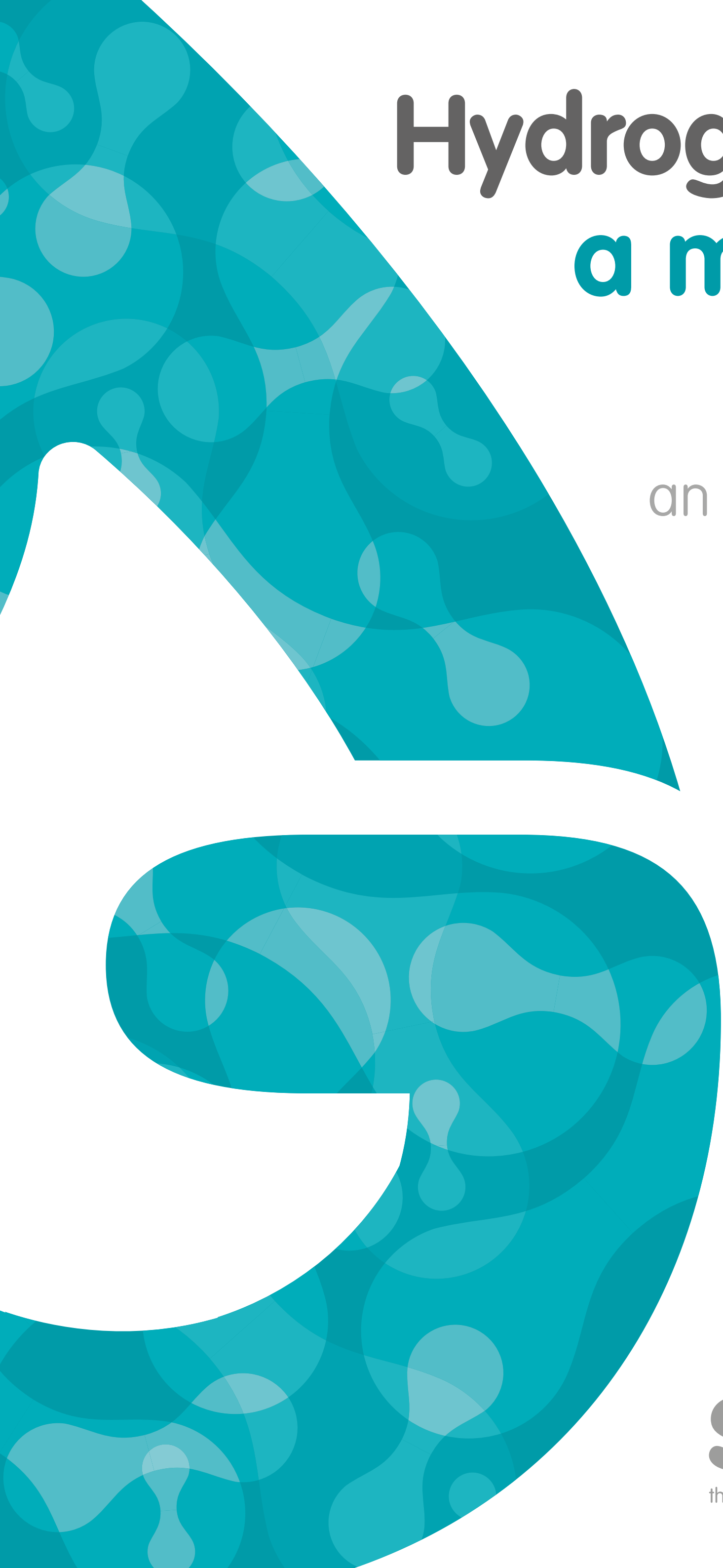

# Hydrogen as a marine fuel

## an introduction

Version 1.0

SGMF
the society for gas as a marine fuel

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## Disclaimer

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## The Society for Gas as a Marine Fuel (SGMF)

The Society for Gas as a Marine Fuel (SGMF) is a membership-based non-governmental organisation (NGO) established in 2013 to promote the safe and sustainable use of gas as a marine fuel. The Society has full consultative status at the IMO and is the recognised representative body for the gas-fuelled shipping industry.

## Acknowledgements

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## About this publication

As its name suggests, **Hydrogen as a marine fuel – an introduction** sets out the key facts about hydrogen ($H_2$):

- what it is
- how it is used
- its safety and environmental profile
- which countries have invested in it
- the technical considerations of a $H_2$-fuelled ship
- systems design
- bunkering facilities and process, and
- how personnel involved in handling hydrogen should be trained and familiarised

Although out of necessity it is a high-level document, the aim of the publication is to provide key information that will assist the eventual hydrogen-fuelled ship industry to develop.

# Hydrogen as a marine fuel

## Marine fuels and emissions in context

Currently, the world's commercial fleet mainly uses fossil fuels. The choice of fuel has been based on availability, energy density and economic considerations.

Today, however, the maritime transport industry is under mounting pressure to improve its environmental performance and reduce its emissions from fuel consumption. Sulphur oxides ($SO_x$), nitrogen oxides ($NO_x$) and particulate matter (PM) harm both the atmosphere and human health, while carbon dioxide ($CO_2$) and other greenhouse gases (GHGs) contribute to climate change.

Since 2005, the International Maritime Organization (IMO), the United Nations body that controls and regulates many aspects of the global shipping industry, has addressed fuel combustion emissions to the atmosphere through the International Convention for the Prevention of Pollution from Ships (MARPOL), Annex VI. This is done under the auspices of its Marine Environmental Protection Committee (MEPC).

As part of this effort, IMO has set targets to reduce $SO_x$, $NO_x$ and GHG emissions.

## Local air pollutants

- $SO_x$ emissions are fuel related. The latest stage of the sulphur emission rules (the 'global sulphur cap') was successfully implemented in 2020 and reduced the global fuel sulphur limit to 0.5%. More stringent emissions controls of 0.1% sulphur limits apply in designated Emission Control Areas (ECAs). Fuels exceeding the limits may only be used in combination with an approved exhaust gas cleaning system (EGCS). Hydrogen fuel does not contain any sulphur, so $SO_x$ will be eliminated.
- $NO_x$ emissions are mainly engine technology related and are regulated under the $NO_x$ Technical Code for marine engines. Engine manufacturers have made improvements to their engine designs to reduce $NO_x$ emissions. In general gas-fuelled engines have lower $NO_x$ emissions than oil-fuelled engines. The combustion properties of hydrogen would suggest that $NO_x$ levels might rise 20-30% above levels produced in methane-fuelled engines. If hydrogen is used

instead in fuel cells, $NO_x$ will be eliminated. However, the reforming of hydrocarbons to produce the hydrogen may produce $NO_x$.
- PM emissions are both fuel and engine technology related and though not individually addressed, PM emissions are improved by regulations on $SO_x$. The lack of carbon and sulphur compounds in hydrogen should eliminate soot and particle emissions.

## Focus on climate change

The industry's attention has increasingly focussed on $CO_2$ and other GHGs including methane ($CH_4$), nitrous oxide ($N_2O$), and black carbon (soot, a subset of PM).

Shipping currently emits 3% of all greenhouse gases worldwide, the equivalent of the contribution of the 5th largest producer country Japan or of Germany (6th) and France (19th) combined. About 80% of these emissions come from deep sea shipping.

IMO's objective is to reduce the industry's total annual GHG emissions by at least 50% by 2050 compared to 2008. The target cannot be met without the introduction of alternative zero-carbon fuels and carbon-neutral fuels produced from sustainable sources.

$CO_2$ emissions are proportional to both the quantity and type of fuel used. Technical and operational measures to reduce carbon intensity of ships have been adopted by IMO. The most recent is the Carbon Intensity Indicator (CII) which came into force in January 2023.

Emissions may be reduced in two ways:

- first, by improving the vessel's fuel efficiency and thus reducing its fuel consumption, and
- second, by introducing low- and zero-emission fuels. All emissions across a fuel's whole lifecycle must be considered for any reductions to be worthwhile.

IMO is under pressure to set even more challenging reduction targets than those mentioned above. A review of the 2018 Initial IMO Strategy on the reduction of GHG emissions from ships is planned for 2023.

## The maritime fuel landscape

Shipowners can today choose from three types of conventional oil fuels: heavy sulphur fuel oil (HSFO), very low sulphur fuel oil (VLSFO) and marine gas oil (MGO).

Shipowners can also opt for lower-carbon options such as liquefied natural gas (LNG), or to use biofuel blends in their engines to reduce GHG emissions. In addition, ethane and liquefied petroleum gas (LPG) are available, but in practice are only used on ethane and LPG carriers.

A variety of alternative fuels including 'oil-like' blended biofuels such as hydrogenated vegetable oils (HVO) and fatty acid methyl esters (FAME) are also being considered, along with sustainably produced methane, methanol, ammonia, and hydrogen ($H_2$).

Blends of biomethane and fossil LNG have been used on IGF vessels (vessels to which the International Code of Safety for Ships Using Gases or Other Low-flashpoint Fuels (IGF Code) applies), and methanol has been successfully introduced on methanol carriers and (so far) one ferry.  January 2022 saw the delivery of the first ammonia-fuel ready container vessel and hydrogen has been used on various small boats since 2000.

The use of combustion enhancing agents (fuel additives), aftertreatment equipment, and onboard carbon capture and storage (CCS) are also being investigated with a view to further reducing ship $SO_x$, $NO_x$, PM and GHG emissions.

It is important to consider and evaluate all alternatives as there will likely be a fuel mix in the future, and every option has its pros and cons. Stakeholders must compare each fuel like-for-like and account for multiple factors including vessel type, fuel characteristics, safety, regulation, environmental footprint, technological maturity, availability and cost.

# Introduction

Hydrogen is seen as 'green'/environmentally acceptable and is therefore very popular with politicians and the public. This is because $H_2$ combusts with oxygen in the air to produce water. No carbon dioxide is produced.

However, the energy produced during combustion is sufficient to oxidise nitrogen in the air to form $NO_x$, so hydrogen is not completely emission free. Also, hydrogen production is currently based on coal and hydrocarbons both as feedstock and as fuels. Only hydrogen produced from renewable energy can be said to be carbon dioxide free. Furthermore, there is growing evidence (see table 2) that hydrogen itself act like a GHG.

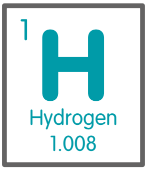
The extent and speed of the introduction of hydrogen will, like LNG, be based on demand, availability and price. If politically driven incentives continue as expected, everyone will want 'green' hydrogen and there will be insufficient supply, at least initially, to meet demand. First movers are likely to be national governments, for example Germany and the Netherlands, which can control both political and regulatory agendas and provide sufficient incentives for investment.

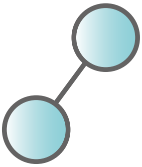
There are a number of safety issues largely unknown to the public. The Hindenburg airship disaster which killed 36 people in 1937 is a rare example of hydrogen going wrong when not handled correctly. Most of the time, hydrogen leaks and their effects cannot be seen. Zoning/spatial planning may need to be extensively used to make sure communities are protected.

Historically, many domestic gas grids utilised an H2/carbon monoxide (CO) gas mixture known as 'towns gas', created from reforming coal, which was used daily by the public. Everyone was aware of the toxic hazard (from the CO) but no memory survives of the flammability issues.

## What is hydrogen?

Hydrogen is the lightest and smallest element in the periodic table. It is found as a molecule, $H_2$, i.e. two hydrogen atoms bonded together (H-H).





Hydrogen as a fuel is used and stored in two ways:

- as a cryogenic liquid ($L_{iquid}H_2$ or $LH_2$) at very low temperatures (-253°C at 1 bar), and
- as a gas under high pressure ($C_{ompressed}H_2$ or $CH_2$) at ambient temperatures (200–700 bar)

The properties and performance of the two hydrogen arrangements – cryogenic and pressurised – are substantially different and are treated differently, effectively as separate fuels.

Two other storage systems may be possible in the future, but neither of these options is currently commercially mature.

Firstly, hydrogen can be stored by adsorption on to the surface of solid materials, and the best known materials for this purpose are metal hydrides. These technologies struggle with the amount of $H_2$ they can adsorb by volume/mass, the reversibility of the process (not all the hydrogen can be recovered), and the complexity of their manufacture. Research in this area is ongoing.

Secondly, hydrogen can be stored in compounds such as unsaturated hydrocarbons, called liquid organic hydrogen carriers (LOHCs), which can absorb and release hydrogen through chemical reactions. Recovering the hydrogen from the organic compound and its purification limits the efficiency of the storage cycle. However, in 2020 Japan built an international supply chain between Brunei and Japan using toluene as the LOHC.

## Physical properties

The boiling point of hydrogen at atmospheric pressure is -253°C, only 20°C above absolute zero. Storing hydrogen as a liquid requires deep cryogenics, much more so than nitrogen (-196°C) or LNG (-162°C).

Hydrogen has a very low volumetric energy density:

- Liquid hydrogen ($LH_2$): 8.5 megajoules per litre (MJ/litre) on a lower heating value (LHV) basis
- Compressed hydrogen ($CH_2$): 4.7 MJ/litre at 690 bar and 25°C on an LHV basis

compared with other fuels, for example:

- MGO: 36.6 MJ/litre on an LHV basis
- LNG: 20.8 MJ/litre on an LHV basis

And proposed fuels:

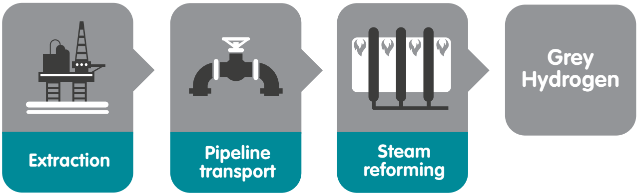
- Methanol: 15.8 MJ/litre on an LHV basis
- Liquid ammonia ($NH_{3(liquid)}$): 12.7 MJ/litre on an LHV basis

As ships need to take their fuel with them, hydrogen-fuelled vessels will need substantially larger fuel storage tanks than other fuels for the same journey distance. For example, $LH_2$ would need about four times as much storage as oil fuels and two and a half that of LNG. Using $CH_2$, the volumes double again. If large scale, high temperature (HT) fuel cells become commercialised, their higher tank-to-wake efficiency would reduce storage requirements for hydrogen by about a third.

Hydrogen will therefore probably be restricted to short sea shipping, as storage requirements for deep sea shipping will considerably limit vessel cargo capacity. For short sea shipping bunkering can be more frequent since the journey distances can be short.

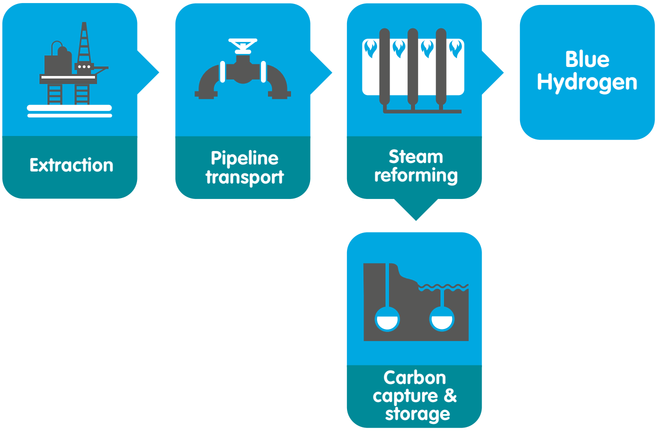
## How hydrogen is made and where it comes from

Most hydrogen (about 62%) is currently produced by the steam reforming of methane (heating in the presence of steam) and other light hydrocarbons, for example LPG. This is 'grey' hydrogen (about 40% from natural gas and 25% from oils during refining). Coal is also widely used as a feedstock, producing about 19% of world hydrogen which is labelled as 'brown' or 'black' hydrogen. Hydrogen is also produced as a by-product of other processes.



*Grey hydrogen production pathway*

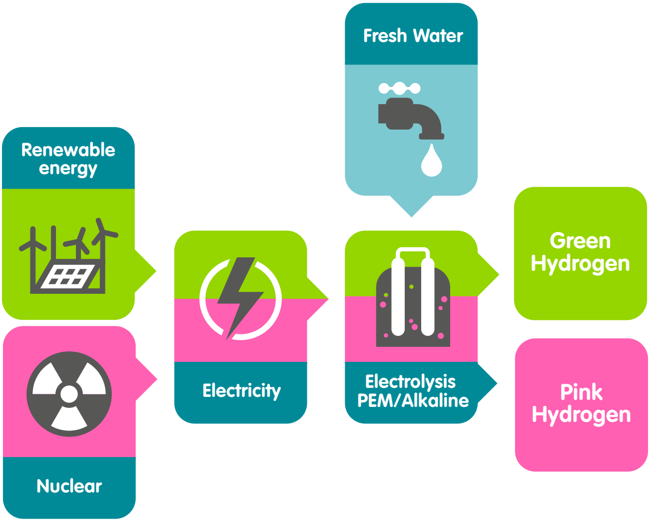
The emissions associated with fossil fuel hydrogen production in 2020 were estimated to be 900 million tonnes of $CO_2$, the equivalent of the total emissions of France and Germany combined or the total impact of current worldwide shipping. If the $CO_2$ produced in hydrogen manufacture from fossil fuels is captured and sequestrated (stored long term), then the hydrogen is known as 'blue' hydrogen.



*Blue hydrogen production pathway*

*Steam methane reforming hydrogen production site in Port-Jérôme (Source: Air Liquide)*

Electrolysis of sea water (passing an electric current through the water) is another production method, which produces about 5% of world supply. Historically this has been expensive so has primarily been used to produce other chemicals, for example chlorine, with hydrogen as a by-product. Electrolysis of pure (non-salt) water produces hydrogen and oxygen and is proposed as the main way of producing hydrogen for energy/fuel use. If the electrical power for the electrolysis is provided by renewable sources, i.e. there is no carbon footprint to the electricity, then this is 'green' hydrogen or, if it derives from nuclear power, 'pink' hydrogen.



*Green and Pink hydrogen production pathway*

*HyLYZER - electrolyser system (Source: Air Liquide)*

Hydrogen manufacture via reforming of hydrocarbons needs catalysts which are highly sensitive to sulphur so sulphur compounds must be removed for long-term operation. Similarly, electrolysers require clean fresh water (i.e. not salt water) so again have no significant sulphur contamination. Combusting hydrogen therefore does not produce $SO_x$.

In 2022, 680 large-scale hydrogen project proposals were proposed, equivalent to USD240 billion in direct investment through 2030. Up until now, approximately 10% of those proposals have reached their final investment decision to proceed to construction.

BP's Energy Outlook prediction for 2050 production shows green hydrogen being the main source of hydrogen (55–65%) but considerable blue hydrogen capacity remains in service.

# Introduction

*Table 1: Hydrogen colour classification*

| Hydrogen | Production |
|---|---|
| **Brown** | $H_2$ produced from lignite coal |
| **Black** | $H_2$ produced from bituminous/hard coals |
| **Grey** | $H_2$ produced from hydrocarbons such as natural gas, LPG or oils |
| **Blue** | Grey, brown or black hydrogen where the $CO_2$ produced by the hydrogen reactions is removed and sequestrated |
| **Yellow** | $H_2$ produced by electrolysis using grid electricity produced, at least in part, by non-renewable sources |
| **Green** | $H_2$ produced by electrolysis using electricity produced from renewables, e.g. solar and wind |
| **Pink** | $H_2$ produced by electrolysis using electricity produced by nuclear power |

## Hydrogen use

Hydrogen is used in large quantities in oil refining and in the chemical industry. The two main uses are firstly upgrading of crude oils (37 million tonnes in 2020) to make higher value petrochemical feedstocks and fuels, using processes called hydrocracking and hydrodesulphurisation; and secondly, the bulk production of ammonia (primarily for fertilisers – 33 million tonnes in 2020) and methanol (13 million tonnes in 2020). The steel industry is also a significant user (5 million tonnes in 2020). About 90 million tonnes of hydrogen is produced annually (2020) for industrial use and this is likely to increase into the mid-2030s when production for industrial use is expected to plateau.

Industries that require intensive heating and high temperatures such as chemicals, cement and iron/steel, are predicted to change to hydrogen and dramatically increase its consumption by between 85 and 130 million tonnes per annum by 2050. There are however, technology issues about how hydrogen generates heat which will need to be overcome, so this prediction might not be accurate. The use of hydrogen for power generation is the most variable prediction, with between 20 and 100 million tonnes per annum suggested in 2050.

Hydrogen is primarily produced where required. The largest hydrogen producer is China with 25% of world production, followed by the USA with 13%.

Hydrogen production was increased significantly in the First World War (1914-18) to increase energy security and this accelerated for the same reasons during the Second World War (1939-45). The first hydrogen pipeline was in Germany in 1938. Germany also used hydrogen for buses, trucks and submarines during this period.

There are about 4,500 km of hydrogen pipelines, primarily in Europe and North America (compared to over 1 million km of natural gas pipelines) but no bulk international transportation of hydrogen currently occurs. Transportation of small volumes of hydrogen by road is widespread, both in the compressed and liquefied forms.

Hydrogen transported via pipeline or by road truck is seen as one of the key ways of reducing emissions from hard to abate industries such as iron and steel, glass making or cement. Most natural gas pipelines are capable of accommodating 5-20% $H_2$ without major modification, allowing wider decarbonisation of residential and commercial sectors.

$CH_2$ can be provided by road truck in 'tube trailers', which are effectively thick-walled pipes on wheels, able to carry about 1,000 kg of $H_2$.

$LH_2$ needs more supply development. It is transported regularly by road tanker and has been for many years, but the scale of the business is much less than maritime would require. There is also an issue with the potential size of $LH_2$ tanks (vacuum insulated) which to date appear limited to about 4,000 kg (56 $m^3$). The largest portable tanks (at 4700 $m^3$) are used by NASA for storing rocket fuel.

$LH_2$ is likely to be preferred to $CH_2$ as the energy density and space efficiency (tank to hull shape) are better. However, there are cost implications of moving from pressurised to deep cryogenic fuels. Liquefaction at a temperature of -253°C is challenging and extremely energy intensive, requiring the consumption of the equivalent of about

30% of the hydrogen. LNG in contrast, liquefied at -163°C, typically requires 8–15% of the natural gas.

*Compressed hydrogen tanks (Source: © Air Liquide)*

*Liquid hydrogen trailer (Source: © Chart Industries, 2022)*

## Hydrogen as a transport fuel

The highest growth in the use of $H_2$ is predicted to be for fuel use where demand is predicted to grow by 2050 to 90–160 million tonnes per annum. Most of this (75-80%) is suggested to be for e-fuel production including methanol, ammonia and synthetic diesel. The rest covers the direct use of hydrogen in the rail and heavy-duty trucking sector. About 0.01 million tonnes (10,000 tonnes) was used by vehicles in 2020.

Hydrogen has been used commercially as a road vehicle fuel since 2013. Three car manufacturers include hydrogen-fuelled vehicles in their commercial product ranges. California has more than 6,500 fuel cell based electric vehicles while there are 2,900 in Europe (2021). Buses are also available which run on hydrogen. The largest providers of hydrogen vehicle fuelling stations in 2021 are Japan (156), USA (107), South Korea (91), Germany (91) and China (39). Worldwide there are nearly 600, 164 of them in Europe.

Canada pioneered using hydrogen to fuel railway locomotives in 2002, with Germany taking hydrogen-fuelled trains into their first commercial use in 2018. Austria, France and Italy have followed. Russia produced a hydrogen-fuelled commercial airliner in the 1980s.

Hydrogen has been used for small boats since 2000, with a 22-person vessel running on $CH_2$ plying the canals around Bonn in Germany. An 18-person water taxi followed in San Francisco Bay, USA, in 2003. Later, larger vessels have had a more chequered history with the Nemo H2, an 88-person sightseeing boat in Amsterdam since 2009, having reliability issues, and the 2013 Hydrogenesis passenger ferry in Bristol, UK, not being cost competitive. Hydrogen has also been used on ships to demonstrate the use of fuel cells as alternatives to auxiliary engines, for example on the Viking Lady offshore support vessel (OSV) in 2010.

The first $LH_2$ vessel in commercial use is the Hydra car ferry in Hjelmeland, near Stavanger, Norway, where it transports up to 300 passengers and 80 cars across the short distances of a fjord, and entered service in late 2021.

The Port of Antwerp-Bruges will see the first $CH_2$ commercial vessel, a harbour tug, which will enter service in the first quarter of 2023.

# Introduction

## Hydrogen availability

Green hydrogen is currently produced in very low quantities and is therefore expensive to buy and consume. As demand increases, and if supply follows, production costs will reduce. Whether production will be sufficient depends on various macroeconomic factors.

Nation states are more in control of their regulatory processes than international bodies such as IMO, which needs to represent the sometimes disparate views of its many national members. Nation states are therefore likely to drive the decarbonisation agenda and the production of green hydrogen.

The main competitor to green hydrogen production will be power generation. Nations are rapidly growing their renewable, wind and solar resources, not for hydrogen production but for power generation. Much residential, commercial and less intensive industrial fuel demand will be converted to electricity, which will need more renewable energy sources. This will potentially reduce the amount of renewable energy available for the production of hydrogen. Shipping, which has traditionally been slow to act and unwilling to pay high fuel prices, is likely to find itself at the back of the queue for green hydrogen. Any shortfalls in green hydrogen production will therefore hit shipping hardest.

## Regulation

Class and marine regulations are perceived to be lagging behind onshore regulation, which has already developed widely, producing hydrogen standards and practices.

Hydrogen fits within the IGF Code functional requirements but needs development of detail on the specific differences between it and LNG. IMO has started developing hydrogen interim guidelines (2021) with a target completion date in September 2023, but it will take a minimum of two years’ experience (2025/26) before they will be considered mandatory (instruments). This is shorter than some IMO norms (for example, the original IGF Code), which can take up to 10 years. Guidance on the design and use of fuel cells has already been published by IMO.

# Environmental

## Local pollution

Air pollution around ports remains a significant, if local, issue with the health of residents negatively impacted. Further reductions in air pollution, both through more action on $SO_x$ and $NO_x$ or through projects on PM (of which black carbon is a part) or on contaminants associated with liquid fossil fuels such as volatile organic compounds (VOCs) are likely. Hydrogen is one means of achieving this.

Hydrogen is produced either from reforming, using catalysis, or electrochemistry, meaning that there are no sizeable contaminants, and being without carbon means that it cannot cause local pollution from black carbon or VOCs.

## Fuel emissions

Hydrogen is an indirect GHG. It affects chemistry in the upper atmosphere by reacting with hydroxyl radicals ($OH^-$) reducing the breakdown of methane and increasing ozone and water vapour (the largest GHG). These last two increase the heat radiation from the stratosphere into outer space, leading to cooling and subsequently less energy dissipation. This then has an overall warming effect on the climate.

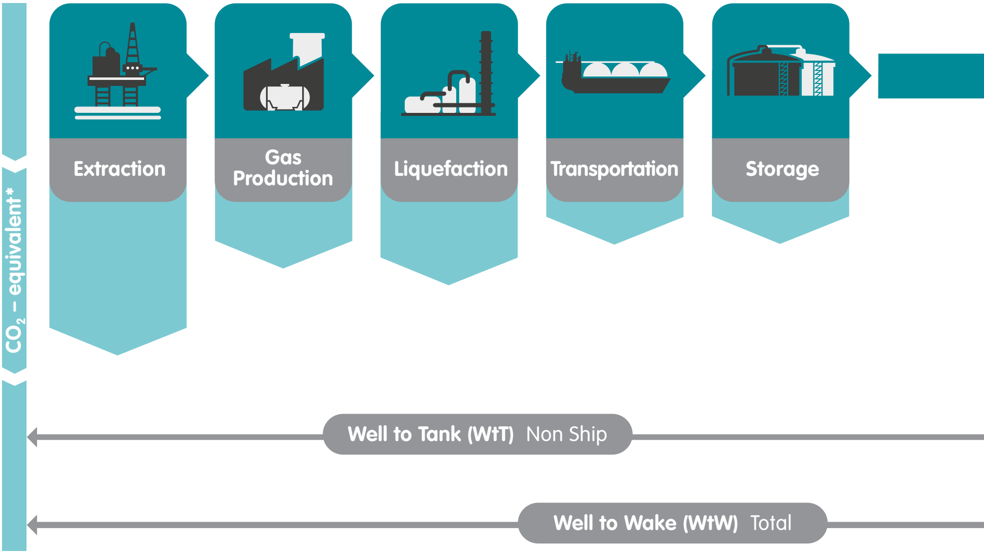
The effects of hydrogen are, like methane, relatively short lived with the peak effect being after about seven years and its global warming potential (GWP) subsequently declining. GHG impacts are shown in the table below.

*Table 2: Global warming potential (GWP) of key GHGs*

| Name | Formula | 20-year GWP | 100-year GWP |
|---|---|---|---|
| Carbon dioxide | $CO_2$ | 1 | 1 |
| Methane | $CH_4$ | 81.2 | 27.9 |
| Nitrous oxide | $N_2O$ | 273 | 273 |
| Hydrogen | $H_2$ | 33 | 11 |

Note: Global warming potential taken from IPCC AR6 and for hydrogen from Warwick et al "Atmospheric implications of increased Hydrogen Use", 2022 report for the UK Government

## Environmental

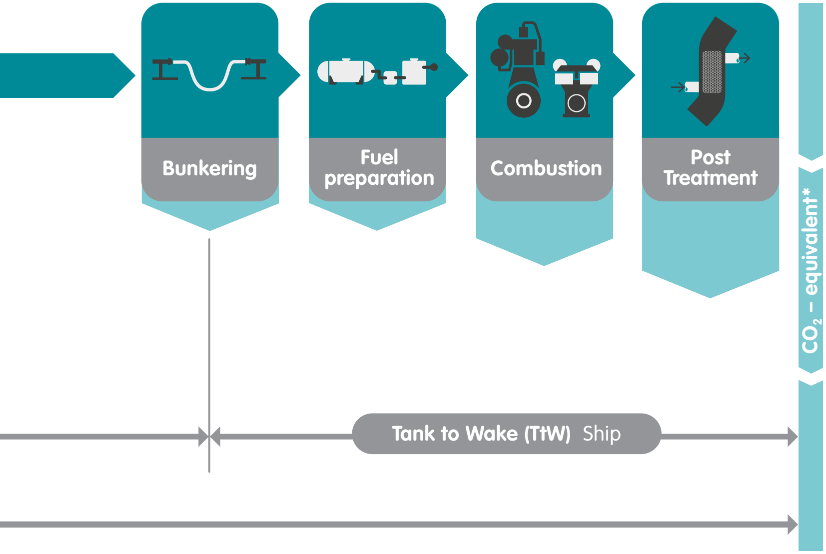


*Life Cycle Emissions Analysis - key stages for a liquefied gaseous marine fuel*

*The size of the GHG emissions ($CO_2$ equivalent) emitted at each of the stages in the delivery chain is for illustrative purposes only and will vary in scale on a project-by-project basis.

Hydrogen will enter the atmosphere from fuel slip, leakage and venting at all stages of its well-to-wake journey. There is no data yet on how much hydrogen leaks from equipment, tanks and pipework. The small molecule size of hydrogen (see Leakage management in the **Safety** section of this publication) means hydrogen leakage may be considerable, with some commentators suggesting between 1 and 10% of all hydrogen produced will leak into the atmosphere by some means, from production all the way up to combustion. Given the short-term GHG effects, this will diminish the emissions reduction effectiveness of hydrogen.

There is no sulphur or nitrogen in hydrogen, so combustion will not create $SO_x$ or $NO_x$ from the fuel. However, the energy produced during combustion is sufficient to oxidise nitrogen in the air to form $NO_x$. Experimental work on shore suggests that $NO_x$ levels may increase by 20–30% over natural gas. Therefore, on a tank-to-wake basis, hydrogen is not completely emission free.



## Climate change

Hydrogen (see figure 1) has a variable effect on GHG emissions (tank-to-wake basis) compared to fossil fuels. If the energy used is carbon neutral (green/yellow $H_2$), a very substantial improvement can be achieved. If fossil fuels are used to produce the (grey) hydrogen, then the carbon footprint is worse. The method used to produce the hydrogen is therefore crucial to its environmental impact.

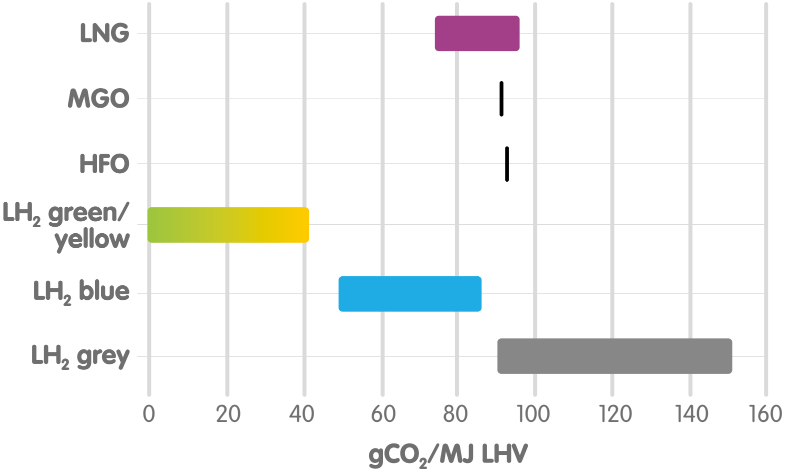
Green and pink hydrogen, although generated by non-fossil fuel energy, do not have zero GHG emission as leaks from these systems will affect the climate. For blue hydrogen, the amount of fuel used to heat up the feedstock and generate the steam has additional impacts even though the $CO_2$ generated during the hydrogen forming reactions is recovered and sequestrated. Grey, brown and black hydrogen have the highest impact because no emissions are captured.

## Environmental

Comparative data on the emissions of the different fuels and production routes from life cycle assessment (LCA) studies does not yet appear to be available. Figure 1 attempts to bring together a range of theoretical assessments on a well-to-tank basis but as can be seen from the size of the bars there is a high level of uncertainty in the estimations.

The figure shows that traditional fuel oils (and LNG) outperform hydrogen made from fossil sources (grey $LH_2$) on an emissions basis. LNG can compare with fossil hydrogen production which has $CO_2$ sequestration, although blue hydrogen is likely to be environmentally superior in most cases. Hydrogen made by electrolysis is the best environmental performer, but its emissions can vary widely depending on the source of the electricity and how the $LH_2$ gets to market.

*Figure 1: Comparative emissions of fuels*



Blue hydrogen may create more GHG emissions than fossil fuels in some worst-case scenarios over the short term. This emphasises the shorter-term nature of hydrogen impacts on the atmosphere. Similarly, the worst-case green hydrogen production would only reduce equivalent emissions of $CO_2$ (the GWP of all gases, for example methane and $N_2O$ expressed as $CO_2$ and referred to as $CO_2e$) by about two thirds.

## Alternative fuels based on hydrogen

Much is being claimed for alternative fuels such as ammonia, methanol and synthetic fuels such as e-LNG. All these fuels are derived from green (or blue) hydrogen.

The emissions profiles of these e-fuels will therefore only be as good as or worse than hydrogen because each will require further processing, resulting in additional energy use and emissions. Only if the carbon is sourced from waste gas streams, for example air capture of $CO_2$, will there be a potential environmental benefit.

Hydrogen will therefore also be the most cost-effective synthetic fuel at a production level, as all other synthetic fuels and ammonia must be derived from hydrogen as their basic building block.

If green/blue hydrogen does not exist in sufficient quantities, these synthetic fuels will also not exist in the required quantities.

# Safety

## Is hydrogen safe?

Hydrogen has a wide flammability range (4–75%) – much wider than methane (5–15%) – and this is its main danger. The amount of energy in a spark or other ignition source is ten times less for hydrogen than all other gaseous hydrocarbon fuels and a thousand times less than MGO. Ignition is easy. Hydrogen can also be ignited by static electricity. It burns with an almost colourless flame which can only be seen at night/in dark spaces. The thermal radiation of the flame is much lower than hydrocarbon flames.

Hydrogen is not toxic.

It is always lighter than air, so large dense gas clouds do not form (unless trapped within structures) and the flammability hazard horizontally around the hydrogen leak point is therefore quite limited. $CH_2$ will have a larger hazard range than $LH_2$ because of the momentum produced by the very high pressure jets formed at the leak point. Jet/torch fires are the design event for the impact for hydrogen as a fuel on third parties, for example during bunkering or while in port.

Leaking $LH_2$ is very cold and can liquefy both oxygen and nitrogen in the air. Liquid oxygen can promote flammability in other materials which would normally be difficult to ignite. For example, spontaneous combustion of asphalt road surfaces is possible. $LH_2$, like LNG, will also quickly cause brittle fracture of ship steels.

Hydrogen has a higher explosive potential than methane. This results from:

- its wider flammability range (7 times that of methane)
- its lower ignition energy ($^1/_{10}$ of methane)
- its shorter burning distance to initiate detonation – a self-powered explosion. (Methane can only deflagrate, meaning that it needs outside assistance such as congestion to explode.)
- the higher explosion pressures created by hydrogen

The safety-related properties for gaseous hydrogen, compared to a similar methane-based system, have more negative than positive effects. The design of ships will need to pay careful attention to this.

## Leakage management

Hydrogen is the smallest chemical molecule, and this affects its behaviour in several ways.

- It has a very low viscosity, enabling it to move through small spaces and creating leak pathways – leakage through welds, flanges, seals, gaskets, etc. occurs – so correct material selection and operational procedures are crucial.
- It can dissolve in metals, both effectively leaking through the metal and corroding it by damaging the crystal structure of the metal, leading to weakness and ultimately failure (hydrogen embrittlement).

The scale of these effects is determined by the amount of energy the hydrogen has, so very cold $LH_2$ systems with very low internal energies release much less hydrogen than 'warm' $CH_2$ systems.

Leakage management for $LH_2$ systems is conceptually similar to LNG. However, for $CH_2$ or warm, vaporised $LH_2$, hydrogen leaks will never be eliminated, only minimised. Rotating equipment can be especially difficult to make leak tight. The important criterion is where to accept leaks and at what scale and where they can be eliminated.

Marine use will benefit from current onshore hydrogen experience. Onshore leaks can freely disperse from tanks, piping and equipment. On a vessel, many of these systems will be within the hull and free ventilation and dispersion of hydrogen will not be possible. Forced ventilation system performance will be critical to successful hydrogen use. But concerns remain over the build-up of static in these systems, and whether this can be avoided or controlled. Classification societies are grappling with these issues and are currently preferring to inert those spaces where hydrogen may congregate.

Welding of pipes and components should be maximised. Secondary barriers to leakage, such as vacuum jackets, are required for insulation but also allow leaks to be detected and monitored. For warm hydrogen, a pipe-in-pipe system may be needed. Gas and flame detection can be used in specific locations, for example flanges. However, the focus needs to be on ventilation.

# Safety

## Safety systems

Inerting $CH_2$ systems uses nitrogen, as with other hydrocarbon fuels. Inerting $LH_2$ systems can only be done directly using helium, as using nitrogen directly would cause solidification of the nitrogen and blockage of the piping/tank. As a result, demand for helium would increase significantly and costs are already high. The alternative is to purge $LH_2$ with warm hydrogen gas. When the temperature is above -195°C then nitrogen gas can be used.

## Safety management

Flammability risks are different for hydrogen and higher than for other fuels, and this is a challenge that needs to be overcome. To design vessels to the same equivalent level as oil-fuelled vessels will not be cost effective. At present, risk assessment can only be performed with any accuracy on a qualitative basis. The lack of data for hydrogen for use in quantitative risk assessment (QRA) type analysis, which is often used in licensing, compromises this type of analysis and so getting statistics on failure in hydrogen equipment and systems from other industries is important.

Hydrogen is a new fuel for the marine industry, so safety awareness and management practices need to be developed and grow to similar levels to those already accepted by land-based industries, where corporate standards and regulations, for example ATEX and ADR in Europe, are well documented. This will be a challenge for hydrogen in shipping which will need more care and attention.

## Emergency response

The primary concerns for hydrogen are fires and explosions resulting from ignition of leaks. If unignited, gaseous hydrogen will rise quickly into the atmosphere or migrate to high points in vessels.

Like all the liquefied gases, hydrogen fires are unlikely to be extinguishable. The procedure should be to isolate the hydrogen supply and allow the fire to burn itself out while protecting the surrounding equipment, piping and systems from heat radiation and any flame impingement, using large amounts of water.

Fires in hydrogen vent systems and masts are also possible. Most are at the top of the mast, but they can also be within the piping. The piping should therefore be designed for deflagration (less energy intensive explosion) so that the contents remain enclosed. (This is also an issue with LNG vents but not widely accepted by the industry.)

To avoid explosions, hydrogen needs to be removed from confined spaces and released into the atmosphere using ventilation systems.

Loss of vacuum insulation on an $LH_2$ storage tank or piping may produce surface temperatures so low that air starts to liquefy; oxygen condenses at -183°C and nitrogen at -196°C. Pure oxygen including liquid oxygen significantly promotes flammability in substances that are normally inflammable, such as waxes, greases, hydrocarbon solids/dirt, clothing and lubricant oils. Even some steels will burn in oxygen atmospheres. Any fire will be more intense in an oxygen atmosphere. Many 'soft' materials such as plastics, epoxies and rubbers will become brittle at these temperatures, potentially resulting in additional leaks as seals fail.

# Technical

Short sea shipping is thought to be the most likely to convert to hydrogen. The pioneer vessels would be those on liner trades which could bunker regularly, such as ferries, platform support vessels and wind farm support vessels.

LNG-fuelled shipping started in the same way with the Glutra in 2000 followed by 11 Norwegian ferries and offshore support vessels between 2003 and 2010. LNG only moved into deep seas shipping with the Coral Star in 2014, 47 ships later.

The amount of fuel that needs to be stored for long distance (deep sea) shipping is the main barrier to its application on larger vessels as cargo space would need to be given up for fuel storage. However, large vessels may use hydrogen to support cleaner operations of their auxiliaries, particularly power generation. Similarly, MGO has traditionally been used in ports instead of heavy fuel oil (HFO). With hydrogen, fuel cells would ultimately replace diesel/dual fuel generators. The widespread development of ‘cold ironing’ (direct electricity supply from shore) at ports may, however, reduce this take-up.

Hydrogen as ship fuel therefore looks likely to follow the same trajectory as LNG did 20 years ago, starting with a few commercial vessels primarily in Europe before spreading globally. Japan and South Korea are also very active in hydrogen research so an East Asian focus may also be possible.

## Who is doing it?

$CH_2$ technology is relatively mature in the automotive sector with fuel cell powered cars (fuelled by $CH_2$) listed in some manufacturers’ brochures. It is already in use on river and short sea vessels which have low fuel demands/frequent bunkerings. The physical structure of $CH_2$-pressurised storage is considerable, and vessels such as ferries where weight is not an issue may continue to be developed with $CH_2$ fuel systems.

*$CH_2$ passenger ferry, Hydrogenesis, Bristol, UK (Source: Bristol Packet)*

$LH_2$ has been around since the early 1960s, but applications have been limited to niche areas (space programmes, e.g. NASA, and science, e.g. CERN). NASA has, and does, move LH2 by marine barge (unpowered). On shore, LH2 is delivered by road tanker and pipeline.

Norwegian ferry operator Norled's 292 passenger/80 car Ro-Pax ferry Hydra entered service in 2021 and is described as the world's first hydrogen-operated vessel (82 m long by 17.5 m beam). The vessel is capable of operating on $LH_2$ (80 $m^3$ $LH_2$ tank) feeding two 200 kW proton exchange membrane (PEM) fuel cells with battery power and biodiesel back-up. As $LH_2$ can currently only be supplied from Germany by road tankers, this ferry has principally operated on batteries and biodiesel.

# Technical

*$LH_2$ vessel - Hydra (Source: LMG Marin)*

## What does a hydrogen ship look like?

Hydrogen design is like LNG, but different, and these differences are important.

The cleaning of the equipment before admitting $H_2$ should meet stringent oxygen service cleaning requirements.

LNG would typically not react with the construction materials of the ship's fuel system, unlike $H_2$, which can chemically impact austenitic stainless steel through a process known as hydrogen embrittlement. Marine assets will have to manage the design of all parts that have contact with the hydrogen by using the correct material – from pressure gauges and simple thread seal tapes to complex machinery/equipment parts.

In $LH_2$ systems, vacuum loss can induce air liquefaction producing liquid drips and an enriched oxygen environment. Construction materials will need to be compatible with both low temperatures and high oxygen environments.

$LH_2$ equipment is similar to that for LNG since it is just another cryogenic fuel. However, tanks are 'super' insulated and all piping needs to be vacuum insulated.

$CH_2$ design will be comparable to the fuel systems that already exist for LNG/gas-fuelled high pressure engines operating under the Diesel cycle, although the high pressure content of the fuel system will be more extensive.

The general principles of the IGF Code are appropriate for designing a hydrogen-powered vessel. However, the behaviour of hydrogen will mean that specific clauses may end up being very different when the IMO publishes its interim guidelines (expected in 2024).

## Fuel systems and storage

$LH_2$ should be handled as little as possible, as any transfer provides opportunities for heat ingress and therefore vaporisation. Boil-off rates are high, because of the very low temperatures, at about 0.3% per day.

$CH_2$ fuel tanks will again be similar to those in natural gas vehicles (NGVs) or compressed natural gas (CNG) shipping. On road delivery systems, pressure vessels or thick-walled pipes are used to maintain and control the $CH_2$ pressures. In larger systems, the weight (and cost) of the thick-walled steel becomes prohibitive and combinations of steels and carbon fibre have been proposed for tank construction.

Pressurised hydrogen behaves differently from other gases. For example, a positive, not negative, Joule-Thomson effect occurs at temperatures above -80°C. This means that hydrogen warms up as it is released/expanded to atmosphere or released to a low pressure environment from a high pressure environment (i.e. pressurised $H_2$ in containment systems or piping).

Yard pressure testing of components for hydrogen containment and vacuum jackets with helium before delivery will be crucial. This type of leak testing is already covered by American System for Testing and Materials (ASTM) regulations, but shipyards will need to invest to be able to employ this standard.

# Technical

*$LH_2$ storage tank being inserted in the Suiso Frontier (see* ***Bunkering*** *section below) (Source: Hystra)*

## Power generation and propulsion

Hydrogen can be burnt in an internal combustion engine or consumed in a fuel cell.

### Internal combustion engines (ICE)

Hydrogen has been used in internal combustion engines for many years. The first practical hydrogen engine was invented in 1806 by de Rivaz, a Swiss engineer. The basis of one extreme of the historical (AVL) methane number calculations (1970s) was an engine operating on pure hydrogen.

Hydrogen burns fast and completely, leading theoretically to good engine efficiency. However, the fast and hot combustion will also result in $NO_x$ production. As a rule of thumb, it can be said that the efficiency of a hydrogen engine will be roughly the same as, or slightly better than, an engine operating on natural gas at the same $NO_x$ emission level.

However, hydrogen knocks – it is too easy to prematurely ignite hydrogen on engine hotspots. The engine must therefore be designed for hydrogen as the fuel, but in practical terms, there are limits.

- Otto cycle engines have limits to ensure ignition and to control combustion speed.
- Diesel cycle engines must limit thermal loads.

The current state of the art is that the output is slightly lower for a hydrogen-fuelled engine than for an engine operating with more traditional fuels.

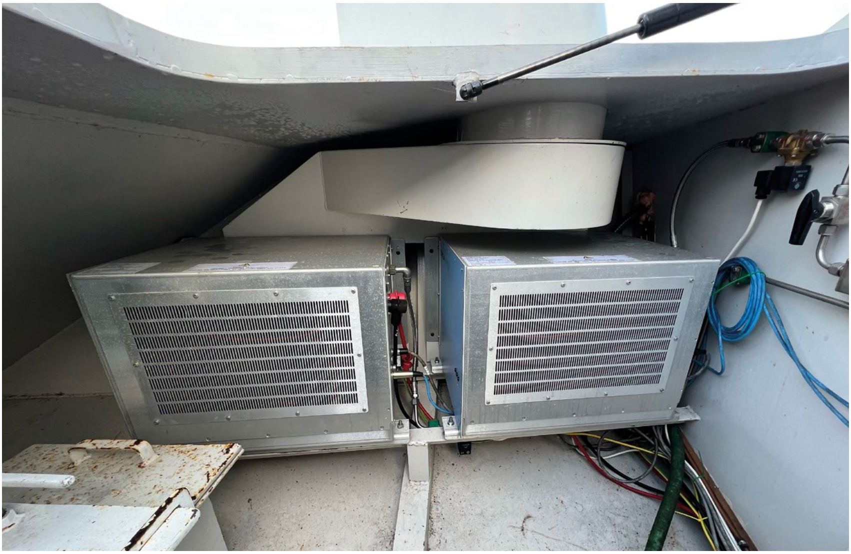
## Fuel cells

Fuel cells will be key to the take-up of hydrogen. Early fuel cells were developed about 150 years ago but apart from a few niche applications, for example within the aerospace industry, commercialisation has continued slowly. On shore, some smaller fuel cell technologies (e.g. phosphoric acid cells at a few megawatts (MW) scale have been in service in Japan for nearly 20 years) have been installed and the maritime industry is now developing considerable interest in these technologies.

Seven types of fuel cell are available. The differences are in the medium (electrolyte) between the anode and the cathode which allows the transfer of hydrogen ions and therefore the generation of an electrical current.

Fuel cells can be divided into two groups based on their operating temperature. High temperature fuel cells, most notably the molten carbonate (MCFC) and solid oxide (SOFC) fuel cells, operate at temperatures above 500°C and are able to reform their feedstock, creating hydrogen from methanol, ammonia and/or LNG/natural gas within the cell itself. This is called internal reforming. They have good electrical efficiencies (50-60%) but can also recover heat to produce overall efficiencies of 85%.

Low temperature fuel cells operate at up to 200°C. Their electrolytes are water based and cannot tolerate higher temperatures. If the fuel needs to be reformed, this needs to take place outside the fuel cell. These cells frequently require high purity hydrogen as a fuel. Electrical efficiencies are more variable, between 20 and 60%, and heat recovery is not possible from most cells.



*Hydrogenesis Fuel Cells (Source: Bristol Packet)*

*FCwaveTM Fuel cells (Source: Ballard)*

Methanol can be used to produce the hydrogen at a relatively lower temperature (300–400°C) while methane/LNG, LPG and diesel need higher temperatures. Reforming creates $CO_2$ as a by-product from these reaction pathways.

The status of the main fuel cell types is shown in Table 3.

*Table 3: Main fuel cell types*

| Fuel cell | Tempe-rature °C | Electrical output, kW | Electrical efficiency | Overall efficiency | Longevity | Status |
|---|---|---|---|---|---|---|
| Alkaline (AFC) | 20–30 | 500 | 50-60% | - | Moderate | Aerospace<br>Trialled on ships |
| Proton exchange membrane (PEM) | 50-100 | 120 | 50-60% | - | Moderate | Fuel cell cars<br>Trialled on ships |
| HT PEM | <200 | 30 | 50-60% | - | Not declared | Trialled on ships |
| Direct methanol (DMFC) | 50-120 | 5 | 20% | 40–50% | Moderate | - |
| Phosphoric acid (PAFC) | <200 | 400 | 40% | 80% | Excellent | Widespread on shore |
| Molten carbonate (MCFC) | 600-700 | 500<br>Eventually 1–10 MW | 50-60% | 85% | Good | Trialled on ships |
| Solid oxide (SOFC) | 500-1000 | 60<br>Eventually 1–10 MW | 50-60% | 85% | Moderate | Trialled on ships |

The maritime industry has conducted several trials of fuel cells on vessels, most of which were used for auxiliary power.

The four trials on larger vessels included:

- a 320 kW MCFC fuel cell stack fuelled by internally reformed LNG on the offshore support vessel Viking Lady in 2009
- a 20 kW SOFC fuel cell, fuelled by externally reformed methanol, was fitted to the car carrier Undine in 2010
- Viking Line's Ro-Pax Mariella installed a 30 kW high temperature PEM fuel cell running on methanol in 2016
- MS Forester, a general cargo vessel, was fitted with a battery and a 100 kW SOFC fuelled by low sulphur diesel in 2017

*Viking Lady (Source: Corvus Energy)*

*Undine (Source: Wallenius Wilhelmsen)*

Fuel cell interim guidance was issued by IMO in 2022 (MSC.1/Circ.1647). Class have approved installations in principle.

Many of the issues on fuel cells revolve around the safety and use of the fuel which has been considered elsewhere in this document.

## Bunkering

For LNG as fuel, the industry took the experience of the bulk transfer of LNG via LNG Carriers (LNGCs), but this experience is absent for hydrogen. LNG bunkering is the closest proxy available.

Some of the smaller vessel trials included trialling hydrogen delivery systems. For example, the Alsterwasser, a small passenger ship with a 100kW PEM fuel cell, started operating in 2008 and had a fast-fill $CH_2$ bunkering system. The fast-fill system provided by Linde was similar to that used in NGV fuelling stations and involved pumping $LH_2$ to pressure (350 bar) and then vaporising it into $CH_2$.

Many different hydrogen supply solutions are possible. For example, inland waterway bunkering is likely to be mostly truck to ship. For $LH_2$, the only current option is to scale up road truck technology, which to an extent mirrors LNG where road tanker operations also contributed to technology development. For $CH_2$, the technology exists from car and bus refuelling systems and is very like the extensive NGV fuelling infrastructure.

Road tankers transporting hydrogen lack scale, with trucks currently limited to 1,000 kg of $CH_2$ and 4,000 kg of $LH_2$.

The first liquid hydrogen carrier, the 1,250 $m^3$ (88,750 kg) Suiso Frontier, has entered service having completed its commissioning voyage in 2022. This vessel is a test bed for various technologies. There remain technical challenges, but these are reported to be solvable in the time that $LH_2$ will take to enter the ship fuel market. Bunker vessels, at least initially, would be based on similar technology.

# Training and Competence

As with SGMF's current competencies for LNG, training on all issues for hydrogen-fuelled ships will be very important. Most of the competencies for LNG will be repeated, albeit modified, for use with hydrogen. Philosophically, hydrogen is almost 'methane on steroids', so training requirements are likely to increase. The existing LNG competencies are not dissimilar to those required in bulk liquid sectors. Hydrogen as a fuel will cover all types of shipping and this represents considerable challenges for most ship types.

LNG bunkering expertise was brought in by people with LNGC cargo experience. This background knowledge is lacking for $LH_2$ so, at least initially, LNG experience will influence training programmes. However, the physical mobility of hydrogen means that more people, perhaps the whole crew, will need to understand the specific risks of $CH_2$ and $LH_2$.

Crew training and competence for $LH_2$ vessels will be similar to LNG, as both are dominated by flammability and cryogenic concerns. However, there is a difference of safety culture between the two: LNG is leak tight, while $LH_2$ will leak slowly but continuously. The depth of the cryogenic temperatures will also lead to magnified issues compared to LNG and probably much greater automation, so there will be differences in emphasis in the detailed training programmes.

The presence of high pressures for $CH_2$ is similar to their use in LNG-fuelled 2-stroke, Diesel cycle engines but must be expanded to encompass the whole fuel system. Again, new interpretations and expansion of current LNG training competences will be required for $CH_2$.

The presumed regular use of some fuel cell types adds another level of complexity to training. High temperature, medium pressure issues now need to be considered with an understanding of their very different material and sealing challenges.

In summary, training will be comparable to that for LNG but much more extensive.

# Summary

Hydrogen is a marine fuel candidate for the following reasons:

- the molecule contains no carbon and can be produced with low GHG emissions.
- it is usable in both fuel cells and internal combustion engines.
- its hazards are known and understood

Its weaknesses are:

- its low volumetric energy density
- the deep cryogenic nature of $LH_2$ and high pressure of $CH_2$
- its availability (from low emission production methods)

Though the molecule contains no carbon, it is necessary to address and eliminate GHG emissions across hydrogen's whole lifecycle if it is to play a significant role in decarbonising the shipping industry. LCAs are the best tools the maritime sector has for analysing and comparing environmental performance, but they require high quality emissions data of which there is currently little for many fuels. Nevertheless, available data shows that only green and blue production pathways will produce hydrogen with a GHG reduction benefit. Commercial production of these variants, however, has not yet begun and will require significant investment into R&D and supply chain infrastructure.

Hydrogen is not a GHG but does impact climate change through the way it behaves in the upper atmosphere by preventing the breakdown of some GHGs and reducing heat loss to outer space. This behaviour effectively makes it a GHG, and a GWP of 11 has been proposed.

Hydrogen is a very small molecule, so small that it can leak through piping and equipment. This will require an enhanced 'gas safety' culture – a 'hydrogen safety' – culture to be developed and used to protect everybody involved.

Current regulation for international shipping does not yet permit the use of hydrogen as a marine fuel. IMO is currently evaluating how the IGF Code needs to change to allow this, a process expected to complete in 2023/2024.

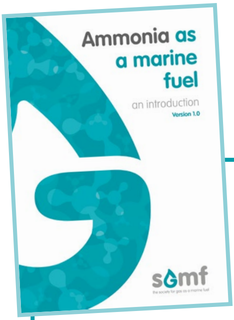
# Summary

Hydrogen is a bulk chemical which has been used for many years in oil refining and the chemical/ammonia industries. Transportation of $CH_2$ by pipeline and $LH_2$ by road tanker are well understood. This in-depth design and operating experience and good safety record should be taken into account and guide ship and bunkering facility designers in developing solutions adapted for hydrogen's use as a marine fuel.

Port procedures will need development to define necessary rules and safety distances for bunkering. Any simultaneous operation of ships for cargo and bunkering requires thought and may require additional risk mitigation.

The speed of transition will be important to allow design and training activities to keep up and provide assurance that leaks/releases affecting the ship's crews, jetty staff, the public, the environment, and other stakeholders can be minimised.

# Introductory Publications



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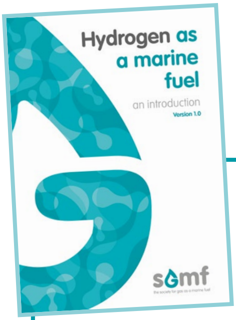

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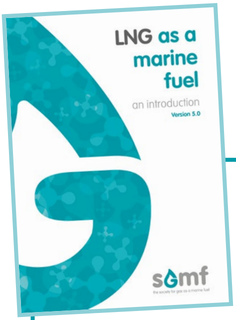

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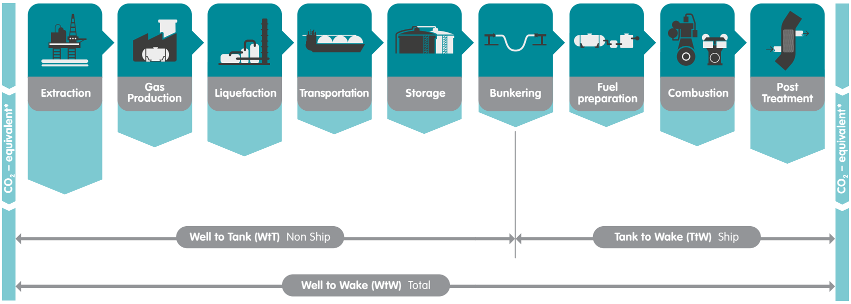
# SGMF Life cycle emission studies

SGMF's *2nd Life Cycle GHG Emissions Study on the Use of LNG as a Marine Fuel* is available at **www.sphera.com**

SGMF has commissioned Sphera for a further study, *1st Life Cycle GHG Emission Study on the Use of* ***$NH_3$*** *as a Marine Fuel,* that is being carried out in 2023.



# Notes

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