

Alternative fuels: present and future of containment technologies and impact on shipbuilding.

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Abstract. In recent years there has been a growing move toward the adoption of Liquefied Natural Gas (LNG) as marine fuel and consideration of other fuels as alternatives to the traditional marine fuel oils, driven by the introduction of new environmental regulations. Such fuels have different properties and as a result different storage requirements to those associated with current marine fuels and are pushing the industry toward both the introduction of containment technologies already established within other sectors of industry and, where necessary, the development of new ones. Existing containment technologies are typically physical, based on storage at ambient temperature, storage at ambient pressure, storage at high pressure (compressed) or storage at low temperature (cryogenic) or a combination of such. Future containment technologies however may well include material based storage, exploiting chemical processes to absorb and release fuels carried in liquid or solid matrices. This paper provides an overview of such alternative fuels, the corresponding containment technologies and the implications for ships design and construction, based on the knowledge and experience gained by Lloyd's Register through collaboration with the industry in a wide variety of conceptual and demonstration projects involving the use of LNG, Ethane, Methanol and Hydrogen fuels and ultimately in assuring their design and construction and entry into Class.

Keywords. LNG, hydrogen, alternative fuels, IMO Type C, LOHC, hydrides.

1. Introduction

Like most, if not all industries, shipping is ultimately shaped by public perception and public opinion. It is easy to understand how ships using fuels which are perceived as clean and safe may be judged more favourably with undeniable advantages for their operators. However, besides public perception, environmental regulations are making an impact.

Until now natural gas, in its liquefied form, (LNG) has been by far the most developed and increasingly utilized alternative fuel in the industry. Its use as fuel started many decades ago with the carriage of LNG as a cargo in gas carriers. Due to their inability to avoid the boil off phenomenon, in which a fraction of the cryogenic liquefied cargo gas evaporates due to the inbound heat leaking through the cargo tank isolation its use as fuel first in steam turbine power plant then in diesel engines became an established solution.

Other gases and chemicals also carried as cargoes in gas or chemical carrier ships for a long time, have also been exploited as fuels including ethane and methanol.

The future may however see the hydrogen as ultimate clean marine fuel. Unlike most hydrocarbons, however, it requires significant energy to obtain reasonably pure hydrogen, as most of it is naturally either combined with oxygen forming water, or with carbon and/or other atoms forming the vast array of existing hydrocarbons and other compounds, such as metal hydrides and once obtained significant energy to compress or liquefy it. Notwithstanding these issues, the advantages of hydrogen as a fuel are seeing and emerging interest in the shipping industry, in particular: zero local carbon emissions and the potential suitability for fuel cells, therefore obtaining very high efficiencies without the use of combustion engines and therefore without noise or vibrations. These alternative fuels range from rather volatile liquids to gases which may need to be cooled down to cryogenic temperatures in order to achieve sufficient volumetric density for practical purposes. This introduces the need to consider storage technologies which in some cases depart radically from those associated with traditional ship design culture and knowledge. While today the mainstream fuel storage technology is based on physical means, future technologies may exploit chemical processes to absorb and release fuels in liquid or solid matrices.

There are no class rules available for marine use of materials storage technologies for hydrogen, due to the novelty of the technology. Class approach would include an in-depth review of the design, its justification and risk assessment.

2. Fuel properties and their implications for design and construction

2.1. Natural gas (Methane)

As the name suggests natural gas is a naturally occurring mixture of hydrocarbon gases in which the bulk is methane which may constitute anything between 80% and 98%. The remaining part is made up of other hydrocarbon gases, such as ethane and propane (and other alkenes in general), which are in general heavier yet exhibit the same basic hydrocarbon gas behaviour, and small percentages of carbon dioxide, nitrogen, helium and hydrogen sulphide. The overall physical and chemical behaviour of the natural gas is therefore rather similar to pure methane. The boiling point of natural gas (at atmospheric pressure) is approximately -163°C . Its critical point is approximately -83°C and 46 bar. This implies that natural gas needs to be stored either in liquid form (LNG) at cryogenic temperatures or as compressed gas (CNG) at room temperature to achieve any realistic energy store. LNG has a density ranging from abt. 430 kg/m^3 to 480 kg/m^3 , depending upon its composition and has an advantage over CNG, even with the later compressed to hundreds of bars.

From a ship design and construction perspective, the extremely large fuel demands of internationally trading ships require alternative fuels to have a high volumetric energy density, ideally equivalent or better than that of the existing fuel oils they will replace otherwise passenger numbers or cargo capacity will suffer. Despite that the volumetric energy density of both CNG and LNG is significantly less than existing fuel oils, the use of LNG is fast becoming an established marine fuel with the need for shipyards to become conversant with the construction of cryogenic containment systems and the installation of cryogenic machinery and equipment.

From a regulatory perspective the use of natural gas as a marine fuel is fully addressed with detailed requirements related to design and construction included in the IMO IGC [9] and IGF Codes [10] and LR's Rules and Regulations [11].

2.2. Methanol

Methanol, also known as methyl alcohol, is a chemical with formula CH_3OH (often abbreviated MeOH). Methanol can be produced both by distilling wood and vegetable products (thus potentially a carbon neutral process) or from hydrocarbons through an industrial catalytic process. At room temperature it is a colourless liquid, with boiling point of abt. 65°C and density of 0.79 kg/l . It is rather volatile, miscible with water and toxic. Its lower heating value (LHV) is approximately 19.9 MJ/kg , which is less than half the typical value of diesel fuel. Methanol vapours have a broad flammability range in air, with LEL abt. 6.7% and UEL abt. 36% by volume.

From a ship design perspective, methanol low LHV and density imply that for a given energy storage capacity the tanks volume would be more than twice as much as those required for diesel fuel, with clear implications for passenger numbers or cargo capacity. Appropriated ventilation and vapour detection is also required, since methanol vapours are in general heavier than air and may therefore accumulate at the bottom of compartments.

From a regulatory perspective the use of methanol as marine fuel is addressed in the high level Functional Requirements of the IGF code which all low flash point fuels intended to be used as a marine fuel are required to satisfy but currently without the supporting detailed requirements. Consequently the IGF Code requires the application of risk assessment techniques in order to demonstrate the functional requirements are satisfied and also that any additional hazards are identified. The development of the supporting detailed requirements is currently underway at the IMO however detailed requirements are already provided in LR's Rules and Regulations [12].

2.3. Ethane

Ethane is an organic chemical compound with chemical formula C_2H_6 . At ambient temperature and pressure it is an odourless, colourless gas. Its properties are similar to methane, even though, being a heavier gas; they are shifted accordingly, with a higher boiling temperature and density and density similar to air at room temperature. This means that it can persist in a space and would require an efficient ventilation system to be removed. Ethane is a common by-product of petroleum refining and natural gas processing. It is widely used as feedstock for the production of ethylene. In recent years the growth of ethane processing has opened some niche market opportunities for its transportation on large scale and its use as fuel is seen as an option in a similar way to natural gas on LNG carriers.

The use of ethane as marine fuel is partially covered by the IGF code. A risk assessment would be need for all the aspects not covered by the rules and may take advantage of the physical and chemical similarities with methane.

2.4. Hydrogen

Hydrogen is a chemical element, with symbol H and atomic number 1. It typically bonds to form the H_2 molecule. It is the most abundant chemical substance in the

universe; however, most of hydrogen on earth is bonded with oxygen in the form of water, H₂O. This implies that, unless obtained by fossil fuels, such as methane through a reforming process, it is not a primary source of energy, but a vector, i.e. energy must be spent in order to generate it from water, which will be recovered when oxidized through combustion or chemical reaction. As such hydrogen has the potential to be generated from renewable energy using well established but energy intensive technologies. Hydrogen at atmospheric temperature and pressure is a light, odourless, colourless, non-toxic gas. It is highly flammable and may easily form explosive mixtures with air. Its liquefaction temperature is abt. -253°C at atmospheric pressure and its critical point is abt. -240°C and 13 bar, making therefore necessary to cool it down at extremely low, cryogenic temperature, to liquefy. Its liquid density is very low, abt. 70 kg/m³, less than one tenth of the typical hydrocarbon fuel. Its lower heating value is abt. 120 MJ/kg, which is abt. three times more than diesel fuel or natural gas.

From a ship design and construction perspective the relatively low volumetric energy density compared to existing diesel fuels means significantly more of the ship will be required for fuel storage even when liquefied. Hydrogen also presents several other significant challenges such as wide flammability range, permeability, and when liquefied the not well understood leakage scenarios. While many of the safeguards recognised as necessary for the safe use of LNG as a marine fuel will certainly be relevant for the use of hydrogen, it needs to be recognised that those safeguards alone will not be sufficient to control many of the additional risks associated with the use of hydrogen as a marine fuel.

From a regulatory perspective the use of hydrogen as a marine fuel is, similar to the previously mentioned fuels, addressed in the high level Functional Requirements of the IGF Code but currently without the supporting detailed requirements. Consequently the IGF Code requires the application of risk assessment techniques in order to demonstrate the functional requirements are satisfied and also that any additional hazards are identified. The need to development of the supporting detailed requirements has not yet been agreed by the IMO however Resolution MSC.420(97) which provides guidelines for the carriage of liquid hydrogen has been adopted and can be expected to inform the eventual development of requirements for the storage of liquid hydrogen for use as fuel. LR recognises the need for Rules and Regulations and is currently engaging with the industry in order to establish the necessary technical expertise to do so.

Table 1. Properties of fuels compare to diesel (various sources)

	Methanol	Natural Gas	Ethane	Hydrogen	Diesel
Boiling temperature [°C]	65	-163	-88	-255	>180
Liquid density [kg/m ³]	790	430	542	70.8	840
Gas density [kg/m ³] @ 20°C	-	0.67	1.25	0.084	-
Flame temperature in air [°C]	1950	2230	2220	2396	2100
Heat of vaporization [J/g]	1200	510.4	498	449	233
Lower flammability lim. [% vol.]	6.7	5	3	4.0	0.6
Upper flammability lim. [% vol.]	36	15	12.4	75.0	7.5
Minimum ignition energy [mJ]	0.14	0.28	0.26	0.017	0.1
Flash point [°C]	12	-188	-135	< -253	> 60
Auto-ignition temp. [°C]	433	537	472	585	315
Toxicity	Yes	No	No	No	Low
Temperature at critical point [°C]	239	-83	32	-240	-
Pressure at critical point [bara]	78.5	45.9	49.0	12.9	-

3. Fuel storage technologies and their implication for design and construction

3.1. Physical containment

3.1.1 Structural tanks

Structural tanks are the simplest form of fuel containment system on board ships. They are spaces within the hull of a ship, with boundaries constituted by decks and bulkheads, which can contain liquid and are extensively used for the carriage of conventional fuels such as diesel fuel and heavy fuel oil. Their advantage lies in the excellent space utilization and simplicity of construction, but their limitation is their inability to withstand pressure or having little or no thermal insulation, to store fuels at temperature significantly different from the sea and air temperatures. The design and construction of such tanks is considered a regular shipbuilding practice. It is likely that alternative fuels which are liquid at ambient temperature and pressure such as methanol and ammonia will be stored in such tanks, albeit constructed from, or coated with, compatible materials and where necessary padding or inerting of the vapour space within the tank. Regulations for the design of these tanks for fuels with flashpoint lower than 60 °C do not currently exist and will need to be derived as part of the risk assessment required demonstrate compliance with the general functional requirements of IMO IGF Code. LR's Rules and Regulations [11] would be expected to provide the detailed requirements necessary to address the risks identified in such a risk assessment.

3.1.2 Prismatic IMO Type A tanks

IMO Type A tanks, as defined by the IGC and IGF codes, are non-pressurized independent prismatic tanks designed using classic ship structural analysis procedures and recognized standards. They are primarily constructed of plane surfaces, and the design pressure is no more than 0.7 barg. For "cold" gases, i.e. with temperature at atmospheric pressure below -10°C, a full secondary barrier is required. A secondary barrier is an additional containment system that can safely contain the worst envisaged leakage and prevent areas of the ship's hull from cooling down to unacceptable temperatures. Type A tanks offer high space utilization a relative simplicity of construction and are common solution for LPG carriers and there design and construction is fully regulated by the IGC and IGF codes and LR's Rules and Regulations.

3.1.3 Prismatic or spherical IMO Type B tanks

IMO Type B tanks are independent tanks designed using refined analytical tools, model tests and analysis methods to determine stress levels, crack propagation and fatigue life of the tanks. They are not considered as pressure vessels and can be of different shapes, including prismatic, even though the most known implementation is the Kvaerner-Moss type spherical design. Since the tank structural behaviour is fully analysed in the design process, only a partial secondary barrier is required, to safely contain potential leakages. The space utilization is very good for prismatic tanks, while quite poor for spherical tanks, although spherical tanks are among the most widely used on LNG carrier ships and are covered by the IGC and IGF codes.

3.1.4 *Pressure vessels, IMO Type C tanks*

IMO Type C tanks are independent tanks designed and built according to pressure vessel criteria and which includes fracture mechanics and crack propagation criteria. There is no upper limit to the design pressure, even though they are in general designed for pressures 5 and 10 barg, with some exception for “fully pressurized” gas carriers. They are typically designed with a cylindrical shape and domes or, to improve space utilization, with a bi-lobe shape. For large tanks and bi-lobe tanks the thermal insulation is made with polyurethane foam or similar, applied to the outer surface. Smaller cylindrical tanks can be built using the “double wall” technology, i.e. the tank is incorporated into another one, creating an annular space which is kept under vacuum and filled with perlite or multilayer insulation. This is a more complex solution however it provides a very efficient thermal insulation and may provide a built-on secondary barrier. Due to the nature of their design and construction, standard code-compliant Type C tanks are not required to have a secondary barrier; however this may be challenged when a tank has pipes connections below the maximum liquid level. While gas carrier tank are usually fitted with suitable domes for piping connections, instruments, etc., that might be an issue for tanks installed in other ships types where tanks may be located in spaces without sufficient height to locate tank penetrations above the liquid level. In this case the requirement for the secondary barrier around the tank may be fulfilled by the outer vessel, provided that it is made of a suitable material.

From an installation point of view, just like the other independent tanks, Type C tanks are supported by means of suitable supports and their interaction with the ship hull is limited to the forces and moments acting on them. This implies that the design and construction of the ship and the tanks can be done separately, provided that suitable information exchanged takes place in order to successfully interface them. This allows also a great deal of flexibility in their design, construction and location on board, which can be above and below the main deck, in enclosed and open spaces. They are already a common choice for natural gas fuelled ships, thanks to their capability to withstand pressure and thus their ability to store gas for relatively long times with little or no consumption, their inherent robust design, with limited issues of sloshing; cost effectiveness and the maturity of the technology well established in other sectors of industry.

Type C tanks are in general limited to sizes of up to a few thousand cubic meters which are in general suitable for ships carrying LPG, liquid ethylene, and other gas and chemical cargoes. On the other hand Type C tanks are in general suitable for small-scale LNG carriers and LNG refuelling or bunkering ships (Ref to Jose’s recent bunkering vessel paper). The design and construction of IMO Type C tanks is fully regulated by the IGC and IGF codes, and LR’s Rules and Regulations. It is likely that IMO Type C tanks will also be used, at least initially, for the first shipboard storage of hydrogen. In this case the concept may be referred as “cryo compressed hydrogen storage”, when the hydrogen is cooled down to its liquefaction temperature in a vessel which is also able to withstand some degree of pressure [1],[2].

3.1.5 *Membrane tanks*

A membrane tank is composed of two gas-tight membranes, the primary and secondary barriers, made of stainless steel or another suitable metal. A layer of thermal insulation material is fitted in the middle and outside of the secondary barrier, lying against the

ship hull, and providing also support to the membranes. All the forces due to pressure, weight of the liquid gas, sloshing, etc, are borne by the ship's hull, since the membranes are thin and flexible and their purpose the prevention of leaks. The insulation space is usually inerted with nitrogen, displacing air, to better control the risk of fire (in case of leakage) and avoid the condensation of moisture.

Membrane tanks therefore are not self-standing, independent tanks, like those introduced in the previous paragraphs, but built as a part of the ship. This requires that the ship and the containment system are designed and built together, requiring a strong collaboration between the yard and the designer of the containment system.

Different technologies exist within the membrane tank market: GTT No 96 technology is based on Invar membranes and insulation layers built up with plywood boxes filled with perlite which are kept in place with couplers and tie-rods. GTT Mark III technology is based on a primary membrane made of stainless steel, with corrugations to accommodate thermal expansion. Insulation layers are made up of load bearing prefabricated panels in reinforced polyurethane foam. The secondary barrier is made of Triplex, a composite laminated material. [6] Other variants and evolutions of these systems exist. The main advantage of membrane systems is the excellent space utilization and adaptability to fit in basically any reasonable hull space and the long and proven in-service record. On the other hand, they are in general complex to build, and, being a non-pressure bearing systems, require careful integration with ship design and precise evaluation of dynamic loads and sloshing phenomena. They are designed to carry liquefied gases at near-atmospheric pressure, thus the boil off gas cannot be simply be left to accumulate in the tank raising the pressure and this may be a limitation for gas fuelled ships. Regulatory requirements for membrane tanks are found in the IGC and IGF code and LR's Rules and Regulations.

3.1.6 Lattice tanks

While traditionally shaped pressure vessels, such as cylindrical and spherical tanks, rely on their shape to accommodate the stresses created by the internal pressure, lattice tanks rely on a set of internal ligaments and reinforcements. This allows them to deviate from the traditional pressure vessel shapes and be built, theoretically, to fit any shape. This would allow a much better space utilization compared to cylindrical or even bi-lobe IMO type C tanks, while retaining their positive characteristics, such as the ability to accommodate boil-off and the relative simplicity of construction when compared to membrane tanks. Their current main limitation when compared to cylindrical tanks is that they can be single wall only, with external thermal insulation which may not be suitable for liquid hydrogen storage, due to the extremely low temperature. However, the technology of lattice tanks is currently under development, and may one day overcome this limitation. Lattice tank are not covered by the existing IGC or IGF Codes or Class Rules and would require a risk based approval demonstrating equivalence to the tanks currently permitted.

3.2. Material containment

3.2.1 Metal Hydrides

Metal hydrides are a solid compound of hydrogen and metal alloys. Hydrogen gas molecules exhibit strong repulsive forces which lead to the low density of the gas. By

embedding the hydrogen in a metal lattice (or through other chemical bonds) these forces are “cancelled”, therefore enabling higher densities of hydrogen storage [3].

Much of the development is carried out for automotive applications, for which the US Department of Energy has set some goals, both for the short and long term, for the values of mass energy density and volumetric energy density which should be achieved for the technology to be competitive. If estimated volume and weight of the containment system (which would be not-negligible for compressed or liquid hydrogen) are included in the stored energy density calculations, the DoE goals (and in general the highest efficiency) would not be reached by compressed or liquid hydrogen, while technologies such as metal hydrides may have the potential to do.

From a ship design perspective one of the characteristics of metal hydrides is that the hydrogenation and dehydrogenation reactions adsorb and release heat energy. To extract the hydrogen on board a ship the whole bulk of the metal hydride tank requires heat energy which therefore becomes a function of the tank size [4]. Noting that the most promising metal hydrides (in terms of storage capacity) are those working at higher temperature, above 150°C [8], this would suggest that for a ship, a significant amount of energy to release the stored hydrogen would be needed. Pressure is another important factor for the ship designer to consider. There is equilibrium between the amount of hydrogen which is “adsorbed” by the metal (or released) and the hydrogen pressure. The pressure needs to be high enough to efficiently take the hydrogen gas to feed the users but low enough to avoid bulky and heavy pressure vessels and compression equipment. This is one of the main topics under research in the development of metal hydrides. [13]

3.2.2 *Liquid Organic Hydrogen Carriers (LOHC)*

The idea behind LOHC storage is that certain hydrocarbons, in particular some cyclic ones, are able to bond and release a certain number of hydrogen atoms through catalytic reactions. These hydrocarbons are not themselves the fuel, they rather are a liquid medium that can absorb and release hydrogen as needed.[7] The amount of hydrogen that can be stored is expressed as weight percentage of the media substance and with current technology can be in the range of 6%. Considering that the density of such hydrocarbon is comparable to water, a simple calculation yields to a hydrogen storage capacity of abt. 60 kg/m³, close to the density of liquid hydrogen, making therefore this technology of comparable volumetric storage efficiency [5].

Once the hydrogen-rich LOHC substance has been used and “depleted” to its hydrogen-poor conditions, the spent LOHC should be unloaded and the tank reloaded with fresh, hydrogen-rich fuel. The spent LOHC would then be transported to a dedicated chemical plant for re-enrichment with fresh hydrogen. One may easily see the advantage of this technology: hydrogen would be bonded to a theoretically non-dangerous chemical, without the need to be liquefied at cryogenic temperatures or compressed, therefore eliminating the associated risks. It is to be said however, that the even though the effects on human health of some of those LOHC chemicals are known, detailed investigation would probably be necessary to ensure safe operation and handling of these substances.

The energy consumption needed in the process hydrogenation is also competitive when compared to liquefaction or compression of hydrogen. Unlike metal hydrides, the hydrogen extraction process would take place in a dedicated catalytic system, through which the needed amount of LOHC would be expected to be pumped. This implies that

the energy involved in the process would be proportional to the LOHC flow rate and therefore to the hydrogen produced by the system, rather than the whole inventory of hydrogen-carrying medium, and is expected to be much lower than the energy required by the known metal hydride technologies. This aspect appears to be a major advantage for application of this technology to the shipbuilding industry.

Going beyond the storage system itself, this technology may offer another advantage: the LOHC media is actually a hydrocarbon, not much different than those usually transported all over the world, such as diesel or petrol. Many LOHC are expected to bear similar or lower risks than diesel fuels. This implies that the existing infrastructure for fuel distribution may be converted to transport and deliver LOHC fluids, from the hydrogenation facilities to the refuelling stations and back. From the shipbuilding side, this would mean that the common design and technology structural tanks and piping, used for diesel fuel, in principle might be suitable for those fluids as well, perhaps with some alterations. Should this solution be adopted in the future, it would grant optimal space utilization and reasonable complications for the fuel storage system based on LOHC.

4. Storage efficiency

The different nature and state of fuels and the different storage technologies, poses the question of how much energy they can actually carry for a given space and weight. Table 2 represents an estimation, based on experience, of what could be the energy storage efficiency of the various fuels on board a ship, considering also these different storage tank technologies have inherently different efficiency in the utilization of the available space. For LOHC the numbers are estimated considering what a ship installation might be in the next future. One may note that hydrogen, even with liquefaction or extremely high compression (possibly difficult to implement) the volumetric energy density is far away from those achieved by all the other fuels. The implications are the necessity of larger tanks, which, besides the increasing cost issue, may be unpractical for smaller vessels. A partial mitigation of this problem is the use of fuel cells, rather than internal combustion engines, where hydrogen is today the fuel of choice. A fuel cell would be more efficient than a diesel generator for the production of electricity, therefore requiring less fuel to deliver a given amount of electric power for a given time, thus partially filling the gap.

Table 2. Energy density of different fuels and storage technologies – approximate values

Fuel	Storage	Bulk density [kg/m ³]	Space utilization	LHV [MJ/kg]	Energy density [GJ/m ³]
Diesel fuel	Structural tank	840	100%	43	36.1
Methanol	Structural tank	790	100%	19.9	15.7
LNG	Membrane	450	95%	48	20.5
LNG	Type C	450	50%	48	10.8
CNG	Press. Tank, 200 bar	180	50%	48	4.3
CNG	Press. Tank, 700 bar	370	50%	48	8.9
LH ₂	Type C double wall	71	50%	120	4.3
CH ₂	Press. Tank, 200 bar	18	50%	120	1.1
CH ₂	Press. Tank, 800 bar	67	50%	120	4.0
LOHC	Structural tank	Abt. 1000	6% H ₂ wt.density	120	7.2

5. Conclusions

Containment technologies for a number of alternative fuels have been reviewed. Currently technologies are based on physical containment technologies for the storage of liquids or compressed and/or liquefied gases which have proved perfectly adequate for the traditional marine fuels, like diesel oils and, heavy fuel oils. While the traditional marine fuels offer unmatched volumetric and gravimetric energy densities, fuels like LNG and methanol are able to achieve reasonably energy densities using the same physical containment systems.

Unfortunately is not the case with hydrogen: in addition to the very low cryogenic temperature required to liquefy, which poses significant risks and technical challenges, it has a very low density both in its liquid state and as compressed gas. This has led to the investigation of alternative hydrogen storage technologies, based on chemical methods, which may have the potential to match and even outperform the physical storage methods. Some hydrogen storage technologies such as metal hydrides and LOHC appear close to industry application stage. For the shipping industry, LOHC might become a feasible storage technology in the next years.

Finally, it is to be considered that perhaps the major driver for the adoption of hydrogen as fuel in the shipping industry is the reduction of emissions, which can compensate for some of the disadvantages of its storage and use as fuel.

However even with such advances in hydrogen storage technology in terms of weight, space and cost, in comparison to the amount of energy that can be obtained, it is still currently far from the levels typical of traditional marine fuels. However, it should be noted that due to its heating value, up to about 3 times those of diesel, its suitability for use in higher efficiency fuel cells, and the overwhelming need to reduce the overall fuel consumption on-board future ships, the point at which hydrogen becomes a realistic marine fuel option is getting closer.

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