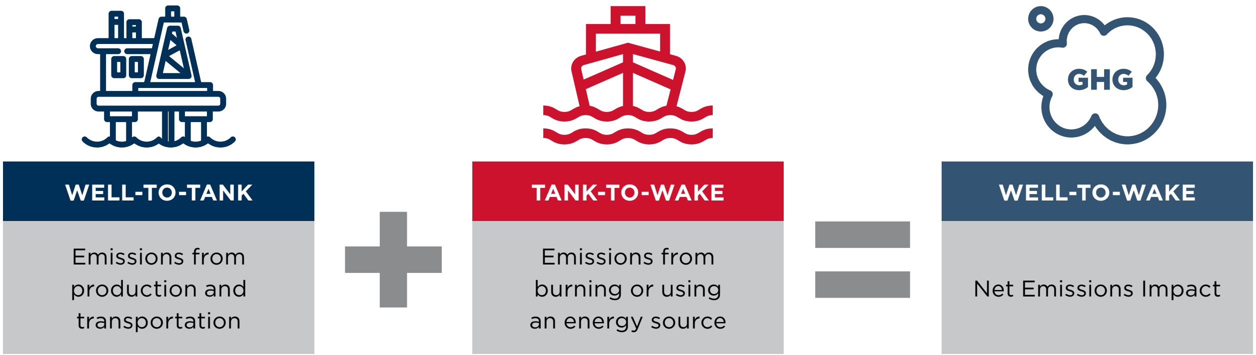

Figure 1: Well-to-Wake Emissions Concept

HYDROGEN PRODUCTION

Emissions from the production of hydrogen compose the majority of the WTW pollutants. There are four types of hydrogen in terms of the emissions released during production:

- Brown hydrogen, produced from the processing of coal
- Grey hydrogen, produced from the processing of other fossil fuels or natural gas
- Blue hydrogen, produced from the processing of fossil fuels accompanied with emission control technologies, including carbon capture, utilization and storage (CCUS) methods
- Green hydrogen, produced from renewable energy sources, typically via electrolysis using water. Sources of electricity can include solar or wind power to provide net-zero carbon hydrogen production

Grey hydrogen produced from natural gas is the primary hydrogen production method, as shown in Figure 2, accounting for 75 percent of global hydrogen production. Brown hydrogen is the second largest source of hydrogen production, primarily in China. Green hydrogen production contributes only two percent of global hydrogen supply, while blue hydrogen production is not yet widespread.

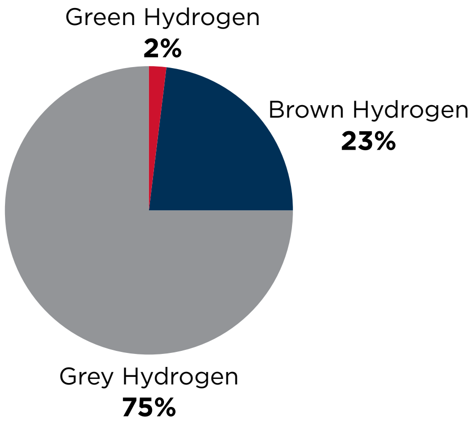

Figure 2: Production Sources of Hydrogen

Carbon capture, utilization and storage (CCUS) involves the collection, transportation, reuse and storage of CO_2 emissions that are separated from other combustion or processing substances originating from fossil-based fuels. In general, hydrogen production is a high energy consumption process. Currently, the energy used worldwide to produce hydrogen is about 275 Mtoe (million tons of oil equivalent), which corresponds to two percent of the world's energy demand. Most of the demand is driven by fossil fuel refineries and the production of ammonia for fertilizer.

Grey hydrogen production is very carbon intensive, ranging between 71 kg CO_2/MJ H_2 for natural gas to 166 kg CO_2/MJ H_2 for coal, but these emissions can be reduced or eliminated by implementing CCUS technology.

Figure 3 shows the WTT amount of CO_2 generated for one megajoule of contained energy. The graph shows the variation of possible emissions from several types of hydrogen production, as high as 325 kg CO_2/MJ H_2 and as low as zero for renewable energy or nuclear generation. These values are compared to the typical estimated CO_2 generated during WTT production of marine gas oil (MGO), 14.2 kg CO_2/MJ MGO.

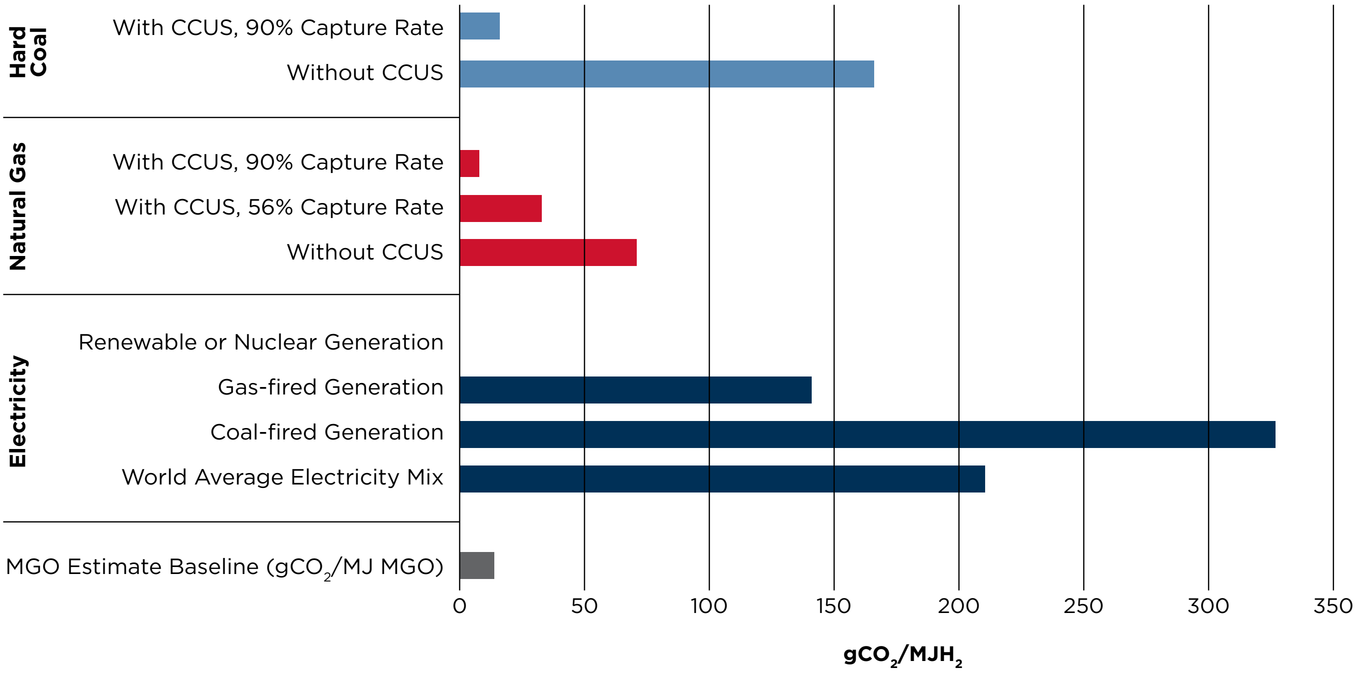

Figure 3: Carbon Release from Hydrogen Production With and Without Using CCUS Compared to Marine Gas Oil (MGO) as Baseline

The extraction of hydrogen from natural gas is accomplished through reformation using three established methods: (i) steam reforming, which uses water as an oxidant and a source of hydrogen; (ii) partial oxidation, which uses the oxygen in air in the presence of a catalyst; and (iii) autothermal reforming, which is a combination of the first two reformation methods. In all cases, syngas (carbon monoxide and hydrogen) is formed and then converted to hydrogen and CO_2 through the water-gas shift reaction. To reduce the carbon intensity of fossil-fuel hydrogen production, renewable and sustainably sourced biomass can be used to produce syngas through gasification. Nuclear plants can also be employed to generate hydrogen from steam reforming of methane or high-temperature thermochemical production, eliminating those hydrogen generation methods that rely on the burning of fossil fuels.


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Alternatively, electricity can be used to electrolyze water. Electrolysers work essentially as reversed fuel cells, by taking in water and electricity, and producing hydrogen and oxygen gas. Renewable energy sources such as wind, solar or nuclear electricity generation can be used to produce green hydrogen from this process. In this case, hydrogen can be considered an electro-fuel with zero-carbon impact from production. Other hydrogen production processes include high temperature water splitting, photobiological water splitting and photoelectrochemical water splitting, but these methods are not yet employed in large-scale hydrogen production.

It may be useful to note when considering alternatives to electrolysis hydrogen production that the high purification required to meet the grade 4.5 purity standard (i.e., 99.995 percent pure) for proton exchange membrane (PEM) fuel cells may add to the costs of production. Conversely, mono-fuel and dual-fuel combustion engines do not require this level of purification, and indeed can handle diluents (e.g., methane, carbon dioxide or carbon monoxide) that would otherwise cause significant degradation to a PEM fuel cell. However, this purity standard may not be a problem in other fuel cells, such as solid-oxide fuel cells (SOFC), although these may have tradeoffs related to emissions, lower operating efficiencies and high temperatures.

When hydrogen production and consumption are zero-emission processes, the only life cycle emissions are produced from the processes of storing and transporting the fuel during distribution, and any required conversion process between carriers.

HYDROGEN AS MARINE FUEL

Hydrogen is characterized by having the highest energy content per mass of all chemical fuels at 120.2 MJ/kg, as shown in Table 1 compared to other marine fuels. In terms of mass energy, it exceeds MGO by 2.8 times, and alcohols by five to six times. Therefore, hydrogen fuel can increase the effective efficiency of an engine and help reduce specific fuel consumption. However, on a volumetric basis, due to its lower volumetric energy density, liquid hydrogen may require four times more space than MGO or about two times more space than liquefied natural gas (LNG) for an equivalent amount of carried energy. Also important to consider when comparing fuel energy and required volumes are the energy efficiencies of the consumer, or electrical energy losses in fuel cells. True for all marine fuels, additional volumes of fuel may be required to account for efficiency losses between the tank to the output shaft power. Hydrogen requires low temperatures below -253° C (-423.4° F) to liquefy. Due to this very low temperature, the required volume to store liquid hydrogen could be even higher when considering the necessary layers of materials or vacuum insulation for cryogenic storage and other structural arrangements.

	UNIT	HYDROGEN	MGO	HEAVY FUEL OIL (HFO)	METHANE (LNG)	ETHANE	PROPANE	BUTANE	DIMETHYL-ETHER (DME)	METHANOL	ETHANOL	AMMONIA
Boiling Point	° C	-253	180-360	180-360	-161	-89	-43	-1	-25	65	78	-33
Density	kg/m^3	70.8	900	991	430	570	500	600	670	790	790	696
Lower Heating Value	MJ/kg	120.2	42.7	40.2	48	47.8	46.3	45.7	28.7	19.9	26.8	22.5
Auto Ignition Temp	° C	585	250	250	537	515	470	365	350	450	420	630
Flashpoint	° C	-	> 60	> 60	-188	-135	-104	-60	-41	11	16	132
Energy Density Liquid (H_2 Gas at 700 bar)	MJ/L	8.51 (4.8)	38.4	39.8	20.6	27.2	23.2	27.4	19.2	15.7	21.2	15.7
Compared Volume to MGO (H_2 Gas at 700 bar)		4.51 (7.98)	1.00	0.96	1.86	1.41	1.66	1.40	2.00	2.45	1.81	2.45

Table 1: Properties of Hydrogen Compared to Other Marine Fuels

Hydrogen can also be stored within other materials, such as metal hydrides. This storage method binds hydrogen to metal alloys in porous and loose form by applying moderate pressure and heat. Subsequently, hydrogen is extracted by removing the pressure and heat. While technologically feasible and safe, metal hydride and other hydrogen storage methods within solid materials may not be a weight-effective solution for hydrogen storage on board ships, and this concept is not addressed further in this whitepaper.

Due to the challenges related to low temperature or high-pressure storage, hydrogen can alternatively be carried within other substances such as ammonia or methanol. These fuels may require less energy than that needed to refrigerate liquefied hydrogen or to compress gaseous hydrogen. Some fuel cells can consume ammonia, methanol or other hydrogen carrier fuels by reforming and extracting hydrogen from the fuel using internal reformers. However, these technologies may require higher energy input to hydrogenate and reform the fuel and therefore may result in less efficient electrical production than pure hydrogen containment and consumption in fuel cells. Figure 4 shows how ammonia as an energy carrier can play a role in the life cycle of hydrogen fuel, leading to either consumption in a fuel cell or combustion engine. For more information on ammonia and methanol as marine fuel, see the ABS Sustainability Whitepaper Publications *Ammonia as Marine Fuel* and *Methanol as Marine Fuel*.

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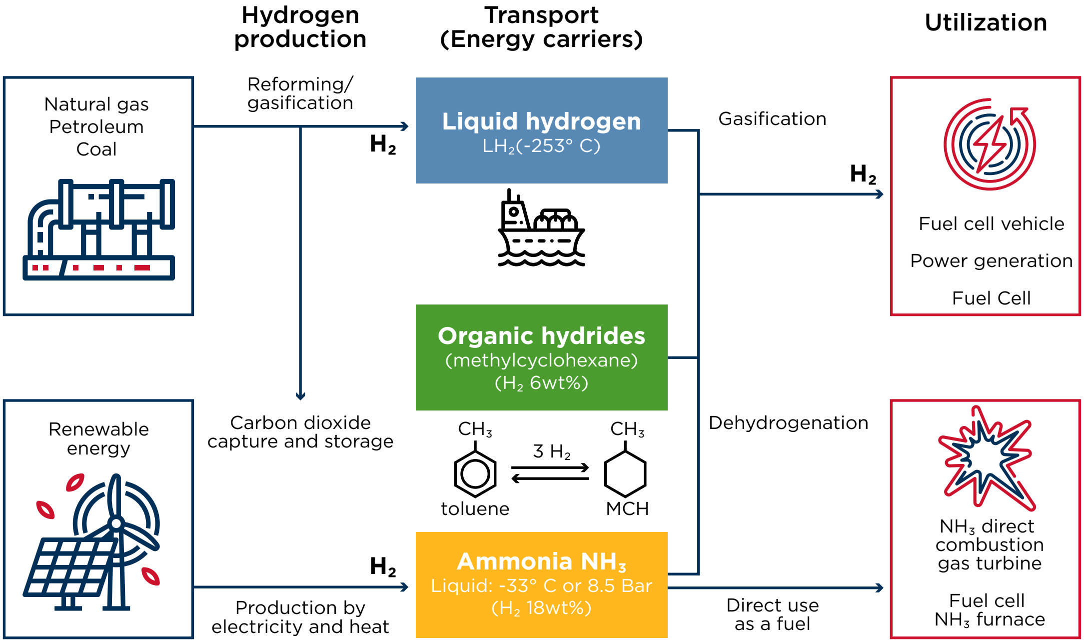

Figure 4: Hydrogen and Ammonia Production and Use
(Source: ABS Setting the Course to Low Carbon Shipping: Pathways to Sustainable Shipping)

Hydrogen and hydrogen carrier fuels are most often consumed in fuel cells to generate zero-emission TTW electricity, regardless of how the hydrogen was produced. There are many completed and ongoing studies of fuel cells, primarily to evaluate and improve fuel cell energy efficiency. There are several types of fuel cells with various operational and cost trade-offs, including alkaline or SOFC, but in general, they consume hydrogen and oxygen and generate heat, water, and electricity, such as the proton exchange membrane fuel cell, shown in Figure 5. For more information on fuel cell technology, see the fuel cells section of the ABS publication Pathways to Sustainable Shipping: Setting the Course for Low Carbon Shipping or the ABS *Guide for Fuel Cell Power Systems for Marine or Offshore Applications.*

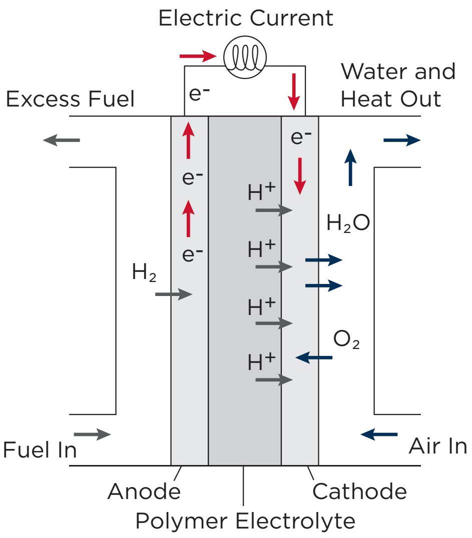

Figure 5: Typical Proton Exchange Membrane (PEM) Fuel Cell
(Source: ABS Setting the Course to Low Carbon Shipping: Pathways to Sustainable Shipping)

Hydrogen fuel blends consist of hydrogen blended with a compatible fuel. The most common are hydrogen and LNG (HLNG) blends which can reduce exhaust gas emissions and GHG footprint. A hydrogen-cryogenic natural gas (HCNG) blend can typically be composed of a combination of 20 percent hydrogen and 80 percent compressed natural gas. Hydrogen blends with natural gas are most likely to be adopted for power generation on land in gas turbines and are not the focus of this whitepaper.

Hydrogen may also be co-combusted with diesel fuel, and depending on the proportions used, reductions of nitrogen oxide (NO_x) emissions may require the use of exhaust gas aftertreatment technologies. Other minor modifications in engine timing and control systems may be required to achieve optimum engine performance. More information on hydrogen consumed in internal combustion engines can be found in the prime mover section.

HYDROGEN SAFETY

CHARACTERISTICS OF HYDROGEN

Hydrogen is a remarkable elemental substance with several important physical and chemical characteristics. Some properties of hydrogen are listed in Table 2 compared to methane, the main component of LNG, and the comparable properties of the common marine fuel MGO.

		HYDROGEN	METHANE (LNG)	MGO
Boiling Temperature (° C)*		-253	-161.5	180-360
Liquid Density (kg/m^3)*		70.8	430	900
Gas Density (kg/m^3)** (Air: 1.198)		0.084	0.668	-
Dynamic Viscosity (g/cm·s x 10-6)	Gas	8.8	10.91	-
	Liquid	13.49	116.79	5.4
Flame Temperature in Air (° C)		2396	2230	-
Maximum Burning Velocity (m/s)		3.15	0.385	-
Heat of Vaporization (J/g)*		448.7	510.4	-
Lower Flammability Limit (% vol. fraction)***		4.0	5.3	0.7
Upper Flammability Limit (% vol. fraction)***		75.0	17.0	5
Minimum Ignition Energy (mJ)***		0.017	0.274	-
Auto-ignition Temperature (° C)		585	537	250
Temperature at Critical Point (K)		33.19****	190.55	-
Pressure at Critical Point (kPaA)		1297	4595	-

* At their normal boiling points for comparison purpose
** At normal temperature and pressure, 20° C and 1 atm.
*** Ignition and combustion properties for gas-air mixtures at 25° C and 101.3 kPaA

Table 2: Comparison of Physical Properties of Hydrogen and Methane (LNG) (Source: MSC.420(97))

The primary safety concerns for hydrogen are its flammable properties and wide flammability range, as shown in Figure 6. The flammability range increases when mixed with pure oxygen.

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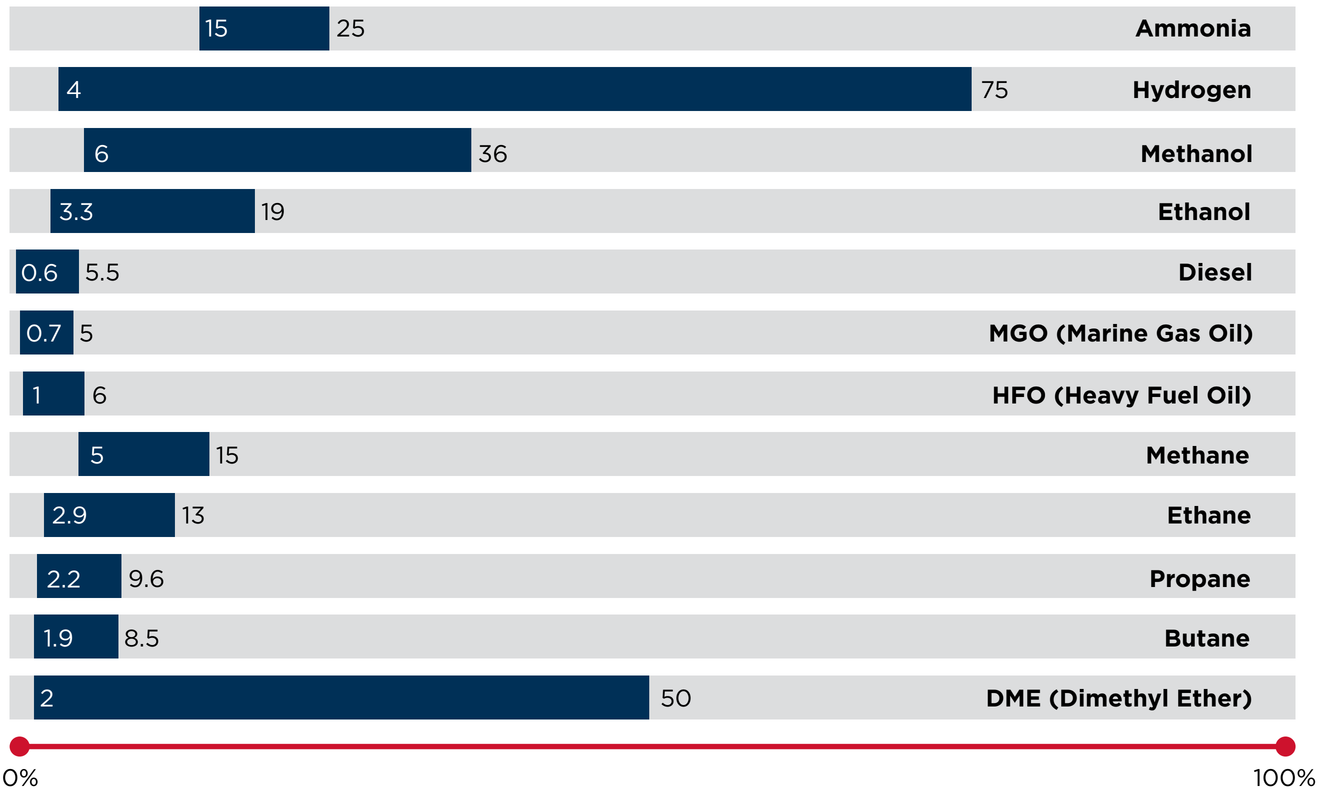

Figure 6: Typical Gas Flammability Ranges in % Volume with Air

While hydrogen leaks in open areas are expected to dissipate quickly, any leak in open or contained spaces can be a serious fire hazard due to the quick formation of flammable gas mixture. More is discussed about hydrogen leaks, fire prevention and leak detection in the fire safety section.

Hydrogen is a gas or cryogenic liquid and has one of the lowest melting and boiling points of all elements except helium. To obtain liquid hydrogen, the fuel must be stored at temperatures below -253° C (-423.4° F), which can require high energy input. At this temperature, other common gases or compounds can liquefy or solidify on contact and should be isolated from liquefied or cryogenic hydrogen. Human contact with cryogenic materials or uninsulated tanks, pipes or valves can cause cold burns or serious skin damage. Although non-toxic, at high concentrations hydrogen can act as an asphyxiant when displacing available oxygen.

FIRE SAFETY

Hydrogen is a flammable gas due to its very low activation and ignition energy. Despite this, the risks of hydrogen explosions can be minimized and mitigated if proper measures and protocols are followed.

The flow or agitation of hydrogen gas or liquid can create electrostatic charges that can result in sparks and ignition of flammable concentrations of hydrogen. For this reason, it is important to make sure all hydrogen handling equipment is protected from electric charge build up and potential sparks to avoid hydrogen ignition.

Hydrogen flames are invisible, burning mostly outside of the visible light spectrum, and can be very difficult to detect. Hydrogen also burns extremely quickly compared to other flammable compounds, with a maximum speed of 3.15 m/s. Depending on the flammable conditions, pressure and concentration of hydrogen, a mixture exposed to ignition sources may combust by either deflagration (subsonic combustion) or detonation (supersonic combustion, not possible in open air). Hydrogen gas systems should account for protections against deflagrations propagating through the piping and containment systems using proper pressure relief systems, rupture disks or relief panels. Detonations can result in extreme pressure increases (up to 20 times atmospheric pressures) and are more challenging to contain than deflagrations. The best practices to mitigate the risks of deflagrations and detonations are to eliminate the possibilities of dangerous concentrations of hydrogen by employing proper gas management, pipe purging and ventilation practices.

Contained areas are especially susceptible to fire hazards if hydrogen leaks inside. Primary safety measures when considering carrying and using hydrogen include proper ventilation, hydrogen gas detection, and appropriately rated electrical equipment in hazardous areas and enclosed spaces into which hydrogen may leak and build to levels that may cause flammable conditions.

The development and possibility of combustible hydrogen and air mixtures depends on the concentration of hydrogen, storage pressures (i.e., the speed of jet from a leak), the amount of stored hydrogen, the amount of insulation, the location of release and weather conditions (such as wind, air, temperature, etc.).

If using gaseous hydrogen as a fuel, compounds that are typically added to natural gases to identify leaks should not be used as the sulfur in those compounds can react with and degrade hydrogen. Dedicated hydrogen sensors may be useful when using gaseous hydrogen, but may not be practicable, for example, in areas of high transient airflow where escaping gas may inadvertently be directed away from sensors. As such, it is also preferable to implement leak detection strategies in the hardware itself, for instance monitoring pressures under conditions of no gas flow and confirming those parameters indicate the absence of leaks.

To extinguish a hydrogen fire, dry chemical extinguishers or carbon dioxide extinguishers can be used. If a hydrogen fire spreads to other materials around or near contained hydrogen in pipes or tanks, appropriate water spray cooling and insulation arrangements should be in place to protect the contained hydrogen from heating up, and pressure relief arrangements should be in place to protect from over-pressurization. Both protective measures can mitigate the risks of gaseous hydrogen reaching the explosive temperature limit within containment or of a liquid hydrogen boiling liquid expanding vapor explosion (BLEVE).

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STORAGE AND HYDROGEN EMBRITTLEMENT

Most applications of hydrogen as a fuel store hydrogen gas in pressurized tanks between 350-700 bar (5,000-10,000 psi), two to three times higher than industrial hydrogen storage which typically is no more than 200 bar (3,000 psi). To increase the density of gaseous hydrogen, insulated pressure vessels can be used between ambient and cryogenic temperatures (-253° C) and between atmospheric and high pressures, depending on the technology or material used for tank insulation and strength. Hydrogen stored in insulated pressure vessels can be known as cryo-compressed hydrogen. Liquefied hydrogen tanks at low pressures can be susceptible to pressure build-up if temperatures rise and the liquid hydrogen begins to vaporize and boil off. For this reason, protection from pressure build up should be in place for gaseous and liquid hydrogen tanks, such as pressure relief valve arrangements. Due to their very low temperatures, cryogenic tanks may require significantly thicker insulation layers, for example two or three times the thickness of thermal insulation of a Type C LNG tank. Alternatively, a vacuum insulated Type C tank may be considered for liquefied hydrogen storage.

Prior to admitting liquid hydrogen into any system, the entire system should be purged of air, oxygen or other oxidizers. The system must also be purged of hydrogen before exposing the system to the atmosphere. This should be done to avoid the formation of flammable gas mixtures. Liquid hydrogen is especially a concern due to its cryogenic temperature. Ordinary atmospheric gases such as oxygen and nitrogen will liquefy or solidify upon contact with cryogenic liquid hydrogen, potentially forming impurities or unwanted build-up in the fuel. Helium is an inert, non-reactive noble gas that should be used to purge liquid hydrogen systems. For gaseous hydrogen systems above -193° C (-316° F), a noble gas or nitrogen can be used to create evacuations.

Due to the very small molecular size of hydrogen, the gas is capable of dispersion through materials, including penetrating into the walls of containment systems and permeation into certain fluids or other solid materials over time to achieve a concentration equilibrium. Hydrogen should be stored in appropriate materials that minimize permeation and reduce the loss of contained hydrogen.

Certain metallic materials and equipment that are exposed to hydrogen gas can suffer from hydrogen embrittlement. These can include tank interior surfaces, weldments, pipes, valves, fuel nozzles, and pressure relief valves or pipes. Hydrogen embrittlement occurs when hydrogen is absorbed by a metal and collects at grain boundaries, creating weak spots within the material, as shown in Figure 7. Hydrogen absorption can lead to brittle failure mechanics, microscopic fractures, material cracks and leakage. Factors that influence hydrogen embrittlement in metals include the material stress level, stress or strain rate, contained hydrogen pressure, temperature, purity, types of impurities, material composition, tensile strength, grain size, material microstructure and material heat treatment history. If left dormant, hydrogen can eventually continue permeating through the material and escape.

The practices used to avoid hydrogen embrittlement include utilizing proper metallic material with appropriate thickness, surface treatments and coatings/films to protect the surface from hydrogen contact. Care should be taken during metal forming to ensure that hydrogen atoms escape during heat treatment, and welding practices should be careful to avoid the formation of hard microstructures.

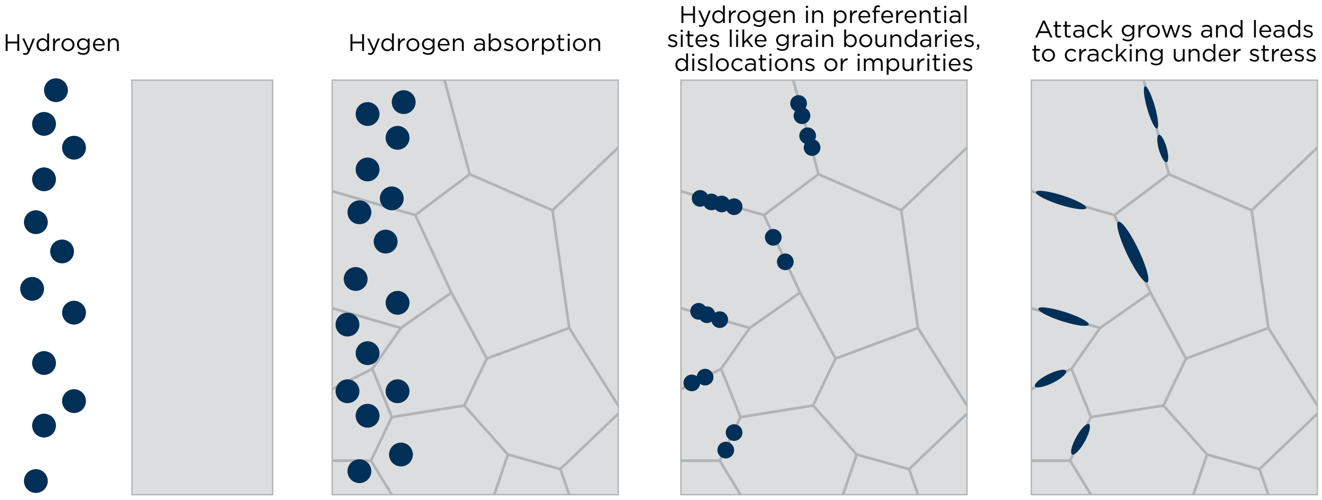

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Figure 7: Hydrogen Embrittlement

Another material concern is high temperature hydrogen attack. Low-alloyed structural steel has been known to degrade from hydrogen attacks that occur at temperatures above 200° C (392° F), where carbon reacts with hydrogen to create methane and cause material embrittlement. Hydrogen attacks may not be common for tanks and pipes unless exposed to high temperatures, such as those experienced in combustion engines, fuel reformers and fuel cells. Metal and non-metal materials shown in Table 3 are listed to describe the acceptability of use for gaseous and liquid hydrogen applications. Note that the data in Table 3 originates from an American National Standard from the American Institute of Aeronautics and Astronautics (AIAA) Guide to Safety of Hydrogen and Hydrogen Systems and may not consider applications on marine or offshore vessels. Contact your local ABS office for specific guidance on compatible materials with hydrogen.

MATERIAL	HYDROGEN PHASE		NOTES
	GAS	LIQUID	
Aluminum and aluminum alloys	Acceptable	Acceptable	N/A
Austenitic stainless steels with > 7% nickel (e.g., 304, 304L, 308, 316, 321, 347)	Acceptable	Acceptable	Beware of martensitic conversion at low temperature if stressed above yield point
Carbon steels	Acceptable[1]	Not acceptable	Too brittle for cryogenic service
Copper and copper alloys (e.g., brass, bronze, and copper-nickel)	Acceptable	Acceptable	N/A
Gray, ductile or cast iron	Not Acceptable	Not Acceptable	Not for hydrogen service
Low-alloy steels	Acceptable[1]	Not Acceptable	Too brittle for cryogenic service
Nickel and nickel alloys (e.g., Inconel and Monel)	Acceptable[1]	Not Acceptable	Susceptible to hydrogen embrittlement[2]
Nickel steels (e.g., 2.25%, 3.5%, 5%, and 9% Ni)	Not Acceptable	Not Acceptable	Beware of ductility loss
Titanium and titanium alloys	Not Acceptable	Acceptable	Beware of susceptibility to hydrogen embrittlement
Chloroprene rubber (neoprene)	Acceptable	Not Acceptable	Too brittle for cryogenic service
Dacron™ (or equivalent)	Acceptable	Not Acceptable	Too brittle for cryogenic service
Fluorocarbon rubber (Viton™ or equivalent)	Acceptable	Not Acceptable	Too brittle for cryogenic service
Mylar (or equivalent)	Acceptable	Not Acceptable	Too brittle for cryogenic service
Nitrile (buna-n)	Acceptable	Not Acceptable	Too brittle for cryogenic service
Polyamides (nylon)	Acceptable	Not Acceptable	Too brittle for cryogenic service
Polychlorotrifluorethylene (PCTFE)	Acceptable	Acceptable	N/A
Polytetrafluorethylene (Teflon™ or equivalent)	Acceptable	Acceptable	N/A

[1] *When applicable, procedures specified by ASTM B849 and SAE USCAR-5 should be applied to reduce risks of hydrogen embrittlement.*

[2] *Hydrogen embrittlement is not an issue at cryogenic temperatures*

Table 3: Materials Compatible with Hydrogen Service (Source: ANSI/AIAA G-095A)

Other considerations for the safe storage of hydrogen at cryogenic temperatures include low temperature embrittlement and material thermal contraction and deformation from thermal cycling. Possible accumulated material damages caused by storing hydrogen and cycling pressures and temperatures may lead to limited storage vessel life. The lifetime of a storage vessel will depend on the number of use cycles and material properties. Hydrogen pressure vessel or cryogenic tank manufacturers can provide service life information for their products.

For cryogenic hydrogen, all system parts including tanks, pipes, fittings, pressure relief valves and vent masts should be insulated from normal air condensation or ice build-up which could potentially block ventilation pathways or cause clogging of system parts. Air condensate is primarily oxygen, and any subsequent condensate evaporation could create an oxygen-rich and potentially flammable gas concentration.

REGULATORY COMPLIANCE CONSIDERATIONS

IMO REGULATIONS

The adoption of the *Initial International Maritime Organization Strategy on Reduction of Greenhouse Gas Emissions from Ships by the Resolution MEPC.304(72)* in April 2018 demonstrates IMO's commitment to support the Paris Agreement. It includes a vision to phase out GHG emissions from international shipping within the century and may be an active driver for member states to initiate decarbonization and reduction of GHGs using policies and procedures. A 2019 International Maritime Organization Sub-committee on Carriage of Cargoes and Containers (CCC) reported that progress is being made on the Interim Guidelines for the Safety of Ships using Fuel Cell Power Installations. At the time of publication of this document, the draft interim guidelines are still being developed by the IMO International Code of Safety for Ships using Gases or other Low-flashpoint Fuels (IGF Code) correspondence group and are to be further developed at the delayed CCC 7 meeting scheduled for September 2021. These draft guidelines detail only the provisions for fuel cell installations and not the storage or use of hydrogen as a fuel.

The IMO IGF Code applies to ships to which the International Convention for the Safety of Life at Sea (SOLAS) Part G Chapter II-1 applies and contains only detailed prescriptive requirements for LNG under Part A-1 of the Code. Other low-flashpoint fuels may also be used as marine fuels on ships falling under the scope of the IGF Code, provided they meet the intent of the goals and functional requirements of the IGF Code and provide an equivalent level of safety. This equivalency is to be demonstrated by applying the Alternative Design risk assessment process and SOLAS novel concepts approval procedure of SOLAS regulation II-1/55, and as required by 2.3 of the IGF Code.

The future possible development and adoption of IMO regulations for hydrogen as marine fuel and fuel cell guidelines may help increase marine hydrogen fuel adoption and associated infrastructure for hydrogen generation and distribution.

For the carriage of liquefied hydrogen as cargo, the Interim Recommendations for Carriage of Liquefied Hydrogen in Bulk, the Maritime Safety Committee (MSC) Resolution MSC.420(97) is the only IMO instrument available that may be applicable to ships carrying a cargo of liquefied hydrogen. Such ships are expected to fall under the scope of the International Code of the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk (IGC Code). However, the Interim Recommendations were initiated by and developed for a liquid hydrogen supply pilot project, and as such may be limited in application to that project. The IMO recognizes that information from this developing pilot project, and other Member State experiences, are required prior to amending the IGC Code to include requirements for the carriage of liquefied hydrogen.


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INTERNATIONAL REGULATIONS AND STANDARDS

Although hydrogen has yet to be widely adopted as a fuel into the maritime industry with a few pilot projects, it has already been implemented in land-based uses. There are no international marine requirements mandated by the IMO; however, some of the information, rules and regulations from land-based resources are referenced in MSC.420(97). These include safety measures, methods of transportation and standard hydrogen production procedures. Various referenced codes and regulations exist for hydrogen component standards and equipment design, fire codes and other hydrogen-specific safety codes, and general safety codes or standards that include hydrogen.

The International Organization for Standardization (ISO) Technical Report ISO/TR 15916 Basic Considerations for the Safety of Hydrogen Systems focuses on providing technical information that form the basis of understanding hydrogen safety issues. The report addresses the recent interest in using hydrogen as a fuel and aims to address the unique hydrogen-related safety properties and phenomena and best engineering practices to minimize risks and hazards from hydrogen.

Further international standards that may be referenced by designers considering marine projects are listed here:

- IEC 60079. The International Electrotechnical Commission Standard for Explosive Atmospheres include hazardous areas and standards for gas detection applicable to hydrogen.
    - 60079 – Part 10.1 Classification of areas – Explosive gas atmospheres
    - 60079 – Part 29.2 Gas Detectors – Selection, installation, use and maintenance of detectors for flammable gases and oxygen
- IEC 61892. The International Electrotechnical Commission Standard for Mobile and Fixed Offshore Units includes ventilation provisions for battery-generated hydrogen.
    - 61982 – Part 7 Electrical Installations – Hazardous Areas
- ISO 11114. The International Organization for Standardization Gas Cylinders Standard includes advisories about compatible materials and test methods for selecting hydrogen embrittlement resistant steels.

NATIONAL STANDARDS

Fire codes for hydrogen have existed in the industry for many years. The National Fire Protection Association (NFPA) code NFPA 2 Hydrogen Technologies Code specifies equipment and system recommendations to address aspects of hydrogen storage, use and handling, including liquefied and gaseous hydrogen for power generation, road, rail and marine applications.

Other national hydrogen standards are listed below for equipment, piping, ventilation and hazardous area guidelines, and may be referenced by any designers considering marine projects:

- ANSI/AIAA G-095A-2017: Guide to Safety of Hydrogen and Hydrogen Systems. This American National Standards Institute and the American Institute of Aeronautics and Astronautics code provides general safety guidance for controls, usage, personnel training, hazard management, facilities, detection, storage, transportation, and emergency procedures, originally developed by the National Aeronautics and Space Administration (NASA) for applications in spacecraft.
- ASME B31-12 Hydrogen Piping and Pipelines. The American Society of Mechanical Engineers Code applies to the design, construction, operation and maintenance requirements for gaseous or liquid hydrogen piping and gaseous hydrogen pipelines. This standard is also referenced within marine guides for piping on board ships.
- NFPA 55 Compressed Gases and Cryogenic Fluids Code. This code formed the basis of NFPA 2 Hydrogen Technology Code.
- CGA G-5.4 Standard for Hydrogen Piping Systems at User Locations. This Compressed Gas Association standard describes the recommended piping systems for gaseous and liquid hydrogen.
- CGA G-5.5 Hydrogen Vent Systems. This standard describes guidelines for the design and safe operation of gaseous and liquid hydrogen vent systems.

ABS RULES ON HYDROGEN

Existing ABS *Rules for fuel cells include the Guide for Fuel Cell Power Systems for Marine and Offshore Applications*, published in November 2019 with references to the *Marine Vessel Rules (MVR)* Part 5C, Chapter 13 for vessels using gases or other low-flashpoint fuels. The *Fuel Cell Power Systems Guide* considers the IMO's draft Interim Guidelines for the Safety of Ships using Fuel Cell Power Installations and will be updated upon finalization of the interim guidelines.

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The *Fuel Cell Guide* mainly focuses on fuel cell design requirements, but also includes provisions for hydrogen as fuel, including the fuel containment system, material and general piping systems, fire safety, electrical systems, and control, monitoring and safety systems. Parts of this guide specific to hydrogen storage and supply systems may also be applicable to internal combustion engines using hydrogen.

The guide references standards for handling hydrogen, including the ASME B31-12 for piping and the ISO 11114-4 for hydrogen embrittlement testing. Certain systems, equipment or components may be required to be certified under ABS's Type Approval program to a certain Tier level to confirm their safe construction, appropriate testing and installation.

RISK ASSESSMENT

Due to hydrogen's relatively new application as fuel on board ships, many regulations and certification schemes require risk assessments to verify that the system is appropriately safe and can exhibit at least an equivalent level of safety as conventional fuel systems and gas applications. See the ABS *Guidance Notes on Risk Assessment Applications for the Marine and Offshore Industries* for more information about risk assessment methods and standard recommended practice.

The ABS *Guide for Fuel Cell Power Systems for Marine and Offshore Applications* includes the risk assessment requirements for fuel cells, including those using hydrogen as a fuel. The risk assessments should include a Hazard Identification (HAZID) analysis to identify potential hazards that could result in consequences to personnel, the environment and property. The Hazard and Operability (HAZOP) study should also be conducted to identify and evaluate hazards that may represent risks to personnel or equipment. A Failure Mode and Effects Analysis (FMEA) may also be used to demonstrate that any single failure will not lead to an undesirable event.

The IGF code states that risk assessments shall be conducted to ensure that risks arising from the use of low-flashpoint fuels affecting persons on board, the environment, the structural strength or the integrity of the ship are addressed. Consideration shall be given to the hazards associated with physical layout, operation and maintenance, following any reasonably foreseeable failure. Where found, risks should be eliminated or mitigated as far as practicable.

Due to the potentially serious consequences in case of an explosion involving hydrogen, the assessment and implementation of risk controlling measures are essential. This aligns with the general requirements outlined in the IGF Code, Part A (paragraphs 4.2 and 4.3). For alternative arrangements, MSC.1/Circ.1455 Guideline for Approval of Alternatives and Equivalents may, subject to flag agreement, be applied. The overall goal of the IGF Code and the Alternative Design approach is to ensure an equivalent level of safety is achieved by new systems or technology as those of other low-flashpoint gases.

DESIGN CONSIDERATIONS

CONCEPT EVALUATION

The various challenges exhibited by hydrogen as marine fuel must be resolved before being commercially available for use by a widespread fleet. Hydrogen is in the early stages of development for marine propulsion.

The requirements for the storage of hydrogen in a liquefied or gaseous form need to be considered at the concept stage, will depend on ship type and will drive the installation of appropriate high-pressure storage tanks or low-temperature containment arrangements. Table 4 summarizes some relative benefits and challenges of using hydrogen as marine fuel. Some of the key considerations of using hydrogen on a marine vessel are:

- Safety and operational management plan
- Equipment failure and emergency procedures
- Personnel training for safe handling
- Fuel availability

BENEFITS	CHALLENGES
• Carbon and sulfur free • Can be produced renewably from electrical energy and bio-renewable processes • Can be stored and transported as a liquid or gas • Established commercial product on land • Gaseous, particulate matter and GHG free emissions with fuel cells • Highly buoyant and disperses if leaked, even at liquid hydrogen temperatures	• Lack of marine transport experience • Possible high fuel cost • Low availability of renewably produced hydrogen • Fuel infrastructure and bunkering need investment • Novel power generation systems will require more technology innovation and cost reductions • High explosion risk in confined spaces • Low cryogenic temperature challenges (storage, management, leaks, etc.) • Material challenges (permeability, hydrogen embrittlement, etc.) • NO_x emissions if burning hydrogen in internal combustion engines.

Table 4: Benefits and Challenges of Using Hydrogen as Marine Fuel

Several concept vessels using hydrogen and fuel cells are described in the ABS *Setting the Course for Low Carbon Shipping: Pathways to Sustainable Shipping.*

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VESSEL ARRANGEMENTS

Future vessels may require integrated designs based on the operational profile, the selected fuel arrangement, power generation and propulsion systems chosen. Power generation systems such as hydrogen integrated with fuel cell and battery storage systems can change the architecture of current engine room design. For example, fuel cell installations may be large, but they may not require as much accessible maintenance space as typical marine engines do, therefore having the potential to use the volume within the engine room more efficiently. However, the weight of large fuel cell installations should be considered. Fuel cells and electrical hybrid systems may achieve more efficient use of space on vessels since they allow the distribution of electrical equipment throughout the vessel.

As hydrogen has low energy content per volume it will require larger tanks for equivalent energy storage and their location on board will be a critical design factor. Many small applications of hydrogen tanks are installed on decks or tops of superstructures to take advantage of natural ventilation in case of small leaks. Other, larger applications may consider storing hydrogen in tanks as independent or integrated structures. The energy content of stored hydrogen varies by its density (i.e., pressure and temperature), but in all cases more hydrogen by volume is required to meet equivalent volumetric energy densities of other marine fuels (see Table 1). The additional space for fuel may require larger vessel sizes, decreased cargo space and/or more frequent bunkering of the vessel. In addition, for hydrogen fueled ships, storage systems may need redesign regarding the hydrogen fuel containment system, gas valve unit and equipment for managing tank temperature and pressure. Liquid hydrogen cargo management systems may also require systems for boil off gas handling, reliquefication, gas valve unit/train, vent piping systems and exhaust masts. Appropriately rated electric equipment should be installed in hazardous zones or ventilation pathways which may be susceptible to gas ingress to limit potential ignition from sparks. Hydrogen detectors should also be located appropriately to identify potential flammable mixtures of gas. Appropriate fire, heat or smoke detectors with alarm systems are also recommended to identify fires early.

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AVAILABILITY

In the United States, the most hydrogen is produced in California, Louisiana and Texas and is typically used for the refining of petroleum, treating metals, producing ammonia or other chemicals and processing foods. The current use of hydrogen could shift as more hydrogen fueling stations begin to become available for road use. Hydrogen is also readily available in Belgium, France and other sites across Europe in the form of an industrial byproduct. For the successful adoption of hydrogen as marine fuel, hydrogen fueling stations at ports will need to be installed, most likely with more support from government entities and policies that can reduce the cost of hydrogen production, distribution and acquisition. The growth of hydrogen clusters in ports can help drive the demand for hydrogen on land, lower the market price in these locations and may allow hydrogen to become a more cost-effective option for marine fuel alternatives.

Hydrogen is being used as a fuel in Scotland, England, Germany, Australia, Norway, Sweden, Denmark, the United States, France, Korea and Japan. Scotland has focused its efforts on producing green hydrogen from tidal power in its offshore waters. If hydrogen is generated from syngas produced from biomass, availability may fluctuate depending on feedstock availability.

A 2020 International Council on Clean Transportation (ICCT) study examined the feasibility of using hydrogen fuel cells for large containerships along the U.S. – China shipping corridor. While hydrogen and fuel cells are typically used in smaller vessels with shorter routes, this study found that by addressing the availability of hydrogen fuel along the route and converting up to five percent of cargo space into fuel storage, 99 percent of the voyages could be achieved. Further, 43 percent of voyages could be accomplished with no loss in cargo space or changes in schedule. These results were justified by the assumption that hydrogen would be available at ports along the corridor by necessity of more frequent hydrogen bunkering due to low energy per volume. Where industry or infrastructure was not available, it was suggested a distributed hydrogen production and delivery network would be necessary. This and associated studies can show that the logistics of low- or zero-emission hydrogen-fueled deep-sea shipping could be possible with strategic planning and investment strategies.

FUEL STORAGE

Significant technical advances may be needed for hydrogen to be considered a viable, large-scale, commercial fuel option, particularly for applications with large volumes of hydrogen fuel that may require increased space on board, especially for long routes and deep-sea voyages. Hydrogen stored as cargo can be kept in its densest cryogenic liquid form to increase trade volume and storage onboard. However, larger fuel volumes and storage arrangements for gaseous and liquid hydrogen onboard may require a trade-off between some cargo space, depending on the hydrogen density, vessel operations, onboard power systems and route. Hydrogen fueled vessels traveling close to or operating near bunkering facilities, with the opportunity to bunker often, may experience minimal problems with fuel reduction or cargo space loss.

For liquefied hydrogen at low pressures, the energy loss during storage and boil off gas generation may be a challenge for long-term storage applications, depending on the pressure rating of the cryogenic tank and the length of time left dormant. The boil off rate is around one to five percent per day for standard land-based liquid hydrogen storage tanks. Improved insulation and slightly higher storage costs can reduce liquid hydrogen boil off down to 0.02 percent volume per day. To avoid losses, the boil off gas from liquefied gas tanks can be consumed in an engine or fuel cell. Tanks of pressurized gaseous hydrogen do not experience boil off gas issues.

FUEL SUPPLY

The purpose of the fuel supply system (FSS) is to deliver fuel at the correct temperature and pressure to the consumer. The use of low-flashpoint fuels and gases further complicates the fuel supply and consumer systems and creates a greater interdependence between the key systems than conventional fuel systems.

The FSS can be one of the more complex and expensive systems required for gas-fueled applications. It may also not be integrated with the original equipment manufacturer (OEM) fuel consumer but is designed to comply with the OEM's specifications. Managing hydrogen injection pressure, speeds, concentration and temperature in combustion engines is essential for proper ignition timing and efficiency.

Many fuel cell installations are accompanied by battery energy storage systems (BESS), and associated power management controls that can shave peak loads from fuel cells, or supply required power at low loads, allowing the fuel cell to operate at optimum performance and fuel consumption rates and protect against transient power loads.

PRIME MOVERS

Hydrogen as a fuel has been demonstrated in internal combustion engines, gas turbines and fuel cells. When consumed in a fuel cell, electric energy, water and heat are generated in a fuel-efficient process. Marinized fuel cells are available with a wide range of available power, especially when connected in series to increase output for any size marine power requirement. For large vessel power requirements, multiple fuel cells may be required to scale up the delivered power. In addition, to manage low or high energy demand, BESSs are typically installed to allow fuel cells to operate at optimum loads. Scaled-up installations of fuel cells and associated hybrid or battery systems may not yet be cost-competitive with alternative power generation options as capital expenses (CAPEX) can be high. Operational expenses (OPEX) may benefit from lower maintenance costs of fuel cells but suffer from high fuel costs in the near term. For this reason, it is important that the prime movers, including both fuel cells and combustion engines, be as fuel efficient as possible and therefore maximize the use of fuel stored onboard and the extent of OPEX. Training and appropriate expertise of fuel cell and hybrid systems should also be provided to crews and operators who may not be familiar with this relatively new technology, vessel arrangement and operational practices.

Hydrogen for combustion engines has typically been implemented as a supplementary/mixed fuel blend in conventional gas and dual fuel (DF) engines. Hydrogen has many properties that contribute to its use as a combustible fuel. The low ignition energy is important in combustion as the amount of energy needed to ignite hydrogen is about one order of magnitude less than that required of MGO. Hydrogen's high autoignition temperature plays a key role in defining the compression ratio of the engine, and affects the maximum power output (i.e., mean effective pressure) that can be delivered. Wartsila and MAN engines state that hydrogen combustion is possible in some engine types as a DF with natural gas or other gas fuels. Several studies of hydrogen combustion in engines show that even small percentages of hydrogen in the blended gas fuel can improve engine efficiency and lower carbon emissions. When used as a mono-fuel, hydrogen engines require modification to optimize the combustion timing and reduce engine knock. Typically, mono-fuel hydrogen engines require larger cylinder and engine size. However, large aftertreatment systems to manage NO_x and particulate matter (PM) may not be required depending on the air-fuel ratio and engine emissions performance.

In addition to mono-fuel hydrogen combustion, hydrogen can also be combusted with gas or other conventional fuels such as diesel. In DF applications, hydrogen is injected into the cylinders, compressed, and a small quantity of pilot diesel fuel is added to initiate combustion. Such a combustion system is used in Behydro© H_2/diesel DF engines with up to 85 percent hydrogen fuel content. The percent volume of hydrogen in the blend is directly related to the load profile and size of the engine, where higher loads can be fueled by higher hydrogen percentages. H_2-diesel co-combustion can combine fuel flexibility and efficiency with environmental performance. There are several possible means of hydrogen combustion within internal combustion engines with various benefits and challenges, as shown in Figure 8.

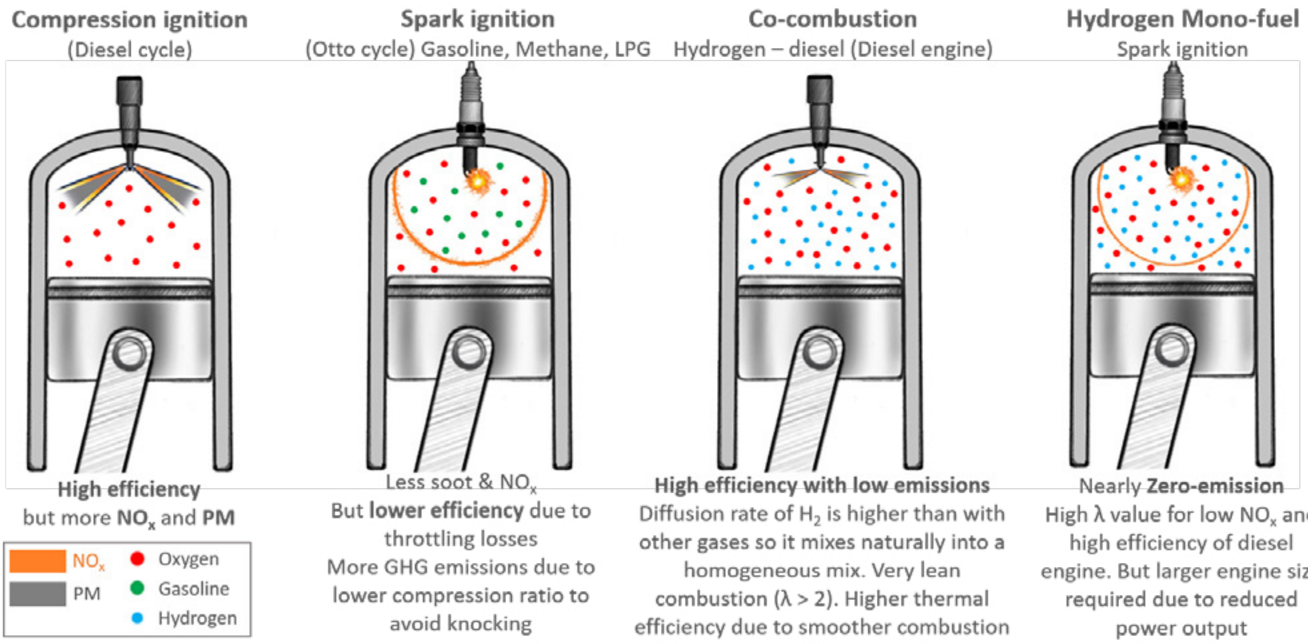

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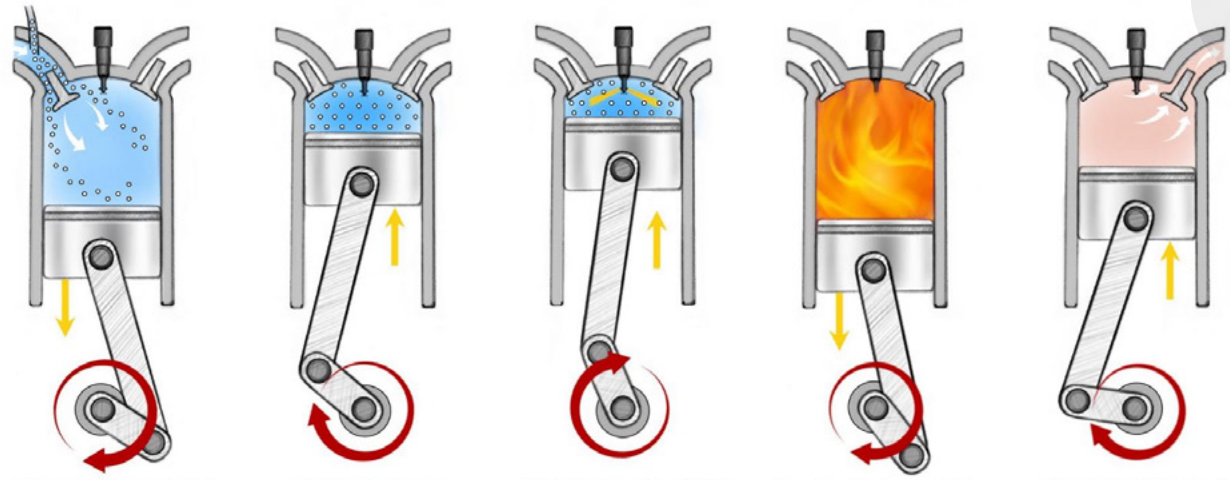
Figure 8: Possible Internal Combustion Systems Involving Hydrogen

With a wide range of flammability, hydrogen engines can run on air to fuel ratios ranging from 34:1 to 180:1. Both mono-fuel and dual-fuel hydrogen engines may operate on a lean-burn combustion cycle and reduce NO_x emissions. However, depending on the air/fuel ratios achieved there is the possibility that NO_x reduction technologies may be required, such as selective catalytic reduction (SCR) or exhaust gas recirculation (EGR) technologies. Figure 9 shows the H_2/Diesel co-combustion process.

VENTING AND EMISSIONS

Effective mechanical ventilation of spaces and adjacent spaces where hydrogen is stored or used is essential for fire safety onboard vessels. Typical ventilation requirements may include air changes, stopping of ventilation fans, closing the ventilation openings, air inlet positioning and exhaust duct positioning. See ABS MVR 5C-13 for low-flashpoint fuel requirements. For cryogenic and liquid hydrogen service, all pressure relief systems should be protected against the formation of water (or other liquefied atmospheric gases) or the build-up of ice (solids) due to very low temperatures.



Hydrogen is injected at the port and aspirated in the cylinder during intake stroke

Hydrogen mixes further into a uniform and homogeneous mixture during the compression stroke

A small amount of pilot fuel (diesel) is injected into the chamber just before top dead centre

Diesel auto-ignites (due to high temperature and pressure) and co-combusts with all the H_2, forcing the piston down during the power stroke

The cylinder is cleaned during the exhaust stroke, having lower NO_x and CO_2 emission in the exhaust gas

© CMB.TECH

Figure 9: Dual Fuel H_2-Diesel Co-combustion Process

Any hydrogen or hydrogen system outlet should be considered a hazardous zone. These should be located an approved distance from air intake openings, accommodation openings, service and control space openings or other non-hazardous areas and any exhaust system outlets.

BUNKERING INFRASTRUCTURE

The bunkering operation supplies fuel to a ship for cargo transfer or use by the onboard machinery. Currently in the industry, liquid hydrogen is expected to be bunkered similarly to LNG, and gaseous hydrogen may be bunkered with frequent loading/unloading between ships and terminals. Hydrogen refueling or bunkering infrastructure must be approved by the related authorities, including regional authorities, governments, fuel suppliers and possible road transport regulations, and must accommodate ship-specific fuel arrangements. Bunkering arrangements may also depend on simultaneous operations such as cargo loading/unloading or other dockside activity.

The bunkering facilities for liquid hydrogen are expected to have higher capital costs than LNG bunkering facilities. This is due to the increased cryogenic storage requirements for liquid hydrogen and the advanced components needed for pipes, seals, and tanks, such as bayonet joints for cryogenic liquid hydrogen. Consideration should be given to hydrogen bunkering infrastructure regarding hydrogen permeation, embrittlement, material compatibility, low-temperature use and hydrogen attack.

For compressed gaseous hydrogen bunkering operations, it may be assumed that a dispensing concept similar to the land-based truck or a bus dispensing could be applied in marine application design facilities. During transfer from one tank to another, the operation needs to be done in a way that keeps the hydrogen at the correct temperatures and volume. This can be done through a ‘cold inbound’ or ‘warm inbound,’ which will change the re-refrigeration process of the fuel.

Alternatively, and depending on the hydrogen volume required for the designed fuel range, many installed hydrogen tanks can be modular or fitted externally and may require simple cylinder replacement procedures to refuel the vessel. In this case, procedures should be in place and followed to verify the proper and safe handling, connection and disconnection of hydrogen cylinders into the ship’s fuel systems.

On-site port availability of hydrogen may be a critical decision factor due to the higher cost of dedicated hydrogen pipelines or distribution supply chains. While infrastructure investment to increase the scale of hydrogen availability may appear large, when considering the total shipping costs (i.e., fuel costs) of a 15- to 20-year-old vessel, infrastructure modifications could be a relatively small fraction.

ONGOING RESEARCH

INDUSTRY PILOT PROJECTS

The successful outcome of hydrogen pilot projects is necessary to prove to the maritime industry that it is possible to manage the operation of hydrogen fuel transportation, availability, use and refueling systems. Various industry pilot projects ongoing or upcoming are listed here, and the diversity of arrangements and applications is the result of trade-offs between required vessel power, range, operations, size, efficiency, fuel availability and overall familiarity with various novel or hybrid technologies.

GOLDEN GATE ZERO EMISSION MARINE HYDROGEN FUEL CELL VESSEL

The first hydrogen fuel cell powered vessel in the United States for operations as a passenger ferry in the San Francisco Bay Area is to launch in late 2021. The project was initiated by Golden Gate Zero Emission Marine (GGZEM), now known as Zero Emission Industries, following a 2018 *SF-BREEZE* hydrogen ferry feasibility study. The 70-foot-long catamaran *Water-Go-Round* (renamed *Switch*) is to be fueled by PEM fuel cells with 242 kg of compressed hydrogen tanks stored on top of the superstructure and use 100 kWh of batteries to handle peak and variable loads. The fuel is expected to allow for up to two full days of ferry operations with a design speed of 22 knots. The project is intended to show that the technology and economy of a hydrogen fueled ship is feasible, with industrial hydrogen availability growing in the Bay Area for refueling the onboard tanks. The hybrid-electric ferry will promote zero emissions and quiet operations.

Image used courtesy of Golden Gate Zero Emission Marine Inc.

Figure 10: The San Francisco Passenger Ferry Water-Go-Round

BEHYDRO© ENGINES AND CMB.TECH'S HYDROVILLE

In Belgium, the ferry *Hydroville* launched in 2017 as the world's first hydrogen-powered passenger vessel owned by CMB Tech. *Hydroville* is powered by a dual-fuel (DF) hydrogen-diesel engine. The Behydro engine (developed by the Joint Venture ABC/CMB.TECH) is available in 6, 8 (in line), 12 or 16 (V) cylinder arrangements to provide a range of power output from 1,000 to 2,670 kW. NO_x emissions produced by this combustion system are reduced to the required limits using selective catalytic reduction (SCR) technology. The combination of a hydrogen combustion system and after-treatment technologies allows the vessel to achieve near-zero emissions. However, one of the limiting factors for application onboard the vessel is the required capacity of the fuel storage tank. CMB Tech is working to develop more H_2/diesel DF small vessels, including the 80-person ferry *Hydrobingo* to be launched in Japan in 2021, a wind farm service vessel *Hydrocat*, to be launched mid-2021, and the *Hydrotug* to be launched mid-2022 to serve the Port of Antwerp.

Figure 11: The Hydroville Passenger Ferry Run on a Hydrogen-diesel Dual-fuel Engine

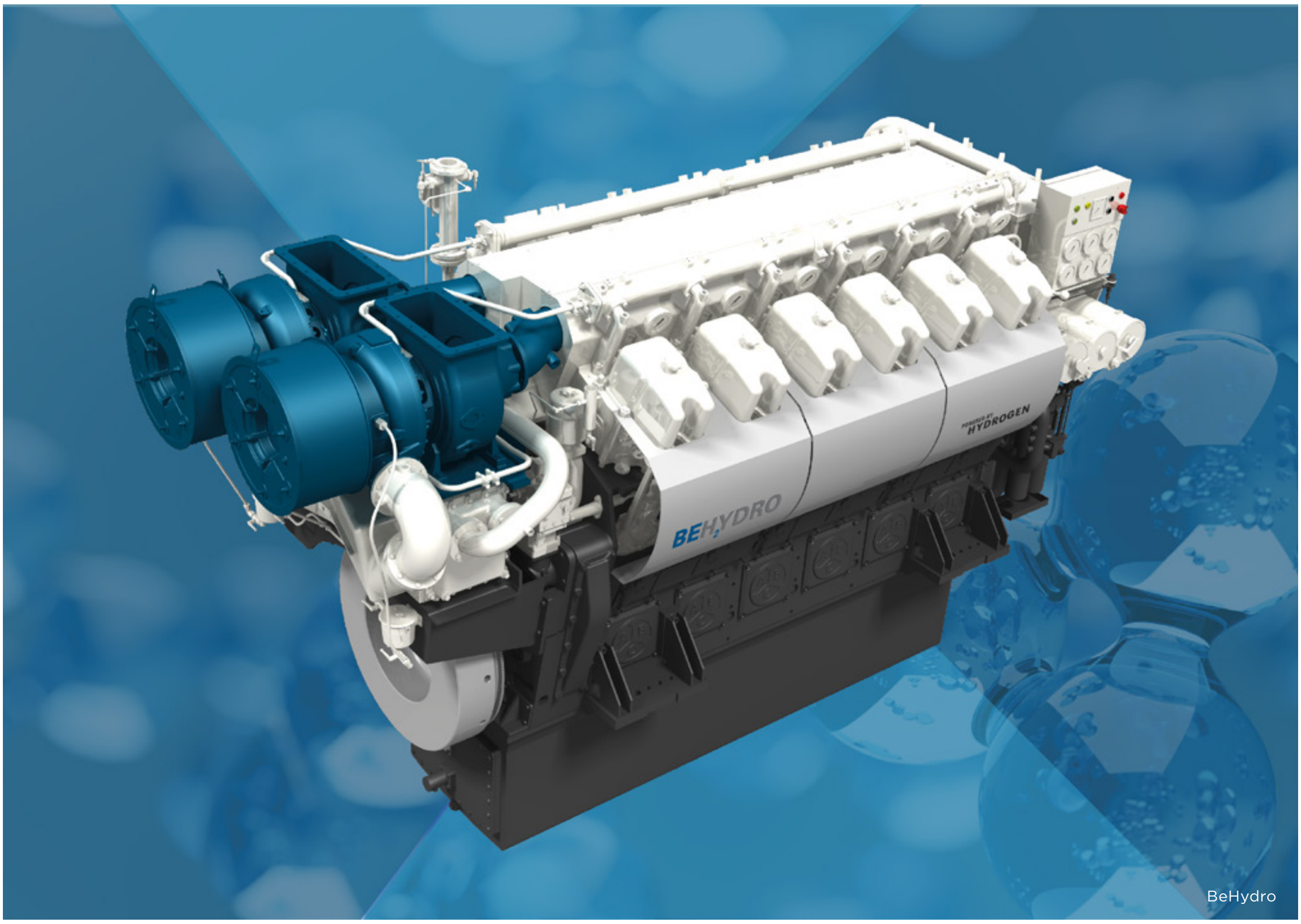


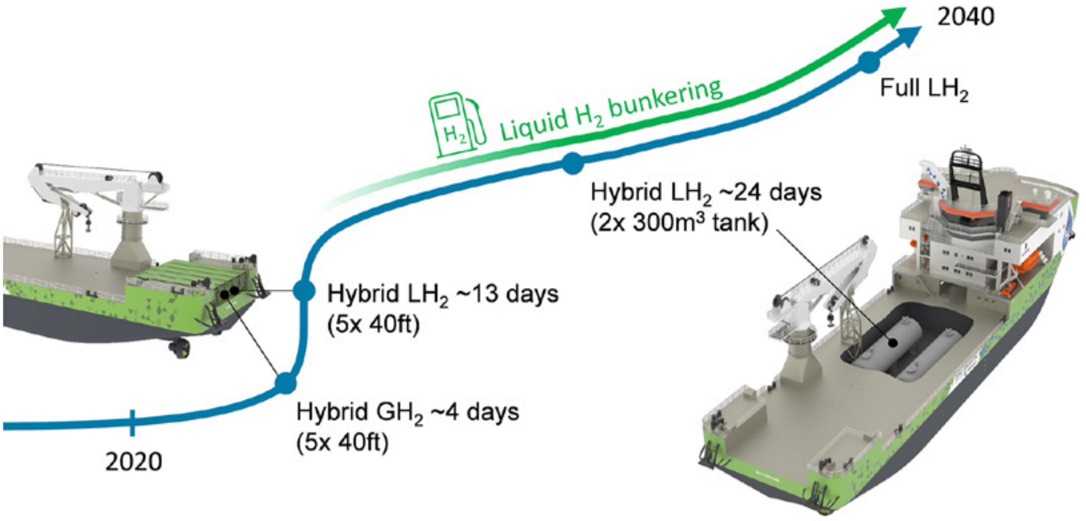
Figure 12: BeHydro Engine Can Run on Hydrogen Gas and Diesel Fuel. Shown: 12DZD 12-cylinder V Engine

ULSTEIN'S SX190 ZERO EMISSION OFFSHORE SUPPORT VESSEL

© Ulstein

Figure 13: Ulstein's SX190 Zero Emission Offshore Service Vessel

The design for an offshore vessel has been published by Ulstein Design & Solutions using Nedstack fuel cell technology. The design claims that sea trails for a newbuild are possible by 2022 and the vessel could be delivered by 2024. The ship was designed around the fuel cells with a design profile of up to two-week, zero-emission operations, achieved by implementing near-future advanced designs for hydrogen storage and fuel cell technologies. For longer voyages, the vessel design includes diesel-electric propulsion systems fueled by low sulfur marine diesel oil (MDO). The Nedstack proton exchange membrane (PEM) fuel cell stacks, located in a separate engine room on board, are to provide 2 MW of the total 7.5 MW of installed onboard power. The hydrogen fuel on board is to be stored in pressurized containers that are handled by normal crane operations, which are replaced for flexible refueling rather than handling expensive hydrogen bunkering infrastructure. The modular fuel containers are expected to be capable of refilling at any hydrogen generation site, allowing for global service opportunities wherever industrial by-product or green hydrogen is available. When the technology and shoreside bunkering infrastructure becomes available, the modular pressurized storage solutions can be replaced by integrated liquefied hydrogen tanks, allowing for approximately three times more hydrogen fuel on board and a longer zero-emission operating range. This zero-emission fueling technology is complemented by other Ulstein ship efficiency solutions, including the iconic X-Bow® shape, onboard battery storage solutions and energy management and recovery techniques.



© Ulstein

Figure 14: Ulstein's Liquid Hydrogen Fuel Roadmap for SX190 Offshore Support Vessel

ULSTEIN'S HYDROGEN POWERED WIND TURBINE INSTALLATION JACK-UP

Ulstein has also designed a hydrogen-powered wind turbine installation vessel (WTIV), the *ULSTEIN J102*. The design claims to be able to operate on zero-emission hydrogen power 75 percent of the time and diesel electric for the rest. Where other hybrid vessels or installations may struggle to fit large battery energy storage systems (BESS) on board, hydrogen and fuel cells are used on this WTIV design to minimize the elevated weight and optimize variable deck loads. The installation has a smaller BESS included to handle peak and variable loads on the main power generation systems. This design uses containerized compressed hydrogen for modular fuel replacement.

CFT AND NORLED FLAGSHIPS HYDROGEN VESSELS

The innovation project FLAGSHIPS in Europe has been awarded five million euros to deploy two new hydrogen fueled vessels, designed by LMG Marine. One will be an inland cargo vessel in Paris, France operated by Compagnie Fluvial de Transport (CFT), and the other is to be a passenger and car ferry operated by Norled for public transportation in Stavanger, Norway. The funds come from the EU's program Horizon 2020 under the Fuel Cells and Hydrogen Joint Undertaking. Both vessels are intended to be fueled by green hydrogen and show the feasibility of using hydrogen to replace biodiesel applications, especially in sensitive environmental areas such as Norway's coastlines and fjords. The Norwegian vessel will sail under the name *MF Hydra* and is intended to be delivered in 2021, and once the hydrogen equipment is installed, the vessel is expected to bunker gaseous H_2 daily between its six stops along the Judaberg-Helgøy route. Onboard PEM fuel cells will be supplied by Ballard Power Systems Europe.

Supporting the expected hydrogen supply is the industrial chemical supply company Linde, which has been chosen by Norled to supply the liquid hydrogen and the related bunkering infrastructure. The company claims green hydrogen will be produced at the Leuna Chemical Complex in Germany using PEM electrolyzers, allowing for the supply of hydrogen to begin in 2022.

PILOT-E PROJECT SUPPORTING LIQUID HYDROGEN IN NORWAY

Hydrogen infrastructure in Norway for a marine application supply chain has been boosted by 33.5 million NOKs from Norway's PILOT-E promotional scheme to deploy new environmentally friendly technology. The country's electrical grid is largely powered by renewable hydroelectric power, therefore the emissions from its widespread petroleum-fueled water transportation network constitute a major portion of the country's total output. Significant funding has been provided to decarbonize Norway's waterways, especially in its populated cities and environmentally sensitive fjords. This project award includes partners BKK, Equinor, Air Liquide, Norled, NorSea Group, Viking Cruises and Wilhelmsen to establish liquid hydrogen green generation, transportation, and bunkering infrastructure for marine applications.

PILOT-E has also supported the SINTEF hydrogen ferry *H_2CarbonCat*, which expects to develop a ferry ready for operational tests by 2022. The ferry is intended to carry cars and passengers through the popular Geirangerfjord between Hellesylt and Geiranger, where hydrogen is expected to become available from the Hellesylt Hydrogen Hub project.

STOCKHOLM'S BOATPLAN 2025

Stockholm's Green City Ferries has released the Boatplan 2025 Strategy for the transition of archipelago traffic based on guidelines from Region Stockholm to transition to renewable and environmentally friendly public transport. Among various energy efficiency methods to be implemented for ships, including lightweight carbon fiber vessels, air lubrication systems, and hybrid battery installations, Green City Ferries intends to replace or refit longer-range vessels with hydrogen fuel capability. Beyond 30 km routes, required battery power is restricted by weight and size. In these applications, hydrogen and fuel cells can provide appropriate clean power requirements, leading to energy savings of up to 65 percent with other efficiency measures, and completely remove TTW emissions.

HYDROGEN ENERGY SUPPLY CHAIN PROJECT – AUSTRALIA TO JAPAN

In Australia, a Hydrogen Energy Supply Chain (HESC) pilot project has been promoted that focuses on a fully liquefied hydrogen supply chain between Australia and Japan. Australia will produce brown coal and liquefy it for export to Japan through the developed supply chain. For the commercial phase expected around 2030, carbon capture will also be used to produce blue hydrogen.

The Hydrogen Energy Supply-chain Technology Research Association (HySTRA) responsible for the pilot project will demonstrate marine transportation with the liquid hydrogen carrier *Suiso Frontier*, designed and built by Kawasaki Heavy Industries and launched in 2019. Based on Kawasaki's' technical experience from storing and carrying LNG, the carrier has an independent cryogenic pressurized tank, with a total liquefied hydrogen capacity of 1,250 m^3 using vacuum insulation and designed to withstand a 20-day trip. The hydrogen is stored at high pressures, so the pressure in the inner shell of the carrier is designed to be at 0.4MPa (3.95 atm). It should be noted that this vessel is intended for hydrogen carriage only and is not fueled by hydrogen, although hydrogen fueled propulsion systems for the commercial carrier may be applied in the future. Once it reaches the commercial phase, the supply chain is expected to increase land-use of hydrogen in Japan. In the future, supply chain infrastructure such as this may be essential to scale up hydrogen availability and provide fuel for marine propulsion.

Courtesy of HySTRA

Figure 15: The Suiso Frontier is the First Liquid Hydrogen Carrier, Launched in 2019 and Intended for Use in the HESC Pilot Project

HYDROGEN COST

The main cost of a vessel's conversion to hydrogen as a marine fuel includes storage and availability. The availability and cost of hydrogen is currently higher than that of natural gas, making it less attractive to the shipping industry. Vessels can use grey or brown hydrogen as it is currently available and switch to blue or green hydrogen as those production pathways become more widespread and cost-effective. Countries such as Chile and Australia which produce green hydrogen can help reduce the cost. A decrease in the production cost and an increase in the availability of hydrogen has the potential to make hydrogen a top fuel alternative option for marine vessels.

As the initiative and efforts continue, the cost of marine hydrogen decreases as more countries develop hydrogen from renewable processes. Many countries are in positions to begin building a large hydrogen economy. Various initiatives in many countries to expand their local hydrogen production or the hydrogen trade can assist in boosting hydrogen investments, export opportunities and drive the hydrogen market to expand.

Currently, it is estimated that hydrogen fuel costs around four to eight times the price of very low-sulfur fuel oil (VLSFO). A focus on the costs of green and blue hydrogen fuel prices is a crucial component to lower the carbon emissions by 2050. If the cost is lowered, the shipping industry will have a much easier transition to access and implement the fuel. Because green hydrogen is dependent on the renewable energy industry, as renewable energy becomes less expensive, the green hydrogen industry is expected to also reflect lower prices.

Green or blue hydrogen have the potential to decarbonize shipping entirely and achieve the IMO's decarbonization goals by 2050. Described in the 2020 ABS Setting the Course to Low Carbon Shipping: Pathways to Sustainable Shipping document as the end goal of the Light Gas Pathway, hydrogen can be produced from a variety of sources which results in a range of fuel cost. Figure 17 shows the correlation between the technology of production and the expense for every kilogram of hydrogen, where near-term 2030 hydrogen production from fossil fuels is expected to remain the least expensive option. However, generation from electrolysis based on an increasing renewable electrical grid is expected to reduce the costs of those carbon-free production pathways.

Many first adopters of hydrogen as marine fuel expect to begin using brown or gray hydrogen in the near-term and focus on eliminating their TTW emissions. As the hydrogen industry expands and begins to generate cost-competitive blue or green hydrogen, these fuels will easily replace dirtier hydrogen streams and allow for fully decarbonized WTW operations.

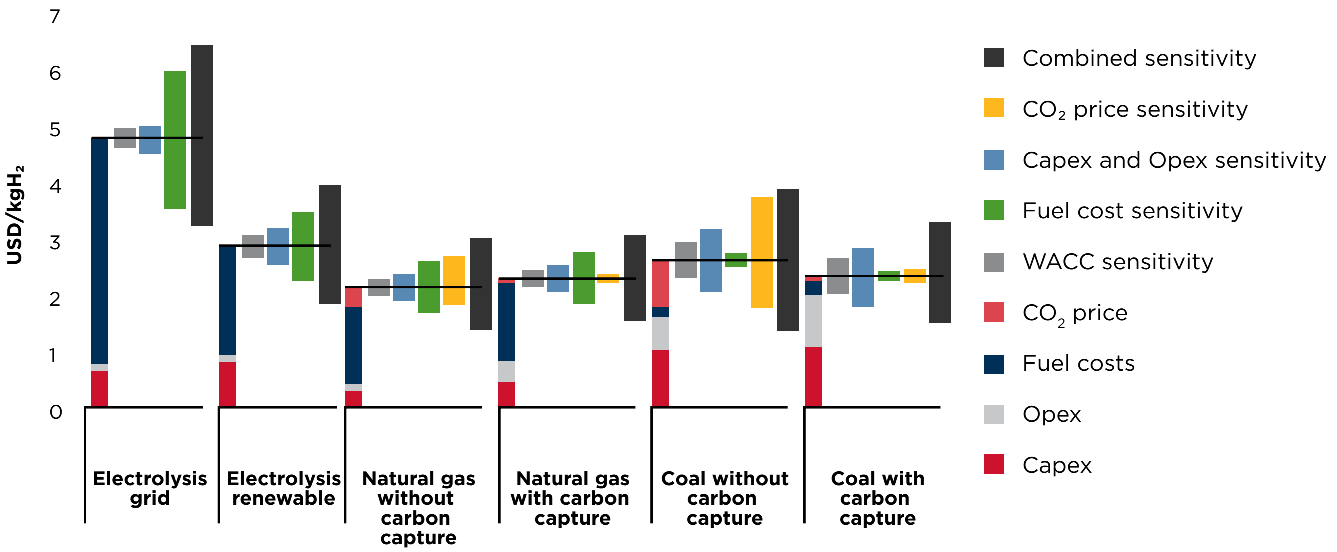


Figure 16: Hydrogen Production Cost for Different Technologies in 2030
Note: WACC = Weighted Average Cost of Capital
(Source: ABS Setting the Course to Low Carbon Shipping – Pathways to Sustainable Shipping)

The bunkering infrastructure for hydrogen may also increase with production rates to allow for global bunkering availability. The bunkering infrastructure for hydrogen can provide terminals, storage tanks, dehydrogenation plants, ammonia terminals, storage tanks and ammonia cracking installations. The ability to store both pure hydrogen fuel and convert to ammonia at bunkering ports can allow for the expansion of both marine fuel options.

While the cost of fuel is estimated to be around 50 percent of the transition, the cost of storage and new fuel consumers needs to be considered when converting to hydrogen fuel. The owner may also need to consider the required range of the fuel and associated volume required, which may also affect the amount of cargo space yielded for fuel storage in the vessel design.

PROJECTED ROLE OF HYDROGEN AS MARINE FUEL

As more experience is gained through hydrogen pilot projects, the marine industry is expected to adopt hydrogen as an environmentally friendly fuel of choice. There are a few countries that have projected roles for hydrogen. Unlike fossil-based petroleum marine fuels, which are exported from resource-rich countries to others around the world, hydrogen production in any country can secure an energy independent ecosystem. For this reason, national governments are developing agendas to include it in their energy plans, which may in turn help to quicken the pace of global hydrogen production, including the available hydrogen for marine fuel.

Australia's independent standards recognize hydrogen's potential role to decarbonize Australia, improve fuel security and create new investment and export opportunities, particularly to Japan, where the demand for hydrogen is growing for zero-emissions transport applications. The global demand for Australian exported hydrogen could reach one million tonnes by 2030 and a GDP growth of AUD $11 billion by the year 2050. Australia projects that hydrogen has the potential to transform the global energy market by partnering with international agencies to provide more support to develop the use of hydrogen.

In Europe, the Renewable Energy Directive 2018/2001 (EU RED) states ambitious claims to source 32 percent of energy produced by member states from renewable sources by 2030. As a part of the European Clean Energy for all Europeans package, which followed the signing of the Paris Climate Agreement, the EU RED includes plans for the widespread uptake of hydrogen, focusing on sustainably-sourced green hydrogen from renewables. The EU Hydrogen strategy aims to install 6 GW of renewable hydrogen electrolyzers between 2020 and 2024, totaling production to up to one million tonnes of renewable hydrogen. By 2030, the strategy further integrates hydrogen into the energy system, with up to 40 GW of renewable hydrogen electrolyzers and total production increase up to 10 million tonnes. Between 2030 and 2050, the goals increase so that renewable hydrogen is a mature industry and will become a large scale decarbonization solution for all sectors. Initiatives deriving from this EU directive and Hydrogen Strategy have already begun to fund initiatives, projects and markets for renewable hydrogen in Europe, including hydrogen and fuel cell vessels and supporting renewable hydrogen infrastructure.

The U.S. also has plans for a hydrogen industry. A Fuel Cell and Hydrogen Energy Association (FCHEA) report maps out how the U.S. can transition to ambitiously adopt hydrogen into the widespread energy industry. The scenario states that hydrogen can be an economic growth driver and a tool for decarbonization with the assistance of federal regulations supported by states and local legislation. This optimistic scenario projects that U.S. hydrogen demand will rise from 10 million tons to 17 million tons by 2030, and 63 million tons by 2050.

Carbon neutral and emissions-free fuels such as hydrogen have a great potential to reduce or eliminate emissions from shipping and achieve the IMO's 2050 goals. In fuel cells, hydrogen can be used to produce zero-carbon, zero-emissions TTW power. In combustion dual-fuel engines, emissions and carbon can be reduced according to the percentage of hydrogen fuel consumed. Green and blue hydrogen production can allow for the life cycle of the fuel to also minimize carbon and GHG emissions from WTW. The use of hydrogen is expected to increase to take advantage of these emissions reductions, initially an investment but over time the fuel and infrastructure can become cost-competitive with other decarbonized fuel options. Figure 18 shows the currently projected marine fuel use to 2050 as the industry strives to meet the GHG emissions-reduction targets mandated by the IMO.

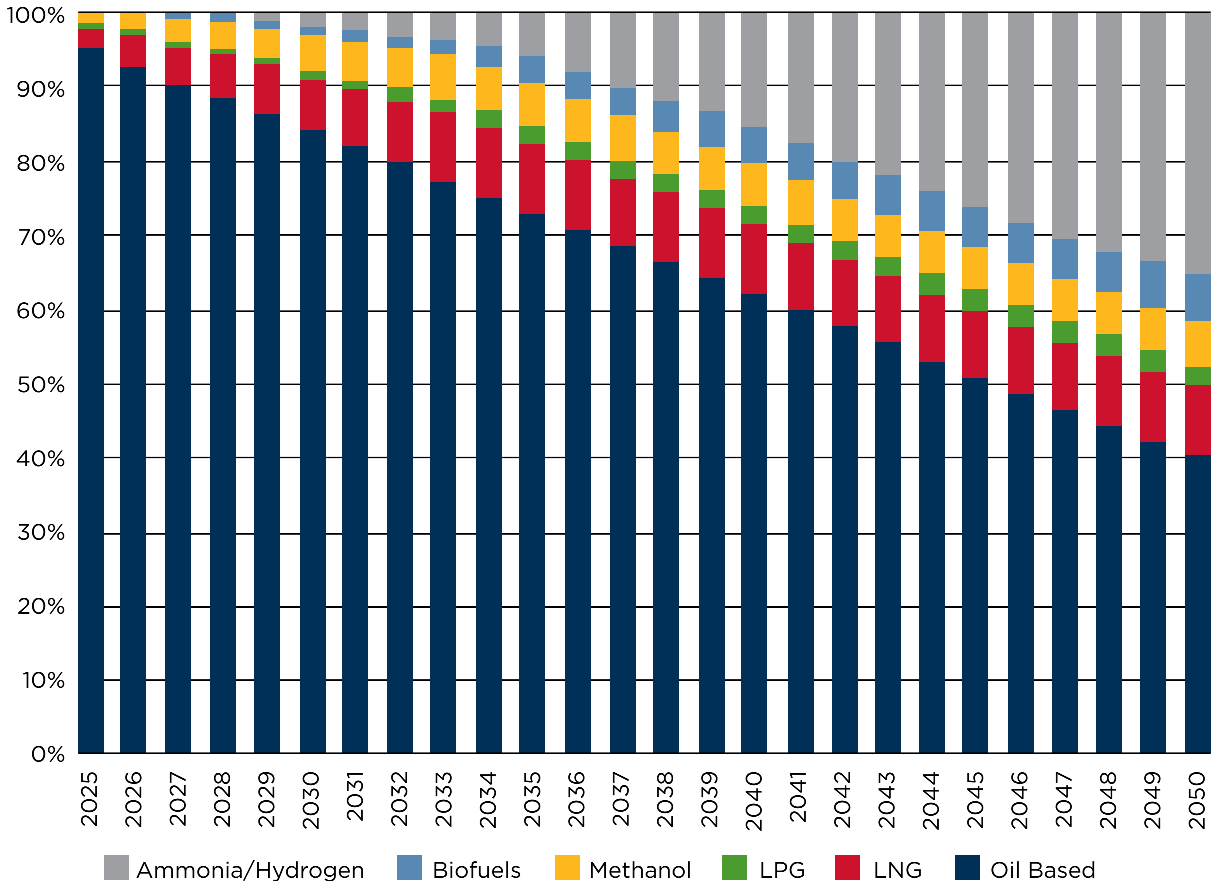


Figure 17: Projected Marine Fuel Use to 2050
(Source: ABS Setting the Course to Low Carbon Shipping – Pathways to Sustainable Shipping)

ABS SUPPORT

ABS can assist owners, operators, shipbuilders, designers and original equipment manufacturers as they consider the practical implications of the use of hydrogen as marine fuel. Services offered include:

- Risk assessment
- Regulatory and statutory compliance
- New technology qualifications
- Life cycle and cost analysis of hydrogen-fueled vessels
- Vessel/fleet benchmarking and identification of improvement options
- Energy Efficiency Design Index (EEDI) verification and identification of improvement options
- Energy Efficiency Existing Ship Index (EEXI) verification and identification of improvement options
- Optimum voyage planning
- Alternative fuel adoption strategy
- Techno-economic studies
- Cybersafety notations and assessments
- Contingency arrangement planning and investigations

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APPENDIX II- LIST OF ACRONYMS AND ABBREVIATIONS

ABS	American Bureau of Shipping
ABC	Anglo-Belgian Corporation
AIAA	American Institute of Aeronautics and Astronautics
ANSI	American National Standards Institute
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
AUD	Australian Dollar
BESS	Battery Energy Storage System
BLEVE	Boiling Liquid Expanding Vapor Explosion
CAPEX	Capital Expenditures
CCC	IMO Subcommittee on Carriage of Cargoes and Containers
CCUS	Carbon Capture, Utilization or Storage
CFT	Compagnie Fluvial de Transport
CGA	Compressed Gas Association
CO_2	Carbon Dioxide
DF	Dual Fuel
DME	Dimethyl Ether
EEDI	Energy Efficiency Design Index
EEXI	Energy Efficiency Existing Ship Index
EGR	Exhaust Gas Recirculation
EU	European Union
FCHEA	Fuel Cell and Hydrogen Energy Association
FMEA	Failure Mode and Effects Analysis
FSS	Fuel Supply System
GDP	Gross Domestic Product
GGZEM	Golden Gate Zero Emission Marine
GH_2	Gaseous Hydrogen
GHG	Greenhouse Gas
GO	Guarantee of Origin
H_2	Hydrogen
HAZID	Hazard Identification Analysis
HAZOP	Hazard and Operability Analysis
HCNG	Hydrogen – Cryogenic Natural Gas blend
HESC	Hydrogen Energy Supply Chain
HFO	Heavy Fuel Oil
HLNG	Hydrogen – LNG blend
HySTRA	Hydrogen Energy Supply-Chain Technology Research Association
IEC	International Electrotechnical Commission
ICCT	International Council on Clean Transportation
IGC Code	International Code for the Construction and Equipment of Ships Carrying Liquefied Gases in Bulk
IGF Code	International Code of Safety for Ships Using Gases or other Low-Flashpoint Fuels
IMO	International Maritime Organization
ISO	International Organization for Standardization
LH_2	Liquid Hydrogen (cryogenic)
LNG	Liquefied Natural Gas
LPG	Liquefied Petroleum Gas
MAN	MAN Energy Solutions
MEPC	Marine Environmental Protection Committee (IMO)
MCH	Methylcyclohexane
MDO	Marine Diesel Oil
MGO	Marine Gas Oil
MSC	Maritime Safety Committee (IMO)
Mtoe	Million Tons of Oil Equivalent
MVR	Marine Vessel Rules
NASA	National Aeronautics and Space Administration
NFPA	National Fire Protection Association
NH_3	Ammonia
NOK	Norwegian Krone
NO_x	Nitrogen Oxides
OEM	Original Equipment Manufacturer
OPEX	Operational Expenditures
PEM	Proton Exchange Membrane Fuel Cell
PCTFE	Polychlorotrifluoroethylene
PM	Particulate Matter
RED	EU Renewable Energy Directive 2018/2001
SAE	Society of Automotive Engineers
SCR	Selective Catalytic Reduction
SOFC	Solid Oxide Fuel Cell
SOLAS	International Convention for the Safety of Life at Sea
TR	Technical Report
TTW	Tank-to-Wake
USCAR	United States Council for Automotive Research
VLSFO	Very Low Sulfur Fuel Oil
WACC	Weighted Average Cost of Capital
WTIV	Wind Turbine Installation Vessel
WTT	Well-to-Tank
WTW	Well-to-Wake

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